RESEARCH PROJECT REPORT: RP4

OCLI Example

Expected loss (£)

The optimal uncertainty value

The actual uncertainty value

Measurement uncertainty ($s_{measurement}$) (contaminant concentration mg kg^{-1})
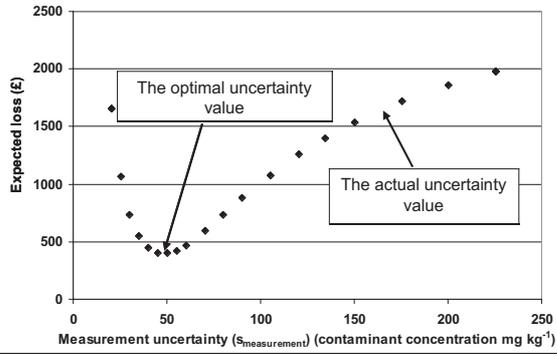
COST-EFFECTIVE INVESTIGATION OF CONTAMINATED LAND

CONTAMINATED LAND: APPLICATIONS IN REAL ENVIRONMENTS

CL:AIRE

WHAT IS CL:AIRE?

CL:AIRE was established as a public/private partnership in March 1999, to facilitate the field demonstration of remediation research and technology, including innovative methods for site characterisation and monitoring, on contaminated sites throughout the UK. The results of project demonstrations are published as research or technology demonstration reports and disseminated throughout the contaminated land community.

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Contaminated Land: Applications in Real Environments (CL:AIRE)

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COST-EFFECTIVE INVESTIGATION OF CONTAMINATED LAND

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EXECUTIVE SUMMARY

This research addresses a crucial step in redeveloping areas of potentially contaminated land; the characterisation of contamination. Measurements are usually required to assess the levels of potentially harmful contaminants. These measurements are used to guide the subsequent decisions that are taken, such as whether remediation is necessary, and may influence the value of the land. The reliability of these measurements is important as the financial penalties arising from misclassifying a site, or sub-areas within it, can be substantial. For example, undetected areas of contamination may be left in place, leading to unforeseen delays in site redevelopment, or litigation. Alternatively, land may be incorrectly classified as contaminated and be unnecessarily remediated. The research undertaken by this project demonstrates that the method employed can be of substantial commercial interest to stakeholders involved with the contaminated land industry. The innovative methods presented in this report are both simple and inexpensive to apply and can significantly improve the reliability and cost-effectiveness of the decisions made.

This research is pioneering, as the estimation of measurement quality ('uncertainty') has been estimated during six commercial investigations of contaminated land using the 'Duplicate Method'. The Duplicate Method is a practical, easy-to-use and inexpensive approach, that is also built on sound science, which enables the quantification of measurement uncertainty. The estimation of measurement uncertainty provides objective evidence to the reliability of any given site investigation and reduces the likelihood of costly misclassification.

The innovative 'Optimised Contaminated Land Investigation' (OCLI) method, which is developed in this research, can be used to objectively assess whether the measurements taken to characterise contaminated land are of an acceptable standard given the costs involved. The OCLI method uses a variety of site-specific financial considerations to make this judgement, such as the measurement costs and the costs arising from misclassifying a site.

The six commercial investigations of contaminated land used in this research showed that the measurement uncertainty, which includes both the field sampling and chemical analysis, could be easily estimated using the Duplicate Method. The six investigations gave a range of values for the measurement uncertainty, and thus reliability, ranging from 19% (Site 3) to 236% (Site 5). For the investigation at Site 5, the 'true' concentration of the key contaminant is actually within ± 158% of each individual measured value reported by the laboratory. This research also demonstrated that it is the field sampling that usually provides the largest source of measurement uncertainty when compared to the contribution from the laboratory. This challenges the approach often taken in which only the analytical uncertainty is considered.

The OCLI method has objectively demonstrated that different site investigations also generate different levels of financial risk, due to the site-specific nature of the measurement uncertainty and the costs. For example, a probable financial loss of approximately £1,200 per sampling location at Site 1 was due to the high likelihood of unnecessary remediation caused by the measurement uncertainty. The OCLI method also indicated that even with a very high financial risk, such as the potential loss of £1m due to litigation at Site 3, a low level of uncertainty produces a low likelihood of financial loss (only £58). The OCLI method has also been able to guide the design of subsequent 'follow-up' investigations at the same site (Site 6), which provided a more optimal level of uncertainty, and thus a reduced level of probable financial loss (from £21,000 to £5,537 per sample location). This indicates a potential saving of nearly £200,000 in the cost of redeveloping the entire area of land because a sufficiently reliable site investigation has been made.

ACKNOWLEDGEMENTS

LAYMAN'S GUIDE TO THE RECENT RESEARCH ON 'COST-EFFECTIVE INVESTIGATION OF CONTAMINATED LAND'

The development of previously used land, often called brownfield sites, is a high priority for the British Government. It will help to protect the remaining greenfield sites, whilst responding to the need for more housing. Development on a brownfield site has a legal requirement that an investigation is made of the extent of any contamination of the site by toxic substances. Such site investigations can never be perfect in their assessment of the concentration of the contaminants, because there is always some degree of uncertainty. The measured value of concentration quoted by the laboratory to the investigator is not the true value, but merely an estimate. There is therefore, always a chance that some proportion of the contamination at the site will be missed or underestimated. This may cause any clean-up, or remediation of the site to be incomplete, and an unsuspected hazard to remain. Similarly there is also a chance that the level of contamination will be overestimated, and the unnecessary expense of clean-up recommended. This may jeopardise the feasibility of the development of the site. The chances of these misclassifications of a site can be reduced by spending more on the site investigation, to reduce the uncertainty. A balance needs to be found therefore, between the expenditure on the site investigation and the benefits that will arise from the greater certainty that this will yield. This research is aimed at evaluating a new approach to find this balance point, and to enable the design of the most cost-effective investigation for any particular brownfield site.

Research funding was provided jointly by the Department of Trade and Industry (Partners in Innovation Scheme) and by CL:AIRE (Contaminated Land: Applications in Real Environments), in order to generate improved guidance to site investigators and thereby to facilitate more efficient development of brownfield sites. The Steering Group for the project included representatives of site investigators (Atkins and Southern Testing), problem holders (National Grid Property, BNFL and Shell) and regulators (Environment Agency and a Local Authority, Brighton and Hove).

Existing guidance to site investigators tends to give generic advice for all sites regardless of their financial value, the chances of misclassifying the contamination at the site, or the potential consequences of such a misclassification. A new method that takes these factors into account had already been devised and published by researchers at the University of Sussex. It is called Optimised Contaminated Land Investigation (OCLI). It incorporates another novel procedure that estimates the uncertainty of measurements made in a site investigation, including that arising from the process of taking samples from the site, called the Duplicate Method. Knowing the uncertainty, it is then possible to calculate the chance of misclassifying the contamination, and hence the risk it poses. Estimates are also required of the financial consequences that could arise from this misclassification. These costs could be due to delays during development, or subsequent litigation after the development has been completed, caused by the discovery of unsuspected contamination. The OCLI method requires application of the Duplicate Method, but even applying the Duplicate Method alone can improve the reliability of the investigation, by giving the investigator new information about the uncertainty of the investigation.

The objectives of the research were to try out this new OCLI methodology on six brownfield sites, in order to evaluate its practicality, strengths, weaknesses and benefits to the various stakeholders in the development process. The six sites were selected to cover a wide range of situations that represent brownfield sites across the country. These site investigations were not initiated specially by the researchers, but were selected from routine investigations already being undertaken by a variety of site investigation contractors across the country. The area of the sites ranges from 0.08 to 45 hectares, and the previous land-uses included gasworks, railway sidings, colliery spoil disposal sites, firing ranges and metal mines. Consequently, the type of contaminants varied widely from metals, such as arsenic, to organic compounds. The levels of contaminant concentration also varied from extremely low, to very high. The intended end-use of the development varied, from activities with high financial value, such as housing development, to uses with low value, such as a nature reserve.

The OCLI method was shown to be applicable to any of the various sampling methods that were selected by the contractors and investigators. These included different sampling designs and sampling devices, used during different phases of investigation. The uncertainty caused by the sampling procedure was estimated using a procedure called the Duplicate Method, which was again shown to be applicable to all six investigations. This method requires the investigator to take a small proportion of the samples twice, or in duplicate (i.e.10% of the total number of samples, but at least eight per site). The investigator takes the

duplicate sample using a fresh interpretation of the sampling instructions. For example, the pile of material from a trial pit may be sampled on one side of the pile for the original sample, and on the other side for the duplicate sample, if the side to be sampled is not specified in the sampling protocol. This enables the investigator to judge how much uncertainty is being caused by the different interpretations that can be made of the instructions. The samples are sent to the laboratory for the measurement of the concentration of the suspected contaminants in the usual way, but the duplicate samples are also sent for analysis. The lab is asked to analyse both of the duplicate samples twice. This allows the investigator to see how much uncertainty is coming from the lab, as opposed to the sampling.

The Duplicate Method gives investigators a whole new type of information with which to judge the reliability of their site investigations. The uncertainty of the measurements of contamination, caused by a combination of the sampling and the analysis, was 25% for one site investigation. This means that the true value of the contaminant concentration, for each sample from that site, is within 25% of the measured value, above or below. This is very much larger than the uncertainty arising from the analysis in the laboratory (5%). The investigator now has a much more reliable estimate of the uncertainty that includes the previously overlooked contribution from the sampling. The uncertainty at the other sites varied greatly from 19% to 236%. This variation is caused primarily by the different extent of heterogeneity, or unevenness, of the selected contaminant distribution in the soil between the different sites. It is also affected by how the samples were taken, including the mass selected and whether the sample was a single grab sample, or a composite sample made up of several increments.

There are important implications of knowing the uncertainty in the investigation. The investigator can make a better judgment as to whether the true concentration of the contaminant exceeds a regulatory threshold, and therefore causes the soil to be classified as contaminated. For example, a measured concentration of 390 mg of lead per kg of soil (i.e. mg/kg) may appear to be well below a regulatory threshold of 450 mg/kg, and therefore indicate that the soil is not contaminated. However, if the uncertainty is known to be 25%, then the true concentration may be as high as 488 mg/kg (390 + 25%), which is well over the threshold and indicated that the soil may well be contaminated. Interestingly, the investigator may think that the uncertainty is 5%, using just the value which is currently quoted by the analytical lab. The investigator would then falsely conclude that the true value could not be higher than 410 mg/kg (390 + 5%), and that the soil is therefore uncontaminated.

The new OCLI method uses this information to assess whether a particular level of uncertainty in measurements is acceptable for any particular site investigation. It balances the cost of taking the measurements, against the cost of misclassifying the land. It uses the uncertainty value to calculate the probable financial loss caused by misclassifying the land. For five of the sites the uncertainty estimated in the routine site investigation is higher than required, typically by a factor of two (range 1.6 – 5.2). This indicates that expenditure on the measurement procedure can usefully be increased, to reduce the uncertainty. This will result in an overall saving of money on the development of the site, as it will reduce the risk of misclassifying the site (e.g. leaving undetected contamination in place) and the costs incurred. In contrast, at one other site, the OCLI method showed that the measurement procedure was better than required, by a factor of 2.5, and that savings could usefully be made on the investigation.

The OCLI method also indicates where extra expenditure, if required, is best applied. A comparison of the two main sources of uncertainty showed that the sampling usually dominates over the analysis by a factor of seven at these sites. This confirms what has often been suspected, that the sampling procedure is often a much more important source of uncertainty than the chemical analysis. There was one site however, where the chemical analysis dominated the overall uncertainty. It is clear therefore that each investigation needs to be assessed individually. Knowing the sources of the uncertainty contributions, and the relative cost of the sampling and analysis, it was possible to show the most cost-effective way to reduce the overall uncertainty. In many cases a modest increase to the expenditure on the sampling (e.g. to take samples made up of five portions or increments, with five-times larger mass) produced the required saving in the overall expenditure on the development overall. The method also help identify were there had been unsuspected difficulties in implementation of the sampling procedure. It can also help therefore in improving the quality of the practical sampling achieved during site investigation.

The potential savings achieved by improving the site investigation in this way were over £10,000 at two sites, and nearly £200,000 at another site.

Overall, this research shows that the OCLI method is applicable to any site investigation, whatever the previous history, intended end-use, or nature of the contamination. It has the benefits of quantifying the uncertainty in the site investigation and therefore showing its degree of reliability, using the Duplicate Method. This is not necessarily any reflection on the competence of the investigator, it may just be caused by a high level of heterogeneity in material at the site. The method also tells the investigator whether that level of uncertainty is acceptable for that particular site investigation. It was shown that quite high levels of uncertainty are acceptable for the reliable interpretation of some sites (e.g. 80% at one site), due to the low chance of it leading to any financial loss. This also has important implications for showing the validity of using some rapid *in situ* measurement techniques, such as hand-held instruments, during site investigations. At other sites, much lower uncertainty is beneficial (e.g. 24% at one of the sites), due to the much higher financial consequences that may arise if the land is incorrectly classified.

The benefits to the stakeholders include giving a valuable new tool to site investigators. They can use OCLI to prove to the developers that it is worthwhile to increase the budget for the initial site investigation, because it can actually reduce the total cost of the development. Moreover, it will increase the confidence that the budget for the remediation of the site is robust, and that it will not suddenly increase due to the finding of unsuspected further contamination. This will therefore reduce the uncertainty on the financial risk of site development, and make it more attractive to developers and financial backers. The regulators could also benefit if they wished, by requesting access to this new quantitative information on uncertainty. They could use it to judge the reliability of the site investigation results quoted by the developer.

Although the feasibility and usefulness of the OCLI method has been clearly demonstrated across this wide range of sites, there is still a need for further developments. The software tool that supports the Duplicate Method is now available and was distributed and demonstrated to 40 investigators and developers at a CL:AIRE Workshop in London in May 2005. The software tool for the OCLI method is however, still at the prototype stage. It works well in the hands of trained researchers, but will need to be 'productised' if it is to be developed into a professional decision support tool for site investigators. If investigators wish to adopt the OCLI methodology, the researchers at University of Sussex will be happy to advise and assist.

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ABBREVIATIONS

TERMS RELATING TO CONTAMINATED LAND

CSM	Conceptual Site Model
RA	Risk Assessment
SI	Site Investigation
SGV	Soil Guideline Value

TERMS RELATING TO MEASUREMENT UNCERTAINTY

$s^2_{sampling}$	Sampling variance
$s^2_{analysis}$	Analytical variance
$s^2_{measurement}$	Measurement variance $(= s^2_{analysis} + s^2_{sampling})$
$s_{sampling}$	Sampling standard deviation
$s_{analysis}$	Analytical standard deviation
$s_{measurement}$	Measurement standard deviation

ANOVA	Analysis of Variance
OCLI	Optimised Contaminated Land Investigation method
OCLI-TOOL	Software programme designed to help implement the OCLI method
ROBAN	Software programme used to quantify measurement uncertainty

TERMS RELATING TO THE OCLI METHOD

Expectation of loss	A technical term that is used to describe the financial loss that will probably be incurred by the site investigation. The expectation of loss value refers to each sampling location that is misclassified as a result of the uncertainty on the measurements of contaminant concentration.
Optimal uncertainty	The level of measurement uncertainty identified by the OCLI method that provides the lowest possible expectation of loss. Each site investigation should therefore aim to achieve the optimal level of uncertainty. The expectation of loss provided by the actual level of measurement uncertainty, estimated during the site investigation, should be compared against the optimal to see if savings can be made.

CONTAMINANTS

As	Arsenic
Cd	Cadmium
Cr	Chromium
Cu	Copper
Hg	Mercury
Pb	Lead
Zn	Zinc
PAH	Polycyclic Aromatic Hydrocarbons
TPH	Total Petroleum Hydrocarbons

OTHER ABBREVIATIONS

DEFRA	Department of the Environment, Food and Rural Affairs
EA	Environment Agency
PXRF	Portable X-ray Fluorescence
USEPA	United States Environmental Protection Agency

A Glossary of Terms is given on page 71.

1. INTRODUCTION

1.1 BACKGROUND

Areas of potentially contaminated land often require measurements of contaminant concentration to be taken to assess whether a risk of significant harm is present (Department of the Environment, 1996; Environment Agency, 2002, 2004; British Standards Institution, 2001). These measurements are very important because they drive the subsequent decisions that are made, such as the site's financial value, and whether the land requires remedial action.

The measurements of contaminant concentration are really only ever estimates of the true concentration however. Uncertainty on each individual measurement is introduced because of the difficulty in achieving a truly representative field sample, which is mainly due to the heterogeneity of contamination at a site, and the analytical errors introduced by the laboratory procedure. The measurement uncertainty can reduce the reliability of the decisions made, and may lead to substantial financial losses. For example, areas of land may be unnecessarily remediated, or contamination may be left undetected. Given the potential for substantial losses, it is clear that stakeholders involved with contaminated land (such as environmental consultancies, regulators and land owners) require methods to increase, and to demonstrate, the reliability of such investigations.

Scientific papers have described methods for estimating the measurement uncertainty that is generated during geochemical investigation (Ramsey *et al.*, 1992; Ramsey & Argyraki, 1997), which can be used to increase the reliability of the subsequent decisions. A promising new approach, called the 'Optimised Contaminated Land Investigation' (OCLI) method is designed to incorporate the site-specific costs of any given site investigation as part of the judgement as to whether the level of measurement uncertainty is acceptable.

These scientific methods have been transferred for the first time to the commercial workplace by collaborating with different environmental consultancies during six routine site investigations.

1.2 OBJECTIVES

The individual research objectives are:

1. To assess the advantages and limitations of the existing OCLI method, by applying it to a series of six contrasting contaminated land sites.

2. To progressively improve the performance and usefulness of the OCLI method by incorporating feedback from stakeholders (e.g. site investigators, problem holders, developers, regulators) after each of the six investigations.

3. To produce a prototype decision support tool version of the OCLI method, called OCLI-TOOL, that can be used by site investigators in general, at any site.

4. To publicize and explain the benefits of the OCLI method to the site investigation community and to developers of brownfield sites.

1.3 ORGANISATION OF REPORT

The report has been designed to be accessible to the non-specialist, which means that scientific detail is not included within the main body of text. A less technical overview is provided within the Layman's Guide. A more detailed description of the methods can be found within the scientific papers that are provided in the References.

The report provides guidance on the rationale of the research and a description of how the innovative scientific methods are applied (Section 2). These methods are demonstrated for each of the six commercial investigations of contaminated land (Sections 3 to 8) in order to explain how they can be adapted to different circumstances and reach different conclusions. The overall conclusions of the project are presented in Section 9.

2. METHODS

The following section provides the research rationale and a description of the general methods used within this research project.

2.1 THE IMPORTANCE OF MEASUREMENT QUALITY WITHIN CONTAMINATED LAND INVESTIGATIONS

Measurements are usually required as part of the risk assessment that is applied to identify areas of potentially contaminated land. As part of this assessment, measurements are made, which usually involves a discrete number of samples being taken from a site and sent to a laboratory for chemical analysis. The measurements reported by the laboratory are usually compared against a threshold value, such as a Soil Guideline Value (SGV) or a value derived from a site-specific risk assessment. The comparison of the measured concentrations against the threshold value is used to update a conceptual model of the site, and ultimately to judge whether the land may be considered for classification as 'contaminated' or 'uncontaminated' using site-specific risk assessment. The measurements will therefore drive the decisions that are subsequently taken, such as whether, and how to remediate any areas of contamination. The measurements, and thus the classification, may also affect the commercial value of a site. It is crucial therefore that the measurements of contaminant concentration are sufficiently reliable.

Each measurement is only ever an *estimate* of the 'true' concentration however, as there is always some uncertainty associated with every measurement. To understand the concept of measurement uncertainty within contaminated land investigations, the reader is invited to imagine the measurement process of a single soil sample. A discrete mass of soil will be taken at a sampling location at a specific depth. This soil sample may be taken with the aim of representing an entire sub-area of land within a site, even though the field sample may be relatively small (<1 kg). The soil sample is then sent to a laboratory where it is sub-sampled before a test portion is chemically analysed. The test portion analysed will be much smaller than the field sample (i.e. 0.001 kg). Following the chemical analysis, the laboratory will report a single measurement of contaminant concentration for the field sample that has been taken at that one specific location.

It is easy to imagine that if another soil sample was taken at the same nominal location, and at the same depth (i.e. the measurement process was repeated), that a different value would be reported. This is partially because of the contaminant heterogeneity that is present across the site and within each sampling location (Taylor *et al.*, 2005). This heterogeneity is present at all sites and cannot be avoided. One of the commercial investigators used in this project commented that taking additional samples at the same sampling location as part of the Duplicate Method was pointless because 'you never got the same value'! The luxury of taking this view is no longer justifiable however due to the substantial financial losses that may occur due to the measurement uncertainty as remediation costs soar and the industry becomes more litigious. Variability within the laboratory procedure is another reason for the difference in reported values. One important question therefore should not be, 'does the duplicated value differ?', but rather 'how *much* do the values differ?' This is equivalent to asking 'what is the level of uncertainty associated with this measurement?'

The term 'measurement uncertainty' can be considered as 'an estimate attached to a test result that characterises the range of values within which the true value is asserted to lie' (ISO, 1993). Measurement uncertainty refers to individual measurements of contaminant concentration and it does not refer to the variance of a population of all of the measurements within a site or 'averaging area' (i.e. the distribution of measured concentrations around the arithmetic mean). For example, each individual measurement may have an uncertainty of ± 25%, within which the 'true' concentration is found. A measured value of 100 mg kg^{-1} with an uncertainty of ± 25% will contain the true value within the range of 75 mg kg^{-1} and 125 mg kg^{-1} (at 95% confidence). Estimating the uncertainty for each measurement can be used to assess the reliability of their interpretation (Figure 2.1) and can thereby reduce the likelihood of costly misclassifications and improve the quality and robustness of the risk assessment process.

Contaminant Concentration
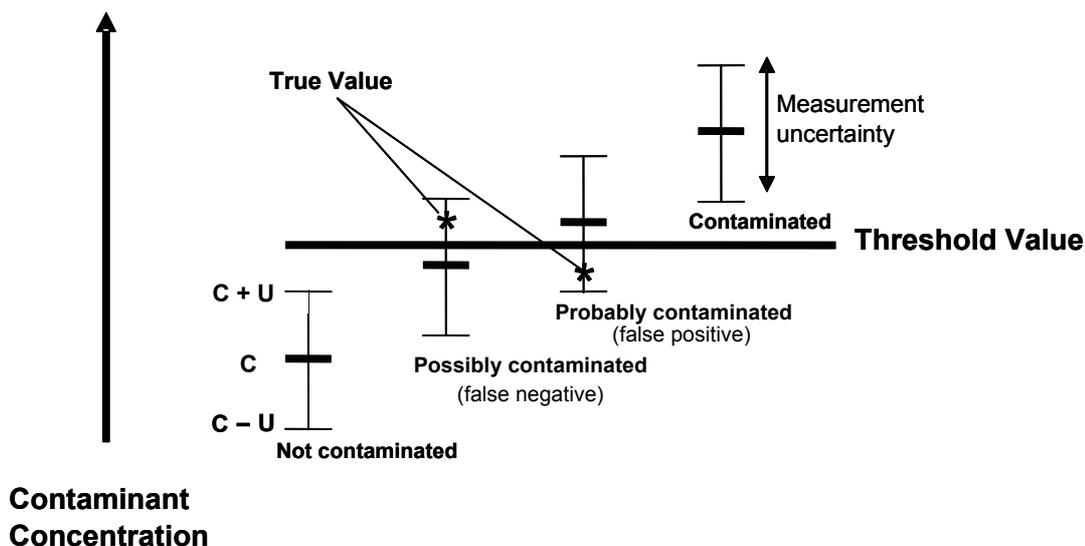
Figure 2.1: Individual measurements of contaminant concentration (C) are usually compared against a threshold value to guide subsequent decisions. The measurement uncertainty (U), within which the true concentration is found, can be used to assess the likelihood of misclassification. (Note uncertainty is a property of individual measurements, not the threshold value).

The temptation has traditionally been to ignore the measurement uncertainty; to treat each measurement reported by the laboratory as the 'true' contaminant concentration. Academic studies have previously shown that the uncertainty generated by the field sampling often greatly exceeds that produced by the laboratory. Currently, estimates of sampling uncertainty are not routinely made. This might have been due to the difficulty in quantifying the sampling uncertainty that arose from the heterogeneity of contamination. This research has demonstrated that the sampling uncertainty can be easily estimated for commercial investigations using the Duplicate Method (Section 2.4).

Once the uncertainty is known, the assessment as to whether the data is reliable enough for that particular site investigation can be made. This is an important assessment because a decrease in measurement uncertainty will usually require an increase in expenditure. Furthermore, acceptable levels of uncertainty will differ due to the site-specific cost considerations that are present. The investigator needs to assess the data requirements for each specific investigation and for testing and updating the site conceptual model upon which the management decisions are made.

2.2 FINANCIAL CONSEQUENCES OF DECISION ERRORS CAUSED BY MEASUREMENT UNCERTAINTY

2.2.1 FALSE NEGATIVE MISCLASSIFICATION

The information produced by the site investigation process, particularly that given by the measurements taken of contaminant concentration, drives the subsequent decisions that are taken. The consequence of measurement uncertainty is that areas of land might be misclassified.

For example, a measurement of contamination concentration may be beneath a threshold value but the true value actually exceeds it (Figure 2.1). This scenario is known as a 'false-negative' misclassification.

Examples of the financial consequences that may arise from a false-negative misclassification are:

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- Litigation after areas of contamination are subsequently detected
- Adverse health effects to those using the site (during or after development)
- Unforeseen delays in the redevelopment of the site
- Poor publicity and damage to the corporate image

2.2.2 FALSE POSITIVE MISCLASSIFICATION

Alternatively, another form of misclassification can occur when an area of land is classified as 'contaminated', as the measured concentration(s) exceeds the threshold value, but the true concentration is actually less than this value (i.e. it is really 'uncontaminated'). This is known as a 'false-positive' misclassification (Figure 2.1).

Examples of financial penalties that can arise when measurements are mistakenly classified as 'contaminated' include:

- Unnecessary remediation for part or all of a site
- Unnecessary delays in the site redevelopment
- Unwarranted loss in land value

2.3 SOURCES OF MEASUREMENT UNCERTAINTY

Measurement uncertainty can be separated into two main sources; the field sampling and chemical analysis (i.e. measurement uncertainty = sampling uncertainty + analytical uncertainty). Traditionally, attention has concentrated on the uncertainty generated by the laboratory only, despite scientific evidence which is further substantiated by this research, that the field sampling usually generates the greatest level of uncertainty. Uncertainty from storage, transportation and physical preparation are included with 'sampling' within this study, but can be quantified separately, if required.

2.3.1 SAMPLING UNCERTAINTY

It is often stated that the objective of sampling is to achieve a 'representative' sample and that a measurement is only as good as the sample upon which it is based. A truly representative sample is rarely, if ever taken however, due to the heterogeneity of the material being sampled. In contaminated land, the concentration of contaminants can vary substantially in-between very short distances and across the site itself. To achieve a truly representative sample the entire mass of material (soil) would need to be removed and analysed. Of course, this approach is practically impossible, due to the cost implications of over-sampling.

2.3.2 UNCERTAINTY FROM CHEMICAL ANALYSIS

Statistical errors and variability inevitably occur within the laboratory procedure and this contributes to the measurement uncertainty. These errors can include volumetric variability, instrumental repeatability, and analytical bias. The introduction of the Monitoring Certification Scheme (MCERTS) by the Environment Agency has provided greater confidence that the data received from certified laboratories demonstrate a prescribed level of precision and bias, but it has not eliminated this source of uncertainty. The introduction of MCERTS has, however, required the quantification and reporting of precision and bias of laboratory analysis which will be used to support regulatory decisions.

2.3.3 REDUCTION OF MEASUREMENT UNCERTAINTY

The uncertainty on individual measurements can never be entirely eliminated but it can be reduced. The analytical uncertainty can be reduced by implementing a more accurate analytical method. The sampling uncertainty, which tends to be the largest source of uncertainty, is predicted to be reduced by increasing the mass of the field sample (Equation 1).

$$s^2_{sampling} \propto 1 / mass \quad ……………………………………..……………… (1)$$

The sampling uncertainty is therefore predicted to be related to the mass or weight of the sample. For example, increasing the sample mass for each individual field sample that is sent to the laboratory by a factor of four is predicted to reduce the sampling uncertainty by half (e.g. a factor of $\sqrt{4} = 2$). This assumes that the field sample preparation is correctly undertaken by the laboratory, which was not evident for the investigation at Site 1 (see Section 3.8). A practical demonstration of the usefulness of this relationship is given for Site 6 (Section 8). In the case of on-site measurement techniques (e.g. PXRF) this reducing in uncertainty ($\sqrt{u}$) can be achieved by averaging 'n' incremental measurements at one location.

2.4 ESTIMATING THE MEASUREMENT UNCERTAINTY USING THE DUPLICATE METHOD

Perhaps the simplest method to estimate measurement uncertainty, from both the field sampling and the laboratory analysis, is the Duplicate Method (Figure 2.2).
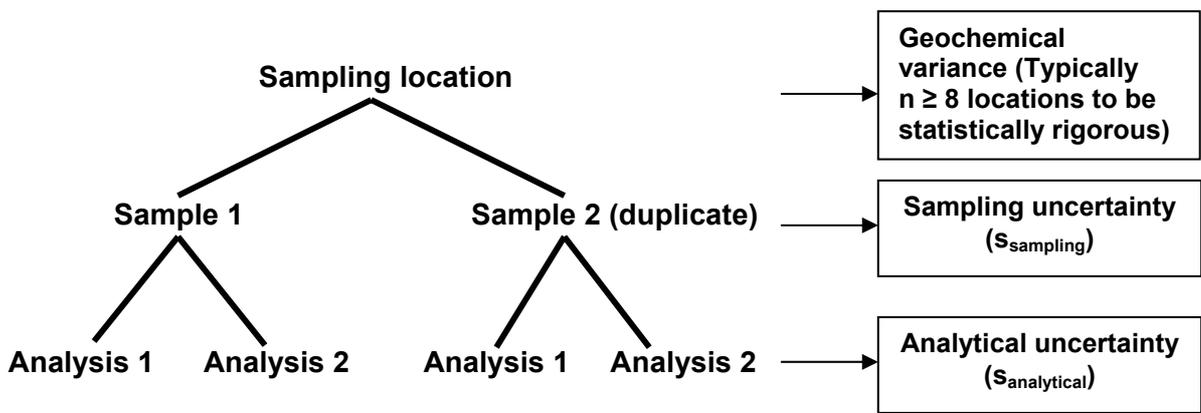
Figure 2.2: Experimental design used in the Duplicate Method. The measurement uncertainty (i.e. uncertainty at a particular location, thus combines variances in sampling and chemical analysis, but excludes geochemical variance) is estimated by applying the Duplicate Method, which requires duplicate samples to be taken and analysed in duplicate. The application of the Duplicate Method is demonstrated for each of the six sites considered in this report.

The Duplicate Method can be easily applied to most contaminated land investigations, as shown by this research. To apply the Duplicate Method and gain an estimate of measurement uncertainty, a small proportion of additional duplicate samples need to be taken during the site investigation. The relatively small extra cost incurred by applying the Duplicate Method is justifiable given the financial penalties that could arise from misclassification (Section 2.2).

The application of the Duplicate Method is explained for each of the six site investigations undertaken for this research project, which used different sampling methods (e.g. window, trial pit, hand auger). To apply the Duplicate Method, an additional eight field samples need to be taken from at least eight of the sampling locations across the site. The original sampling strategy was not altered or affected by applying the Duplicate Method; the estimation of measurement uncertainty formed just one extra component to the routine investigation. The greater the number of duplicated samples, the more reliable the estimate of uncertainty, but eight duplicates is sufficient for a reliable estimate in most cases (Lyn *et al.*, 2007). A very large complex site may require separate estimates of measurement uncertainty in each of several zones.

In general, the locations where the duplicate field samples are taken during the site investigation are chosen by the investigator. Ideally, these locations should be situated across the site and not concentrated within any particular sub-area. The removal of a duplicate sample at each of these locations should aim to represent the repeatability of the particular sampling protocol that is

applied. For example, if field samples are taken from trial pits at a depth of 0.2 m, then a duplicate sample will also be taken from this depth. The duplicate field sample is taken after the original sample (Sample 1 in Figure 2.2) has been removed. The sampler must aim to remove the duplicate sample as though they were re-applying their sampling method. Using this example, a duplicate field sample may be taken from the opposite side of the trial pit at the depth of 0.2 m, or from the opposite side of the excavated material if sampling from the material removed from the pit. In the case of borehole sampling, comparing the two halves of one drill core does not constitute use of independent duplicates, but use of duplicated boreholes at nominally the same location would (Section 5.4.1). Essentially, the duplicate sample aims to represent the repeatability of taking field samples during the investigation, using the existing protocol.

The difference in measured concentrations of contamination between field Sample 1 and Sample 2 (the duplicate) averaged over all duplicated locations (e.g. 8) (Figure 2.2) provides a rough estimate of the sampling uncertainty. The value of sampling uncertainty is therefore largely characteristic of the inherent short-range heterogeneity of contaminant concentration present at the site (i.e. within-location contaminant variability).

For some of the commercial investigations used in this research, it became evident that duplicate samples were already being taken routinely. The removal of sample duplicates is also suggested as part of the British Standard. The differences in measured concentrations between the duplicate and original field samples were then used by the consultants for a qualitative inspection only. The methods developed by this research will allow consultants to use these measurements to provide a quantitative estimate of uncertainty, which can then be used to estimate the financial risk from the site investigation using the OCLI method (Section 2.7).

To provide a separate estimate of the analytical uncertainty, each of the 16 samples ((8 × Sample 1) + (8 × Sample 2)) are all analysed twice by the laboratory (i.e. known as 'true analytical duplicates' by some laboratories). For example, the laboratory will remove two test portions from each of the field samples taken as part of the Duplicate Method. The difference in values reported by the laboratory between Analysis 1 and Analysis 2 for each of the samples gives a rough estimate of the analytical uncertainty. These measurements of analytical duplicates can also be used for the assessment of MCERT compliance (Environment Agency, 2004).

The difference (variance) in measured concentration of contamination between all of the locations taken as part of the Duplicate Method (e.g. at each of eight different sampling locations) quantifies the geochemical variance. The geochemical variance represents the variation in contaminant concentration between locations and across the site.

2.5   QUANTIFICATION OF MEASUREMENT UNCERTAINTY

The measurements of contaminant concentration from field samples that have been taken as part of the Duplicate Method are entered easily into a user-friendly Windows-based computer package ('ROBAN'). The ROBAN software applies robust analysis of variance (RANOVA) statistics to provide an estimate of measurement uncertainty and its components.

Statistical analysis of data can often be off-putting to non-specialists and the authors recognise that the methods need to be accessible by those from a non-statistical background. The ROBAN software was provided by the authors and tested by delegates at a CL:AIRE workshop (Section 9), which included consultants, land owners, regulators and local authority representatives. The delegates were able to use and interpret the data provided by ROBAN with minimal training.

Simply, the ROBAN software separates the variance of measurements taken as part of the Duplicate Method into three main components:

1.   Analytical variance ($s^2_{analytical}$)
2.   Sampling variance ($s^2_{sampling}$)
3.   Geochemical variance ($s^2_{geochemical}$)

Total variance of the measurements is therefore the sum of these three components:

$$s^2_{total} = s^2_{geochemical} + s^2_{analytical} + s^2_{sampling} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2)$$

As discussed in Section 2.4, the variance in contaminant concentration that is generated by the analytical procedure ($s^2_{analytical}$) is calculated from the variability between the measured concentrations between the analytical duplicates taken as part of the Duplicate Method (Figure 2.2). Similarly, the difference in contaminant concentration between the sample duplicates (Sample 1 and Sample 2), which are taken to represent the uncertainty in relocating the original sampling location, provides an estimate of the sampling uncertainty ($s^2_{sampling}$). The geochemical variance ($s^2_{geochemical}$) represents the distribution of contaminant concentration across the site (i.e. between sampling locations).

The measurement variance ($s^2_{measurement}$) is the sum of the sampling and analysis variance:

$$s^2_{measurement} = s^2_{analytical} + s^2_{sampling} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3)$$

The proportion of the chemical analysis to the total measurement uncertainty is calculated as:

$$\% \text{ analysis} = (s^2_{analytical} / s^2_{measurement}) \times 100 \quad \dots\dots\dots\dots\dots\dots\dots\dots (4)$$

Similarly, the proportion of field sampling to the total measurement uncertainty:

$$\% \text{ sampling} = (s^2_{sampling} / s^2_{measurement}) \times 100 \quad \dots\dots\dots\dots\dots\dots\dots\dots (5)$$

The measurement uncertainty can be expressed as a percentage (U%) using the standard deviation of measurement relative to the mean concentration of contamination ($\bar{x}$) for 95% confidence, as:

$$U\% = 200 \, s_{measurement} / \bar{x} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (6)$$

Equation 6 provides a percentage value that can be applied to each individual measurement that has been taken during the site investigation. For example, a measurement of 200 mg kg^{-1} with an uncertainty of 10% essentially means that the true concentration is within the range of 180 mg kg^{-1} to 220 mg kg^{-1}. This assumes that any systematic errors (i.e. 'bias') have already been corrected for. Use of ROBAN assumes that the underlying frequency distributions (geochemical, sampling and analytical) are normal, but can accommodate up to 10% outlying values.

2.6 ALTERNATIVE WAYS OF ASSESSING MEASUREMENT QUALITY

Non-experts may ask the laboratory, and those conducting the site investigation, to provide the lowest level of uncertainty possible, or even request data that does not contain any uncertainty. This approach fails to recognise that measurement uncertainty can never be entirely eliminated, and that a decrease in uncertainty will require an increase in expenditure.

Another approach may be to provide measurements with a certified level of uncertainty. For example, an analytical precision of 15%, which can be used as a rough estimate of analytical uncertainty. This is an approach taken for the MCERT laboratory scheme. This approach provides a greater confidence to those using the data, such as investigators, regulators and land owners, that the data is 'reliable', but this approach ignores the importance of sampling uncertainty and fails to address the site-specific costs that are present. For example, laboratory precision of 15% may be too good, and thus too expensive, for some sites where the site financial value is especially low, or there is little chance of misclassification because the measured concentrations are far from the threshold value. Conversely, a reduction in uncertainty may be required at contrasting, high value sites. Furthermore, if the uncertainty is dominated by the field sampling, a much higher analytical uncertainty (>>15%) may be acceptable because the reduction in analytical costs will allow the measurement budget to be concentrated on the reduction of sampling uncertainty.

Another way of ensuring data quality is to follow the generic guidance given for contaminated land investigations (e.g. British Standards Institution, 2001). This approach fails to include the important effect of sampling uncertainty, the costs of measurement and the potentially substantial costs that can arise from misclassifying land (i.e. it does not address the site-specific nature of most site investigations). However, a good consultant could cover these points as part of best practice.

2.7   THE OPTIMISED CONTAMINATED LAND INVESTIGATION (OCLI) METHOD

2.7.1   INTRODUCTION

The 'Optimised Contaminated Land Investigation' (OCLI) method is central to the research presented in this report. A user-friendly description of the OCLI method is presented in the following section, with further explanation provided in Ramsey *et al.*, (2003). Real-life applications of the method are presented for each of the six commercial site investigations used for this project.

Explained simply, the OCLI method provides an objective assessment to whether the level of measurement uncertainty is acceptable for a particular investigation given the site-specific costs that are involved. The OCLI method is potentially a very useful decision-support tool that can provide substantial commercial advantages to those working within the contaminated land industry.

The OCLI method uses a number of site-specific parameters, which are estimated during the site investigation. These parameters are entered into an Excel spreadsheet, which currently executes the OCLI method. After the input parameters have been entered into their appropriate Excel cells, the prototype OCLI method provides a cost-based indication of whether the measurements are of acceptable quality.

The five input parameters that are required for an application of the OCLI method are described in the following sections:

2.7.2   MEASUREMENT COSTS

The measurement costs are taken from the laboratory fees, for a single analysis of the contaminant under consideration. For example, an approximate cost of £20 per sample may be appropriate if the organic contaminant group Polycyclic Aromatic Hydrocarbon (PAH) is being determined. The costs units in the application of the OCLI method in the United Kingdom use Pounds Sterling (£) but any other currency can also be used.

The sampling cost is more difficult to quantify accurately but can be easily estimated by considering the samplers time costs and/or the costs required for any machinery required to take the field samples. This cost must also be quantified per measurement. For example, for a one day site investigation where 15 samples were taken, the sampling cost may be estimated as the consultants day rate (£400) and the equipment hire (£500) divided by the total number of measured samples ((£400 + £500) / 15 = £60 per sample).

2.7.3   CONTAMINANT CONCENTRATION

The contaminant concentration is an important input parameter since it affects the calculated probability of misclassification. For the investigations used in this research the choice of contaminant and its concentration has usually been based upon the following criteria.

If there is a range of different contaminants present at the site, the key contaminant is usually chosen on the basis of the financial importance of its effect on the decisions that will be made at the site. The key contaminant is determined from the suite of analytes considered during each investigation as that which will drive the subsequent decision taken at the site (i.e. it poses the most serious risk to human health given its toxicity and concentration). For example, if a site is predominately contaminated with lead, then this will be the key contaminant driving the redevelopment. Several separate applications of the OCLI may be necessary if there are a number of contaminants that are driving the site redevelopment.

Once the key contaminant(s) has been selected, the choice of concentration must be decided. Several options have been discussed in the literature (Ramsey *et al*, 2002). This usually represents the measured concentrations that have been measured during the investigation and that may lead to a misclassification. For example, if there is a range of measured values of the key contaminant(s) close to the threshold, then a value may be chosen for the OCLI method that aims to reflect these values, such as the arithmetic mean. Separate applications of OCLI may be made using the actual measured values, but this may lead to variable outcomes and be time-consuming if there are a large number of measurements. The choice of contaminant concentration is a topic that is further developed and discussed for each of the six site investigations used for this research.

2.7.4 THRESHOLD VALUE

A threshold value is usually used to compare the measured values against after the site measurements have been completed. The threshold value may take the form of a Soil Guideline Value (SGV) or be derived from a site-specific risk assessment. For example, a threshold value for lead contamination may be 450 mg kg^{-1} (the SGV for domestic properties with gardens).

2.7.5 MEASUREMENT UNCERTAINTY

The measurement uncertainty value is estimated by applying the measurements taken as part of the Duplicate Method to the ROBAN software (see Section 2.3 and 2.4). The uncertainty includes values for both the analytical and sampling uncertainty which are entered into the OCLI method in contaminant concentration (e.g. mg kg^{-1}) as 1 standard deviation ($s_{analytical}$ and $s_{sampling}$).

2.7.6 CONSEQUENCE COSTS

The consequence cost is an estimate of the increased cost that will result if the land is wrongly classified. It is estimated from the misclassification scenario that is being considered. For example, if the range of measured concentrations of the key contaminant exceeds the threshold value then a determination may be made that these areas of land are 'contaminated' (i.e. liable for consideration of that designation). Subsequently, remedial action may be taken to remove the risk posed by the contamination. The consequence cost applied in this scenario is for a 'false-positive' misclassification (i.e. where areas of land are unnecessarily remediated). This type of misclassification can occur when the measured value exceeds the threshold value but the 'true' concentration is actually beneath it because of the measurement uncertainty (see Figure 2.1). The consequence cost in this scenario would be the expenditure used to (unnecessarily) remediate that area of land.

Another type of consequence cost may arise from a 'false-negative' misclassification. This is when the measured values are beneath the threshold value but the true concentration is actually above it, because of the measurement uncertainty. Consequence costs for a false-negative may include delays to site redevelopment if the contamination is subsequently detected, or litigation (Section 2.2).

The most likely misclassification scenario is usually chosen for the OCLI method, although contrasting scenarios can also be applied if required. For example, different remediation strategies can be applied to the measurements taken during an investigation (shown in Section 6) and can be useful in making the subsequent decisions taken at a site. A limitation of the current OCLI approach is that it can only account for consequences that result in financial loss. However, certain types of environmental damage may not lead to immediate financial loss.

2.7.7 OCLI CURVE

A U-shaped curve is typically produced by the OCLI method in the form of an Excel graph after the site-specific parameters have been entered into the spreadsheet (Figure 2.3). The OCLI method uses the input parameters with a range of different values of measurement uncertainty, which includes the actual values that have been estimated from the Duplicate Method.

The OCLI curve (Figure 2.3) displays a range of different measurement uncertainty values, each with a corresponding expectation of loss (£) per sample location on the y-axis. There are two reasons for the changes in the loss value that produces the U-shape. The first reason is that there is an increasing likelihood of misclassification, and thus financial penalty, as the level of uncertainty increases. Therefore, as the different values of measurement uncertainty increase, there is an increase with each associated loss (£). This is shown to the right of the U-shape. The second reason is that more and more expenditure is required to reduce the measurement uncertainty as it approaches zero. Although the likelihood of misclassification decreases as the uncertainty value is reduced, the increased costs that are necessary to achieve the reduction of uncertainty make this financially unjustifiable. Somewhere between these two high increased loss values, the optimal uncertainty is found (i.e. the uncertainty value that gives the lowest loss).

As shown in Figure 2.3, a range of uncertainty values are shown that make the U-shaped curve. This range of uncertainty values includes the actual uncertainty that has been estimated during the site investigation using the Duplicate Method. The actual uncertainty value will have a corresponding loss value (£). The comparison of the loss values given by the optimal uncertainty and the actual uncertainty allows the investigator to assess whether the data is of an acceptable quality. This comparison of uncertainty values also provides an opportunity to assess how much the actual uncertainty needs to be reduced to achieve the optimal value, or to provide a more acceptable loss value (Section 2.2.3).
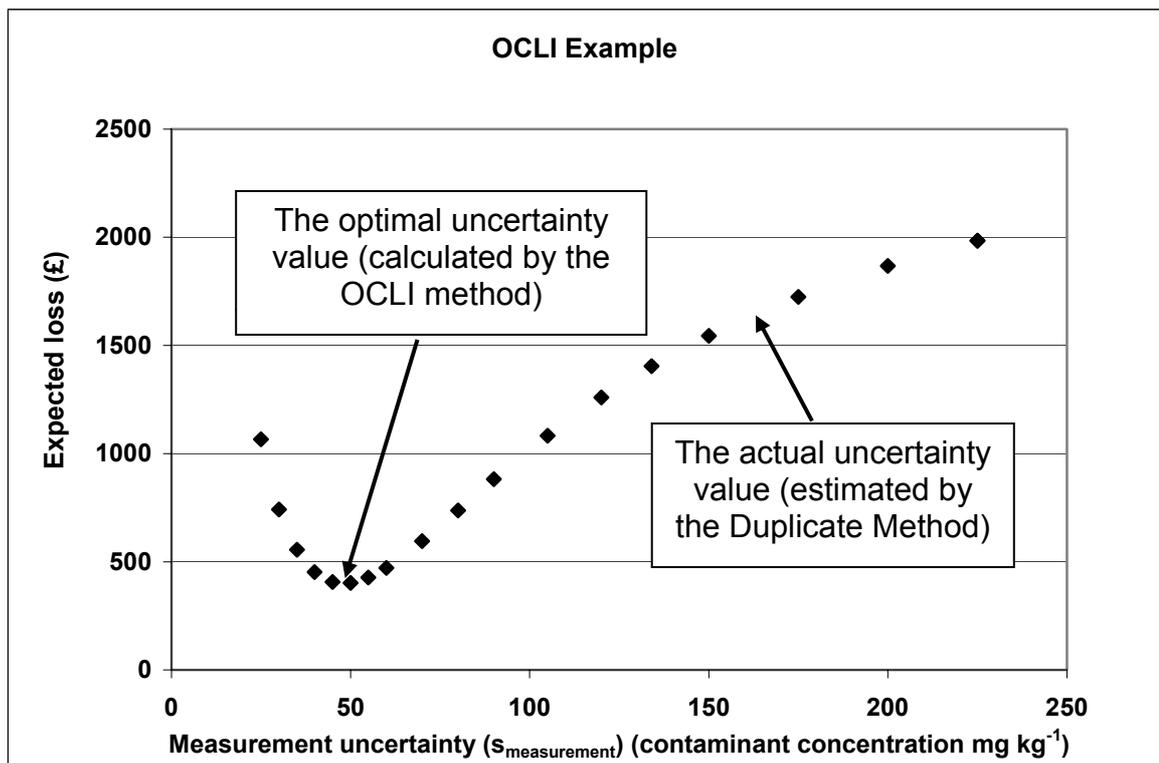
Figure 2.3: The output from the OCLI method equation, using the parameters that are required (Section 2.6), produces a U-shaped graph. The horizontal x-axis shows a wide range of uncertainty values ($s_{measurement}$), which includes the actual uncertainty that has been estimated as part of the site investigation using the Duplicate Method. The vertical y-axis has a corresponding expectation of loss value (£) at each sample location. The optimal level of uncertainty is located at the bottom of the U-shape since it represents the lowest loss value on the y-axis (i.e. the maximum financial saving).

2.8 INCORPORATING THE OCLI METHOD INTO ROUTINE INVESTIGATIONS OF CONTAMINATED LAND

The OCLI method is designed to be easily applied in conjunction with a routine site investigation (Figure 2.4). Additional 'duplicate' field samples are taken during the sampling investigation and are all sent to the same laboratory for analysis. The field samples that are taken as part of the Duplicate Method are analysed twice by the laboratory. The measurements taken as part of the Duplicate Method will be reported by the laboratory along with the data for that phase of the site investigation. When the investigator interprets the data, the measurements taken as part of the Duplicate Method are entered into the ROBAN software to provide an estimate of uncertainty for both the field sampling and chemical analysis. The estimates of measurement uncertainty allow the investigator to evaluate the reliability of the data (e.g. the true value of each measured concentration is within ± 30%). The ROBAN software also provides the investigator with information of the relative contributions of uncertainty from the sampling and laboratory analysis.

The interpretation of the data from the site investigation may indicate a key contaminant, or a number of contaminants, that is influential in the subsequent decisions, or classification, taken for the site. The key contaminant(s) that has been identified is entered into the OCLI method (Section 2.7) to assess whether the measurements are of an appropriate quality given the financial considerations for the site.

The characterisation of the site may require a further site investigation, to confirm areas of contamination for example. The OCLI method may also indicate that an unacceptably high loss is caused by the measurement uncertainty (i.e. the uncertainty is clearly sub-optimal), which may motivate the investigator to re-sample the site. In both cases, the estimates of uncertainty gained from the site investigation can be used to provide a more optimal level during the follow-up investigation. The investigator may also apportion the measurement expenditure more optimally between the field sampling and chemical analysis (e.g. more money may be spent on the sampling and less on the chemical analysis if the uncertainty is dominated by the sampling uncertainty). For an advanced application of the OCLI method, estimates of measurement uncertainty that have been derived from investigations at similar sites, or from a preliminary study at the site, can be used to design the main survey with the aim of achieving a more optimal level of uncertainty.

The measurement uncertainty that has been estimated during the site investigation should be included within the site report, which provides evidence to the client and regulators that a good quality survey has been completed.

Routine Site Investigation

Desk-top study

Conceptual site model

Design a investigation strategy (if required) using existing protocols (e.g. BSI 10175:2001)

Field sampling
Preliminary/ main/ supplementary

Chemical analysis of field samples

Interpret data

Assess whether additional field sampling is required. Reduce the measurement uncertainty by taking composite samples or by increasing the sample mass.

OCLI

Take additional 'duplicate' field samples to allow the assessment of measurement uncertainty (n ≥ 8 or 10% of total number of samples)

The duplicate samples should be analysed twice (if an estimate of analytical uncertainty is required). Measurements reported in un-rounded form.

Enter the extra duplicate measurements taken for OCLI within the ROBAN software to estimate the measurement uncertainty. Use the estimates of uncertainty to assess the reliability of the data. Apply the OCLI method

Are the measurements of an appropriate quality

No   Yes

Report site characterisation
Include estimates of uncertainty

Advanced OCLI

Use the OCLI method to guide the sampling strategy (i.e. the mass of sample required). Estimates of measurement uncertainty may be taken from previous investigations at similar sites and/or from measurements taken during an exploratory study (see Section 8).

Figure 2.4: Schematic representation of how the OCLI method can be integrated within routine site investigation

2.9 SUMMARY OF METHODS

Measurements taken for the purpose of characterising contaminated land always contain some uncertainty, from both the field sampling and the chemical analysis. Each individual measurement is only an estimate of the true contaminant concentration. The measurement uncertainty can affect the reliability of the decisions that are subsequently made, which are based on these values, and may lead to substantial financial losses.

The measurement uncertainty can be easily estimated during a site investigation using the Duplicate Method, where a small portion of duplicate samples (typically n ≥ 8 (Lyn *et al.*, 2007), but 10% of total number of samples for larger surveys) are chemically analysed in duplicate.

The estimates of uncertainty, and other site-specific costs such as the measurement expenditure and the misclassification penalties, can be assessed by the 'Optimised Contaminated Land Investigation (OCLI) method. The OCLI method provides an estimate of the probable loss (£) for any site investigation and can indicate the optimal level of uncertainty that provides the lowest loss.

2.9.1 OVERVIEW OF HOW TO APPLY THE DUPLICATE AND OCLI METHODS

1. Decide on the number (typically n = 8) and position of the sampling locations where duplicate field samples will be taken during the site investigation

2. Decide at which depths the duplicate field samples will be taken (assuming that field samples are going to be taken at a variety of depths at each location)

3. Take the duplicate field samples during the site investigation. This procedure should aim to represent the repeatability of the sampling protocol that is being employed (examples are given for each of six sites used in this research)

4. The containers holding the duplicate field samples should be marked in such a way as to ensure anonymity from the laboratory

5. The duplicate field samples should be included with all of the other field samples taken as part of the site investigation and sent to the same laboratory for chemical analysis at the same time

6. The laboratory should be instructed to analyse all of the duplicate field samples, and their 'partner' field samples twice (e.g. Sample 1 and Sample 2 of the Duplicate Method shown in Figure 2.2). This is known as 'true analytical duplicates'

7. The laboratory should also be instructed that all of the field samples should each be homogenised before test samples are sub-sampled for analysis

8. The measurements taken as part of the Duplicate Method are inserted (unrounded) into the ROBAN software to produce estimates of measurement uncertainty for each of the contaminants

9. Make an initial interpretation of the data provided by the site investigation to decide which is the key contaminant(s) driving the subsequent decisions

10. Decide and quantify the input parameters for the OCLI method (see Section 2.7)

11. Interpret the information provided by the OCLI method (Section 2.7.7) to decide whether the level of measurement uncertainty is acceptable

The following Sections (3 to 8) describe how these methods were applied, for the first time, to a series of six contrasting, commercial contaminated land investigations (Project Objective 1) to assess the advantages and limitations of the existing OCLI method. Each of the six site investigations are presented in chronological order to highlight the lessons learned and improvements made following feedback from stakeholders (Project Objective 2).

Each site investigation is presented by describing the site conditions and history and the sampling strategy employed by the commercial consultancy. The implementation of the Duplicate Method is also given before displaying the estimates of uncertainty which are subsequently used in the OCLI method. The main conclusions and lessons learned from each site investigation complete each section.

2.10   OVERVIEW OF SITE SELECTION

The general properties of the six sites used to study of the performance of the OCLI approach are shown in Table 2.1. The sites were selected to have contrasting values of each of the properties, so as to examine the effects that they have on the practicality of application and usefulness of the findings of this method. Each site will be discussed individually in the following chapter.

Table 2.1: Summary of the six sites used in this project.

Site	Area	Main type of contamination	Suspected source	Site end-use	Sampling method	Primary contaminant
1	80,000 m^2	Heavy metal	Tin mining	Housing	Trial pits	Arsenic
2	15,000 m^2	Organic	Infill from waste originating at former gas works	Recreational land	Trial pits	Indeno(123-cd) pyrene
3	810 m^2	Heavy metal	Infill after WWII bombing	Garden and allotment	Window sampling	Lead
4	120,000 m^2	Organic	Gas works	Hazard assessment	Trial pits	Total PAH
5	450,000 m^2	Heavy metal	Railway sidings and colliery spoil	Nature reserve	Trial pits	Arsenic
6	10,000 m^2	Heavy metal	Ex-firing range	Housing	Hand auger	Lead

3.   SITE 1 – ARSENIC CONTAMINATION

3.1   SITE HISTORY AND CONDITIONS

The first site used for this research (Site 1) was situated in southwest England and covered an area of land approximately 400 m × 200 m. The purpose of the commercial site investigation was to determine the risk presented by contamination at the site as a housing development was planned for this area of land.

Historical information indicated a previous use of mining, which was substantiated by physical evidence of an engine house and mineshaft on the site. The site consisted mainly of disturbed topsoil (made ground), shrubs and green fields currently used for equestrian stables.

A geochemical investigation had previously been conducted on an adjacent area of land. This previous investigation indicated high levels of metal contamination within the soil as a result of the mining, particularly arsenic (As) with the highest measurement of 4825 mg kg^{-1} total As. The high levels of As, and associated metals (Pb, Cu, Zn) meant that remedial action was taken before the houses were built at this adjacent site. To break the pollutant linkage with those using the adjacent site, and thus remove the possibility of significant harm, clean topsoil had been placed upon geotextile membranes.

The main aim of the investigation was to determine the extent of heavy metal contamination, particularly arsenic, within the soil prior to building a housing development. The investigation was wholly designed and implemented by the commercial consultancy in charge of the investigation at Site 1.

3.2   SAMPLING PLAN EMPLOYED AT SITE 1

A total of 16 trial pits (Figure 3.1) were excavated across the site using a mechanical digger (e.g. JCB). Soil was removed to an approximate depth of 2 m at each trial pit. Essentially, a trial pit is a short trench excavated by a JCB with the removed material placed to the side of the pit. A trial pit allows the investigator access for a visual inspection of the soil properties, and the removal of soil samples at increasing depths (although this practice is considered unsafe in the UK). At this site the location of each individual trial pit corresponds to where a house was planned to be built.

An employee from the commercial consultancy removed a total of two soil samples from each of the 16 trial pits, at depths of 0.5 m and 1.5 m. To achieve this, the sampler entered into the trial pit, measured the approximate depth from the surface and removed a soil sample (~650 g dry wt) from one side of the pit wall using a rock hammer. The soil samples were collected into separate plastic containers and sent to a commercial laboratory for chemical analysis.
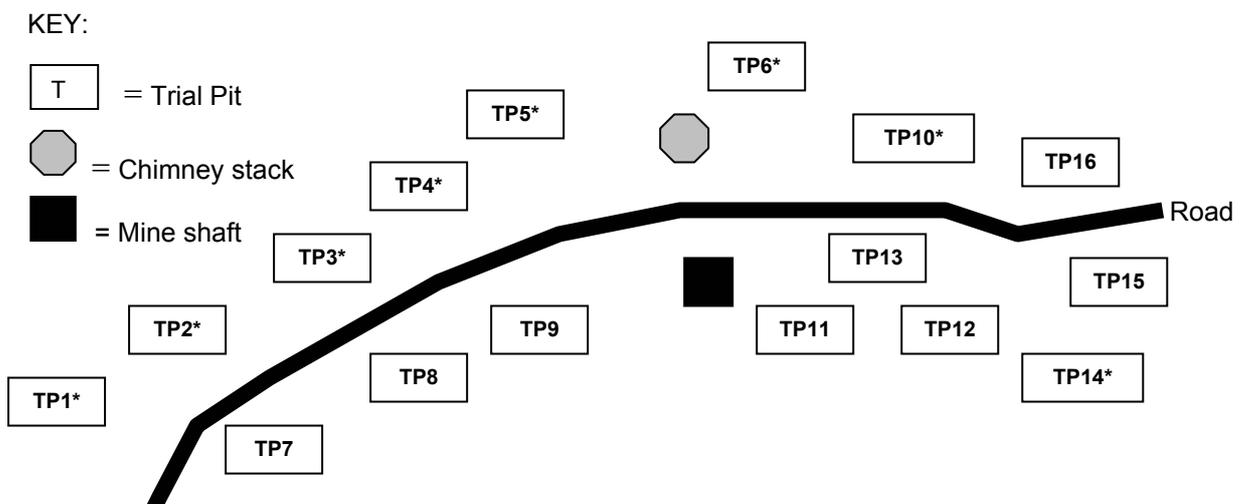
Figure 3.1: Sampling strategy implemented by the commercial consultancy at Site 1. A total of 16 trial pits were excavated across the site with two soil samples removed from each pit and sent to a laboratory for chemical analysis. The trial pits marked with '*' are the locations where duplicate soil samples were removed.

3.3   THE ESTIMATION OF MEASUREMENT UNCERTAINTY AT SITE 1

The Duplicate Method (Section 2.4) had previously only been applied to sampling surveys of contaminated land as part of academic studies (Ramsey and Argyraki, 1997; Taylor and Ramsey, 2003) that employed hand augers or *in situ* Portable X-ray Fluorescence Spectrometry (PXRF). The Duplicate Method had not been applied prior to this research project to commercial investigations (e.g. trial pit and window sampling).

Put simply, the aim of applying the Duplicate Method is to represent the uncertainty in repeating the investigation using whatever sampling protocol and technology are employed. The implementation of the Duplicate Method at Site 1 involved taking an additional duplicate sample at at least eight randomly selected trial pits across the site (denoted by an '*' next to the sample location in Figure 3.1).

It was decided that the duplicate samples should be taken from the opposite wall of the trial pit wall at identical depths (0.5 m and 1.5 m) because this represented the uncertainty that could arise in repeating this sampling methodology. It was equally likely that the sampler would take a soil sample from either side of the trial pit wall on any given day.

Duplicate samples were taken at both depths by the commercial investigator using the same procedure (0.5 m and 1.5 m) to assess whether the depth of sampling would generate different estimates of measurement uncertainty. It should be noted that only eight duplicate field samples are usually recommended/ necessary during a site investigation (Figure 2.2) but 16 duplicate samples were taken at Site 1 to assess whether the depth of sampling would produce different estimates of uncertainty. This approach was not especially expensive to implement at this particular site due to the relatively low costs for chemical analyses (i.e. total arsenic concentration).

The samples taken as part of the Duplicate Method were analysed twice by the laboratory so that estimates of uncertainty from the field sampling and the chemical analysis would be provided.

3.3.1   MEASUREMENTS OF ARSENIC CONCENTRATION TAKEN AS PART OF THE DUPLICATE METHOD AT SITE 1

The measurements of arsenic concentration (Table 3.1 and Appendix 1) are those taken as part of the Duplicate Method (Figure 2.2) for the estimation of measurement uncertainty. The measurements taken at the greater depth of 1.5 m are shown in Appendix 1.

The soil samples taken by the primary site investigator (highlighted column 'Sample 1) provide a highest measured concentration for total As concentration of 837 mg kg^{-1} at trial pit 10. The duplicated sample taken from the other side of the trial pit wall as part of the Duplicate Method (Sample 2) indicated a mean value of 20168 mg kg^{-1}, which is nearly 25 times greater than the estimate provided by the single measurement taken by the consultancy. The substantial difference in recorded arsenic concentration is mainly due to the heterogeneity of contamination within the sampling location. Another example of the within-location heterogeneity is the measurements taken at trial pit 05 where the duplicate sample provides a mean measurement of contaminant concentration of 689 mg kg^{-1} As that is a factor of five times greater than the original sample of 132 mg kg^{-1} As.

If the Duplicate Method had not been implemented at this site, it is clear that substantially different interpretations and decisions may have been made. The values provided by the Duplicate Method at Site 1 (Table 3.1) demonstrate that the within-location heterogeneity of contamination may lead to misclassification of sample locations. These results also indicate that taking duplicate measurements can provide greater reliability of the survey interpretation, by providing an estimate of the uncertainty on each measurement.

Table 3.1: Measured concentrations of total As from soil samples taken as part of the Duplicate Method at Site 1. The values in column 2 ('Sample 1' shown in bold type) are the routine measurements taken by the primary site investigator (commercial consultancy). Full details and 1.5 m depth data are given in Appendix 1.

	0.5 m depth of sampling - Total As in soil (mg kg^{-1})			
	Commercial consultancy		University of Sussex	
Trial pit	**Sample 1**	Sample 1 (analysis 2)	Sample 2	Sample 2 (analysis 2)
01	**153**	153	144	144
02	**412**	457	459	477
03	**314**	342	343	419
04	**124**	134	325	315
05	**125**	139	654	723
06	**675**	778	704	676
10	**837**	878	20428	19908
14	**145**	152	257	288

3.3.2 ESTIMATES OF MEASUREMENT UNCERTAINTY AT SITE 1

The measurement uncertainty was estimated separately for both depths of sampling at the trial pits by applying the ROBAN software to the measurements of total As taken as part of the Duplicate Method (Table 3.2). The estimates of measurement uncertainty for both depths of sampling were not statistically different (at 95% confidence) using an F-test ($F_{16,16}$ = 164.33^2/ 130.61^2 = 1.58, < F_{rab} = 2.86). This is reflected by the similar estimates of relative expanded uncertainty of 64% and 68%. This means that the true concentration is estimated to be within ± 64% of every individual measurement of total As concentration that has been taken at the depth of 0.5 m at Site 1.

The similarity of uncertainty estimates for samples taken at both depths within the trial pits (0.5 m and 1.5 m) indicates that the depth at which duplicate samples are taken does not significantly affect the estimate of uncertainty. This is important because most site investigations remove samples at a variety of depths within each location and across the site. The estimates of uncertainty for both depths again show that it is the field sampling, and not the chemical analysis, that generates the largest uncertainty during the measurement process. Sampling accounted for 94% of the measurement variance (100 × (126.67^2 / 130.61^2)), whereas the chemical analysis was only 6% (at the 0.5 m depth).

Table 3.2: Estimates of measurement uncertainty for soil samples taken from the site of planned housing. Separate estimates of uncertainty are shown for measurements of total arsenic concentration at 0.5 m and 1.5 m depth.

	Soil samples taken at 0.5m			
	Geochemical	Sampling	Analysis	Measurement
Standard Deviation / mg kg^{-1}	244.39 ($s_{geochemical}$)	126.67 ($s_{sampling}$)	31.83 ($s_{analytical}$)	130.61 ($s_{measurement}$)
Percentage (of total) Variance	77.8%	20.9%	1.3%	22.2%
Expanded Relative Uncertainty (95% conf.)	-	61.7%	15.5%	63.6%
Robust mean ($\overline{x}$)	410.5			

	Soil samples taken at 1.5 m			
	Geochemical	Sampling	Analysis	Measurement
Standard Deviation / mg kg^{-1}	167.80 ($s_{geochemical}$)	162.31 ($s_{sampling}$)	25.68 ($s_{analytical}$)	164.33 ($s_{measurement}$)
Percentage (of total) Variance	51.0%	47.8%	1.2%	49.0%
Expanded Relative Uncertainty (95% conf.)	-	67.0%	10.6%	67.8%
Robust mean ($\overline{x}$)/ mg kg^{-1}	484.75			

3.4 MEASUREMENTS OF ARSENIC CONCENTRATION TAKEN ACROSS SITE 1

The measurements for total As concentration of soil samples taken from the proposed housing development (Site 1) show significantly elevated levels of pollution across the site. The concentration map for Site 1 (Figure 3.2) indicates substantially elevated levels of As concentration, with a particularly high level of As contamination (~10,000 mg kg^{-1}) at sample location 10, presumably as a result of its close proximity to the mine shaft and source of contamination. Individual measurements of arsenic contamination are considered for this interpretation because each location corresponds to the garden of the planned housing and therefore individual averaging areas.
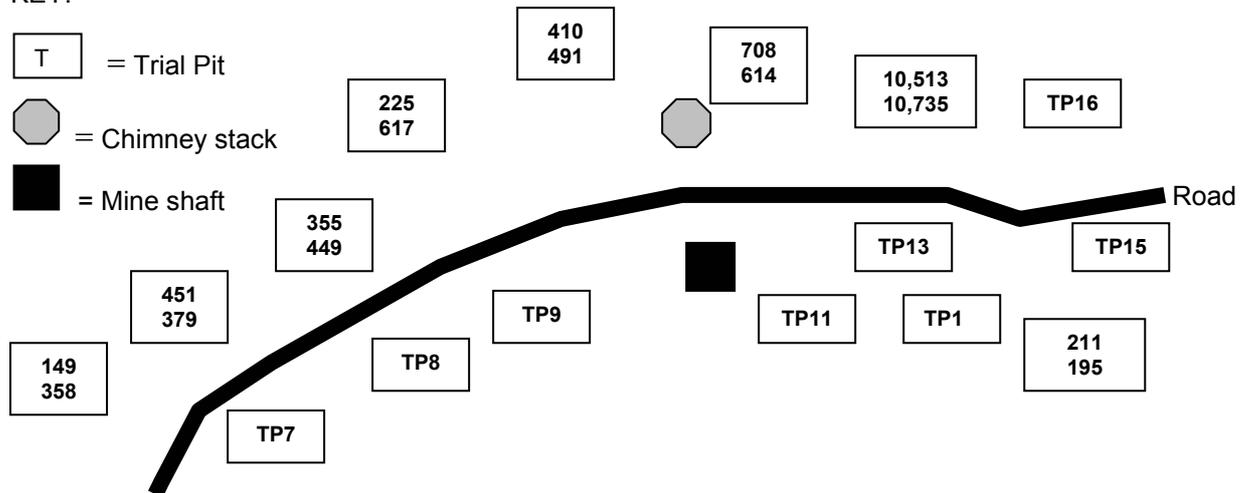
Figure 3.2: Average measurements of total arsenic concentration, shown in mg kg^{-1}, in soil samples taken from trial pits across Site 1 at depths of 0.5 m (top number) and 1.5 m (bottom number). The remaining data for this investigation is not included in this study because the commercial consultancy was not able to release this information.

3.5 APPLICATION OF THE OCLI METHOD AT SITE 1

The following section describes the input parameters chosen for Site 1 that are required for the assessment to be made by the OCLI method.

3.5.1 COST OF MEASUREMENT

The **costs per sample analysis of £10** for total As was used within this OCLI calculation. This value was the cost charged by the commercial consultancy for this site investigation. The **sampling cost of £30 per sample** is based upon the estimated cost of sampling of £480 and the total number of sample locations (i.e. £480 / 16).

3.5.2 CONTAMINANT CONCENTRATION

The choice of contaminant concentration has been chosen here as **500 mg kg^{-1} As** and therefore reflects the scenario of a 'false-positive' misclassification (i.e. that the measured value is above the threshold value of 400 mg kg^{-1} (see Section 3.5.3) but the true concentration is actually beneath it). The value of 500 mg kg^{-1} As has been chosen for Site 1 following an interpretation of the measured values at locations that might be misclassified as 'contaminated' at locations TP02, 06 and 10 (Table 3.1).

3.5.3 THRESHOLD VALUE

It is unlikely the value of 20 mg kg^{-1} (i.e. the generic SGV for As) will be used for this site investigation because of the high background concentration of As in this area of the UK, and it is therefore not applied here. The value of **400 mg kg^{-1} As** has been suggested by the consultancy as a rough estimate of the locally applicable threshold value that would be acceptable to the Local Authority, and has therefore been chosen here. This value may not strictly represent the actual threshold value that may eventually be applied, but is sufficient to demonstrate the feasibility of the OCLI method.

3.5.4 MEASUREMENT UNCERTAINTY

The measurement uncertainty estimated after the investigation at Site 1 using the Duplicate Method is given in Table 3.2. The rounded estimates of measurement uncertainty for samples taken at the depth of 0.5 m are used for this application of the OCLI method ($s_{analytical}$ = **31.8 mg kg^{-1}**, $s_{sampling}$ = **126.7 mg kg^{-1}**). The measurement uncertainty can therefore be estimated using Equation 3 as **130.6 mg kg^{-1}**.

3.5.5 CONSEQUENCE COST

The choice of consequence cost must relate to the misclassification scenario. In this instance the financial penalty arising from a false-positive has been estimated as **£6,000 per sampling location**. This value is based upon the unnecessary remediation of a single plot/ private garden that each sample location represents. The remediation option that is under consideration here is the same approach that was used for the adjacent area of land where houses had already been built following an investigation. This cost has been calculated using an estimate of the dimensions of each location (10 m × 10 m), the depth of the imported topsoil (0.4 m) and its cost (£70 per cubic metre), and the cost of the geotextile layer (£30 m^2).

3.6 RESULTS OF THE APPLICATION OF THE OCLI METHOD AT SITE 1

A visual inspection of the OCLI curve for Site 1 (Figure 3.3) illustrates a range of uncertainty values which include both the actual and optimal uncertainty values. A closer inspection of the U-shaped graph indicates that the actual uncertainty ($s_{measurement}$ = 131 mg kg^{-1}) is approximately 2.5 times greater than the optimal value (49 mg kg^{-1}). The actual uncertainty value, which was estimated during the site investigation, produces a loss of over £1,100 per location (i.e. due to unnecessary remediation). The optimal uncertainty produces a loss of less than £400 per location, a potential saving of over £700 (65%) per location that may be misclassified.
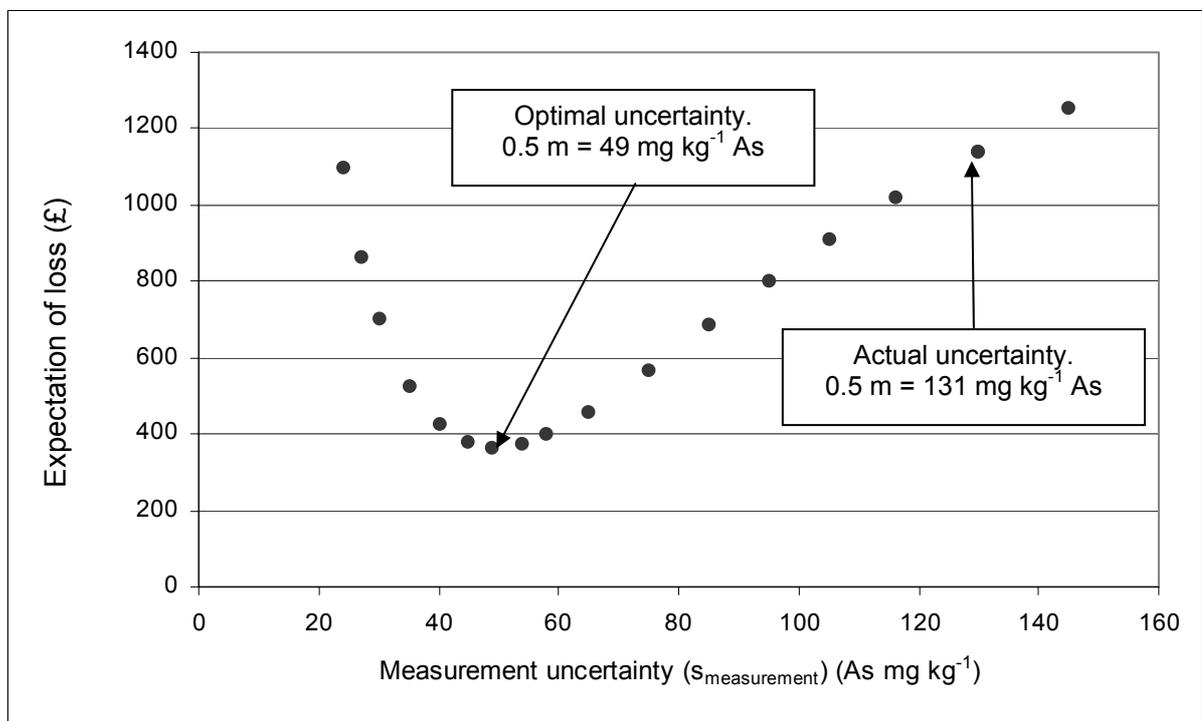
Figure 3.3: The OCLI curve for the site investigation at Site 1. A range of possible values for measurement uncertainty are displayed by the OCLI method, which includes that actual value estimated during the investigation at Site 1 of 131 mg kg^{-1}. The OCLI method indicates that the value of actual uncertainty for measurements taken at the 0.5 m depth gives a loss value of £1,147 per location misclassified. The optimal level of uncertainty (49 mg kg^{-1}) provides the lowest loss value of just under £400.

The measurement uncertainty at Site 1 was mostly due to the field sampling and not the chemical analysis (Section 3.3.2). The optimal level of uncertainty is predicted to be achieved by increasing the sample mass by a factor of 6 as described in Section 2.3.3 (e.g. (131 mg kg^{-1} / $\sqrt{6}$) = 53 mg kg^{-1}). This information could be used in future investigations at the site, or similar sites to provide a more optimal level of measurement uncertainty and its associated optimal loss. It would require the taking of a six-fold composite sample around the walls of the trial pit at the specified depth. The practice of composite sampling is demonstrated for the site investigation shown in Section 8.

3.7 BROAD CONCLUSIONS FOR THE INVESTIGATION AT SITE 1

The broad conclusions at Site 1 are that:

- The measurement uncertainty from both the field sampling and the chemical analysis has been easily estimated for the first time during a commercial site investigation using the Duplicate Method. This indicates that other commercial consultancies should also be able to estimate the measurement uncertainty, which will increase the reliability of the decisions that are made upon them.
- The field sampling, not the chemical analysis, generated the largest component of the measurement uncertainty. For example, the field sampling accounted for 94% of the measurement variance compared to only 6% for the chemical analyses at Site 1.
- The uncertainty estimated for measurements of arsenic concentration at Site 1 was ± 64%. This means that the true arsenic concentration is estimated to be within ± 64% of each individual measured value. The uncertainty of the measurements taken to characterise the contamination at Site 1 means that areas of land may be misclassified and decision errors may be made.
- The research indicates that the estimates of measurement uncertainty can be used within the 'Optimised Contaminated Land Investigation' (OCLI) method. The OCLI method provides an estimate as to whether the measurements are of acceptable quality, given the site-specific costs of measurement and the potential costs of misclassification.
- For the site investigation at the proposed housing development (Site 1), a false-positive misclassification was possible (i.e. locations are classified as 'contaminated' but the 'true' concentration is actually beneath the threshold value because of the measurement uncertainty). The OCLI method indicated that the measurements gave an expectation of loss of approximately £1,200 per sampling location that is misclassified.
- The OCLI method also indicated that the optimal level of measurement uncertainty at Site 1, or similar sites, would produce a probable loss of only £400 per location misclassified. A reduction in sampling uncertainty, by a factor of 2.5, would achieve the optimal uncertainty value and this is predicted to be achieved if the sample mass was increased by a factor of 6 (e.g. taking six-fold composites from around the walls of each trial pit).

3.8 LESSONS LEARNED FROM THE INVESTIGATION AT SITE 1

- The soil samples were returned to the University of Sussex by the laboratory after they had completed the chemical analysis. Visual inspection of the returned field samples showed that they had remained largely untouched by the laboratory, despite our specific request that the entire soil sample be homogenised before sub-samples were taken for analysis. It seems that the laboratory had only removed enough soil from the top of the sample container to allow for the analysis, and this discovery would not have been made unless the samples had been returned to us (which is not routine practice for commercial consultancies).
  The consequence of not homogenising the field sample is that it increases the sampling uncertainty (see Section 2.3.3), which was estimated to be the largest source of uncertainty at Site 1. The failure of the laboratory to comply with the specified procedure effectively means that only a very small field sample was used to characterise Site 1 (e.g. 1 g per sample location).
- The investigation conducted at Site 1 has demonstrated that duplicate samples can be taken by commercial samplers with minimal training.

4. SITE 2 – ORGANIC CONTAMINATION FROM GAS WORKS MATERIAL

4.1 SITE CONDITIONS

The second site chosen for this research provided contrasting characteristics to Site 1 (housing development), such as the type and extent of contamination and the site's end-use. Site 2 was situated adjacent to a public beach in southern England and covered an area of approximately 300 m × 50 m (Figure 4.1). The site was currently used by the public for recreational purposes, such as walking, and had previously been used as a lorry park. The relatively flat site was covered with a mix of soil and shingle, with patches of vegetation.

A gas works was operated close to the site between 1871 and 1971. The area of land investigated was thought to be contaminated because it may have been partly constructed from material taken from the demolition of the gas works. A range of contaminants, both organic and inorganic, were investigated to reflect the range of pollutants that may be present.

4.2 DESCRIPTION OF THE SAMPLING PLAN

The sampling plan implemented by the commercial consultancy consisted of ten trial pits, each of which was separated by a distance of approximately 30 m (Figure 4.1). The trial pits were excavated by a JCB to a depth of 3 m to 5 m.
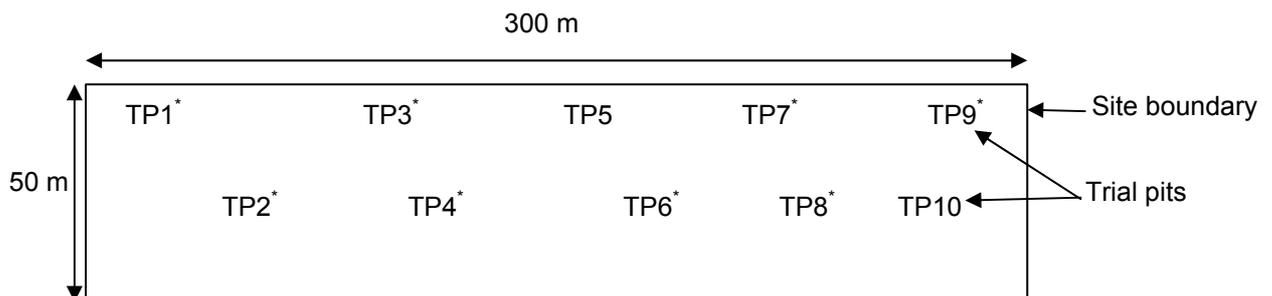
Figure 4.1: Schematic of the sampling pattern implemented by the commercial consultancy at Site 2. Soil samples were taken at different depths within each of the ten trial pits excavated at the site (TP1 to TP10). Duplicate samples were taken from 8 of the 10 trial pits (denoted as '*') as part of a Duplicate Method for the estimation of measurement uncertainty.

4.3 SAMPLING STRATEGY IMPLEMENTED AT SITE 2

Soil samples were removed from each trial pit (3 – 4 at each), ranging in depth from 0.25 m to 3 m, although not all of these were sent for chemical analyses. All of the soil samples taken at the upper depth of 0.25 m to 0.5 m were chemically analysed. The strategy was to remove soil samples that may show particularly elevated levels of contamination based on their smell or colour (i.e. a judgemental and targeted sampling strategy). This is in contrast to the strategy used at Site 1 by different consultants where samples were systematically removed at the same depths from each trial pit (i.e. a non-judgemental strategy).

4.3.1 REMOVAL OF SOIL SAMPLES AT SITE 2

The commercial consultancy did not take the soil samples from directly within the trial pit because of health and safety concerns (i.e. collapsing of the trial pit wall). The soil samples were therefore taken from the material already excavated by the JCB. For example, sampling at the desired depth of 0.5 m was achieved by sampling the material at the top of the excavated pile of soil beside the pit after the JCB had reached this depth. Occasionally the soil was sampled directly from the JCB bucket.

One consequence of this sampling methodology is that the process of removal by the JCB has partially mixed each sample, unlike the discrete samples taken at Site 1. The samples taken at Site 2 were also

mixed with the material previously removed from the trial pit at a different depth (i.e. the soil is mixed as it is added to the material already excavated at the side of the pit). It is unlikely therefore that the soil sample is representative of the material actually present at the depth specified by the sampling plan. The uncertainty generated by this methodology is not necessarily a function of 'bad sampling', but a consequence of the ambiguous sampling protocol and its interpretation made under the constraints apparent in routine site investigation.

4.3.2 METHOD EMPLOYED FOR THE ESTIMATION OF MEASUREMENT UNCERTAINTY AT SITE 2

The Duplicate Method (Section 2.4) was implemented at eight of the ten trial pits to estimate the measurement uncertainty. The removal of a duplicate sample aims to estimate the repeatability of whatever sampling strategy is being employed. For the investigation at Site 2, eight duplicate samples were taken after the commercial investigator had removed their soil sample from the pile of material removed by the JCB that was beside the trial pit, or directly from the JCB bucket. For example, if the consultant took the original sample from one side of the excavated pile, the duplicate sample was taken by approaching the pile from the other side (180°). It was considered that it was equally likely for the consultant to take the original sample from either side of the excavated material. For all of the eight duplicate samples that were taken, the distance between the original and duplicate (both taken from either the pile of excavated material or directly from the JCB bucket) did not exceed 0.2 m.

The removal of duplicate samples was applied only to the upper layer of sampling (e.g. 0.25 m to 0.5 m) because this represented the most sensitive consequence to any possible misclassification (i.e. as it was the most likely exposure route of contaminants to those using the site). Duplicate chemical analysis was made upon the samples taken as part of the Duplicate Method to assess the uncertainty generated by the chemical analyses (Section 2.4).

4.4 MEASUREMENTS OF CONTAMINANT CONCENTRATION AT SITE 2

The samples taken from Site 2 were analysed for both organic and inorganic contaminants. The range of contaminants analysed at this site presented the opportunity to apply the OCLI method to a multi-element site investigation, which had not been undertaken before.

4.4.1 ESTIMATES OF MEASUREMENT UNCERTAINTY AT SITE 2

The uncertainty estimates ranged from 40% to 79% for the contaminants measured during the investigation at Site 2 (Table 4.1). As shown for the previous investigation conducted for this research (Site 1), the field sampling generated significantly more uncertainty than that caused by the chemical analysis (Table 4.1). For example, the contribution towards total variance for indeno(123cd)pyrene was 93% for the field sampling compared to only 7% for the chemical analysis (Section 2.5 Equations 4 & 5). This is not necessarily a consequence of poor sampling *per se* but signifies the effect of the short-range heterogeneity of contaminants that is always present within the soil.

Table 4.1: Estimates of measurement uncertainty, from both the primary sampling and chemical analysis, for the investigation at Site 2.

Contaminant	Measurement uncertainty (U%)	Proportion of laboratory **analysis** to the total measurement variance	Proportion of **sampling** to total measurement variance
Total As	40%	4%	96%
Chromium	52%	8%	92%
Nickel	56%	7%	93%
Lead	68%	48%	52%
Total PAH	51%	3%	97%
Indeno (123cd) pyrene	51%	7%	93%
Total Petroleum hydrocarbons	79%	62%	38%

The measurements taken at Site 2 indicated elevated concentrations of several polycyclic aromatic hydrocarbons (Appendix 1.2), most importantly indeno(123cd)pyrene, which ranged from 1.0 mg kg^{-1} to 42.0 mg kg^{-1}. Indeno(123cd)pyrene is an organic compound that can be potentially harmful to human health and is probably present at this site as a result of the material used to construct this area (i.e. waste construction material from a decommissioned gas works). These elevated and potentially harmful values are shown by the measurements taken as part of the Duplicate Method (Table 4.2). The other measurements taken by the consultancy at Site 2 were not released due to confidentiality constraints.

Commonly, the measured concentrations are compared against a threshold value to guide the subsequent decisions on site management. A threshold value of 6.9 mg kg^{-1} is used for indeno(123cd)pyrene to inform the preliminary decision of whether the sampling location is classified as, in simple terms, 'contaminated' or 'uncontaminated'. This threshold has been taken from a number of Soil Screening Values (SSVs) that are contained within the **AT**RISK^{SOIL} database (Atkins, 2004).

Given the financial consequences that may arise from misclassification, an important question is 'are the measurements of acceptable quality for this particular site investigation?' The 'Optimised Contaminated Land Investigation' (OCLI) method is presented to assess this question for the measurements of indeno(123cd)pyrene. This contaminant was chosen as most likely to constrain the remediation of the site. Concentration values for other contaminants are given in Appendix 1.2.

Table 4.2: Measurements of indeno(123cd)pyrene concentration from soil samples taken as part of the Duplicate Method. Values in column 2 (in bold) are the measurements routinely available to the commercial consultant.

	Indeno(123cd)pyrene / mg kg^{-1}			
	Commercial consultancy		University of Sussex	
Trial pit	**Sample 1**	Sample 1 (analysis 2)	Sample 2	Sample 2 (analysis 2)
TP1	**10**	9	19	20
TP2	**2**	2	2	2
TP3	**41**	42	23	25
TP5	**7**	7	3	1
TP6	**17**	15	19	20
TP7	**3**	3	3	3
TP8	**27**	26	28	26
TP9	**9**	8	10	10

4.5   APPLICATION OF THE OCLI METHOD FOR SITE 2

4.5.1   COST OF MEASUREMENT

The **laboratory cost** for the chemical analysis at this site was approximately **£28 per soil sample** (speciated PAH in soil). The **sampling cost** is more difficult to quantify, but is estimated here as **£50 per sample**. This value is based upon the number of days required to sample the site (3) and the total estimated costs of equipment hire and staff fees (£1500). Given that a total of number of 30 soil samples were taken from the trial pits, this therefore gives a cost per sample of £50.

4.5.2   CONTAMINANT CONCENTRATION

The misclassification scenario chosen here to demonstrate the OCLI method is that sub-areas of the site are unnecessarily remediated due to false-positive misclassification of measurements taken at particular locations. The scenario of unnecessary remediation has been chosen, as this cost tends to be significant, immediately encountered and easier to estimate. Other applications of the OCLI method may also be applied to assess the financial risk arising from false-negative misclassification however.

An important decision that has to be made is the choice of contaminant concentration. The value used here of **13.8 mg kg^{-1}** (the arithmetic mean value) was chosen for this particular application of the OCLI method to reflect the measurements that may be misclassified as false positives. Further applications of the OCLI method can be made to reflect individual measurements if so desired.

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4.5.3 MEASUREMENT UNCERTAINTY

The uncertainty for the measurements of indeno(123cd)pyrene was estimated using the Duplicate Method at Site 2. The uncertainty was estimated as 1 standard deviation for the **sampling uncertainty** as **3.3 mg kg⁻¹** and the **analytical uncertainty** as **0.9 mg kg⁻¹**. The **measurement uncertainty**, as expressed as 1 standard deviation, is the sum of the sampling and analytical variances and has been calculated as **3.45 mg kg⁻¹**.

4.5.4 COST ARISING FROM MISCLASSIFICATION

The remediation option is based upon the removal of contaminated material for disposal within a landfill (i.e. 'dig and dump'). The consequence cost is based upon the approximate mass of soil that would be removed if the area surrounding a sampling location (60 m × 25 m) was excavated to a depth of 0.5 m and clean material placed upon it. The cost of **£65,625 per location** is chosen based upon the approximate (current during the site investigation in 2003) cost of landfill charges (£50 per tonne), the approximate density of material removed (1.75 g cm⁻³), and the area dimensions of 60 m × 25 m (which gives a total of 1312.5 tonnes). This site investigation, and the calculation of remedial costs, was conducted before the introduction of the Landfill Directive. It is likely that the increased costs of this form of remediation would only increase the potential losses from this type of misclassification. The ability to assess the measurement quality by the OCLI method for when considering different remediation strategies may become increasingly useful given the increased costs following the implementation of the Landfill Directive (European Union, 1999) in England. The reduction in the number of landfill sites that are permitted to accept hazardous materials, such as contaminated soil, and the increase in transport costs, should further increase the need for more effective characterisation of contaminated land.

4.6 RESULTS FROM THE APPLICATION OF THE OCLI METHOD

A visual inspection of the U-shaped curve for Site 2 shows that the actual uncertainty has an associated probable loss of just over £1,500 for every location that is misclassified as 'contaminated' with indeno(123cd)pyrene. The optimal level of measurement uncertainty, which has been calculated by the OCLI method as 2.1 mg kg⁻¹ indeno(123cd)pyrene, produces a loss of only £217 per location.
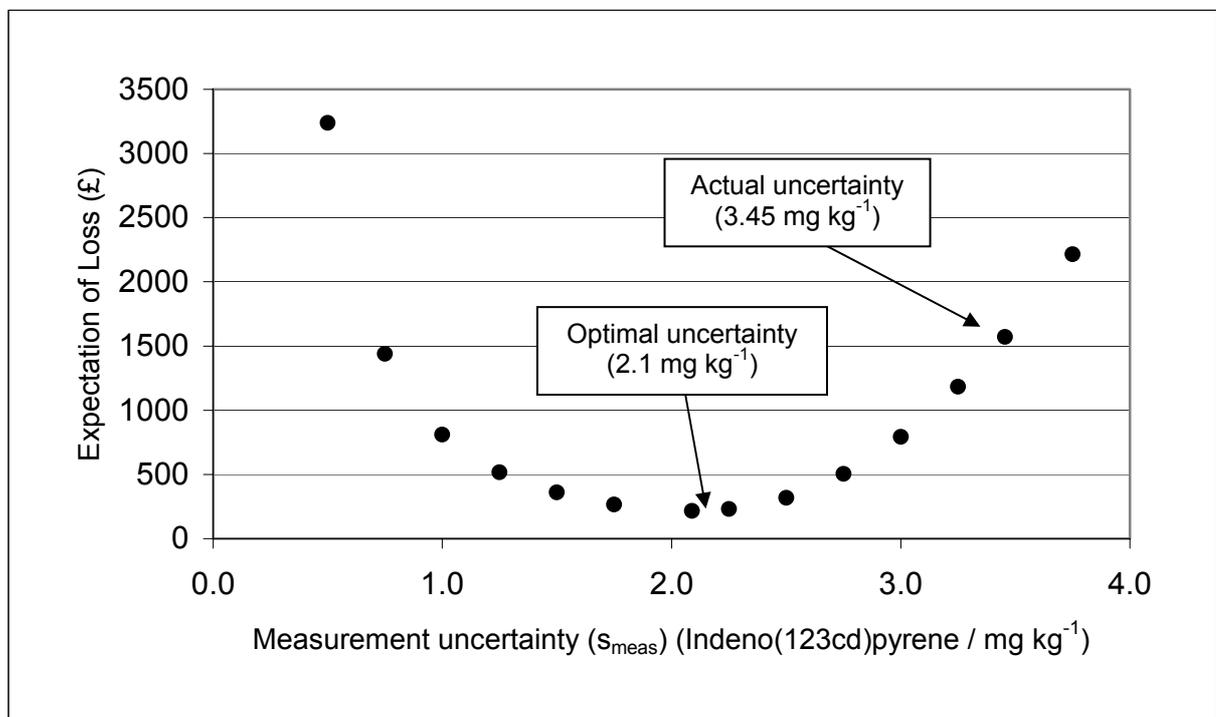
Figure 4.2: The U-shaped curve produced by the OCLI method for Site 2. The graph allows a comparison between the actual uncertainty that has been estimated during the investigation at Site 2 and the optimal uncertainty value, which has the lowest expectation of loss (£).

As with the previous investigation at Site 1, the sampling uncertainty would need to be reduced, as this is much greater than the uncertainty generated by the laboratory analysis. It is predicted that the optimal level of measurement uncertainty can be achieved by increasing the sample mass by a factor of three, by taking a three-fold composite sample at each sampling location for example. A three-fold increase in sample mass is predicted to reduce the sampling uncertainty (3.45 mg kg^{-1}) by a factor of 1.7 to the optimal value of 2.1 mg kg^{-1} (i.e. 3.45 / ($\sqrt{3}$) (see method described in Section 2.3.3). This small and easily achievable modification in sampling strategy would substantially reduce the probable loss from over £1500 to only £217 per location that may be misclassified. Achieving this reduced uncertainty to a more optimal value of 2.1 mg kg^{-1} would incur little, if any, additional expense or time to the site investigation. This improved procedure could be used either for subsequent investigations at this site or similar sites. Over the whole site this would be predicted to potentially save £12,000 (10 locations × £1,200).

4.7   CONCLUSIONS FOR THE INVESTIGATION AT SITE 2

- The application of the Duplicate Method at Site 2 again demonstrated that measurement uncertainty (generated by both the field sampling and the chemical analysis) can be easily estimated as part of a commercial site investigation.
- The measurement uncertainty was estimated for a range of contaminants at Site 2. This study indicated that the uncertainty values varied greatly between contaminants, such as ± 40% for arsenic and ± 79% for total hydrocarbons.
- As evident for the investigation at Site 1, the field sampling, not the chemical analysis, tended to generate the largest component of the measurement uncertainty at Site 2.
- The OCLI method was applied to the measurements of one organic contaminant in soil; Indeno(123cd)pyrene. The actual uncertainty for these measurements ($s_{measurement}$ = 3.45 mg kg^{-1}) produced an expectation of loss of over £1500 per sampling location compared to only £217 at the optimal level uncertainty ($s_{measurement}$ = 2.1 mg kg^{-1}). The OCLI method indicates that a small reduction in uncertainty (from the actual value of 3.45 mg kg^{-1} to the optimal of 2.1 mg kg^{-1}) would achieve the optimal loss value.
- To achieve the optimal uncertainty and its corresponding loss value, the sample mass would need to be increased by a factor of three, by taking a three-fold composite sample for example. The predicted decrease in sampling uncertainty using this approach (for future investigations at this or similar sites) would require little, if any additional expenditure or time. This approach is trialled in the investigation undertaken at Site 6.

4.8   LESSONS LEARNED FROM THE INVESTIGATION AT SITE 2

- The measurement uncertainty could not be estimated for all of the contaminants at Site 2 because the commercial laboratory did not provide values of measured concentrations that fell beneath the detection limit. If the majority or all of the measured concentrations for a particular contaminant are below the detection limit then there is insufficient information for the ROBAN software that calculates the uncertainty. This has implications for how commercial laboratories implement the OCLI method.

  It is still possible to estimate the uncertainty however if only a small proportion of the measurements of a particular contaminant is reported as beneath the detection limit by using the reported detection limit as the measured value. For example, if a reported concentration fell beneath the detection limit of <1 mg kg^{-1} then a value of 1 mg kg^{-1} has been used within the ROBAN software. The disadvantage of taking this approach is that the uncertainty will tend to be underestimated, especially that from the laboratory analysis, and is not generally recommended.

5. SITE 3 – HEAVY METAL CONTAMINATION WITHIN RESIDENTIAL GARDENS

5.1 SITE DESCRIPTION

Site 3 was located in London, and was positioned between two residential houses. This gap in the terraced housing is a consequence of aerial bombing during World War II. The origin of the material that was subsequently used to infill this area is unknown.

The site covers an area of approximately 27 m × 30 m. Wire fencing currently divides the site into two sub-areas of approximately equal size: a private, residential garden to the south and an unused, overgrown plot, previously used as an allotment to the north. The northern sub-area contained a number of permanent structures, such as a poorly maintained greenhouse and trellises.

5.2 INVESTIGATION OBJECTIVES

The commercial consultancy involved with this site investigation had previously completed an intrusive survey of the same site for the local Council in October 2003. The University of Sussex investigated the site again in May 2004 together with this consultancy for the purposes of this research project. The same sampling strategy was employed for both of these investigations at Site 3. It was expected that different measurements of contaminant concentration would be obtained between the two investigations. Conducting two investigations at Site 3 would provide an indication of how repeatable the measured concentrations and interpretations are. This repeatability can be compared against the estimates of measurement uncertainty made within one investigation.

The objective of the first investigation at Site 3, which was solely conducted by the consultancy in October 2003, was to present a risk assessment report for the consideration of the client (Council). The site investigation and report was compliant with the Contaminated Land Exposure Assessment (CLEA) framework.

The objectives of the second investigation at Site 3, conducted by the University of Sussex together with the same consultancy in May 2004, were to:

1. Assess the concentration of heavy metals in soil, using the same sampling strategy and analytical suite used previously by the commercial consultancy at the site.
2. Estimate the measurement uncertainty arising from both the field sampling and chemical analysis, when using window-sampling equipment. This form of sampling has not been undertaken before and represents a novel assessment into the commercial feasibility of the OCLI methodology.
3. Compare the differences in measured concentrations obtained between both site investigations.
4. Assess whether the differences in measured concentrations taken between investigations are predicted by the uncertainty estimates.
5. Evaluate whether applying the OCLI method during this site investigation (University of Sussex, May 2004) had demonstrated advantages, when compared to the first investigation (October 2003) where it was not applied.

5.3 SITE HISTORY AND PREVIOUS SITE INVESTIGATION

The original sampling plan implemented by the commercial consultancy at Site 3 in October 2003 (shown in Figure 5.1) consisted of a total of 13 window samples (designated 'BH1' to 'BH13'), with each taken for the aim of assessing the geology of the site. Expressed simply, window sampling involves pneumatically driving a hollow metal tube into the ground to a specified depth. The tube is then removed and the soil contained within the tube is sampled and sent to a laboratory for chemical analysis. Window sampling allows the investigator to remove samples from specific depths, although only a relatively small mass is recovered (e.g. tube diameter ~8 cm).

The soil types were categorised generally by the consultancy into three groups with increasing depth: *i*) the '**topsoil**' (Dark brown, organic content), *ii*) the '**fill**' (loose grey or brown silty sandy fill with brick, fragments and flint and occasionally ashy) and *iii*) the '**natural soil**' (orange brown, slightly clayey sand with occasional gravel).

All of the soil samples removed from the 13 window sample locations were inspected on-site by the consultant to assess the soil type. A sub-set of these soil samples (n = 8) was sent to the laboratory and analysed for both heavy metals and selected organic contaminants (phenols and selected PAH). The sampling locations where soil samples were removed and sent for chemical analyses (BH1, BH3, BH4, BH6, BH7, BH9, BH11 & BH13) are underlined in Figure 5.1. **Duplicate samples were not taken as part of the original survey conducted by the commercial environmental consultancy and therefore an estimation of measurement uncertainty for that survey is not possible.**
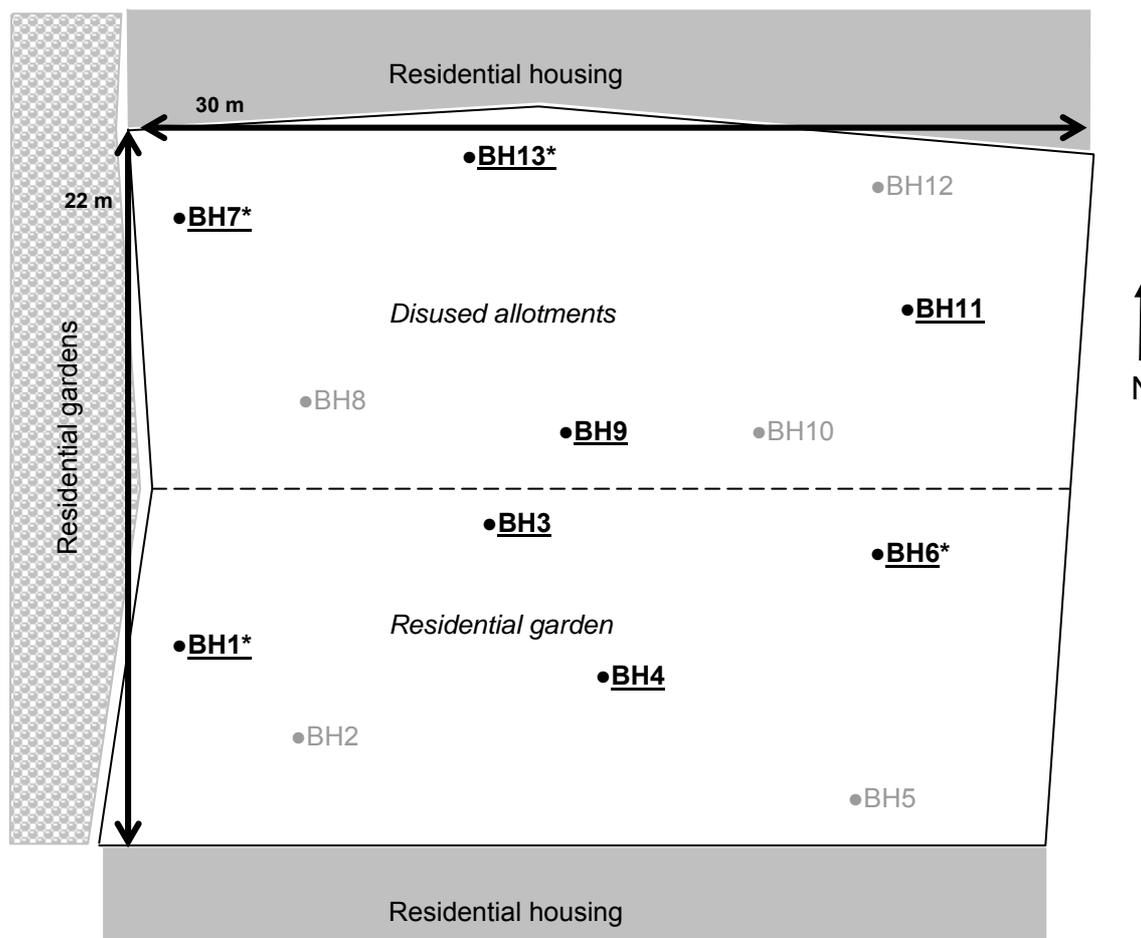
Figure 5.1: Schematic map of the sampling strategy employed at Site 3. The 8 locations where soil samples were taken for chemical analysis during both surveys are <u>underlined</u> and shown in bold. Soil samples were removed during both investigations using window sampling equipment. The Duplicate Method was only applied during the second investigation at Site 3, conducted by the University of Sussex, to estimate the measurement uncertainty. The locations where duplicate samples were taken are marked by '*'.

The original survey completed by the commercial consultancy in October 2003 indicated significantly elevated levels of heavy metals, in particular lead, zinc and copper. Given the suspected source of contamination at this site (i.e. bomb damage), it was hypothesised that the contamination would be more heterogeneously distributed than normal and would therefore generate a relatively high level of (sampling) uncertainty. For example, the distribution of heavy metals would be particularly heterogeneous as the bombing would probably scatter the debris across the site unevenly. Given the high levels of uncertainty that were expected at Site 3, a different interpretation was expected between that based upon the first investigation (October 2003) and that based upon the repeated investigation, which used the same strategy, in May 2004. This was only a prediction of the uncertainty however,

based upon the suspected source of contamination. The implementation of the Duplicate Method during the second investigation at Site 3 would provide an <u>actual</u> estimate of uncertainty.

5.4 SUPPLEMENTARY SURVEY AT SITE 3

The second sampling strategy implemented in May 2004 aimed to repeat the first investigation by the commercial environmental consultancy conducted in October 2003. This second sampling strategy therefore represented the implementation of a 'real-life' commercial site investigation. The sampling conducted for this project was undertaken by the same senior consultant that had previously completed the investigation in October 2003 at the request of the local council. Soil samples were taken at the same nominal locations and depths used in the initial survey. The precise locations previously sampled could not be relocated exactly (as expected), but the effect of this uncertainty in sampling was estimated by implementing the Duplicate Method.

5.4.1 IMPLEMENTATION OF THE DUPLICATE METHOD FOR WINDOW SAMPLING AT SITE 3

Duplicate samples were taken by driving in a second borehole in close proximity to the 'original' sampling location. The distance that separated the 'original' and 'duplicate' sampling locations aimed to represent the uncertainty in relocating the borehole in the site investigation. For example, duplicate samples were taken in a pseudo-random direction (to be unbiased) at a distance of 1 m away from the original location. Duplicate soil samples were taken at the same depths that were taken for the original sample. Duplicate soil samples were taken at four of the eight sampling locations at two depths (to give a total of eight sample duplicates). For example, if the original samples were taken at depths of 0.3 m and 1.0 m then duplicates samples were taken at the same nominal depths (subject to compaction errors), at a distance of 1 m away from the original location.

5.5 CHEMICAL ANALYSIS

The soil samples were sent to the same laboratory previously used by the consultancy at Site 3 in October 2003. The laboratory was given specific instructions to sieve and grind the entire field sample before removing two separate test portions for chemical analysis (for 'true analytical duplicates' as part of the Duplicate Method). Concentration values are given in Appendix 1.

5.6 ESTIMATES OF MEASUREMENT UNCERTAINTY

The measurements taken as part of the Duplicate Method were entered into the ROBAN software and estimates of measurement uncertainty were calculated. The estimates of measurement uncertainty were generally low, ranging from ± 19% to ± 35% (Table 5.1). The relatively low values of measurement uncertainty suggest that the contamination at Site 3 is not as heterogeneously distributed as expected. The lower levels of uncertainty contrast those estimated during the first two investigations of the research project (i.e. Site 1 U = ± ~67% and Site 2 U = ± ~80%). This indicates that the level of measurement uncertainty is site-specific and cannot always be predicted (i.e. it is better to estimate the uncertainty than to rely on prediction alone).

Table 5.1: Estimates of uncertainty from measurements taken as part of the balanced design at Site 3. The general levels of measurement uncertainty are quite low (19 – 35%) which indicates the reliability of the survey.

Contaminant	Measurement uncertainty (U%)	Proportion of laboratory **analysis** to the total measurement variance	Proportion of **sampling** to total measurement variance
Total Arsenic	24%	13%	87%
Chromium	19%	22%	78%
Nickel	26%	15%	85%
Lead	25%	4%	96%
Mercury	28%	21%	79%
Zinc	35%	4%	96%
Copper	21%	15%	85%

The lower estimates of measurement uncertainty at Site 3, compared to Site 1 and 2, may be a consequence of the correct sieving and grinding of the entire field sample by the laboratory. The high values of uncertainty at one of the previous site investigations used for this research (Site 1 Housing development) may have been due partly to incorrect sub-sampling within the laboratory (Section 3.8). The sieving and grinding of the entire field samples taken for the investigation at Site 3 reduces the effect of within-sample heterogeneity, and may therefore reduce the overall uncertainty. This demonstrates the importance of correct laboratory procedure. For example, the relatively high uncertainty estimate (~67%) for the investigation at Site 1 (Housing development) may have resulted from only a small sub-sample being used for the chemical analysis. It is likely that this gave a low, yet unrealistic, estimate of analytical uncertainty but also generated higher overall uncertainty.

Another explanation for the low levels of measurement uncertainty at this site may be due to the sampling method. For example, the window sampling equipment used for Site 3 removed an un-mixed soil sample from specific depths. The strategy of trial pits employed for Sites 1 and 2 excavated a much larger mass of soil, which was also partially mixed, before a field sample was taken.

The smaller level of uncertainty at Site 3 would intuitively lead to the interpretation that a misclassification is much less likely, but this judgement does not consider the site-specific financial aspects that are present. The OCLI method is employed at this stage for this purpose.

5.7 RESULTS FOR SITE 3

5.7.1 INTERPRETATION OF THE MEASURED CONCENTRATIONS

Two separate investigations were conducted at Site 3 (Section 5.2) and this allows for a comparison between the two sets of measurements and the interpretations that are made.

The measurements taken for this research project (May 2004) are presented in the following discussion and compared with those previously taken solely by the consultancy (October 2003). An initial comparison of the measurements taken in both investigations at corresponding locations was made using a linear regression model. The regression models (not shown) indicated a significant correlation for Pb and Zn but a poor correlation for the majority of contaminants.

Rather than comparing the individual measurements, perhaps a more useful comparison would be to compare the classifications that are made for each contaminant, as this will help to explain the usefulness of the OCLI method. The results of both investigations are therefore presented and interpreted here in the same manner as the original consultants report.

The commercial consultancy wrote a report for their client that presented and interpreted the results using a comparison of the 95th percentile (of the mean) value of heavy metal concentration against their associated Screen value (i.e. the Soil Guideline Value or a value estimated from a site-specific risk assessment as directed within DEFRA document CLR7). The measurements taken by the consultancy were reported to the client by separating the interpretation into the three main soil types (i.e. the 'topsoil fill', the 'fill' and the 'natural soil'). The measurements taken within each of these three horizons were interpreted as being three separate averaging areas, as described in the CLR7 guidance. This approach requires that the measurements taken within each designated 'averaging area' are treated to a statistical test where first the arithmetic mean value is calculated, then the 95th percentile (of the mean) is determined. The 95th percentile value ('US 95') is then compared against the respective Screen value.

To allow a comparison between the two investigations, this interpretation was also taken for the investigation conducted by the University of Sussex in May 2004. The two separate investigations at Site 3 had indicated elevated concentrations of heavy metals (with the exception of selenium). The uppermost layers of soil, classified as 'topsoil fill' and 'fill', provided the highest measured concentrations, particularly of Zn and Pb with average (arithmetic mean) values, of all the measurements in both surveys, of 760 mg kg^{-1} and 3204 mg kg^{-1} respectively. The classification to whether the site possibly poses an unacceptable risk to site users and may require further investigation or remedial action (i.e. if the 95th percentile of each of the nine heavy metals exceeded their Soil Guideline Value) showed an 81% agreement between the two separate investigations. This good agreement of interpretation was obtained despite the majority of contaminant concentrations being relatively close to their associated Screen values, which often means that a different classification is

more likely. The good agreement in interpretations/ classifications between the two site investigations at Site 3 is substantiated by the relatively low levels of measurement uncertainty estimated at this site (± 19% to ± 35%).

5.7.2 COMPARISON OF THE MEASUREMENTS AND INTERPRETATION MADE BY BOTH INVESTIGATIONS

Comparison of the interpretations for both site investigations for the averaging area known as 'topsoil fill' (Table 5.2) indicates that **the same interpretation is made for all contaminants** when comparing the 95th percentile of the mean (US 95) value against their respective SGV. Sampling location BH1 indicated particularly high concentrations of heavy metals and is thought to be due to remains of bomb remnants within this sub-area of the residential garden.

Table 5.2: Measurements of heavy metal contamination (in mg kg^{-1}) within the 'topsoil fill' at Site 3 made by both site investigations. Although individual measurements vary between the two investigations, the classification (according to CLR7) agrees. The low levels of uncertainty estimated during the second investigation are validated by the good agreement between the interpretation of the two sets of data.

Investigation 1 at Site 3 by the commercial consultancy									
Location	depth	As	Cd	Cr	Cu	Pb	Hg	Ni	Se	Zn
BH1	0.1 m	45	2.4	70	234	15042	4.3	33	<3	3153
BH4	0.1 m	25	<1.0	27	144	1729	3.2	21	<3	821
BH9	0.1 m	29	1.5	37	137	2258	2.1	25	<3	705
BH13	0.05 m	30	<1.0	32	137	1160	2.6	27	<3	534
	mean	32.3	2.0	41.5	163.0	5047.3	3.1	26.5	-	1303.3
	1 std dev	8.8	0.6	19.4	47.4	6678.2	0.9	5.0	-	1238.8
	US 95*	42.6	2.7	64.4	218.8	12904.2	4.2	32.4	-	2760.7
	Screen value	20.0	8.0	130.0	200.0	450.0	8.0	50.0	35.0	200.0
Investigation 2 by the University of Sussex									
Location	depth	As	Cd	Cr	Cu	Pb	Hg	Ni	Se	Zn
BH1	0.1 m	46	2.6	93	326	15758	7.1	35	4	3181
BH4	0.1 m	27	1.8	40	138	2245	5	28	4	1518
BH9	0.1 m	26	<1.0	32	129	1757	3.4	19	<3	458
BH13	0.05 m	21	<1.0	42	147	1183	3.2	24	3	556
	mean	30.0	2.2	51.8	185.0	5235.8	4.7	26.5	3.7	1428.3
	1 std dev	11.0	0.6	27.8	94.3	7028.2	1.8	6.8	0.6	1262.6
	US 95*	42.9	2.9	84.5	295.9	13504.5	6.8	34.5	4.3	2913.7
	Screen value	20.0	8.0	130.0	200.0	450.0	8.0	50.0	35.0	200.0
Uncertainty estimate		24%	-	19%	21%	25%	28%	26%	-	35%
Agreement of interpretation between investigations (e.g. above or below SGV)		Y	Y	Y	Y	Y	Y	Y	-	Y

*US 95 = Upper 95th percentile value of the measured concentrations compared against the associated Soil Guideline Values (SGV), as directed within the legislative guidance of report CLR7. The 'screen values' are either SGVs or values chosen by the consultancy using a site-specific risk assessment for this comparison.

For measurements of Pb and Zn in particular, this good agreement is largely because the measured values greatly exceed their associated Screen values and therefore the interpretation is not significantly affected by the measurement uncertainty. For the other metals however, the measured concentrations are in relatively close proximity to their Screen value. For example, the mean values of 163 mg kg^{-1} Cu and 32.3 mg kg^{-1} As for the first investigation undertaken by the consultancy, are close to their respective Screen values of 200 mg kg^{-1} and 20 mg kg^{-1}. Comparing these against the mean values of 185 mg kg^{-1} Cu and 30.0 mg kg^{-1} As for the second investigation undertaken by the University of Sussex, there is a good agreement between the measured values and the same interpretation is made.

This is despite the increased likelihood of disagreement due to the close proximity of the measured concentrations to the Screen value. The agreement in interpretation between the two investigations is largely due to the low level of measurement uncertainty at Site 3, which is substantiated by the estimates given by the Duplicate Method (range = 19% to 35% for the different elements considered).

There is also a relatively good agreement (for six of the eight metals) between the measurements of contamination taken on 'fill' material during both site investigations (Table 5.3). Only the two contaminants of copper and mercury (Cu and Hg) showed disagreement when comparing the US 95 value against their associated Screen values.

This disagreement is probably due to two outlying measurements of Cu and Hg that were made at sampling location BH1 during the investigation conducted by the consultancy. These particularly high and outlying values of Cu and Hg are probably a consequence of the relatively high degree of contaminant heterogeneity within this location.

Table 5.3: Measurements of inorganic contaminants in material classified as 'fill'. This shows that two elements (Cu and Hg) resulted in different management decisions between the two surveys.

Investigation 1 at Site 3 by the commercial consultancy									
Location	depth	As	Cd	Cr	Cu	Pb	Hg	Ni	Se	Zn
BH1	0.75 m	27	<1.0	11	364	7423	41	15	<3	369
BH3	0.7 m	15	<1.0	16	42	514	0.85	13	<3	109
BH6	0.3 m	21	<1.0	16	105	1360	1.7	18	<3	393
BH7	0.5 m	45	<1.0	41	202	1717	2.7	37	<3	1015
BH9	0.4 m	29	<1.0	32	129	1957	3.8	23	<3	541
BH11	0.1 m	24	<1.0	29	107	1028	2.8	21	<3	497
BH13	0.5 m	27	<1.0	28	112	1845	2.8	24	<3	467
	mean	26.9	-	24.7	151.6	2263.4	8.0	21.6	-	484.4
	1 std dev	9.3	-	10.7	104.8	2330.7	14.6	7.9	-	273.2
	US 95*	33.7	-	32.6	228.5	3974.9	18.7	27.4	-	685.0
	Screen value	20.0	8.0	130.0	200.0	450.0	8.0	50.0	35.0	200.0
Investigation 2 by the University of Sussex									
Location	depth	As	Cd	Cr	Cu	Pb	Hg	Ni	Se	Zn
BH1	0.75 m	30	<1.0	48	199	3619	3.8	20	3	368
BH3	0.7 m	21	<1.0	23	113	4371	3.7	19	<3	99
BH6	0.3 m	28	7.1	37	239	1781	6.4	28	<3	896
BH7	0.5 m	35	<1.0	27	152	994	2.7	26	<3	448
BH9	0.4 m	6	<1.0	37	76	574	1.7	15	<3	80
BH11	0.1 m	14	<1.0	53	125	1086	2.6	24	3	51
BH13	0.5 m	16	<1.0	48	145	1096	3.4	24	<3	464
	mean	21.4	-	39.0	149.9	1931.6	3.5	22.3	3.0	343.7
	1 std dev	10.2	-	11.3	54.5	1469.5	1.5	4.5	-	301.7
	US 95*	28.9	-	47.3	189.9	3010.6	4.6	25.6	-	565.2
	Screen value	20.0	8.0	130.0	200.0	450.0	8.0	50.0	35.0	200.0
Uncertainty estimate		24%	-	19%	21%	25%	28%	26%	-	35%
Agreement of interpretation between investigations (e.g. above or below SGV)		Y	-	Y	N	Y	N	Y	-	Y

*US 95 = Upper 95th percentile value of the measured concentrations compared against the associated Soil Guideline Values (SGV), as directed within the legislative guidance of report CLR7. The 'screen values' are either SGVs or values chosen by the consultancy using a site-specific risk assessment for this comparison.

This is evidence that the uncertainty on individual measurements, caused mainly by the short-range heterogeneity, can affect the interpretation even when using the 95th percentile test (US 95) described

in DEFRA document CLR7. A similar extent of agreement was also found for the classification of measurements made upon five of seven metals in soil samples taken from the greatest depth that was classified as 'natural soil'.

5.8 CHOICE OF INPUT PARAMETERS FOR THE OCLI METHOD

5.8.1 COST OF MEASUREMENT

The analytical costs per sample are taken directly from the **laboratory fees**. The value of **£12 per sample** has been estimated by dividing the total laboratory cost by the total number of analyses (£480 / 39). The **sampling costs** of **£50 per sample** have been estimated by dividing the cost of the equipment hire (£500) and the consultant's day rate (£300) by the total number of field samples (16).

5.8.2 CONTAMINANT CONCENTRATION

A range of contaminants was measured in this site investigation. Since the OCLI method currently only considers one contaminant at a time, a decision is required as to which element to select as the most appropriate. In this case, the choice is based upon the 'key' contaminant(s) that are present within the range of heavy metals measured. The categorisation of a key contaminant is based upon (*i*) the contaminants' influence as to whether the site is likely to be classified as 'contaminated' (i.e. its concentration) and (*ii*) its ability to present the possibility of significant harm to those using the site (i.e. a pollutant linkage and toxicity). The contaminant that is considered using the OCLI method in this study is Pb. This is due to its particularly high concentration values within the 'topsoil fill' and 'fill' material, which is a likely source to the receptor in terms of inhalation and ingestion. It is likely that subsequent decisions based upon these site investigations would be based upon the measured concentrations of Pb, rather than those of any other element or combination of elements.

Given the relatively small size of the site it is likely that any decisions associated with redevelopment would involve the 95th percentile on the mean value (US 95) of contaminants present across the whole site, and not just around individual sample locations, as demonstrated previously on larger sites used for this project. The entire site needs to be considered as a single averaging area for the application of the CLR7 approach as it was by the consultant in the first investigation. It is also likely that the measurements taken within the two particular soil types (designated as 'topsoil fill' and 'fill') would be considered during any subsequent decision-making due to the receptor pathway model, and the likely depth of any remediation. The arithmetic mean value for Pb of **3133 mg kg^{-1}** for the measurements taken within both the 'topsoil fill' (Table 5.2) and 'fill' (Table 5.3) as part of the 'University of Sussex OCLI site investigation' has therefore been chosen as the choice of contaminant concentration for this application of the OCLI method.

5.8.3 THRESHOLD VALUE

The threshold value of **450 mg kg^{-1}** (SGV) for Pb has been chosen by the commercial consultancy for the original investigation at Site 3 and has therefore been used within the OCLI method.

5.8.4 MEASUREMENT UNCERTAINTY

The **analytical uncertainty** for lead has been calculated using the measurements taken as part of the Duplicate Method by the ROBAN software as **41.5 mg kg^{-1}** (1 standard deviation). The **sampling uncertainty** has been estimated as **196.0 mg kg^{-1}**. The **measurement uncertainty** can therefore be estimated using Equation 3 as **200.3 mg kg^{-1}**.

5.8.5 COST OF MISCLASSIFICATION

The final input parameter that has to be chosen for the OCLI method is the cost that may arise from misclassification. Previous applications of the OCLI method (i.e. Sites 1 and 2) have considered the costs arising from unnecessary remediation. As a contrast, and to demonstrate a different application of the OCLI method, a much higher cost has been applied here, which may arise from subsequent litigation. The estimate of **£1m** has been considered here to represent the approximate costs that may be incurred in this scenario, based on previous legal settlements.

5.9   RESULTS OF THE OCLI METHOD FOR THE SUPPLEMENTARY SURVEY AT SITE 3

The OCLI curve (Figure 5.2) provides a visual comparison of the actual measurement uncertainty, which was estimated during the site investigation conducted by the University of Sussex, and the optimal uncertainty estimated by OCLI.
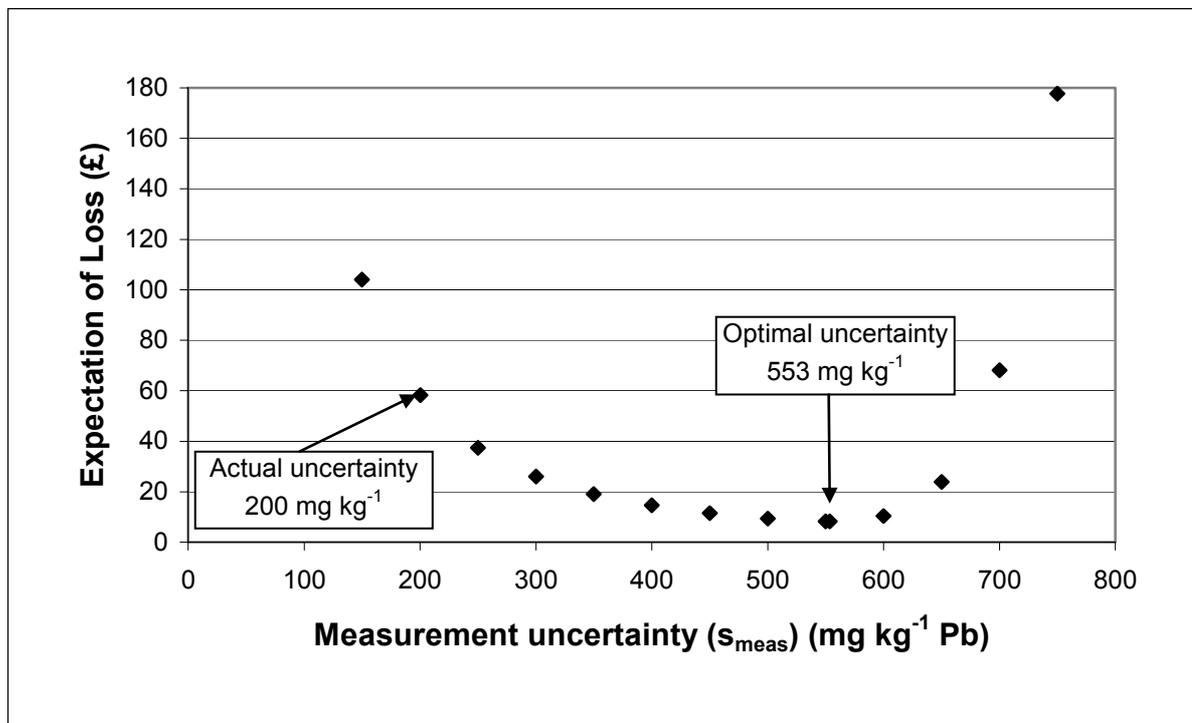
Figure 5.2: The OCLI curve for the investigation at Site 3. An initial visual inspection of the OCLI curve for the investigation at the Site 3 suggests that the uncertainty of measurements of Pb are not of an appropriate quality. This is because of the large difference (a factor of 2.5) between the actual uncertainty estimated during the investigation and the optimal value given by the OCLI method. However, the measurement uncertainty may be acceptable given the relatively small difference between optimal and actual values (£8 and £58 respectively) (adapted from Boon *et al.*, 2007).

The OCLI method indicates that the actual uncertainty for the measurements of Pb concentration (200 mg kg^{-1}) gives an expectation of loss of only £58, despite the high consequence cost that may arise from litigation of £1m (Figure 5.2). The expectation of loss at the optimal uncertainty (553 mg kg^{-1}) gives an expectation of loss of only £8. A substantial change in measurement uncertainty would be needed to achieve this relatively small decrease in the likely loss.

Interestingly, the actual uncertainty value is positioned to the left of the optimal value on the OCLI curve (Figure 5.2.); this has not been seen in previous applications of the OCLI method. Unlike previous site investigations used for this project (Sites 1 and 2), the OCLI method indicates that the uncertainty can be increased (i.e. *less* precise measurements) to reach the optimal level (e.g. actual $s_{measurement}$ = 200 mg kg^{-1}, optimal $s_{measurement}$ = 553 mg kg^{-1}). The OCLI method shows that a much less precise, and therefore less expensive, measurement strategy could be used at this, or similar sites (such as *in situ* Portable X-ray Fluorescence Spectrometry).

Put simply, the high concentrations of Pb (i.e. $\bar{x}$ = 3133 mg kg^{-1}), which greatly exceed the associated SGV, coupled with the relatively low level of expanded relative uncertainty of 25%, means that misclassification is extremely unlikely at this site. Even with a particularly high potential consequence cost of £1m arising from litigation, the OCLI method has shown that the measurements are acceptable at this site. The uncertainty may however become an issue after any remediation has been applied to Pb at the site.

5.10   BROAD CONCLUSIONS FROM THE INVESTIGATION CONDUCTED AT SITE 3

- The investigation conducted by the University of Sussex at Site 3 indicated elevated levels of heavy metals, particularly of Zn and Pb (mean values of 760 mg kg^{-1} and 3204 mg kg^{-1} respectively). This confirms the site conceptual model in which contamination arose as a consequence of bomb damage during the Second World War.

- Low values of measurement uncertainty were estimated for the second investigation at Site 3, ranging from only ± 19% for Cr to ± 35% for Zn. This contradicts the expectation that high (sampling) uncertainty would be generated at Site 3 because of the suspected high levels of contaminant heterogeneity within the soil. This indicates that the heterogeneity of the contamination, and hence the level of measurement uncertainty, cannot always be accurately predicted. It is better to estimate or quantify the uncertainty during the investigation than only to predict it.

- There was generally good agreement between the measured concentrations, and subsequent interpretations, that were made independently for the site investigations conducted initially by the commercial consultancy (October 2003) and again by the University of Sussex (May 2004). There was an 81% agreement of the 21 classifications made in each of the two investigations (i.e. whether the US 95 value exceeded the Soil Guideline Value).

- The uncertainty estimates derived from the second investigation at Site 2 (conducted by the University of Sussex) were relatively low. The good agreement in measured concentrations during both investigations, as well as the agreement in interpretation, is consistent with what would be expected from such low estimates of measurement uncertainty.

- The Duplicate Method and the OCLI method were not applied to the first investigation conducted by the commercial consultancy. Application of the OCLI methodology to the subsequent investigation by the University of Sussex demonstrated several advantages:
  - Estimating the measurement uncertainty, using the easy to implement and relatively inexpensive Duplicate Method, provided greater confidence in the reliability of the measurements. For example, although many of the measured concentrations of contamination were in close proximity to their respective Soil Guideline Value, and hence presented an increased likelihood of misclassification, the low values of uncertainty provided an increased confidence in the interpretations made.
  - The estimates of measurement uncertainty could be used to demonstrate to the client or regulator that the investigation was subject to extra quality assurance procedures that increase the validity and quality of the subsequent report.
  - The low values of loss shown by the OCLI method (e.g. only ~£60) can be used to indicate to the investigator, and to the client, that the measurements are of acceptable quality, despite such the high consequence cost of £1m.

6. SITE 4 – GAS WORKS

6.1 SITE DESCRIPTION

Site 4 is located in London, and covers a total area of approximately 400 m × 300 m. The site is currently used for storage and transportation of natural gas and contains eight operational gas tanks (Figure 6.1). The site is divided into two sub-areas by iron railings; the larger sub-area containing the gas storage tanks and scrub-land. The soil types at the site are classified generally as made ground, over gravel, over alluvium.

The entire site has been involved with gas production and storage for over 100 years and was investigated by a commercial environmental consultancy for the land owner to assess the levels of contamination and risk presented from this activity. The eventual end-use of this site is not known at this time.

The central sub-area of land (Figure 6.1) was not investigated by the University of Sussex due to the health and safety concerns associated with the storage tanks (i.e. University staff did not hold the appropriate training certifications). This does not greatly affect the validity of this research however because the adjacent sub-area is treated as an independent investigation.
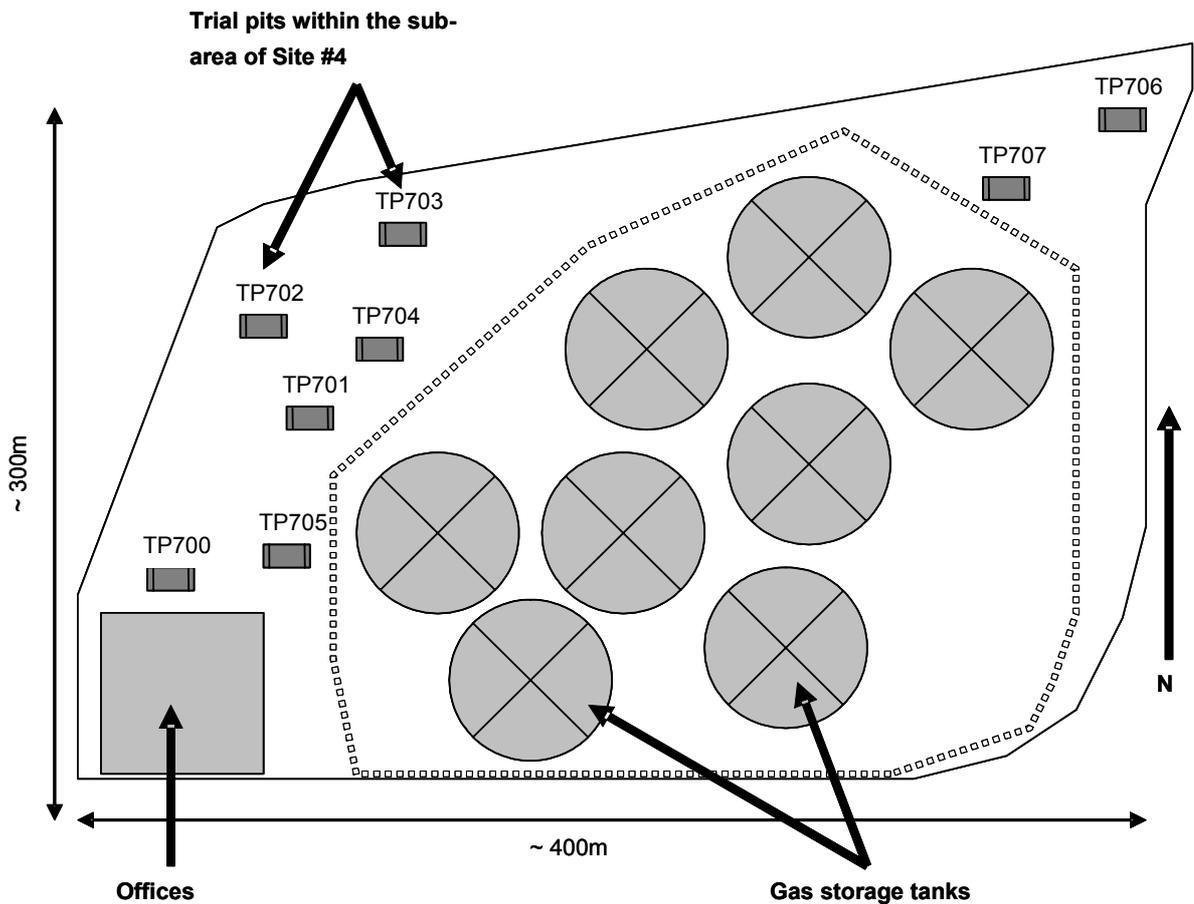
Figure 6.1: Schematic of Site 4 in London. Soil samples were removed from eight trial pits situated in the sub-area of land outside where the gas storage tanks are positioned.

6.2 INVESTIGATION OBJECTIVES AT SITE 4

The investigation at Site 4 represented another 'real-life' survey with which to evaluate the practicality and usefulness of the OCLI method. The sampling strategy was designed wholly by the commercial consultants with the general aim of assessing the levels of contamination at the site. Site 4 also provided contrasting characteristics to previous site investigations used for this project. For example, there are potentially two different consequence costs that may apply here. The first may occur due to litigation or a loss of corporate image if the site is redeveloped, but contamination is subsequently found (i.e. a 'false-negative' scenario). This is a high consequence cost. The second may also be experienced if areas of the site are unnecessarily remediated (i.e. a 'false-positive').

6.3 SAMPLING STRATEGY IMPLEMENTED AT SITE 4

The general sampling strategy at Site 4 employed a range of techniques to characterise the contamination present, such as boreholes, window sampling and trial pits. These techniques were employed by the consultancy within both the sub-area of land containing the gas storage tanks (Figure 6.1) and the surrounding sub-area that is the focus of this investigation.

Trial pits were chosen for the purpose of this research project for several reasons: (*i*) a sufficient number of sampling locations available to the University of Sussex (i.e. n ≥ 8) to apply to OCLI methodology, (*ii*) previous experience of implementing the Duplicate Method using this approach that allowed a comparison (i.e. Sites 1 and 2), and (*iii*) the University of Sussex personnel were only allowed access to the sub-area of land outside the central area containing the gas tanks.

Soil samples were taken at a variety of depths (e.g. 3 – 4 per pit) by the consultants at each of the eight trial pits ('TP 700' to 'TP 707'). The sampling strategy was similar to that used at Site 2 where soil samples were removed directly from the pile of material excavated from the trial pit. The consultancy sent a selection of soil samples to an external laboratory for analysis of organic and inorganic contaminants. All eight soil samples taken by the consultancy from the uppermost depth (0.5 m) of the trial pits were sent for analysis.

6.3.1 REMOVAL OF DUPLICATE SAMPLES

The aim of collecting duplicate samples (as part of the Duplicate Method) is to represent the repeatability of the sampling strategy. The soil samples were taken by the consultant by removing literally handfuls of soil from the pile of excavated material, that had been removed at a particular depth by the JCB, into sample containers. The removal of duplicate soil samples replicated this procedure but took the handfuls of soil as though approaching the pile from another direction, which was equally likely.

6.3.2 LABORATORY ANALYSIS

In order to estimate the analytical uncertainty, each of the eight duplicate samples taken by the University of Sussex and the corresponding eight samples taken by the consultancy, were analysed in duplicate (i.e. twice) by the same commercial laboratory. For the purposes of this project, only organic contaminants were measured because it was expected that they would present the most elevated concentrations, due to the site use, and therefore would be the key drivers for the risk assessment at this site.

6.4 ESTIMATES OF MEASUREMENT UNCERTAINTY

The estimates of uncertainty for the measurement of organic contaminants at Site 4 (Table 6.1) are particularly high (56% to 151%), and exceed the values evident at the previous sites (1 – 3). In most cases the sampling or sampling preparation procedures generated the majority of the measurement uncertainty, as has often proved to be the case in other contaminated land investigations. By contrast, for benzo(k)fluoranthene and chrysene, analytical procedures contribute around 80% to the measurement uncertainty, probably due to the proximity of the concentration to the respective analytical detection limit.

Table 6.1: Estimates of measurement uncertainty for the investigation at Site 4 (ranging from 56% to 151%).

Contaminant	Measurement uncertainty (U%)	Proportion of **analysis** to the total measurement variance	Proportion of **sampling** to total measurement variance
Total PAH (n=10)	89%	36%	64%
Benzo(a)pyrene	92%	26%	74%
Fluorene	128%	34%	66%
Naphthalene	128%	20%	80%
Indeno(123cd)pyrene	151%	20%	80%
Benzo(k)fluoranthene	56%	87%	13%
Chrysene	72%	77%	23%
Acenaphthene	123%	49%	51%

6.5 RESULTS FOR THE INVESTIGATION AT SITE 4

The measurements of polycyclic aromatic hydrocarbon (PAH) concentrations from soil samples taken from the eight trial pits at Site 4 are summarised below in Table 6.2. The elevated concentrations of PAH compounds measured during the investigation at Site 4 suggests the soil has been contaminated as a result of the gas related activities conducted at the site.

In the absence of an SGV at the time of interpretation, the Dutch Guideline values have been chosen here for comparison against the measured values of PAH concentration for the classification of either 'contaminated' or 'uncontaminated'. For example, if a measured concentration of total PAH exceeds the threshold, a significant risk of harm is identified and thus a classification of 'contaminated' is used.

The question of whether the quality of the measurements (i.e. high level of uncertainty) was acceptable for the investigation at Site 4 is evaluated using the OCLI method below.

Table 6.2: Measurements of 16 individual Polycyclic Aromatic Hydrocarbons (PAH) concentration in soil samples from a depth of 0.5 m in eight separate trial pits across Site 4. The results substantiate the presence of total PAH contamination above the Dutch intervention value of 40 mg kg^{-1}.

	Sample locations							
Contaminant	TP700	TP701	TP702	TP703	TP704	TP705	TP706	TP707
Acenaphthene	0.2	1.5	0.5	0.6	1.2	0.7	0.8	0.9
Acenaphthylene	0.2	0.6	3.5	0.2	3.5	8.9	1.0	0.3
Anthracene	*0.2*	*2.3*	*1.4*	*0.4*	*7.6*	*3.9*	*1.8*	*0.9*
Benzo(a)Anthracene	*1.1*	*5.4*	*5.8*	*1.2*	*23.6*	*16.4*	*7.0*	*1.7*
Benzo(a)pyrene	*1.1*	*7.9*	*6.9*	*1.0*	*23.6*	*21.8*	*7.3*	*1.7*
Benzo(b)fluoranthene	0.8	5.7	4.9	1.3	13.4	16.8	5.1	1.0
Benzo(k)fluoranthene	*0.7*	*4.9*	*5.9*	*1.0*	*19.8*	*15.3*	*5.3*	*1.4*
Benzo(g,h,i)perylene	*0.8*	*5.5*	*7.9*	*0.6*	*13.5*	*14.9*	*4.5*	*1.1*
Chrysene	*1.3*	*6.4*	*7.6*	*1.4*	*24.4*	*16.6*	*8.3*	*2.0*
Di-benzo(a,h)anthracene	0.2	1.2	0.2	0.5	1.0	2.0	0.7	0.2
Indeno(1,2,3-cd)pyrene	*1.3*	*7.9*	*12.7*	*0.8*	*14.5*	*25.6*	*8.6*	*1.6*
Fluoranthene	*2.1*	*12.1*	*16.7*	*2.9*	*56.7*	*36.2*	*19.6*	*5.1*
Fluorene	0.1	1.1	0.6	0.4	2.8	0.5	0.8	0.7
Naphthalene	*0.5*	*1.9*	*2.8*	*0.5*	*4.8*	*6.3*	*2.1*	*0.8*
Phenanthrene	*1.3*	*10.1*	*5.7*	*2.8*	*35.5*	*13.0*	*8.2*	*5.2*
Pyrene	1.8	10.4	20.4	2.3	44.4	38.4	18.0	4.1
Selected total PAH* (n=10)	10.2	64.3	73.1	12.4	224	169.8	72.6	21.3

*The Dutch guidance uses only ten of the selection of the PAH compounds measured at Site 4 for the comparison against the 'total PAH intervention' value of 40 mg kg^{-1} used here. These ten selected PAH compounds are highlighted in **italic bold** in Table 6.2.

6.6 APPLICATION OF THE OCLI METHOD

6.6.1 INTRODUCTION

Two applications of the OCLI method were applied to Site 4 using two contrasting remediation strategies that may be employed (i.e. false-negative and false-positive, Section 2.2). This approach provided an initial estimate of the financial risk for different potential end-uses of the site.

Unlike the interpretation applied for Site 3, where the entire site was considered as one single averaging area, the interpretation for Site 4 considers each individual sampling location. This is largely due to the greater area of the site and also the likelihood of more localised sub-areas of contamination resulting from point sources. The input parameters for the first application of the OCLI are given below.

6.6.2 COST OF MEASUREMENT

The **analytical cost** is taken from the charges given by the commercial laboratory of **£45 per sample analysis**. The **sampling costs** of **£100 per sample** have been estimated by dividing the total number of soil samples taken during this investigation (30) by the consultant's rate (£1200) and the equipment hire (£1800). The higher sampling costs for this investigation are due to the increased time required to complete the sampling (3 days).

6.6.3 CONTAMINANT CONCENTRATION

Site 4 is likely to be classified as being 'contaminated' since the mean value for total PAH of 81.0 mg kg^{-1} across these locations exceeds the Dutch intervention value of 40 mg kg^{-1} (i.e. sum of selected total PAH measurements / total number of trial pits = 648 mg kg^{-1} / 8). When considering individual sampling locations (Table 6.2), measured concentrations at three of the eight trial pits ('TP700', 'TP703' & 'TP707') fell beneath this threshold value. The concentration of total PAH that has been selected for the optimisation within the OCLI method is **13.0 mg kg^{-1}**. This aims to represent a typical value for the three measured concentrations of total PAH at these potentially misclassified trial pits.

6.6.4 THRESHOLD VALUE

The threshold value of **40 mg kg^{-1}**, taken from the Dutch values, was used within the OCLI method, because no SGV values were currently available for PAH at that time.

6.6.5 MEASUREMENT UNCERTAINTY

The measurement uncertainty was estimated at Site 4 using the Duplicate Method. The **analytical uncertainty** for measurements of total PAH was estimated by the ROBAN software as **20.4 mg kg^{-1}**. The **sampling uncertainty** was estimated as **27.0 mg kg^{-1}**. The **measurement uncertainty** can therefore be estimated using Equation 3 as **33.8 mg kg^{-1}**.

6.6.6 POTENTIAL COSTS ARISING FROM MISCLASSIFICATION

The first application of the OCLI method for Site 4 uses a cost of **£50,000 for each trial pit that is misclassified**. This value is an estimate of the costs that may be incurred from the subsequent unscheduled remediation and potential delays that may be incurred as a result of misclassification. For example, these costs may be incurred if contamination is subsequently found at the trial pits where the measured value of total PAH is below the threshold value.

6.7 APPLICATION OF THE OCLI METHOD TO REMEDIATION SCENARIO 1 AT SITE 4

The application of the OCLI method to the first remediation scenario at Site 4 (Figure 6.2) indicates that the level of measurement uncertainty for measurements of total PAH produces a potentially large loss for the locations that are misclassified. The actual uncertainty of 33.8 mg kg^{-1} total PAH that was estimated using the Duplicate Method produced an expectation of loss value of ~£11,000 per sample location misclassified. This gives a total expectation of loss of ~£33,000 for the three trial pits where this type of misclassification (i.e. a false-negative) may occur.

The optimal level of uncertainty of 11.2 mg kg^{-1} total PAH was estimated using the OCLI method. This corresponds to the minimal expectation of loss value of ~£1,700, or a total of ~£5,100 for the three trial pits in question.
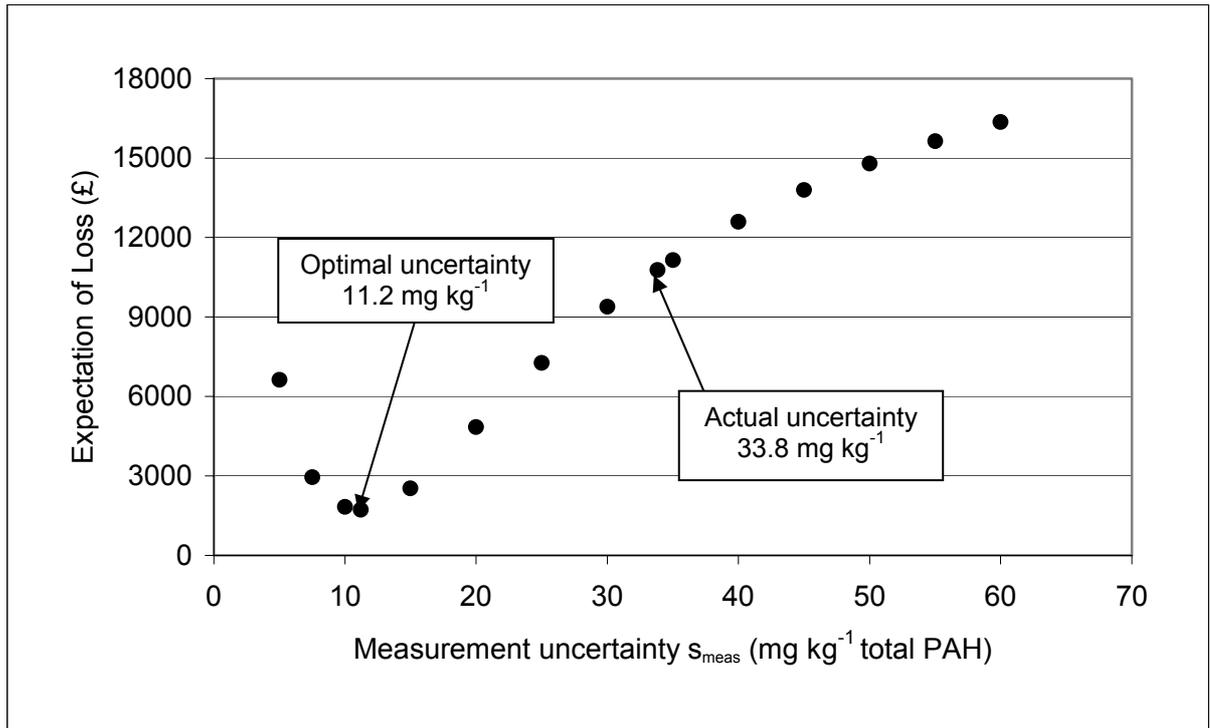
Figure 6.2: The OCLI curve for the first scenario at Site 4. An initial inspection of the OCLI curve for Scenario 1 at Site 4 shows that the probable loss of £11,000 at the actual uncertainty estimated during the investigation (33.8 mg kg^{-1} total PAH) is a factor of five times greater than the loss value (£1,700) for the optimal uncertainty value of 11.2 mg kg^{-1} (adapted from Boon _et al._, 2007).

6.8 APPLICATION OF THE OCLI METHOD TO REMEDIATION SCENARIO 2 AT SITE 4

The second application of OCLI for the measurements taken of total PAH at Site 4 is different in terms of the type of misclassification and the financial penalty caused by misclassification.

6.8.1 CONTAMINANT CONCENTRATION

A 'false-positive' misclassification is considered here for this application of the OCLI method. This misclassification occurs when the measured values exceed the threshold value (40 mg kg^{-1}) but the true concentration is actually beneath it. The choice of total PAH concentration has been chosen as **60 mg kg^{-1}** to represent the measured values at trial pits that could potentially be misclassified as 'contaminated' (i.e. 'TP701', 'TP702' and 'TP706').

6.8.2 FINANCIAL COSTS ARISING FROM MISCLASSIFICATION

A different cost has been chosen for the second application of OCLI at Site 4 that corresponds to the different misclassification scenario (e.g. a false-positive). The value of **£3,000 per location** has been used to estimate the low-value option of removing the pollutant linkage at these locations using fencing and soil barriers.

All of the other input parameters, such as the threshold value, measurement costs and measurement uncertainty, are the same as for the first application of the OCLI method at Site 4 (Section 6.7).
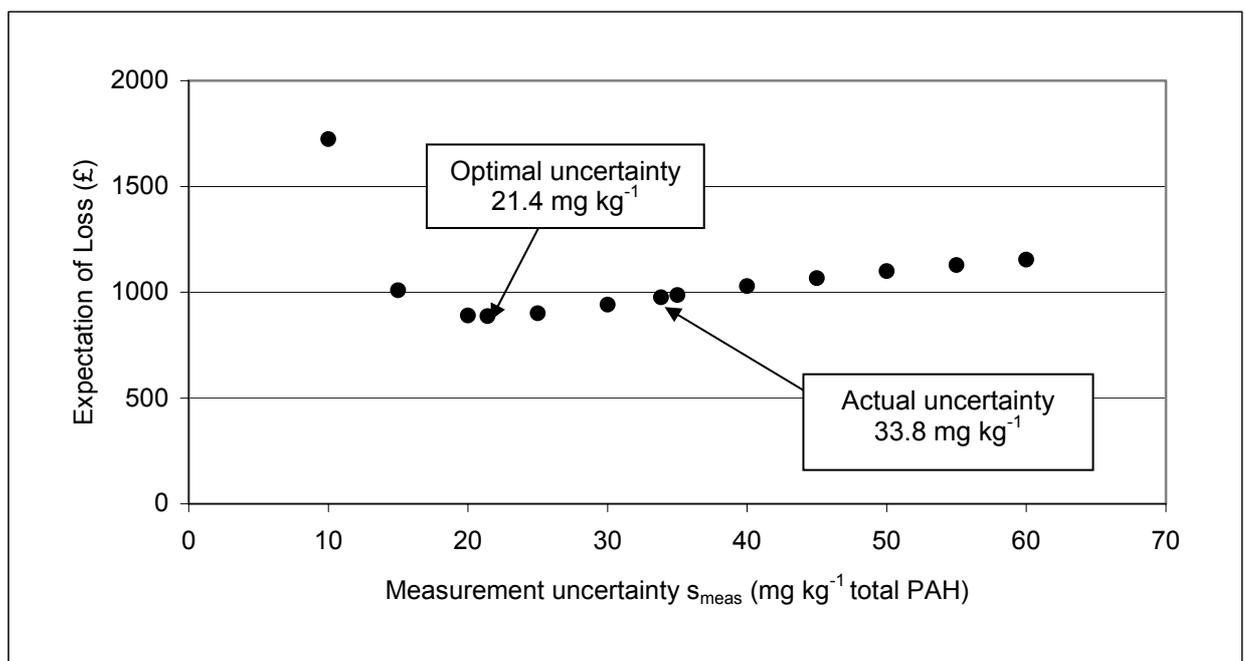
Figure 6.3: The OCLI curve for the second scenario at Site 4. The curve indicates that the actual uncertainty value of 33.8 mg kg^{-1} total PAH is in close proximity to the optimal value (21.4 mg kg^{-1}) for Scenario 2, where low-cost materials are used to remove the pollutant link. An inspection of the loss values at the actual and optimal uncertainty shows a small difference of only ~£90, which indicates that the data quality is acceptable.

The actual uncertainty value of 33.8 mg kg^{-1} is higher than the optimal of 21.4 mg kg^{-1}, which initially suggests that the measurements are not of an acceptable quality. A closer inspection of the loss values that are associated with the actual and optimal uncertainty values indicates only a relatively small difference. For example, the likely loss produced by the actual uncertainty of £980 per sampling location is only marginally greater than that at the optimal value of £890. The level of measurement uncertainty is therefore acceptable.

6.9 COMPARISON OF THE TWO APPLICATIONS OF THE OCLI METHOD FOR CONTRASTING REMEDIAL OPTIONS AT SITE 4

The two applications of the OCLI method for the investigation at Site 4 indicated that the same level of measurement uncertainty can provide substantially high losses (Scenario 1) or acceptably low losses (Scenario 2) depending on the type of misclassification, and more importantly, the financial implications of misclassification.

The false-negative misclassification, considered in Scenario 1, generated a likely loss of £11,000 per sampling location misclassified. Compare this to the substantially lower loss of only £980 per location for the second application of the OCLI method for the low-cost remediation scenario.

6.10 CONCLUSIONS FOR THE INVESTIGATION AT SITE 4

- The measurement uncertainty was estimated for measurements of organic contaminants as part of a routine commercial site investigation using the Duplicate Method. The measurement uncertainty for the range of contaminants measured was particularly high, ranging from ± 56% to ± 151%, which may substantially reduce the reliability of the decisions that are made at this site. For example, the true concentration of total PAH was within ± 89% of each individual measured value. It is likely that areas of land may be misclassified due to this uncertainty and lead to expensive financial penalties.
- The analytical uncertainty was particularly high in comparison to the uncertainty from the field sampling. This contrasts the other site investigations presented in this research where the field sampling is much greater than the uncertainty from the laboratory analysis.
- The OCLI method was applied to two contrasting remediation scenarios that may be taken at Site 4. The measurements of total PAH concentrations gave a high loss value of £11,000 per sampling location misclassified using the high-cost Scenario 1 where undetected contamination could lead to delays in site redevelopment. The same measurements, and uncertainty, of total PAH generated a much lower loss of only £980 per location when considering the alternative misclassification of a false-positive when using a low-cost remediation strategy.
- It has been demonstrated that the OCLI method provides the investigator and site owner with an estimate of the financial risk associated with different cost-options for remediation due to the measurement uncertainty. The OCLI method has also shown that the acceptability of the same measurements can differ substantially depending upon the subsequent actions that are taken at a site, even when a relatively high level of uncertainty is generated (89%).

6.11 LESSONS LEARNED DURING THE INVESTIGATION AT SITE 4

- The laboratory costs for analysis of organic contaminants are substantially greater than those for heavy metals, which were primarily considered for Sites 1 to 3 in this research. The substantial increase in laboratory costs may make the implementation of the Duplicate Method commercially unjustifiable.

  For example, if each analytical measurement cost £45 then the extra eight soil samples taken as part of the Duplicate Method adds an extra £360 to the investigation costs. If the full Duplicate Method is applied then each of the 16 soil samples are analysed twice (e.g. true analytical duplicates), which adds an extra £720 to the investigation. The extra cost incurred by estimating the measurement uncertainty may be justifiable given the substantial penalties that might be avoided to misclassification and subsequent decision errors. A lower-cost application of the Duplicate Method may be required at certain sites, however, and this is considered during the investigation at Site 5.

7.   SITE 5 – COLLIERY SPOIL IN NORTHERN ENGLAND

7.1   SITE DESCRIPTION

An area of potentially contaminated land, situated in the northeast of England, covered an area of approximately 115 hectares. The entire area was investigated by a commercial consultancy, and was divided into 18 separate zones corresponding to the variety of previous or current land uses, such as a sewage works, a street tip and abstraction pits for sand and gravel.

For this study (i.e. Site 5), two separate sub-areas of the site were considered. One sub-area was a former colliery spoil tip (Area C5) and the other sub-area a former railway siding (Area C4) (Figure 7.1). Both areas currently contain a mix of scrubby vegetation and woodland.
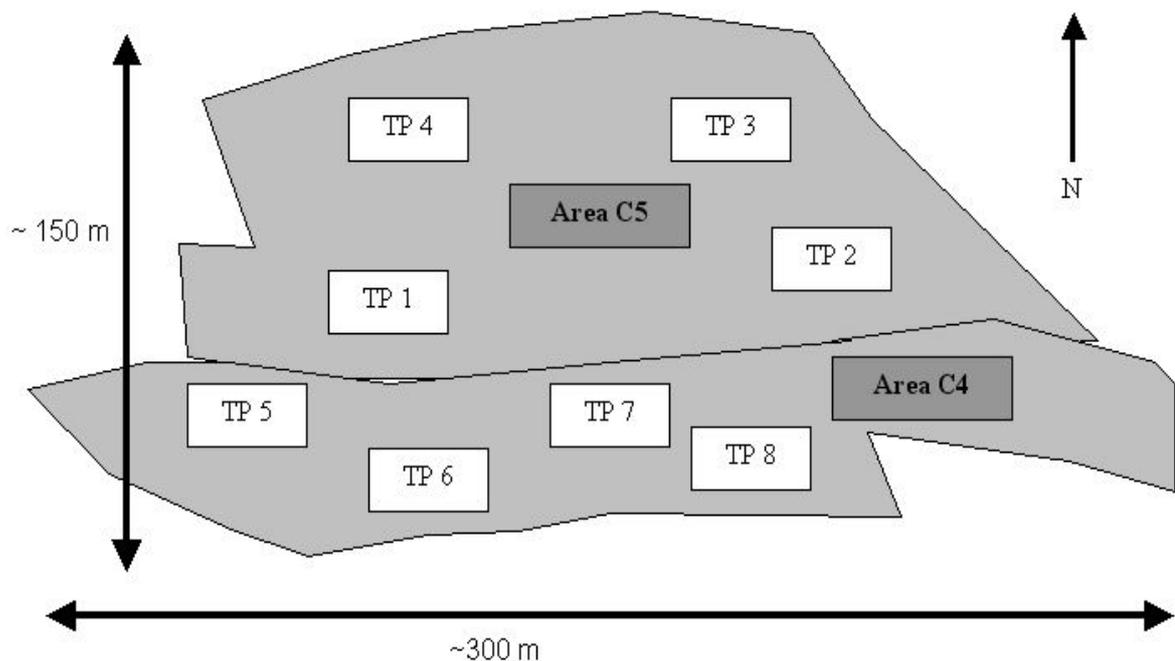
Figure 7.1: Map of Site 5 showing the location of the eight trial pits. The site consisted of two previous land uses. Area C4 was previously used as a railway siding and Area C5 as a colliery spoil tip.

7.2   INVESTIGATION STRATEGY

The sampling plan at Site 5, as for all of the sites, was wholly designed by the commercial consultancy and consisted of eight trial pits, four within each sub-area (Figure 7.1). Soil samples (approximate mass = 1 kg) were removed at two depths at each pit; one at approximately 0.2 m and another at approximately 1 m. The soil was sampled from the pile of material excavated by the JCB beside the trial pit.

The commercial sampler at this site used a method that was different from the other investigations used for this project where trial pits were dug. The sampler simply scraped the sample container alongside the pile of excavated material. Previous samplers at Site 1 and 4, although poor health and safety practice, had used their hands to remove grab-samples to make each field sample. The sampler at Site 2 had entered the trial pit (again poor safety practice) and taken soil samples directly from the wall using a rock hammer. By contrast, the sampling method here was surprisingly different for its indiscriminate approach.

For this investigation, the heavy metal concentrations in soil were investigated. The field samples were all chemically analysed by the same commercial laboratory.

7.3   ESTIMATION OF MEASUREMENT UNCERTAINTY

The Duplicate Method was employed at Site 5 in its most economical ('basic') design. Sample duplicates were taken at eight trial pits, at a range of depths (Appendix 1.5), but in contrast to other investigations used in this research, only single chemical analyses were performed (Figure 7.2).
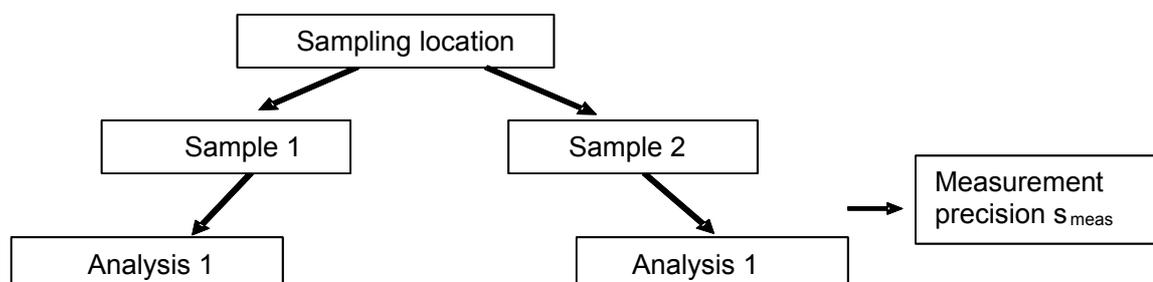
Figure 7.2: Illustration of the 'basic' Duplicate Method, which was applied at Site 5. Analytical duplicates are not analysed within the laboratory for the basic version of the Duplicate Method. The decision not to measure each soil sample in duplicate within the laboratory (as applied in the full Duplicate Method) was taken to minimise the extra costs required to apply the OCLI method at this low-cost site.

Implementation of the full Duplicate Method (Section 2.4) requires that sample duplicates are taken (typically n = 8) and each of these 16 field samples are analysed in duplicate (i.e. 32 chemical analyses). The decision to apply the 'basic' Duplicate Method (Figure 7.2) was based upon a number of criteria, (*i*) the site was 'low value' and the increased cost for including analytical duplicates (an extra 16 chemical analyses) would substantially increase the relative analytical costs for this site, (*ii*) taking sample duplicates would still provide an estimate of measurement uncertainty that includes both the field sampling and chemical analysis with minimal extra cost (i.e. eight additional measurements) and (*iii*) the analytical uncertainty, which is not quantified using this approach, is usually much smaller and less significant than the uncertainty generated by the field sampling (this has been shown for the other measurements of heavy metals at Sites 1, 2 and 3).

7.4   MEASUREMENT UNCERTAINTY

The ROBAN software was used to assess the measurements taken as part of the basic Duplicate Method (Figure 7.2). The analytical uncertainty was not estimated as part of this study because the soil samples taken as part of the (basic) Duplicate Method were not analysed twice. The estimate of measurement uncertainty therefore includes the contribution from both the field sampling and chemical analysis, but these cannot be separated. This is a consequence of applying the lower-cost, basic version of the Duplicate Method.

The particularly high levels of uncertainty (Table 7.1) may be due to high heterogeneity of the contamination, or as a result of the sampling method (Section 7.2). Expressed simply, the measured concentrations tended to differ more between samples taken from the same trial pit (i.e. sample duplicates) than differences in concentration between trial pits across the site. This is due to very high levels of contaminant heterogeneity within the sampling locations and relatively low variability between locations.

Table 7.1: Estimates of measurement uncertainty for the investigation at Site 5. Particularly high levels of uncertainty for measurements of heavy metal contamination were estimated at Site 5 (94% for nickel to 236% for lead). The threshold values, against which the measured concentrations are compared, are those used by the commercial consultancy at Site 5 (raw values are shown in Appendix 1).

Contaminant	Measurement uncertainty (U%)
Zinc	127%
Lead	236%
Nickel	94%
Arsenic	158%
Chromium	111%
Copper	211%

7.5   RESULTS FOR SITE 5

Interpretation of the measurements of heavy metals suggests that Site 5 would be classified as 'uncontaminated' since the majority of concentrations fall beneath their associated threshold values (Table 7.2). For example, the greatest measured concentration of lead is 156 mg kg^{-1} at trial pit location 7, is approximately a third of the Soil Guideline Value of 450 mg kg^{-1}.

Table 7.2: Measurements of heavy metal concentrations in eight selected soil samples taken at each of the eight trial pits at Site 5. All concentrations given in mg kg^{-1} (a full listing is given in Appendix 1.5).

Contaminant	Threshold Value	Trial pit number and depth (m)							
		TP1	TP2	TP3	TP4	TP5	TP6	TP7	TP8
		1.00	0.20	0.90	0.10	0.20	0.90	0.20	0.20
Arsenic	20	17.2	26.3	5.3	12.9	8.0	8.0	14.5	48.0
Boron	3	0.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Cadmium	30	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Chromium	200	36.5	16.0	17.5	18.0	16.5	18.0	15.5	14.5
Copper	190	27.5	105.0	15.5	24.0	26.5	25.0	136.0	50.5
Lead	450	32.0	153.0	18.5	46.0	35.0	86.0	156.0	30.5
Mercury	15	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.2
Nickel	75	28.5	33.0	13.2	15.8	19.5	17.5	43.5	19.0
Selenium	260	1.0	0.6	0.4	0.5	0.6	0.4	0.7	1.0
Zinc	720	51.5	81.5	74.0	34.0	72.5	102	111.5	37.0

7.6   CHOICE OF INPUT PARAMETERS FOR THE OCLI METHOD AT SITE 5

Site 5 contrasts with the other sites used for this research project because of its low financial value and particularly low measured concentrations and this is reflected in the application of the OCLI method.

7.6.1   COST OF MEASUREMENT

This value is estimated by adding the cost per laboratory analysis with the sampling costs. The **analytical costs** have been taken directly from the charges given by the commercial laboratory at **£12 per sample**. The **sampling cost** has been estimated as **£50 per sample** by dividing the approximate cost (£400 equipment hire + £300 consultant fee) by the number of field samples (14).

7.6.2   CONTAMINANT CONCENTRATION

At Site 5, the majority of measured concentrations fall substantially beneath their associated threshold values (Table 7.2). The mean arsenic concentration is, however, relatively close to the threshold value (SGV) of 20 mg kg^{-1} and therefore arsenic has been selected as the contaminant for the OCLI method at Site 5. The choice of concentration at which to optimise the system reflects the measurements that

may lead to a misclassification at the site. For example, the majority of measurements for arsenic concentration fall beneath the threshold value of 20 mg kg^{-1} although there are two locations where the concentration actually exceeds it (26 mg kg^{-1} at location 2 and 48 mg kg^{-1} at location 8). The value of **30 mg kg^{-1}** has been chosen to represent these values (although individual applications of OCLI could also be used).

7.6.3 THRESHOLD VALUE

The SGV for arsenic of **20 mg kg^{-1}** has been selected as the threshold value.

7.6.4 MEASUREMENT UNCERTAINTY

The **measurement uncertainty** (1 standard deviation) has been estimated by using the values taken as part of the 'basic' Duplicate Method as **16.4 mg kg^{-1} As**.

7.6.5 POTENTIAL COST ARISING FROM MISCLASSIFICATION

The site end-use will remain largely unchanged since the pathways of suspected contamination will be removed by creating a physical barrier by planting additional trees in such areas. The site's location is also remote which means that the public rarely use it for recreation.

The consequence cost used within the OCLI method at Site 5 is for a 'false-positive' misclassification (i.e. the 'true' concentration is actually beneath the threshold). The cost used here is £2,000, which is an estimate of the costs involved with replanting vegetation around these locations to remove the pollutant pathway.

7.7 APPLICATION OF THE OCLI METHOD

An initial inspection of the OCLI curve (Figure 7.3) indicates that the measurement uncertainty estimated during the investigation at Site 5 (16 mg kg^{-1}) is close to the optimal uncertainty value (8 mg kg^{-1}). The actual uncertainty for measurements of arsenic was calculated by the OCLI method to produce a probable loss of £592 for every location that is misclassified as being contaminated. The optimal level of uncertainty (8 mg kg^{-1}), which is half that of the actual uncertainty, produces a lower loss value of £421. The reduction in measurement uncertainty that is required to achieve the optimal value, from 16 mg kg^{-1} to 8 mg kg^{-1} (the optimal) would only reduce the loss value by £171 per location.
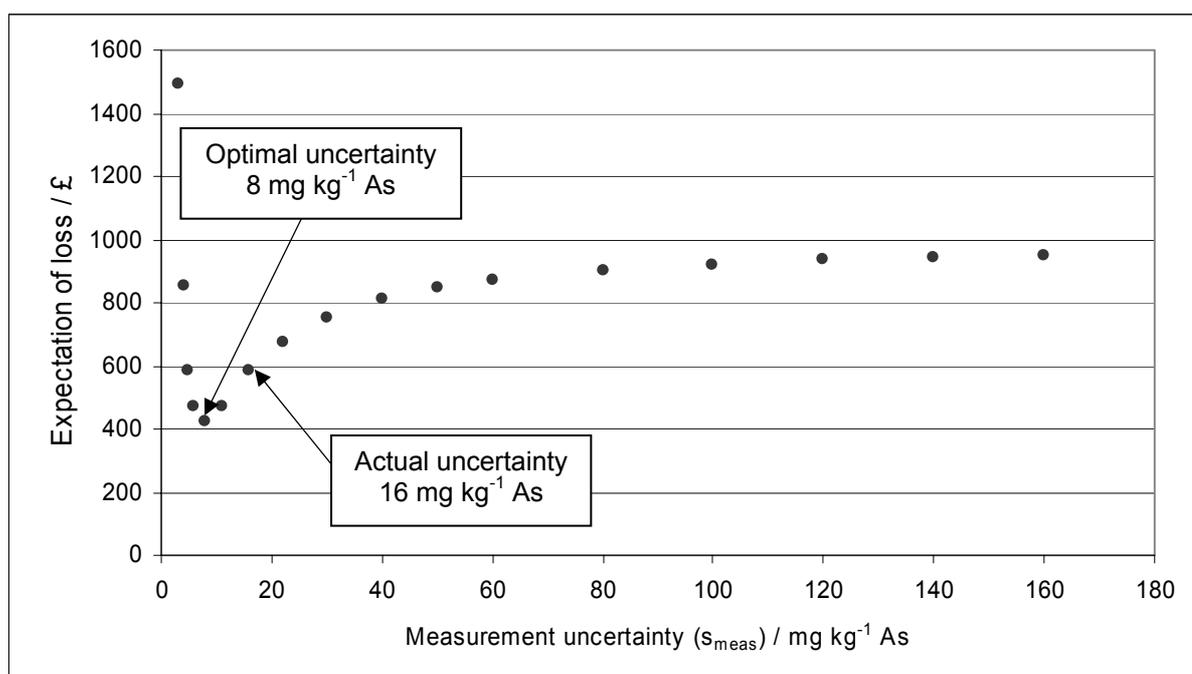
Figure 7.3: The OCLI curve for the site investigation at Site 5. The measurements taken at Site 5 are judged to be acceptable by the OCLI method, as the expectation of loss at the actual uncertainty is only £592 compared to £421 at the optimal.

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The reduction in uncertainty is predicted to be achieved by increasing the sample mass by a factor of 4 (Section 2.3.3). This assumes however that the uncertainty is dominated by the contribution from sampling so that Gy's sampling theory is applicable to this model (Gy, 1979). The relative contribution of field sampling and laboratory analysis cannot be quantified because the basic Duplicate Method was applied for the investigation at Site 5. It is arguable that the reduction in uncertainty is not necessary at Site 5 however due to the relatively small decrease in the loss values calculated by the OCLI method.

7.8   CONCLUSIONS FROM SITE 5

- The basic Duplicate Method has been applied at Site 5, a 'low-value' site, for the first time. The decision to use the basic Duplicate Method substantially reduced the extra costs that are necessary for the estimation of uncertainty. For example, only an additional eight sample measurements were made at Site 5. A full application of the Duplicate Method would have required an additional 24 measurements (8 duplicate samples + 16 analytical duplicates), which is difficult to financially justify at lower value sites, such as Site 5, or when analytical costs are particularly expensive (Site 4).

- Site 5 contrasted with other sites used for this research in that it was low-value in terms of the redevelopment/ remediation costs. Site 5 also presented a lower likelihood and extent of financial losses that might arise from misclassification because the majority of measured values were substantially less than their respective threshold values.

- The OCLI method has again provided objective, quantitative and cost-based information on the acceptability of the measurements taken during an investigation of contaminated land. The measured values of arsenic concentration were however in relatively close proximity to the threshold value (SGV) of 20 mg kg^{-1}, which may have led to a misclassification due to the high measurement uncertainty of ± 158%. The OCLI method indicated that the uncertainty associated with the arsenic measurements gave an expectation of loss of £592, for each location misclassified as being 'contaminated', or in need of a site-specific risk assessment (i.e. the true concentration is actually below the threshold value). The optimal level of uncertainty, which indicates the lowest loss value, was only £171 less than the actual uncertainty. The objective, and cost-based information provided by the OCLI method indicates that measurements with high uncertainty (e.g. ± 158%) can be acceptable at certain sites. This particular site is not generally contaminated with these metals, except for As, for which site-specific risk assessment using physiologically-based extraction testing (PBET) would be justified.

7.9   LESSONS LEARNED FROM THE INVESTIGATION AT SITE 5

- There was some difficulty in arranging the laboratory analysis of samples taken as part of the Duplicate Method at this, and other sites used for this research project. For example, reporting measured values that fall below the detection limit (discussed for Site 2, Section 4.8) would assist those using these methods. It has also been suggested by the Project Steering Group that a commercially available laboratory package may encourage consultancies to use these methods. The feasibility of establishing and using an 'OCLI laboratory package' is assessed during the final investigation at Site 6.

- Site 5 was the fourth site investigation that used trial pits as the main sampling strategy (also used during the investigations at Sites 1, 2 and 4). However, it is evident that the way in which samples are collected can differ greatly, even though the 'same' method of sampling is used (i.e. 'trial pits'). For example, soil was removed directly from the side of the trial pit wall, at specific depths, during the investigation at Site 1. The sampler at Site 5 however, took samples by scraping the sample container (plastic tub or glass jar) alongside the pile of material removed from the trial pit.

The differences in commercial sampling are an important discovery. It seems that there is little training given in field sampling and that more junior members of staff are often asked to complete this important activity. A measurement is only as good as the sample upon which it is based, and this is especially important in commercial investigations of contaminated land when considering all of the decisions and financial implications that are drawn from the site investigation.

8. SITE 6 – EX-FIRING RANGE IN WEST LONDON

8.1 SITE DESCRIPTION

Situated in West London, Site 6 is currently open to the public as a recreational park and nature reserve. The sub-area of Site 6 investigated for this study covers an area of 100 m × 100 m that has previously been used as a firing range during the First World War. The soil at the site is contaminated with heavy metals, primarily lead, as a consequence of this previous activity. The proposed end-use considered for this site is a housing development.

8.2 PREVIOUS MAIN INVESTIGATION AT SITE 6

The area of land used for Site 6 had previously been investigated as part of an academic study (Taylor, 2003), and this information was used with the OCLI method here to plan the supplementary survey for this study. It is common for investigations of contaminated land to have a number of sampling phases, each of which uses the information gained from the previous survey. Site 6 provided an opportunity to assess the advantages of applying the OCLI method during a multi-phased investigation.

The site had previously been investigated (i.e. the 'main investigation') for levels of heavy metals in soil using a regular-grid with 20 m sample spacing. Soil samples were removed to a depth of 0.15 m at each location using a hand auger. The results from this initial survey indicated that two distinct areas of the site were contaminated with lead (Figure 8.1). This interpretation is made using the criterion of lead concentration exceeding the Soil Guideline Value of 450 mg kg^{-1}.

Duplicate soil samples were also taken during the previous main investigation at Site 6, which were analysed in duplicate (i.e. a full application of the Duplicate Method – Section 2.4) within a laboratory at the University of Sussex. The uncertainty for measurements of lead was estimated by the ROBAN software as ± 83%.

Access to measurements taken during the main investigation, and the estimate of measurement uncertainty, provided an opportunity to apply the OCLI method *prior* to the planned supplementary survey (below). All of the previous five investigations used for this research have provided an estimate of the optimal level of uncertainty, which provides the lowest financial loss value, using the OCLI method. The conclusions from these site investigations, in terms of the OCLI method, are that the uncertainty often needs to be altered to provide a more acceptable level. The sampling strategy is usually cited as the most appropriate way to reduce the uncertainty, by increasing the sample mass (Section 2.3.3). The final investigation at Site 6 provides an opportunity to assess whether the sampling uncertainty can indeed be reduced to the optimal level of uncertainty.
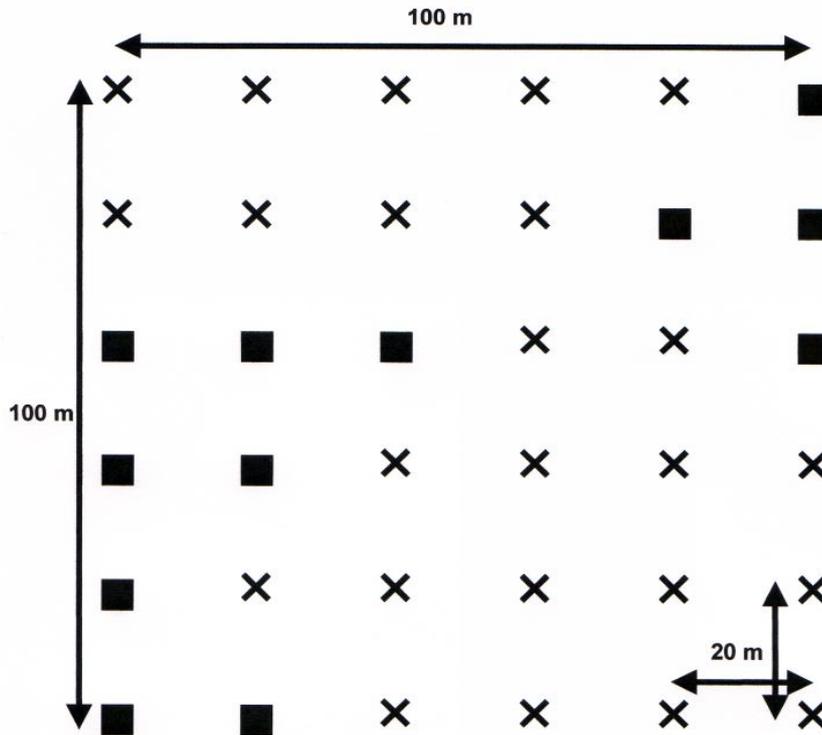
Figure 8.1: Diagram of the sampling pattern previously implemented for the main investigation of Site 6. The regular grid design had 36 sampling locations separated by a distance of 20 m. Sample locations with measured concentrations of lead that exceeded the threshold value of 450 mg kg^{-1} Pb are marked with an '■'. There are two distinct contaminant 'hotspots', where the threshold value is exceeded (Taylor, 2003).

8.3 INPUT PARAMETERS FOR THE APPLICATION OF THE OCLI METHOD FOR THE PREVIOUS MAIN INVESTIGATION AT SITE 6

8.3.1 COST OF MEASUREMENT

The **analytical cost** has been estimated as **£5 per sample**. This is a relatively low value since the analysis was performed by the laboratories at the University of Sussex and the analytical method was for lead, which does not require expensive materials or equipment. The sampling cost has been estimated as £14 per sample, which is based upon the total number of field samples divided by the 'day rate' of the samplers (£500 for 2 days).

8.3.2 CONTAMINANT CONCENTRATION

The value of lead concentration at which the system is optimised within OCLI has been chosen as **650 mg kg^{-1}** which represents measurements above the threshold (450 mg kg^{-1}) that may be misclassified.

8.3.3 THRESHOLD VALUE

The threshold value has been taken from the Soil Guideline Value for lead of **450 mg kg^{-1}**.

8.3.4 MEASUREMENT UNCERTAINTY

The **analytical uncertainty**, which was estimated from the measurements taken as part of the Duplicate Method during the previous main investigation at Site 6, was estimated as **13.8 mg kg^{-1} Pb**. The **sampling uncertainty** was estimated as **310.3 mg kg^{-1} Pb** (Appendix 1). The **measurement uncertainty** can therefore be estimated using Equation 3 as **310.6 mg kg^{-1}**.

8.3.5   COST ARISING FROM MISCLASSIFICATION

The OCLI method applied prior to the supplementary survey at Site 6 used the misclassification scenario of a 'false-positive' misclassification. A consequence cost of £80,000 per location was estimated for each sampling location that is unnecessarily remediated and used within this application of the OCLI method. This value is based upon the estimated cost of removing contaminated soil from around each sampling location for disposal at landfill. For example, removing contaminated soil from an area around each sampling location (40 m × 40 m grid) of 1600 m^2 to a depth of 0.3 m at £120 per tonne (for hazardous waste) gives a value of **£57,600** (assuming a soil density of 1.75 g cm^{-3}). The value of £80,000 used in this scenario also includes the extra cost of applying uncontaminated ground cover (i.e. clean soil) and construction fees.

8.4   APPLICATION OF THE OCLI METHOD FOR THE MEASUREMENTS TAKEN AT SITE 6 AS PART OF THE PREVIOUS MAIN INVESTIGATION

The OCLI method indicates that the measurements taken during the previous main investigation at Site 6 give a particularly high loss of over £20,000 per location misclassified. The optimal level of uncertainty of 60 mg kg^{-1} Pb is 5 times less than the actual level of uncertainty that was estimated during this investigation (310 mg kg^{-1}). Achieving the optimal level of uncertainty is financially justifiable given the large difference in loss calculated by the OCLI method. For example the optimal uncertainty gives a loss of only £450 for every location misclassified which is nearly 50 times less than that at the actual value.
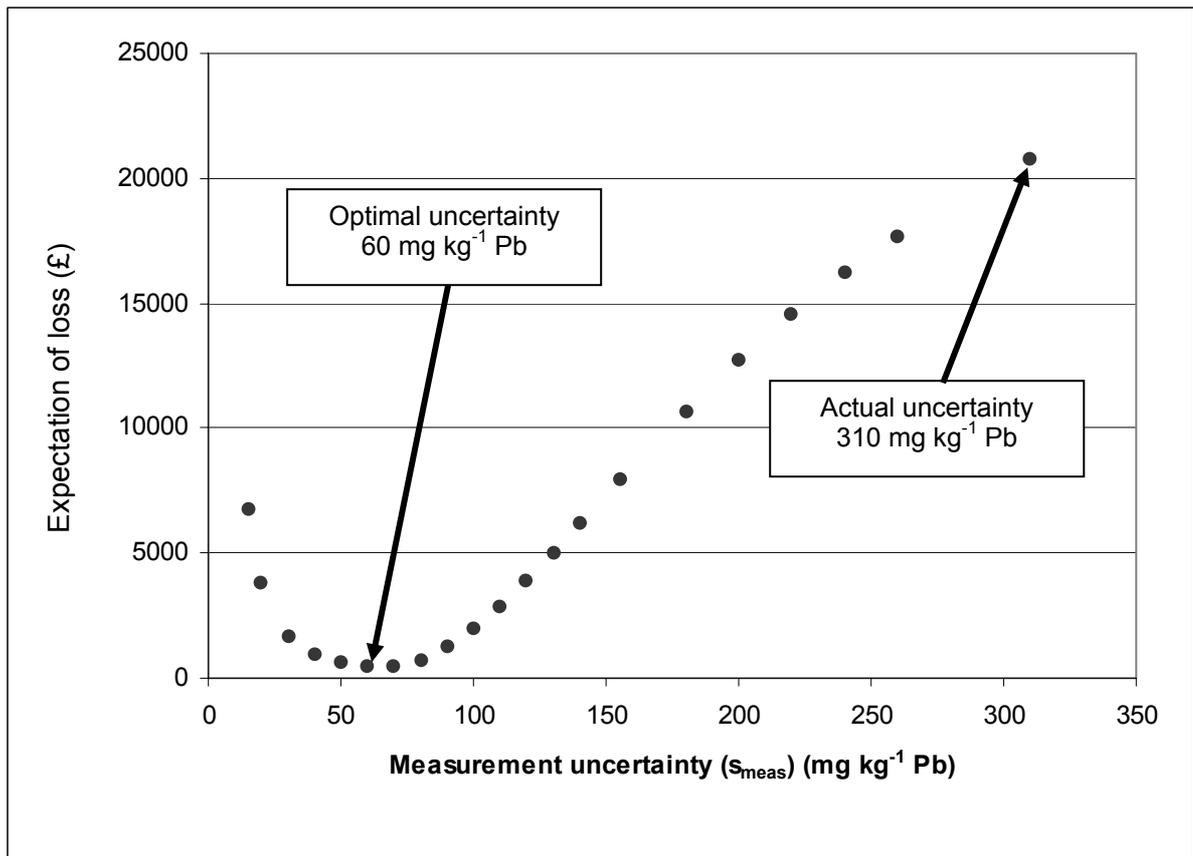
Figure 8.2: Application of the OCLI method for measurements taken as part of the previous main investigation at Site 6. The actual uncertainty gives an expectation of loss of approximately £21,000 per location misclassified, compared to only £450 at the optimum.

Clearly, achieving a more optimal level of measurement uncertainty at this site is vital given the costs involved. The information given by the OCLI method here for the previous main investigation (Figure 8.2) has been used to design the supplementary strategy at Site 6 with the aim of achieving a more optimal level of uncertainty. This is the first time that the OCLI method has been used to do this.

8.5 SUPPLEMENTARY SAMPLING STRATEGY AT SITE 6

8.5.1 OBJECTIVES

There are two main objectives for the supplementary sampling strategy at Site 6:

- To further delineate the two lead hotspots identified in the main investigation (Figure 8.1).

- To reduce the sampling uncertainty to a more optimal value (i.e. than that shown in Figure 8.2) and hence test the model used to predict such reductions (Section 2.3.3). The supplementary sampling design and its implementation were conducted by a commercial consultant in collaboration with the University of Sussex personnel.

8.5.2 SAMPLING DESIGN

The investigation presented here for this research project represents a 'supplementary' survey of Site 6, which was designed based upon the information derived from the main investigation (Figure 8.1). To satisfy Objective 1 of the supplementary sampling strategy at Site 6, additional soil samples were taken around the edges of the two hotspots uncovered during the initial site investigation (Figure 8.3). The supplementary survey was designed to confirm and refine the findings from the initial investigation and potentially to reduce the mass of soil that needs to be removed to remediate the contamination (i.e. the resolution of the lead hotspot is increased).
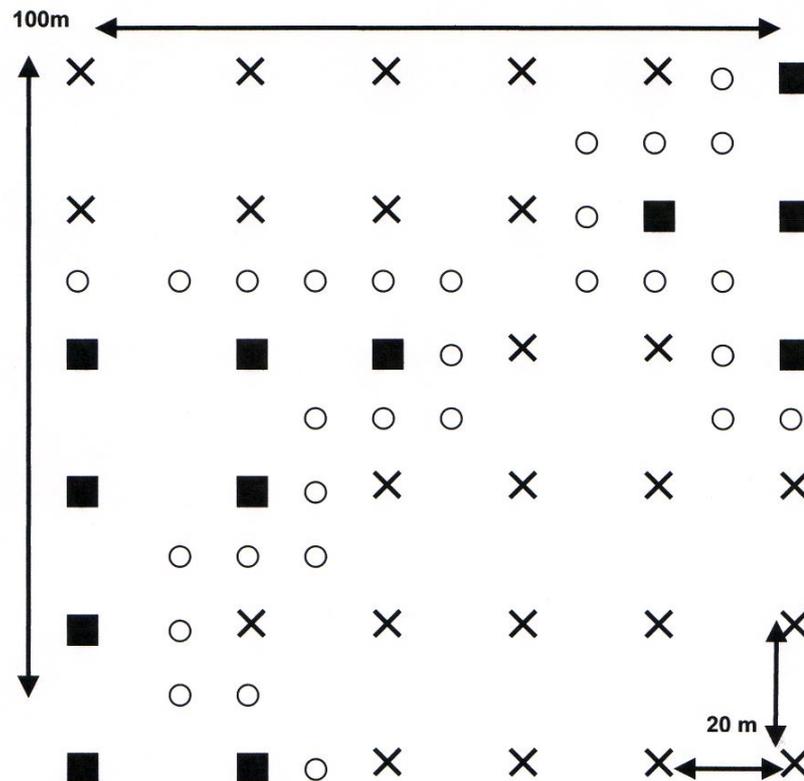
Figure 8.3: The sampling plan implemented for the supplementary survey at Site 6. A total of 29 additional sample locations (marked as 'o') were taken from Site 6 as part of the supplementary survey. The additional sample locations were designed to further delineate the two lead hotspots discovered by the initial site survey (locations with concentrations > 450 mg kg^{-1} Pb are marked by '■').

8.5.3 STRATEGY FOR THE REDUCTION OF SAMPLING UNCERTAINTY AT SITE 6

The second objective of the supplementary survey was to reduce the measurement uncertainty to a more acceptable/optimal level. A change in sampling uncertainty, which was the largest source of uncertainty in the previous main investigation survey (relative contribution to the total measurement

uncertainty = 95.6% sampling and 4.4% analytical), is predicted to be achieved by changing the sample mass collected. The OCLI method was applied before the supplementary survey was implemented (Figure 8.2) and estimated the optimal level of uncertainty (60 mg kg^{-1} Pb). It is predicted that a four-fold increase in sample mass will produce a decrease in sampling uncertainty of $\sqrt{4}$ (i.e. halving of the sampling uncertainty). Using the parameters from the OCLI application in Figure 8.2, halving of the actual level of uncertainty (from 310 mg kg^{-1} to 155 mg kg^{-1}) produces an expectation of loss of only £8000 per location (actual uncertainty = £21,000). A four-fold composite was chosen as it was predicted to significantly reduce the expectation of loss but did not require an excessive extra time to complete in the field.

To test this approach, four-fold sample composites were taken at each sample location during the supplementary survey (Figure 8.4). At each location, four sample increments were taken using a hand auger to a depth of 0.15 m and combined to form one single composite sample, i.e. all four sample increments were placed into the same sample container and sent to the laboratory.
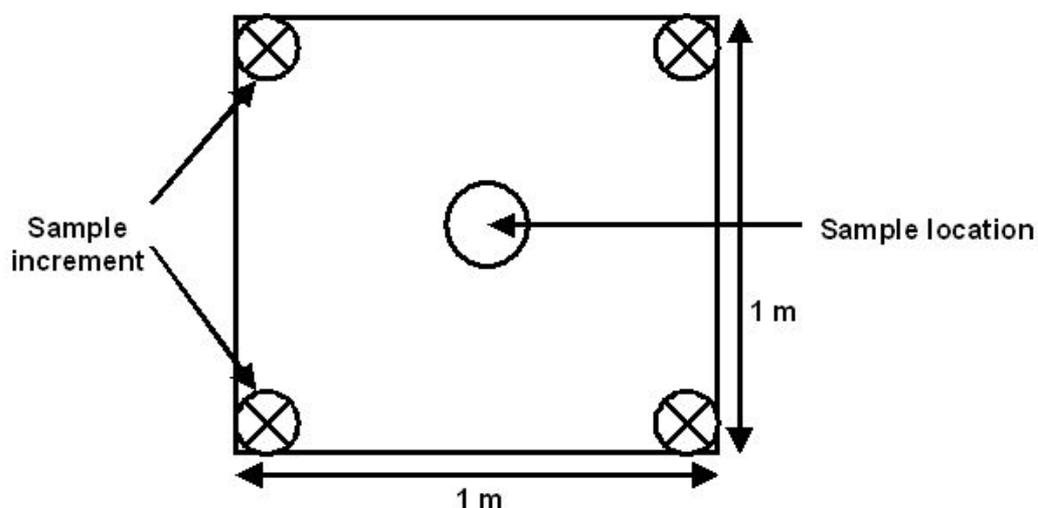
Figure 8.4: Schematic of how the four-fold composites were taken at Site 6. Four-fold sample composites were taken at each sampling location during the supplementary survey at Site 6. Each of the four-fold sample increments was taken by hand auger to a depth of 0.15 m around each sampling location and added together to form one individual sample.

8.6   DEVELOPMENT OF A COMMERCIAL OCLI LABORATORY PACKAGE

The soil samples taken from Site 6 were sent to a commercial laboratory (ALcontrol) for chemical analysis of heavy metals. ALcontrol laboratories were willing to test the feasibility of providing a commercially available OCLI laboratory package. For example, a correct application of the Duplicate Method would be adhered to. This included *i*) allocating duplicated chemical analyses on the duplicated samples, *ii*) reporting all measurements in unrounded and untruncated form (i.e. not reporting all values as 'less than detection limit') prior to the estimation of uncertainty. The test results would be reported in a format that allowed an easier interpretation and application of the robust analysis of variance software. The laboratory also analysed all solutions on three different days, but the interpretation of these readings is beyond the scope of this report.

8.7   ESTIMATION OF MEASUREMENT UNCERTAINTY FOR THE SUPPLEMENTARY SURVEY AT SITE 6

All eight of the top soil samples taken as part of the Duplicate Method were analysed in duplicate using the same digestion (analysis on day 1) to provide a full estimate of measurement uncertainty (i.e. both the field sampling and chemical analysis). A reduction in measurement uncertainty was expected for the supplementary survey when compared to the initial investigation due to the increase in sample mass.

A comparison of the uncertainty estimates between both investigations at Site 6 (Table 8.1) shows that a significant decrease in sampling uncertainty (-62%) has been achieved. This is close to the 50%

reduction predicted for the use of a four-fold composite (Section 8.5.3). However, inspection of the total measurement uncertainty (U%) indicates only a slight reduction in measurement uncertainty from ± 83% to ± 75%. It is important to remember that increasing the sample mass, by taking a four-fold composite in this scenario, is predicted to reduce the sampling uncertainty only, and should not affect the analytical uncertainty. One possible explanation for the relatively small decrease in total measurement uncertainty (from ± 83% to ± 75%) is the increase in analytical uncertainty (by 390%). This could be due to the change in selection of laboratory between the two surveys. The intended improvement in financial risk at Site 6 is assessed using the OCLI method.

Table 8.1: Comparison of the estimates of measurement uncertainty for the initial investigation and supplementary survey at Site 6.

Site investigation	Sampling SD / mg kg^{-1} Pb	Analytical SD / mg kg^{-1} Pb	Measurement SD / mg kg^{-1} Pb	Robust Mean / mg kg^{-1} Pb	Total U %
Main	310.8	13.8	311.1	748.8	83%
Supplementary	191.7	53.8	199.1	529.9	75%
% Change	-62%	390%	-56.3%	-41%	

8.8   RESULTS FOR THE SUPPLEMENTARY SURVEY AT SITE 6

The supplementary survey confirmed the presence of lead contamination at Site 6. The additional measurements taken during the supplementary survey also provided more information on the boundary of the two lead hotspots (Figure 8.5).
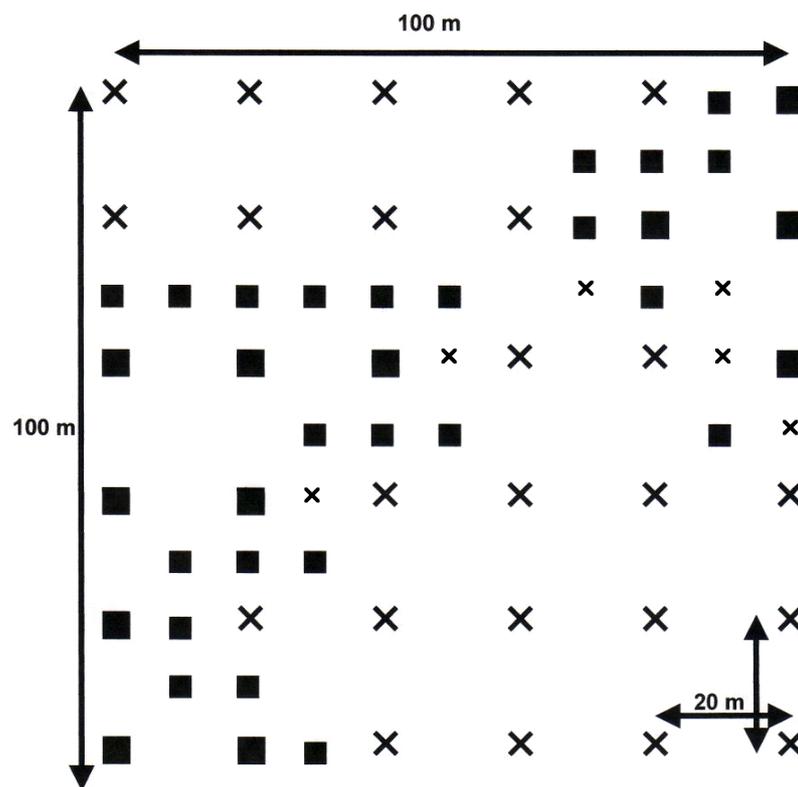
Figure 8.5: The supplementary survey conducted at Site 6 confirmed, and further delineated the lead hotspot identified during the previous main investigation. The supplementary sampling locations marked with a small '▪' indicate measured values that exceed the 'threshold' of 450 mg kg^{-1} Pb and those marked with a small 'x' do not.

8.9 INPUT PARAMETERS FOR THE OCLI METHOD FOR THE SUPPLEMENTARY SURVEY

The OCLI method has been applied to assess the improvement achieved by implementing the supplementary survey at Site 6.

8.9.1 COST OF MEASUREMENT

The costs of **sampling** were estimated as **£17 per sample** by dividing the consultant's day rate (£500) by the number of field samples (29). The **analytical costs** were taken directly from the charges given by the commercial laboratory at **£8 per sample**.

8.9.2 CONTAMINANT CONCENTRATION

The same type of misclassification error was considered for the investigation at Site 6 (i.e. a false-positive). The same concentration of **650 mg kg^{-1} Pb** used for the OCLI method for the previous main investigation at Site 6 (Section 8.5) was used again for this application.

8.9.3 THRESHOLD VALUE

The threshold (SGV) of **450 mg kg^{-1}** was again used at this site.

8.9.4 MEASUREMENT UNCERTAINTY

The values of measurement uncertainty that were estimated for the supplementary survey at Site 6 were used for this application of the OCLI method. The **analytical uncertainty**, calculated by the ROBAN software using the measurements taken as part of the Duplicate Method, is **53.8 mg kg^{-1}**. The **sampling uncertainty** is **191.7 mg kg^{-1}**. The **measurement uncertainty** can therefore be estimated using Equation 3 as **199.1 mg kg^{-1}**.

8.9.5 POTENTIAL FINANCIAL PENALTY DUE TO MISCLASSIFICATION

The value of **£35,000** was used to represent the cost of each sampling location that was misclassified as being contaminated and unnecessarily remediated. This was calculated as for the main survey but with a reduced volume of soil remediation per location.

8.10 APPLICATION OF THE OCLI METHOD FOR THE SUPPLEMENTARY SURVEY AT SITE 6

The measurement uncertainty (199 mg kg^{-1}) estimated for the supplementary survey at Site 6 still produced a relatively large loss of £5,537 for every location misclassified, when judged by the OCLI method (Figure 8.6). The optimal uncertainty (66 mg kg^{-1}) in comparison produces a much smaller value of £247 per location.

The aim for the use of a four-fold composite sampling (Section 8.6.2) was to reduce the sampling uncertainty, from the previous main investigation to the supplementary survey, by a factor of two (i.e. √4). According to the data from the previous main investigation this should have reduced the expectation of loss from £21,000 to £8,000 (Figure 8.2). The level of measurement uncertainty that was actually achieved during the supplementary survey (using the four-fold composite sampling) substantially reduced the expectation of loss by 76% from £21,000 to £5,537 per location. This reduction is due to the reduction in measurement uncertainty that was achieved during the supplementary survey but also to the reduction in remediation costs brought by the smaller sample spacing (i.e. the reduction from 40 m to 20 m sample spacing reduces the estimates of remediation costs from £80,000 to £35,000 per location).

The objective and cost-based information that is provided by the OCLI method has indicated that the reduction in uncertainty during the supplementary survey has produced a worthwhile reduction of financial risk of 76% at Site 6.
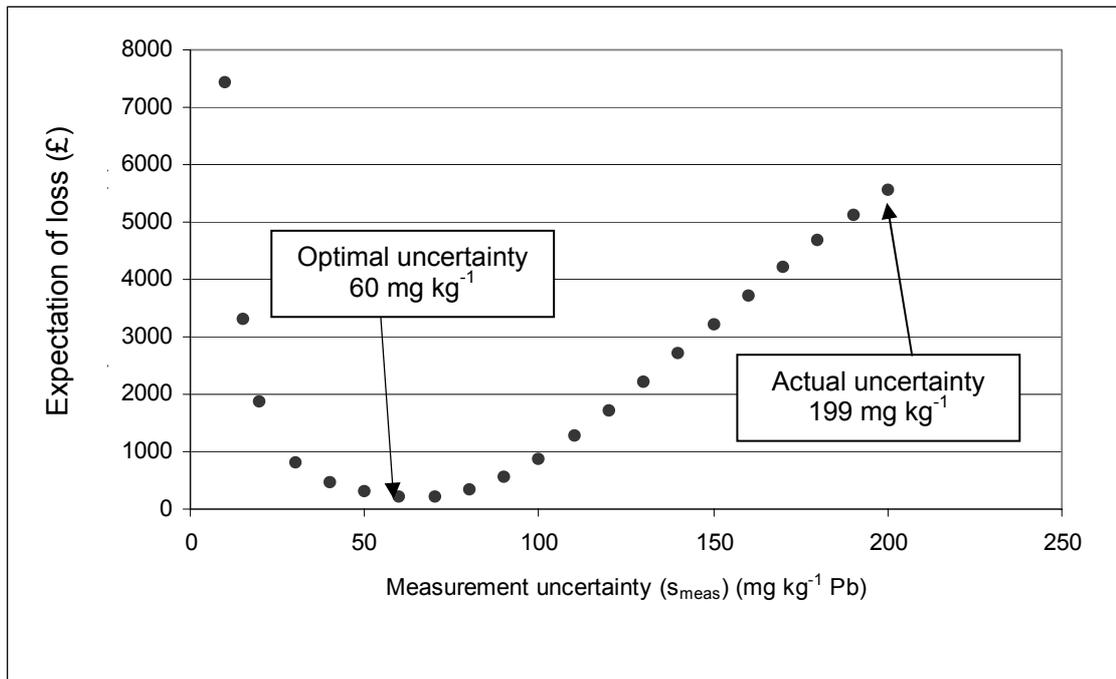
Figure 8.6: The OCLI method indicates that the uncertainty generated during the supplementary survey at Site 6 is not acceptable as the actual uncertainty gives an expectation of loss of £5,537 for each location compared to only £247 at the optimal. This loss is a significant reduction on the £21,000 for the previous Main Investigation (Figure 8.2)

8.11   CONCLUSIONS FOR SITE 6

- The Duplicate Method was successfully applied to the technique of auger sampling, allowing the estimation of measurement uncertainty with equal ease to previous applications of window and trial pit sampling.

- Estimates of uncertainty made during a preliminary or main investigation can be used to improve the design of subsequent surveys. For example, the OCLI method was applied ***prior*** to the supplementary survey at Site 6. The OCLI method used the uncertainty estimates from a previous main investigation undertaken at Site 6. The output from OCLI indicated that the measurement uncertainty was not acceptable with an expectation of loss of £21,000 per location misclassified and that increasing the sample mass using a four-fold composite would provide a more acceptable level of uncertainty (£8,000). This is the first time that the OCLI method has been used prior to a site investigation to improve the sampling strategy.

- The feasibility of producing a commercially available OCLI laboratory packaged was tested by collaborating with ALcontrol, who analysed the field samples from Site 6. It was substantially less time-consuming to communicate the exact analytical requirements to ALcontrol, than had been the case during previous case studies. The measurements of contamination were also reported in a much more 'user friendly' format that was suitable for use during routine investigations by commercial consultancies.

- The reduction of sampling uncertainty (by 50%), predicted for the four-fold composite implemented during the supplementary survey showed an actual decrease of 62%. The relatively small overall decrease in uncertainty (from 83% to 75%) between the two site investigations was due to the unexpected increase in analytical uncertainty generated during the supplementary survey.

- The OCLI method indicated that the supplementary survey gave a substantially reduced (76%) expectation of loss of £5,537 per location misclassified when compared against loss estimated by OCLI for the previous investigation at Site 6 of £21,000. This indicates that the use of the OCLI approach enabled an improved reliability and cost-effectiveness of the site investigation. This could lead up to £200,000 being saved in the redevelopment of this site.

8.12   LESSONS LEARNED AT SITE 6

- The laboratory package will help commercial consultancies implement the OCLI method.
- The sampling uncertainty can actually be reduced by using composite sampling, to an extent that is predicted by the theory (Section 2.3.3). The OCLI method can be used to design more suitable sampling strategies that reduce the potential financial losses.

9. PROJECT CONCLUSIONS AND SUMMARY

9.1 BROAD CONCLUSIONS

In terms of the individual Research Objectives (Section 1.2), it can be concluded that:

1. The Optimised Contaminated Land Investigation (OCLI) method has been successfully applied to a series of six contrasting contaminated land sites. The OCLI method has been proven to be a commercially valuable decision-support tool, as it is able to estimate the probable financial loss that might arise from the uncertainty of measurements taken to characterise contaminated land. The research has also demonstrated that the scientific methods used to estimate the measurement uncertainty (Duplicate Method) can be easily implemented to improve the reliability of routine commercial site investigations. Implementing the OCLI method before a supplementary site survey (Site 6) was shown to substantially reduce (76%) the expectation of loss from £21,000 to £5,500 per sampling location, resulting in a potential saving of £200,000 for the development of the site.
2. Feedback from key industry stakeholders, such as commercial consultancies and regulators, has been used to improve the performance and usefulness of the OCLI method. For example, a new laboratory package was assessed in site investigation 6, and a low-cost method for uncertainty estimation was used at Site 5.
3. The ROBAN software programme, that is used for the estimation of measurement uncertainty, is available as a Windows-based package. A prototype decision-support tool for OCLI has been developed as a user-friendly Excel spreadsheet.
4. The benefits of using the OCLI method has been publicized at a specially designed workshop conducted by the authors, at a variety of international conferences, within scientific and industry papers and within a new OCLI website.

9.2 SUMMARY OF RESULTS

- Measurement uncertainty can be easily estimated during routine investigations of contaminated land. The levels of measurement uncertainty can vary greatly between sites. In the six sites assessed the measurement uncertainty varied from ± 25% for lead concentrations at Site 3 to ± 236% for the same contaminant at Site 5. The uncertainty from the field sampling tended to be substantially greater than the contribution from the laboratory analysis. Currently, attention to measurement quality is usually confined to the chemical analysis only.
- The uncertainty can be estimated for different sampling methods, such as trial pits or window sampling. The way in which field samples are collected, even when using the same method (e.g. trial pits) was seen to vary greatly between different consultancies and individual samplers (Section 7.9). Often, junior members of staff are asked to complete the important field sampling, sometimes without adequate training.
- The analytical uncertainty was achieved using different commercial laboratories for each of the six site investigations. A new laboratory OCLI package, which should provide greater ease in applying these methods commercially, was implemented during the investigation at Site 6 (by ALcontrol labs).
- The small extra cost of applying the Duplicate Method, which is required to estimate the measurement uncertainty, was shown to be cost-effective (Table 9.1), by generating an overall cost saving of £18,112 at Site 1 and £15,010 at Site 2.
- The OCLI method provided objective evidence that a site investigation can produce appropriate levels of measurement uncertainty, even when a potentially costly decision error is considered, such as the £1m litigation penalty used for Site 3. This information can be used to justify the quality of the investigation to the stakeholders involved, such as the land owner or regulatory authority, and/or prove that a supplementary investigation at the site is not necessary.
- The OCLI method was shown to be a useful decision-support tool for the assessment of financial risk when considering different remedial options at a site. The investigation at Site 4 used two remediation strategies which resulted in substantially different potential losses (£84,144 and £6,840). This type of information derived from the OCLI method can be used to justify conducting further investigations at the site in order to reduce the uncertainty and thus financial risk, or used to choose the most cost-effective remedial strategy.

- At low-value sites (e.g. Site 5) a full implementation of the Duplicate Method to estimate the uncertainty may not be justifiable (e.g. an extra 8 field samples and 24 chemical analyses). The 'basic' Duplicate Method, where only an additional 8 field samples are taken and analysed, was shown to be cost-effective by providing a potential saving of over £4,000.
- Applying the OCLI method before completing a supplementary survey was shown to be particularly beneficial for the investigation at Site 6. The more optimal level of measurement uncertainty achieved during the supplementary survey, as identified and designed using the OCLI method, was shown to reduce the potential losses by £556,668.

Table 9.1 Summary of the six site investigations used for this research project.

Site	Area	Main type of contamination	Suspected source	Site end-use	Sampling method	Primary contaminant	Mean Value mg/kg	U%	Proportion of uncertainty due to analysis	Proportion of uncertainty due to sampling	OCLI input parameters*	Expectation of loss per location**	Expectation of loss across the site	Money saved***
1	80,000 m²	Heavy metal	Tin mining	Housing	Trial pits	Arsenic	2868	64	6%	94%	T = 400 mg/kg c = 500 mg/kg samp = £30 analysis = £10 C = £6,000 (unnecessary remediation)	£1,147	£18,352	£18,112
2	15,000 m²	Organic	Infill from waste originating at former gas works	Recreational land	Trial pits	Indeno(123) pyrene	13.8	51	7%	93%	T = 6.9 mg/kg c = 13.8 mg/kg samp = £50 analysis = £28 C = £65,625 (unnecessary remediation)	£1,571	£15,710	£15,010
3	810 m²	Heavy metal	Infill after WWII bombing	Garden and allotment	Window sampling	Lead	3204	25	4%	96%	T = 450 c = 2820 mg/kg samp = £50 analysis = £12 C = £1m (litigation)	£58	n/a	Measurements acceptable despite v. high potential costs (£1m). No further SI, and expenditure required
4	120,000 m²	Organic	Gas works	Hazard assessment	Trial pits	Total PAH	68.9	89	36%	64%	T = 40 mg/kg c = 13 mg/kg samp = £45 analysis = £100 C = 50,000 (a) C = 3000 (b)	£10,768 (a) £980 (b)	£86,144 (a) £7840 (b)	£84,144 (a) £6840 (b)
5	450,000 m²	Heavy metal	Railway sidings and colliery spoil	Nature reserve	Trial pits	Arsenic	17.5	158	Unable to separate as the 'basic' Duplicate Method was applied to reduce costs		T = 20 mg/kg c = 30 mg/kg samp = £50 analysis - £12 C = £2000	£592	£4,736	£4,448
6	10,000 m²	Heavy metal	Ex-firing range	Housing	Hand auger	Lead	2791	83 75	SI #1 = 4.4% SI #2 = 7%	95.6% 93%	T = 450 mg/kg c = 650 mg/kg samp = £17 analysis - £8 C = £35,000	SI #1 = £21,000 SI #2 = £5,537	£756,000 £199,332	£756,000 - £199,332 = £556,668

* The cost of field sampling (samp) and laboratory charges (analysis) are given per sample location.

** At the actual measurement uncertainty

***Money saved is calculated by subtracting the additional costs incurred by applying the Duplicate Method from the expectation of loss across the site, unless stated otherwise.

10. FUTURE WORK

1. Further work is required to test the application of the OCLI method during a wider range of commercial site investigations. Collaboration with the commercial consultancies in this research only allowed the authors access to investigation during the field sampling (i.e. to take the duplicate samples). The next stage of OCLI development would require collaboration throughout the investigation process, from the initial conceptual site model to the remediation strategy. The authors would collaborate during this investigation in an advisory role, to further assess the practical difficulties in using the OCLI during routine site investigations and extend studies to include greater emphasis on the third dimension (i.e. depth of contamination), organic contaminants (e.g. volatile organic compounds), on-site measurements, and zoning of sites. This collaboration would also provide more accurate values, such as remedial costs, within the OCLI method and a further assessment of the special laboratory package developed with ALcontrol during the investigation at Site 6.

2. The publicizing of the OCLI method (Project Objective 4) indicated substantial interest from a range of stakeholders, such as developers, consultancies and local authorities, both in estimating the measurement uncertainty and in applying the OCLI method. There is, however, a need to increase the motivation of investigators to actually use these methods. This may be accomplished by introducing legislation or guidance that requires the sampling and analytical uncertainty to be included within site reports. The financial benefits of using these methods, such as the savings from the reduction in possible losses or enabling better estimates of the remediation budget, should also provide additional motivation.

3. Another approach to encouraging the use of these methods is for a commercial laboratory to develop, adopt and market a fully OCLI-compatible package.

4. The OCLI method, and the ROBAN software that is used to quantify the measurement uncertainty, are currently presented separately within a Window and Excel-based formats. A more robust, and user-friendly software design is required if it is be made fully accessible and useful to practitioners.

5. The choice of contaminant concentration that is chosen within the OCLI still requires further work. Previous academic studies applied default values, such as 1.1 and 0.9 of the threshold value (Ramsey *et al.*, 2002) or values that aimed to actually represent the measured concentrations, such as the site mean (Taylor *et al.,* 2003). The investigations used in this research built upon these approaches by choosing values that represented the range of contaminant concentrations that were actually measured and that may lead to misclassification. The development for the choice of OCLI input values should be accomplished by trialling the OCLI method during a complete commercial site investigation (see Further Work #1).

6. The estimates of measurement uncertainty refer to individual measurements and do not implicitly include the uncertainty of the entire site investigation, which would also be useful. The ability to assess the 'whole-site uncertainty' in terms of potential financial losses, currently forms part of an ongoing PhD research studentship funded by this project.

7. In this study, the term 'sampling' uncertainty has been used to include contributions from all of the sources from soil heterogeneity, primary sampling and physical preparation of the sample in the field and laboratory (e.g. packing, storage, drying, grinding, splitting and subsampling). It was not possible to know the precise cause of the uncertainty, in order to reduce it, if required. In future it would be possible to design experiments to separate contributions from these different sources, and to identify where improvements can be made (e.g. Lyn *et al.*, 2003).

8. The case studies revealed that the quality of sampling in routine site investigations and physical sample preparations are often unsatisfactory, often due to poor training of samplers. Wider application of the Duplicate Method in routine site investigation will enable the quality of sampling to be quantified, and used as a training tool to monitor and improve the quality of site investigation practice (rather than just in terms of written procedures).

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GLOSSARY OF TERMS

Terms related to measurement in general:

(Expanded) uncertainty (U%): **The quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand.** *International Standards Organisation (ISO) (1993c). Guide to the expression of uncertainty in measurement. Geneva.*

Homogeneity, heterogeneity: **The degree to which a property or a constituent is uniformly distributed throughout a quantity of material. (Note: (1) A material may be homogeneous with respect to one analyte or property but heterogeneous with respect to another. (2) The degree of heterogeneity is the determining factor of sampling error**. *W. Horwitz (1990). "Nomenclature for sampling in analytical chemistry." Pure and applied chemistry 62 (6): 1193-1208.*

Increment: **An individual portion of material collected by a single operation of a sampling device. (Note: (1) Increments may be reduced individually or tested either (a) individually or (b) combined with other increments with the resulting composite reduced in size and tested as a single unit. (2) Increments are created by the sampling operation and are usually taken from parts of a lot separated in time or space. (3) Increments of a bulk population correspond to units of a packages population.** *W. Horwitz (1990). "Nomenclature for sampling in analytical chemistry." Pure and applied chemistry 62 (6): 1193-1208.*

Measurement: **A set of operations having the object of determining a value of a quantity.** *International Standards Organisation (ISO) (1993a). International vocabulary for basic and general terms in metrology, 2nd Edition. Geneva.*

Measurement uncertainty: **An estimate attached to a test result which characterises the range of values within which the true value is asserted to lie'.** W. Horwitz (1990). "Nomenclature for sampling in analytical chemistry." Pure and applied chemistry 62 (6): 1193-1208.

Precision: **The closeness of agreement between independent test results obtained under prescribed conditions.** *International Standards Organisation (ISO) (1993b). Statistics, vocabulary and symbols. Part 1. Probability and general statistical terms. Geneva.* **[The terms 'bias' and 'precision' can be used to describe the quality of the methods of measurement, whereas the terms 'uncertainty' and 'error' refer to individual measurements]**. *M.H. Ramsey (1998). "Sampling as a source of measurement uncertainty: techniques for quantification and comparison with analytical sources." Journal of analytical atomic spectroscopy 13: 97-104.*

Random error: **A component of the error, which in the course of a number of test results for the same characteristic, varies in an unpredicted way.** *International Standards Organisation (ISO) (1993b). Statistics, vocabulary and symbols. Part 1. Probability and general statistical terms. Geneva* **[When the sample population is normally distributed, random errors are quantified by precision as a standard deviation or a variance using statistical methods].**

Representative sample: **A sample resulting from a sampling plan that can be expected to reflect adequately the properties of interest in the parent population. The degree of representativeness of the sample may be limited by cost or convenience**. *British Standards Institution (1999). Soil quality - Part 1: Terminology and classification. BS 7755. Section 1.2: Terms and definitions relating to sampling. ISO 11074-2.*

Sample: **A portion of material selected to represent a larger body of material.** *W. Horwitz (1990). "Nomenclature for sampling in analytical chemistry." Pure and applied chemistry 62 (6): 1193-1208.*

Test sample: **The actual material weighed or measured for analysis.** *W. Horwitz (1990). "Nomenclature for sampling in analytical chemistry." Pure and applied chemistry 62 (6): 1193-1208.*

Terms related specifically to contaminated land investigations:

Contaminant: A substance which is in, on or under the land and which has the potential to cause harm or to cause pollution of controlled water. *Department of the Environment (1996). Part IIa of the environmental protection act 1990. Part II of the environment act 1995, Department of the Environment.*

Contaminated land: Any land which appears to the local authority in whose area it is situated to be in such a condition by reason of substances in, on or under the land, that – (a) significant harm is being caused or there is a significant possibility of such harm being caused; or (b) pollution of controlled waters is being, or is likely to be caused. *Department of the Environment (1996). Part IIa of the environmental protection act 1990. Part II of the environment act 1995, Department of the Environment.*

Composite Sample: Two or more increments/subsamples mixed together in appropriate proportions, either discretely or continuously (blended composite sample), from which the average value of a desired characteristic may be obtained. *British Standards Institution (1999). Soil quality - Part 1: Terminology and classification. BS 7755. Section 1.2: Terms and definitions relating to sampling. ISO 11074-2.*

Pathway: One or more routes or means by, or through, which a receptor: (a) is being exposed to, or affected by, a contaminant, or (b) could be so exposed or affected. *Department of the Environment (1996). Part IIa of the environmental protection act 1990. Part II of the environment act 1995, Department of the Environment.*

Receptor: Either (a) a living organism, a group of living organisms, an ecological system or a piece of property which is listed as a type of receptor and is being, or could be, harmed, by a contaminant, or (b) controlled waters which are being, or could be, polluted by a contaminant. *Department of the Environment (1996). Part IIa of the environmental protection act 1990. Part II of the environment act 1995, Department of the Environment.*

Risk: Defined as the combination of – (a) the probability, or frequency, of occurrence of a defined hazard (for example, exposure to a property of a substance with the potential to cause harm); and (b) the magnitude (including the seriousness) of the consequences. *Department of the Environment (1996). Part IIa of the environmental protection act 1990. Part II of the environment act 1995, Department of the Environment.*

Risk assessment: Assessment of damaging effects of a polluted site on man and the environment with respect to their nature, extent and probability of occurrence. *British Standards Institution (1997). Soil Quality Part 1: Terminology and classification. BS 7755. Section 1.1: Terms relating to the protection and pollution of soil. ISO 11074-1.*

Sampling: Process of drawing or constituting a sample. For the purpose of soil investigation, 'sampling' also relates to the selection of locations for the purpose of *in situ* testing carried out in the field without removal of material. *British Standards Institution (1999). Soil quality - Part 1: Terminology and classification. BS 7755. Section 1.2: Terms and definitions relating to sampling. ISO 11074-2.*

Sampling pattern: System of predetermined sampling points designed to monitor one or more specified sites. *British Standards Institution (1999). Soil quality - Part 1: Terminology and classification. BS 7755. Section 1.2: Terms and definitions relating to sampling. ISO 11074-2.*

Sample point (synonymous with sampling 'location'): Precise position within a sampling site or within each soil-constituting horizon from which samples are collected. *British Standards Institution (1999). Soil quality - Part 1: Terminology and classification. BS 7755. Section 1.2: Terms and definitions relating to sampling. ISO 11074-2.*

Significant Harm: Death, disease, serious injury, genetic mutation, birth defects or the impairment of reproductive functions. *Department of the Environment (1996). Part IIa of the environmental protection act 1990. Part II of the environment act 1995, Department of the Environment.*

Threshold or Guideline value: Value recommended by an authoritative body without legal obligation. *British Standards Institution (1997). Soil Quality Part 1: Terminology and classification. BS 7755. Section 1.1: Terms relating to the protection and pollution of soil. ISO 11074-1.*

APPENDIX 1 - GEOCHEMICAL MEASUREMENTS

1.1 SITE 1 – HOUSING DEVELOPMENT

Measurements of total arsenic concentration at 0.5 m depth / mg kg^{-1}				
Location	Sample 1		Sample 2 (duplicate)	
Trial pit	Analysis 1	Analysis 2	Analysis 1	Analysis 2
01	153	153	144	144
02	412	457	459	477
03	314	342	343	419
04	124	134	325	315
05	125	139	654	723
06	675	778	704	676
10	837	878	20428	19908
14	145	152	257	288

Measurements of total arsenic concentration at 1.5 m depth / mg kg^{-1}				
Location	Sample 1		Sample 2	
Trial pit	Analysis 1	Analysis 2	Analysis 1	Analysis 2
01	302	322	410	399
02	268	305	482	460
03	462	494	419	422
04	466	460	756	787
05	335	382	629	619
06	601	617	643	594
10	12471	13429	8553	8486
14	191	223	188	178

SITE 1 - UNCERTAINTY ESTIMATES
ROBUST ANALYSIS OF VARIANCE

0.5 m DEPTH (TRIAL PITS)

Mean = 410.52173
Standard Deviation (Total) = 277.1048

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	244.39531	126.66766	31.832525	130.60631
Percentage Variance	77.785319	20.89505	1.3196358	22.214687
Relative Uncertainty	-	61.710577	15.508327	63.629425
(% at 95% confidence				

1.5 m DEPTH (TRIAL PITS)

Mean = 484.75
Standard Deviation (Total) = 234.8636

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	167.79605	162.31419	25.680775	164.33319
Percentage Variance	51.042509	47.761894	1.1955969	48.957488
Relative Uncertainty	-	66.968208	10.595472	67.801213
(% at 95% confidence)				

1.2 SITE 2 - MEASUREMENTS OF CONTAMINANT CONCENTRATION TAKEN AS PART OF THE INVESTIGATIONS (GAS WORK WASTE)

Location	Chloride.	Arsenic (MS)	Cadmium (MS)	Chromium (MS)	CN- (total)
1	115.2	6.0	0.2	21.0	1.0
2	81.6	9.5	0.2	9.5	3.3
3	162.0	20.1	0.4	13.8	16.5
4	60.1	8.3	0.3	11.4	6.0
5	97.6	16.9	0.2	20.1	10.8
6	106.4	8.0	0.2	21.7	2.5
7	98.7	22.1	0.4	11.4	11.5
8	200.0	24.2	0.5	15.8	6.3

Location	Lead (MS)	Mercury (MS)	Nickel (MS)	pH units	SO4-- (acid sol)
1	37.2	0.1	49.2	8.9	773.0
2	61.1	0.3	16.4	9.9	2752.5
3	180.4	0.8	24.1	8.2	2562.5
4	343.8	0.3	21.0	8.5	20302.5
5	100.4	0.4	26.5	9.2	2957.5
6	167.9	0.2	8.3	10.5	1460.0
7	308.3	0.7	25.8	9.7	8280.0
8	299.9	0.7	21.1	10.2	3250.0

Location	TPH GCFID (AR)	Benzene	Toluene	Ethyl Benzene	Xylenes
1	647	<10	<10	<10	<20
2	627	<10	<10	<10	<20
3	1795.5	<10	<10	<10	<20
4	391.5	<10	<10	<10	<20
5	1600.25	<10	<10	<10	<20
6	855	<10	<10	<10	<20
7	2354.25	<10	<10	<10	<20
8	1166.25	<10	<10	<10	<20

Location	Acenaphthene	Fluorene	Phenanthrene	Anthracene	Fluoranthene	Pyrene
1	<1	<1	122.25	43.5	107.25	87.75
2	<1	<1	4.5	1.5	7.5	7
3	<1	<1	99	34.75	138.25	124
4	<1	<1	5.75	1.75	11.5	11
5	<1	<1	25.25	7.75	50.5	47.25
6	<1	<1	6.25	2.5	8.5	10.25
7	<1	<1	49.5	20.25	95.75	81
8	<1	<1	13.75	3.5	23.75	21.75

Location	Benzo(a)anthracene	Chrysene	Benzo(b)fluoranthene	Benzo(k)fluoranthene
1	31.5	36.25	29	19.25
2	3.5	3.5	2.5	2.5
3	52	57.5	60	32.5
4	6.75	7	7	5.75
5	21.5	24	30.5	17
6	4	5	5.25	4.75
7	47	49.5	60	26.5
8	11.25	13	14.5	10

Location	Benzo(a)pyrene	Indeno(123-cd)pyrene	Dibenzo(ah)anthracene	PHEHPLC
1	30.25	14.5	2.5	Trimethylphenols
2	2.5	2	>1	<0.3
3	53	32.75	6.5	<0.3
4	6.75	4.5	>1	<0.3
5	27.75	17.75	3.25	<0.3
6	5.75	3	>1	<0.3
7	51.25	26.75	6	<0.3
8	14	9.25	2	<0.3

Location	Phenol	Cresols	Xylenols	Total Phenols
1	<0.3	<0.3	<0.3	<1.2
2	<0.3	<0.3	<0.3	<1.2
3	<0.3	<0.3	<0.3	<1.2
4	<0.3	<0.3	<0.3	<1.2
5	<0.3	<0.3	<0.3	<1.2
6	<0.3	<0.3	<0.3	<1.2
7	<0.3	<0.3	<0.3	<1.1
8	<0.3	<0.3	<0.3	<1.2

MEASUREMENTS TAKEN AS PART OF THE DUPLICATE METHOD AT SITE 2

Indeno(123)pyrene

	S1A1	S1A2	S2A1	S2A2
1	10	9	19	20
2	2	2	2	2
3	41	42	23	25
4	7	7	3	1
5	17	15	19	20
6	3	3	3	3
7	27	26	28	26
8	9	8	10	10

Total PAH

	S1A1	S1A2	S2A1	S2A2
1	199	191	992	979
2	25	25	57	58
3	609	626	937	1072
4	108	104	83	0
5	273	268	341	371
6	59	66	70	70
7	498	548	633	608
8	140	140	173	168

Lead

	S1A1	S1A2	S2A1	S2A2
1	33.3	33.2	26.3	29.8
2	71.3	53.1	53.5	66.3
3	190.2	167.6	184.6	179.2
4	790.1	92.5	0.5	492.2
5	89.5	110.3	114.1	87.6
6	37.5	542.8	53.8	37.6
7	340.3	267.3	276.4	349.3
8	253.3	242.5	253.8	445

Arsenic

	S1A1	S1A2	S2A1	S2A2
1	7.5	5.4	5.5	5.5
2	8.5	8.4	10.5	10.5
3	21.8	21.5	18.7	18.5
4	10.1	1.0	11.5	11.2
5	15.3	16.2	17.9	18.2
6	9.6	9.2	6.1	7.2
7	25.2	26.7	18	18.6
8	23.4	23.5	24.4	25.4

Nickel

	S1A1	S1A2	S2A1	S2A2
1	58.3	57.1	41.7	39.8
2	19.3	18.7	14.2	13.2
3	16.8	17.5	28.8	33.4
4	20.4	23	26.7	13.8
5	31.3	30.5	20.8	23.5
6	5.7	7.6	10.8	9
7	22	25.9	27.4	27.7
8	21.2	22.6	20.4	20

Total petroleum hydrocarbons

	S1A1	S1A2	S2A1	S2A2
1	962	568	692	366
2	687	263	755	803
3	2230	312	2230	2410
4	743	328	485	10.0
5	1070	757	1785	2789
6	917	692	980	831
7	2670	1580	2640	2527
8	1330	784	1099	1452

Chromium

	S1A1	S1A2	S2A1	S2A2
1	24.5	22.7	18.9	18
2	11	9.5	9.1	8.2
3	9.3	9.8	17.7	18.5
4	12.2	12.4	15.6	5.6
5	23.1	18.2	17.9	21.1
6	15.5	15.4	30.7	25
7	9	9.2	14	13.2
8	16.6	16.1	15.1	15.3

SITE 2 - UNCERTAINTY ESTIMATES
ROBUST ANALYSIS OF VARIANCE

INDENO(123)PYRENE
Mean = 13.603139
Standard Deviation (Total) = 12.698133

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	12.219117	3.3268158	0.93169463	3.4548168
Percentage Variance	92.597638	6.8640079	0.53835336	7.4023617
Relative Uncertainty	-	48.912473	13.69823	50.794406
(% at 95% confidence)				

TOTAL PAH
Mean = 324.17651
Standard Deviation (Total) = 331.25415

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	320.90063	81.05162	13.517604	82.171104
Percentage Variance	93.846596	5.9868831	0.16652399	6.1534067
Relative Uncertainty	-	50.004622	8.3396565	50.695285
(% at 95% confidence)				

TOTAL PETROLEUM HYDROCARBONS
Mean = 1156.8099
Standard Deviation (Total) = 812.73529

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	671.7428	282.13617	360.13812	457.49347
Percentage Variance	68.313695	12.050894	19.635408	31.686301
Relative Uncertainty	-	48.77831	62.264009	79.095702
(% at 95% confidence)				

LEAD
Mean = 186.39999
Standard Deviation (Total) = 144.26831

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	129.77386	45.405895	43.708042	63.024506
Percentage Variance	80.915667	9.905642	9.1786931	19.084335
Relative Uncertainty	-	48.718773	46.897042	67.622862
(% at 95% confidence)				

NICKEL
Mean = 22.462502
Standard Deviation (Total) = 8.2458353

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	5.3027062	6.0983062	1.6388319	6.3146739
Percentage Variance	41.354787	54.695186	3.9500214	58.645205
Relative Uncertainty	-	54.297658	14.591713	56.224138
(% at 95% confidence)				

CHROMIUM
Mean = 15.575001
Standard Deviation (Total) = 6.1952271

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	4.6746492	3.9017329	1.1423551	4.0655251
Percentage Variance	56.935558	39.664373	3.4000692	43.06444
Relative Uncertainty	-	50.102507	14.669085	52.205777
(% at 95% confidence)				

ARSENIC
Mean = 14.390625
Standard Deviation (Total) = 8.4656353

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	7.9502325	2.8498538	0.58233738	2.9087427
Percentage Variance	88.194312	11.332509	0.47318422	11.805694
Relative Uncertainty	-	39.607088	8.0932882	40.425522
(% at 95% confidence)				

1.3 SITE 3 - GEOCHEMICAL MEASUREMENTS TAKEN (RESIDENTIAL GARDENS)

	CLIENT ID	BH1.1	BH1.1	BH1.1	BH1.1	BH1.1
	Depth (m)	0.1	0.1	0.75	0.75	3.0
DETERMINAND	LAB ID	326274	326274	326275	326275	326276
			Repeat		Repeat	
Arsenic	mg/Kg	45	45	30	29	30
Cadmium	mg/Kg	2.3	2.4	<1.0	<1.0	<1.0
Chromium	mg/Kg	92	99	23	24	735
Copper	mg/Kg	339	320	181	180	99
Lead	mg/Kg	13456	13129	5157	5198	70
Mercury	mg/Kg	6.8	7.6	3.5	3.2	0.12
Nickel	mg/Kg	32	33	20	21	441
Selenium	mg/Kg	4	5	<3	<3	<3
Zinc	mg/Kg	2564	2508	288	282	60
Loss on Drying						
Wt. loss on drying (% of wet)	%	8.0	-	9.6	-	4.9
Retained on 2mm sieve (% of dry)	%	49.7	-	34.2	-	25.5
	CLIENT ID	BH1.2	BH1.2	BH1.2	BH1.2	BH3
	Depth (m)	0.1	0.1	0.75	0.75	0.7
DETERMINAND	LAB ID	326277	326277	326278	326278	326279
			Repeat		Repeat	
Arsenic	mg/Kg	45	48	30	29	21
Cadmium	mg/Kg	2.7	3.0	<1.0	<1.0	<1.0
Chromium	mg/Kg	86	95	25	24	23
Copper	mg/Kg	310	336	215	219	113
Lead	mg/Kg	17445	19003	2093	2026	4371
Mercury	mg/Kg	7.0	6.9	4.4	4.1	3.7
Nickel	mg/Kg	35	40	20	19	19
Selenium	mg/Kg	4	4	4	3	<3
Zinc	mg/Kg	3643	4010	458	444	99
Loss on Drying						
Wt. loss on drying (% of wet)	%	9.9	-	12.6	-	9.8
Retained on 2mm sieve (% of dry)	%	40.8	-	34.4	-	27.8
	CLIENT ID	BH4	BH6.1	BH6.1	BH6.1	BH6.1
	Depth (m)	0.1	0.3	0.3	1.2	1.2
DETERMINAND	LAB ID	326280	326281	326281	326282	326282
				Repeat		Repeat
Arsenic	mg/Kg	27	30	27	18	20
Cadmium	mg/Kg	1.8	7.5	7.1	<1.0	<1.0
Chromium	mg/Kg	40	37	34	25	27
Copper	mg/Kg	138	264	245	28	27
Lead	mg/Kg	2245	1949	1725	52	67
Mercury	mg/Kg	5.0	9.7	9.4	0.27	0.24
Nickel	mg/Kg	28	30	27	20	18
Selenium	mg/Kg	4	<3	3	<3	<3
Zinc	mg/Kg	1518	852	784	47	61
Loss on Drying						
Wt. loss on drying (% of wet)	%	10.9	9.2	-	7.5	-
Retained on 2mm sieve (% of dry)	%	28.5	27.7	-	20.1	-

	CLIENT ID	BH6.2	BH6.2	BH6.2	BH6.2	BH7.1
	Depth (m)	0.3	0.3	1.2	1.2	0.5
DETERMINAND	LAB ID	326283	326283	326284	326284	326285
			Repeat		Repeat	
Arsenic	mg/Kg	28	28	21	22	38
Cadmium	mg/Kg	7.0	6.8	<1.0	<1.0	<1.0
Chromium	mg/Kg	38	37	28	27	29
Copper	mg/Kg	225	222	38	34	157
Lead	mg/Kg	1719	1729	47	45	1128
Mercury	mg/Kg	3.4	3.2	<0.10	<0.10	2.7
Nickel	mg/Kg	27	27	25	19	28
Selenium	mg/Kg	4	<3	<3	<3	3
Zinc	mg/Kg	979	967	55	52	440
Loss on Drying						
Wt. loss on drying (% of wet)	%	9.6	-	7.0	-	8.9
Retained on 2mm sieve (% of dry)	%	31.5	-	16.3	-	36.0
	CLIENT ID	BH7.1	BH7.1	BH7.1	BH7.2	BH7.2
	Depth (m)	0.5	1.3	1.3	0.5	0.5
DETERMINAND	LAB ID	326285	326286	326286	326287	326287
		Repeat		Repeat		Repeat
Arsenic	mg/Kg	39	19	19	34	30
Cadmium	mg/Kg	<1.0	<1.0	<1.0	<1.0	<1.0
Chromium	mg/Kg	31	27	25	24	23
Copper	mg/Kg	176	34	31	142	133
Lead	mg/Kg	1161	45	35	884	803
Mercury	mg/Kg	2.6	<0.10	<0.10	2.9	2.6
Nickel	mg/Kg	29	36	34	23	22
Selenium	mg/Kg	3	<3	<3	<3	<3
Zinc	mg/Kg	470	61	53	454	426
Loss on Drying						
Wt. loss on drying (% of wet)	%	-	10.9	-	8.5	-
Retained on 2mm sieve (% of dry)	%	-	19.5	-	21.0	-
	CLIENT ID	BH7.2	BH7.2	BH9	BH9	BH11
	Depth (m)	1.3	1.3	0.1	0.4	0.1
DETERMINAND	LAB ID	326288	326288	326289	326290	326291
			Repeat			
Arsenic	mg/Kg	24	23	26	6	14
Cadmium	mg/Kg	<1.0	<1.0	<1.0	<1.0	<1.0
Chromium	mg/Kg	26	29	32	37	53
Copper	mg/Kg	25	24	129	76	125
Lead	mg/Kg	27	29	1757	574	1086
Mercury	mg/Kg	<0.10	<0.10	3.4	1.7	2.6
Nickel	mg/Kg	21	23	19	15	24
Selenium	mg/Kg	<3	<3	3	<3	3
Zinc	mg/Kg	46	50	458	80	490
Loss on Drying						
Wt. loss on drying (% of wet)	%	12.9	-	7.1	7.2	7.6
Retained on 2mm sieve (% of dry)	%	9.2	-	17.4	11.0	13.6

DETERMINAND		CLIENT ID	BH11	BH13.1	BH13.1	BH13.1	BH13.1
		Depth (m)	1.3	0.05	0.05	0.5	0.5
		LAB ID	326292	326293	326293	326294	326294
					Repeat		Repeat
Arsenic	mg/Kg		11	26	28	17	17
Cadmium	mg/Kg		<1.0	<1.0	<1.0	<1.0	<1.0
Chromium	mg/Kg		47	34	34	49	49
Copper	mg/Kg		40	148	149	147	144
Lead	mg/Kg		42	1196	1240	1161	1196
Mercury	mg/Kg		0.12	2.9	3.4	3.8	3.7
Nickel	mg/Kg		25	23	23	25	25
Selenium	mg/Kg		<3	3	<3	<3	4
Zinc	mg/Kg		51	580	597	479	481
Loss on Drying							
Wt. loss on drying (% of wet)	%		8.7	12.6	-	6.8	-
Retained on 2mm sieve (% of dry)	%		9.7	11.7	-	17.9	-
		CLIENT ID	BH13.2	BH13.2	BH13.2	BH13.2	
		Depth (m)	0.05	0.05	0.5	0.5	
DETERMINAND		LAB ID	326295	326295	326296	326296	
				Repeat		Repeat	
Arsenic	mg/Kg		15	16	14	15	
Cadmium	mg/Kg		<1.0	<1.0	<1.0	<1.0	
Chromium	mg/Kg		50	50	46	48	
Copper	mg/Kg		148	142	139	149	
Lead	mg/Kg		1163	1134	995	1032	
Mercury	mg/Kg		3.3	3.2	2.9	3.2	
Nickel	mg/Kg		25	25	23	24	
Selenium	mg/Kg		3	3	<3	<3	
Zinc	mg/Kg		529	519	441	456	
Loss on Drying							
Wt. loss on drying (% of wet)	%		11.6	-	7.9	-	
Retained on 2mm sieve (% of dry)	%		7.4	-	20.6	-	

MEASUREMENTS TAKEN AS PART OF THE DUPLICATE METHOD AT SITE 3

Lead

	S1A1	S1A2	S2A1	S2A2
1	13356	13129	17445	19003
2	5157	5198	2093	2026
3	1949	1670	1719	1729
4	55	57	47	45
5	1128	1161	884	803
6	45	35	27	29
7	1196	1240	1163	1134
8	1161	1196	995	1032

Nickel

	S1A1	S1A2	S2A1	S2A2
1	32	33	35	40
2	20	21	20	19
3	30	27	27	27
4	20	18	25	19
5	28	29	23	22
6	36	34	21	23
7	23	23	25	25
8	25	25	23	24

Copper

	S1A1	S1A2	S2A1	S2A2
1	339	320	310	336
2	181	180	215	219
3	264	245	225	222
4	28	28	38	34
5	157	176	142	133
6	34	31	25	24
7	148	149	148	142
8	147	144	139	149

Mercury

6.	S1A1	S1A2	S2A1	S2A2
1	8	7.6	7	6.9
2	3.5	3.2	4.4	4.1
3	9.7	9.4	3.4	3.2
4	0.3	0.2	0.1	0.1
5	2.7	2.6	2.9	2.6
6	0.1	1.0	1.0	1.0
7	2.9	3.4	3.3	3.2
8	3.8	3.7	2.9	3.2

Arsenic

	S1A1	S1A2	S2A1	S2A2
1	45	45	45	48
2	30	29	30	29
3	30	27	28	28
4	18	20	21	22
5	38	39	34	30
6	19	19	24	23
7	26	28	15	16
8	17	17	14	15

Zinc

	S1A1	S1A2	S2A1	S2A2
1	2564	2508	3643	4010
2	288	282	548	444
3	852	784	979	967
4	47	61	55	52
5	440	470	454	426
6	61	53	46	50
7	580	597	529	519
8	479	481	441	456

Chromium

	S1A1	S1A2	S2A1	S2A2
1	7.8	8.5	20.7	20.7
2	64.5	75	118.9	118.9
3	136.2	142.2	118.3	118.3
4	10	7.8	45.8	45.8
5	303	500.5	213.3	213.3
6	187.9	154.5	359.8	359.8
7	62.3	115.6	75.8	75.8
8	19.3	46.1	26.8	26.8

SITE 3 UNCERTAINTY ESTIMATES
ROBUST ANALYSIS OF VARIANCE

LEAD
Mean = 1585.5403
Standard Deviation (Total) = 1673.6908

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	1661.6561	196.01053	41.467976	200.349
Percentage Variance	98.567076	1.3715396	0.061386834	1.4329265
Relative Uncertainty	-	24.724762	5.2307691	25.272016
(% at 95% confidence)				

COPPER
Mean = 156.19342
Standard Deviation (Total) = 108.7168

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	107.46833	15.150409	6.3533115	16.428617
Percentage Variance	97.716457	1.9420276	0.34151282	2.2835406
Relative Uncertainty	-	19.399548	8.1351846	21.036248
(% at 95% confidence)				

ARSENIC
Mean = 26.342636
Standard Deviation (Total) = 9.4885778

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	8.9238348	3.0139463	1.1464752	3.2246361
Percentage Variance	88.450608	10.08948	1.4599134	11.549394
Relative Uncertainty	-	22.882648	8.7043316	24.482258
(% at 95% confidence)				

CHROMIUM
Mean = 115.71797
Standard Deviation (Total) = 122.19055

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	116.6058	36.28336	4.1394563	36.518726
Percentage Variance	91.067849	8.8173834	0.1147655	8.9321495
Relative Uncertainty	-	62.709982	7.1543879	63.116776
(% at 95% confidence)				

NICKEL
Mean = 25.25351
Standard Deviation (Total) = 5.0776396

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	3.8731542	3.0337787	1.2559007	3.2834585
Percentage Variance	58.184303	35.698014	6.1176821	41.815696
Relative Uncertainty	-	24.026591	9.9463462	26.003978
(% at 95% confidence)				

MERCURY
Mean = 3.4437499
Standard Deviation (Total) = 2.7529945

	Geochemical	Sampling	Analysis	Measurement
	-----------	--------	--------	-----------
Standard Deviation	2.7116916	0.42236167	0.21752846	0.47508737
Percentage Variance	97.02192	2.3537388	0.62434041	2.9780792
Relative Uncertainty	-	24.529172	12.633232	27.591282
(% at 95% confidence)				

ZINC
Mean = 486.02914
Standard Deviation (Total) = 406.87512

	Geochemical	Sampling	Analysis	Measurement
	-----------	--------	--------	-----------
Standard Deviation	397.80417	83.902206	16.113316	85.435471
Percentage Variance	95.590858	4.2523056	0.15683664	4.4091425
Relative Uncertainty	-	34.525587	6.6305964	35.156522
(% at 95% confidence)				

1.4   SITE 4 - MEASUREMENTS OF CONTAMINATION (GAS WORKS)

	Sample locations							
Contaminant	TP700	TP701	TP702	TP703	TP704	TP705	TP706	TP707
Acenaphthene	0.2	1.5	0.5	0.6	1.2	0.7	0.8	0.9
Acenaphthylene	0.2	0.6	3.5	0.2	3.5	8.9	1.0	0.3
Anthracene	*0.2*	*2.3*	*1.4*	*0.4*	*7.6*	*3.9*	*1.8*	*0.9*
Benzo(a)Anthracene	*1.1*	*5.4*	*5.8*	*1.2*	*23.6*	*16.4*	*7.0*	*1.7*
Benzo(a)pyrene	*1.1*	*7.9*	*6.9*	*1.0*	*23.6*	*21.8*	*7.3*	*1.7*
Benzo(b)fluoranthene	0.8	5.7	4.9	1.3	13.4	16.8	5.1	1.0
Benzo(k)fluoranthene	*0.7*	*4.9*	*5.9*	*1.0*	*19.8*	*15.3*	*5.3*	*1.4*
Benzo(g,h,i)perylene	*0.8*	*5.5*	*7.9*	*0.6*	*13.5*	*14.9*	*4.5*	*1.1*
Chrysene	*1.3*	*6.4*	*7.6*	*1.4*	*24.4*	*16.6*	*8.3*	*2.0*
Di-benzo(a,h)anthracene	0.2	1.2	0.2	0.5	1.0	2.0	0.7	0.2
Indeno(1,2,3-cd)pyrene	*1.3*	*7.9*	*12.7*	*0.8*	*14.5*	*25.6*	*8.6*	*1.6*
Fluoranthene	*2.1*	*12.1*	*16.7*	*2.9*	*56.7*	*36.2*	*19.6*	*5.1*
Fluorene	0.1	1.1	0.6	0.4	2.8	0.5	0.8	0.7
Naphthalene	*0.5*	*1.9*	*2.8*	*0.5*	*4.8*	*6.3*	*2.1*	*0.8*
Phenanthrene	*1.3*	*10.1*	*5.7*	*2.8*	*35.5*	*13.0*	*8.2*	*5.2*
Pyrene	1.8	10.4	20.4	2.3	44.4	38.4	18.0	4.1
Selected total PAH (n=10)*	10.2	64.3	73.1	12.4	224	169.8	72.6	21.3

MEASUREMENTS TAKEN AS PART OF THE DUPLICATE METHOD AT SITE 4

Total PAH

	S1A1	S1A2	S2A1	S2A2
1	6.4	6.5	13.6	14.2
2	52.3	55.2	70.2	79.4
3	99	96.5	36.1	59.6
4	8.1	6	3.7	31.6
5	247.4	368.4	133.7	146.3
6	148.8	109.3	187.9	233.2
7	50.1	85.5	112.2	42.6
8	15.2	33.9	17.6	18.5

Indeno(1,2,3,c-d)pyrene

	S1A1	S1A2	S2A1	S2A2
1	0.6	0.6	2.6	1.2
2	3.5	4.5	15.2	8.3
3	11.8	11.5	7.6	19.7
4	0.5	0.4	1.0	1.4
5	17.5	22.8	8.5	9.1
6	15.0	11.3	54.1	21.9
7	2.9	5.1	23.2	3.3
8	0.9	2.0	2.6	1.0

Benzo(a)pyrene

	S1A1	S1A2	S2A1	S2A2
1	0.4	0.7	1.9	1.4
2	5.1	6.1	11.9	8.4
3	9.0	8.0	7.2	3.2
4	0.4	0.7	2.5	0.3
5	27.5	38.5	14.4	14.1
6	18.1	13.0	29.1	26.9
7	4.0	6.6	5.4	13.0
8	1.2	2.4	1.6	1.6

Benzo(k)fluoranthene

	S1A1	S1A2	S2A1	S2A2
1	0.8	0.7	0.5	0.9
2	4.0	4.7	3.3	7.6
3	10.3	8.8	1.6	2.9
4	0.7	0.6	0.3	2.2
5	22.4	31.6	12.6	12.7
6	16.7	12.0	10.5	21.8
7	4.3	6.9	5.6	4.3
8	1.2	2.4	0.6	1.2

Fluorene

	S1A1	S1A2	S2A1	S2A2
1	0.1	0.1	0.1	0.2
2	1.2	1.1	0.9	1.0
3	0.9	0.8	0.1	0.5
4	0.2	0.1	0.9	0.2
5	2.9	5.7	1.4	1.2
6	0.3	0.7	0.5	0.4
7	1.1	1.9	0.1	0.2
8	0.4	1.0	0.6	0.6

Chrysene

	S1A1	S1A2	S2A1	S2A2
1	0.9	0.9	1.8	1.5
2	5.6	5.9	8.0	6.1
3	11.9	10.7	5.3	2.5
4	1.0	0.9	3.4	0.1
5	27.3	37.1	17.7	15.6
6	17.1	12.7	24.0	12.6
7	5.9	9.9	5.4	11.8
8	1.6	3.6	1.9	0.8

Naphthalene

	S1A1	S1A2	S2A1	S2A2
1	0.4	0.4	0.5	0.5
2	2.1	1.4	2.1	2.0
3	0.9	8.0	0.4	1.7
4	0.2	0.2	1.2	0.3
5	4.5	9.9	2.6	2.3
6	2.3	4.3	0.6	1.2
7	5.7	6.0	6.1	7.3
8	0.6	0.8	0.8	1.0

Acenaphthene

	S1A1	S1A2	S2A1	S2A2
1	0.1	0.1	0.2	0.2
2	1.4	1.6	1.4	1.4
3	0.5	0.6	0.1	0.6
4	0.2	0.1	1.5	0.1
5	1.2	2.1	0.8	0.7
6	0.7	0.5	1.0	0.4
7	1.0	1.8	0.2	0.2
8	0.6	1.4	0.8	0.7

SITE 4 - UNCERTAINTY ESTIMATES
ROBUST ANALYSIS OF VARIANCE

TOTAL PAH
Mean = 75.773491
Standard Deviation (Total) = 80.649475

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	73.210205	26.976385	20.417583	33.831982
Percentage Variance	82.402462	11.188309	6.4092265	17.597534
Relative Uncertainty	-	71.202698	53.891099	89.297672
(% at 95% confidence)				

BENZO(A)PYRENE
Mean = 8.787756
Standard Deviation (Total) = 10.420721

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	9.6097231	3.4614441	2.0647166	4.0304651
Percentage Variance	85.040576	11.033647	3.9257744	14.959421
Relative Uncertainty	-	78.778795	46.990758	91.729109
(% at 95% confidence)				

FLUORENE
Mean = 0.66218948
Standard Deviation (Total) = 0.5291481

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	0.31488562	0.34443313	0.24942049	0.42525846
Percentage Variance	35.412058	42.369697	22.218247	64.587942
Relative Uncertainty	-	104.02857	75.332061	128.44011
(% at 95% confidence)				

NAPHTHALENE
Mean = 2.3290832
Standard Deviation (Total) = 2.4095502

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	1.8922143	1.3349397	0.6658777	1.4917966
Percentage Variance	61.669253	30.69385	7.6368981	38.330747
Relative Uncertainty	-	114.63221	57.179383	128.10162
(% at 95% confidence)				

INDENO(1,2,3,c-d)PYRENE
Mean = 8.3089771
Standard Deviation (Total) = 9.0118904

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	6.4817553	5.6029339	2.7943068	6.2610717
Percentage Variance	51.731305	38.654421	9.6142705	48.268692
Relative Uncertainty	-	134.86459	67.259946	150.7062
(% at 95% confidence)				

BENZO(k)FLUORANTHENE
Mean = 6.2973294
Standard Deviation (Total) = 7.0931044

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	6.8721313	0.64212584	1.6351178	1.7566831
Percentage Variance	93.866415	0.81953523	5.3140472	6.1335821
Relative Uncertainty (% at 95% confidence)	-	20.393592	51.930514	55.791368

CHRYSENE
Mean = 7.7105665
Standard Deviation (Total) = 7.8526907

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	7.3394861	1.3246913	2.4580245	2.7922556
Percentage Variance	87.356322	2.8457215	9.7979551	12.643677
Relative Uncertainty (% at 95% confidence)	-	34.360414	63.7573	72.426731

ACENAPHTHENE
Mean = 0.75062472
Standard Deviation (Total) = 0.59211671

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	0.37041247	0.32830384	0.32498217	0.46194893
Percentage Variance	39.134208	30.742366	30.123429	60.865793
Relative Uncertainty (% at 95% confidence)	-	87.474829	86.589786	123.08386

1.5   SITE 5 - MEASUREMENTS OF CONTAMINATION TAKEN DURING THE INVESTIGATION AT THE FORMER COLLIERY AND RAILWAY SIDINGS

			Trial pit number and depth					
		Threshold	1	2	3	4	4	5
		Value	1.00m	0.20m	0.90m	0.10m	1.00m	0.20m
Arsenic	mg/kg	20	17.15	26.25	5.3	12.85	7.15	7.95
Boron	mg/kg	3	0.455	0.25	0.25	0.25	0.25	0.31
Cadmium	mg/kg	30	0.5	0.5	0.5	0.5	0.5	0.5
Chromium	mg/kg	200	36.5	16	17.5	18	18	16.5
Copper	mg/kg	190	27.5	105	15.5	24	17.35	26.5
Lead	mg/kg	450	32	153	18.5	46	54	35
Mercury	mg/kg	15	0.2	0.2	0.2	0.2	0.2	0.29
Nickel	mg/kg	75	28.5	33	13.2	15.8	12.7	19.5
Selenium	mg/kg	260	0.98	0.645	0.36	0.49	0.455	0.63
Zinc	mg/kg	720	51.5	81.5	74	34	74	72.5

		Trial pit number and depth					
		Threshold Value	5 1.00m	6 0.90m	7 0.20m	7 1.00m	8 0.20m	8 1.00m
Arsenic	mg/kg	20	5.95	8	14.5	5.5	48	21.75
Boron	mg/kg	3	0.31	0.28	0.25	0.25	0.325	0.31
Cadmium	mg/kg	30	0.5	0.5	0.545	0.5	0.5	0.5
Chromium	mg/kg	200	12.5	18	15.5	10.45	14.5	12.95
Copper	mg/kg	190	18.5	25	136	18.5	50.5	39.5
Lead	mg/kg	450	48	86	156	13.5	30.5	19
Mercury	mg/kg	15	0.2	0.2	0.2	0.295	0.2	0.275
Nickel	mg/kg	75	20.5	17.5	43.5	18	19	18.5
Selenium	mg/kg	260	0.455	0.385	0.65	0.3	0.95	0.9
Zinc	mg/kg	720	45.5	102	111.5	50	37	42

MEASUREMENTS TAKEN AS PART OF THE 'BASIC' DUPLICATE METHOD AT SITE 5

Arsenic

	S1A1	S1A2	S2A1	S2A2
1	5.3	5.3	29	29
2	3.8	3.8	6.8	6.8
3	7.7	7.7	18	18
4	10	10	4.3	4.3
5	8.6	8.6	71	71
6	8.5	8.5	44	44
7	10	10	19	19
8	42	42	54	54

Lead

	S1A1	S1A2	S2A1	S2A2
1	25	25	39	39
2	22	22	15	15
3	10	10	82	82
4	98	98	10	10
5	52	52	170	170
6	16	16	290	290
7	250	250	62	62
8	31	31	30	30

Chromium

	S1A1	S1A2	S2A1	S2A2
1	39	39	9.7	9.7
2	22	22	13	13
3	25	25	11	11
4	25	25	11	11
5	18	18	13	13
6	21	21	11	11
7	20	20	11	11
8	16	16	13	13

Nickel

	S1A1	S1A2	S2A1	S2A2
1	34	34	23	23
2	8.4	8.4	18	18
3	22	22	9.6	9.6
4	20	20	5.4	5.4
5	23	23	40	40
6	16	16	50	50
7	37	37	50	50
8	17	17	21	21

Copper

	S1A1	S1A2	S2A1	S2A2
1	10	10	45	45
2	15	15	16	16
3	14	14	34	34
4	27	27	7.7	7.7
5	38	38	140	140
6	10	10	200	200
7	32	32	240	240
8	53	53	48	48

Zinc

	S1A1	S1A2	S2A1	S2A2
1	73	73	30	30
2	90	90	58	58
3	37	37	31	31
4	120	120	28	28
5	100	100	41	41
6	43	43	120	120
7	93	93	130	130
8	40	40	34	34

SITE 5 - UNCERTAINTY ESTIMATES - ROBUST ANALYSIS OF VARIANCE

ARSENIC
Mean = 20.858717
Standard Deviation (Total) = 20.102789

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	11.566746	16.441792	0	16.441792
Percentage Variance	33.106231	66.893765	0	66.893765
Relative Uncertainty (% at 95% confidence)	-	157.64912	0	157.64912

CHROMIUM
Mean = 16.812115
Standard Deviation (Total) = 9.2992258

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	0	9.2992258	0	9.2992258
Percentage Variance	0	99.999999	0	99.999999
Relative Uncertainty (% at 95% confidence)	-	110.6253	0	110.6253

COPPER
Mean = 56.951954
Standard Deviation (Total) = 65.372894

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	26.032681	59.96595	0	59.96595
Percentage Variance	15.857777	84.14222	0	84.14222
Relative Uncertainty (% at 95% confidence)	-	210.58435	0	210.58435

LEAD
Mean = 75.125
Standard Deviation (Total) = 89.45578

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	12.707688	88.548584	0	88.548584
Percentage Variance	2.0179773	97.982025	0	97.982025
Relative Uncertainty (% at 95% confidence)	-	235.73666	0	235.73666

NICKEL
Mean = 24.373249
Standard Deviation (Total) = 14.54424

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	8.8907957	11.510372	0	11.510372
Percentage Variance	37.367944	62.632057	0	62.632057
Relative Uncertainty (% at 95% confidence)	-	94.450864	0	94.450864

ZINC
Mean = 65.661873
Standard Deviation (Total) = 41.532967

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	0	41.532967	0	41.532967
Percentage Variance	0	100	0	100
Relative Uncertainty (% at 95% confidence)	-	126.50558	0	126.50558

1.6   SITE 6 - HEAVY METAL CONTAMINATION AT PROPOSED HOUSING DEVELOPMENT

Sample id	Depth[a]	Cd	Cr	Cu	Ni	*Pb*	Zn
A01	topsoil	1.019	27.38	764.5	35.9	*843*	857.5
	20 - 40 cm	4.46	21.1	809.5	48.06	*537*	580.5
	40 - 60 cm	1.284	28.78	467.3	36.69	*3,312*	460.5
A02	topsoil	0.632	121	385.2	25.87	*3,767*	224.2
A03	topsoil	1.104	17.16	104.8	43.19	*3,102*	260.4
	20 - 40 cm	0.437	22.58	100.8	68.01	*2,197*	94.21
	40 - 60 cm	0.218	15.87	42.14	31.38	*977.5*	55.52
A04	**S1A1**	0.951	14.21	65.22	21.91	*12,830*	249.9
	S1A2	0.981	14.42	67.58	21.8	*13,425*	259.6
	S2A1	1.471	11.57	58.01	20.3	*24,440*	401.7
	S2A2	1.439	13.84	61.53	25.37	*20,695*	424.5
A05	topsoil	2.09	58.08	156.6	99.37	*19,440*	1,015
A06	topsoil	0.732	27.21	99.06	16.15	*379.8*	128.4
A07	topsoil	1.848	39.86	71.28	30.66	*686.5*	171.5
A08	**S1A1**	0.762	73.65	197.2	109.5	*102.6*	297.5
	S1A2	0.554	69.53	185.7	103.8	*115.7*	305.2
	S2A1	0.769	106.2	317.5	147.4	*85.3*	722
	S2A2	0.449	91.11	282.9	124.4	*80.45*	641
A09	**S1A1**	0.285	53.12	181.3	75.46	*222.2*	113
	S1A2	0.285	59.54	210.4	84.79	*206.9*	123.7
	S2A1	0.221	30.45	96.21	34.84	*570.5*	127.3
	S2A2	0.155	26.61	96.27	32.22	*464.5*	82.78
	20 - 40 cm	0.094	19.56	82.04	16.65	*74.45*	46.74
	40 - 60 cm	0.101	27.98	131.4	27.7	*62.13*	43.33
A10	topsoil	2.02	50	637.5	26.71	*987.5*	689.5
A11	topsoil	0.97	17.8	1,915	14.93	*255*	222.7
	20 - 40 cm	0.466	20.6	209.9	16.74	*147.4*	143.6
	40 - 60 cm	0.324	17.9	111.1	14.2	*122.2*	103
A12	topsoil	0.632	18.99	137.4	18.58	*483*	287.3
A13	**S1A1**	0.185	18.58	37.47	10.94	*91.13*	62.86
	S1A2	0.204	19.57	29.24	10.61	*111.1*	59.92
	S2A1	0.684	19.66	287	27.19	*273.8*	445.8
	S2A2	0.759	21.23	323.1	28.58	*313.2*	473.5
	20 - 40 cm	0.104	22.62	12.6	11.73	*33.96*	52.17
	40 - 60 cm	0.089	21.88	13.3	11.18	*36.27*	53.17

[a] Topsoil = 0-15 cm, used for both 'digests' 1 and 2.

Sample id	Depth[a]	Cd	Cr	Cu	Ni	*Pb*	Zn
A14	**topsoil**	0.728	36.36	127.7	44.24	***794***	987
A15	**topsoil**	0.569	28.07	127.2	47.9	***461.3***	415.2
A16	**topsoil**	0.561	28.77	778.5	29.72	***499.6***	387.4
A17	**topsoil**	0.92	210.5	357.1	356.6	***668***	848.5
A18	**S1A1**	0.357	22.89	53.22	28.26	***277***	126.2
	S1A2	0.372	22.23	47.81	26.63	***204.4***	120.2
	S2A1	0.447	26.03	106.2	35.23	***230.4***	140.4
	S2A2	0.404	22.18	97.04	30.22	***239.8***	134
A19	**topsoil**	0.289	34.07	128.7	38.47	***192.2***	182
	20 - 40 cm	0.153	24.29	53.96	22.33	***89***	78.57
	40 - 60 cm	0.072	27.72	30.92	17.34	***53.84***	61.54
A20	**S1A1**	0.344	57.05	119.8	66.23	***204.1***	140.3
	S1A2	0.287	57.44	125.5	68.09	***206.7***	130.9
	S2A1	0.322	42.44	81.28	48.04	***153.9***	109.1
	S2A2	0.362	35.12	70.25	40.01	***175.2***	104.6
A21	**topsoil**	0.593	22.5	147.9	23.54	***869.5***	254.7
	20 - 40 cm	0.368	35.41	104.8	122.3	***172.2***	194.1
	40 - 60 cm	0.26	18.07	131.2	18.03	***222.4***	125.8
A22	**S1A1**	0.43	17.87	99.85	20.46	***417***	167.8
	S1A2	0.424	18.09	101.6	21.03	***394.3***	179.8
	S2A1	0.539	18.26	131.1	17.73	***461.6***	275.2
	S2A2	0.506	19.86	121.2	18.57	***422.6***	267.1
A23	**topsoil**	0.76	37.71	1,782	55.37	***1,158***	529.5
	20 - 40 cm	0.158	12.09	872.5	17.58	***263.9***	143.9
	40 - 60 cm	0.373	21.75	2,567	27.79	***456.1***	683.2
A24	**topsoil**	0.48	17.83	389.4	28.96	***1967***	216.8
A25	**topsoil**	0.327	18.27	179.4	24.89	***674.5***	118.3
A26	**topsoil**	0.29	25.63	253.2	62.77	***1,337***	182.8
A27	**topsoil**	0.593	19.57	1,348	227.7	***6,225***	312
	20 - 40 cm	0.654	21.84	1,905	281.7	***8,728***	385.6
	40 - 60 cm	0.505	20.62	701.5	187.6	***3,430***	268
A28	**S1A1**	0.491	20.09	1,722	266.7	***10,725***	291.4
	S1A2	0.493	20.49	1,604	265.3	***9,425***	282.9
	S2A1	0.658	22.09	1,790	248.4	***15,475***	284.5
	S2A2	0.557	21.66	1,560	230.5	***14,060***	260.7
A29	**topsoil**	2.29	25.23	944.5	148	***5,413***	776

[a]Topsoil = 0-15 cm, used for both 'digests' 1 and 2.

Pb MEASUREMENTS TAKEN AS PART OF THE 'BASIC' DUPLICATE METHOD AT SITE 6

	S1A1	S1A2	S2A1	S2A2
1	12830	13425	24440	20695
2	103	116	85	81
3	222	207	571	465
4	91	111	274	313
5	277	204	230	240
6	204	207	154	175
7	417	394	427	423
8	10725	9425	15475	14060

ROBUST UNCERTAINTY ESTIMATES

LEAD
Mean = 529.85175
Standard Deviation (Total) = 616.05078

	Geochemical	Sampling	Analysis	Measurement
Standard Deviation	583	191.67	53.779324	199.07185
Percentage Variance	89.557931	9.6799969	0.76207482	10.442071
Relative Uncertainty (% at 95% confidence)	-	72.348539	20.299763	75.142473

APPENDIX 2 - PROJECT DISSEMINATION

The innovative methods developed as part of this research have been disseminated in a variety of media to publicize and explain the benefits of the OCLI method to the site investigation community, and to developers of brownfield sites (Project Objective 4). This work is summarised below:

PRESENTATIONS
- A CL:AIRE workshop 'Cost-Effective Investigation of Contaminated Land' was conducted by Mike Ramsey and Paul Taylor in London on the 18th May 2005. The Environment Agency view was represented in a presentation given by Bob Barnes. A total of 35 people attended the workshop from positions within Local Authorities and commercial consultancies. The delegates were given copies of the ROBAN software and shown how to estimate measurement uncertainty. The prototype OCLI method was also demonstrated during the workshop.
- The research project, 'Cost-Effective Investigation of Contaminated Land', is now available on-line as part of the University of Sussex webpages: http://www.sussex.ac.uk/cer/1-2-2-10.html
- Paul Taylor presented the OCLI method as part of a conference held by the Society of Environmental Geochemistry and Health (SEGH) held in April 2004. Mike Ramsey also presented a paper on the wider implications of measurement uncertainty. Katy Boon presented a poster at this conference detailing the development of the OCLI methodology.
- Mike Ramsey attended a meeting attended by SAGTA members (Soil and Groundwater Technology Association) to present the OCLI method to key industry members (June 2004). The research attracted interest and encouragement from those present, who also provided suggestions for the development of OCLI.
- Paul Taylor presented a talk to specialist contaminated land investigators and managers at Atkins' offices in Epsom (July 2004). The actual Atkins staff who were involved with one of the site investigations used for this project were part of the audience. The group provided very useful comments and ideas for the application and further development of the OCLI method.
- The OCLI method was also presented by Paul Taylor at the conference, 'Contaminated Land: Achievements and Aspirations' held by the Society of Chemical Industry (September 2004). The presentation was titled 'Cost-based optimisation of measurement uncertainty: a case study of contrasting remedial options within a contaminated land investigation'. The presentation received positive feedback and interest from many of the delegates. Mike Ramsey also presented at the conference, giving evidence of how measurement uncertainty is generated during investigations of contaminated land, describing methods for its estimation and highlighting the consequences of misclassification that may arise if uncertainties are ignored. Both presentations were submitted as written papers that were included within the conference proceedings given to every delegate. Katy Boon presented a poster at the conference on new developments in OCLI. This poster generated substantial interest from the delegates, and was awarded a prize for being the best poster at the conference.
- Paul Taylor presented the OCLI method to Contaminated Land Officers working for Local Authorities within the southeast region (July 2004). Paul Slaughter at Brighton and Hove Council arranged for this presentation to be made.
- The OCLI method and related research was presented during 3 separate presentations by Mike Ramsey, Paul Taylor and Katy Boon at the Society for Geochemistry and Health conference held in Paisley, Scotland from the 4th to the 6th of April 2005.

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- Taylor, P.D., Ramsey, M.H. 'Cost-Effective Investigation of Contaminated Land: Application of the innovative OCLI method to organic contamination'. *Contaminated Land and Reclamation.* 2005. 13:1, 11-21.
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