

Site investigation and monitoring techniques for contaminated sites and potential waste disposal sites

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ABSTRACT: The techniques available for investigation and monitoring of soil, groundwater and vapour at sites which have been contaminated by past industrial or waste disposal practices and sites which are being considered for future waste disposal uses are discussed. The emphasis is on field techniques specifically related to contamination assessment and potential contaminant behaviour. Considerations related to the planning and scoping of site assessment studies are reviewed, followed by descriptions of the geological, hydrogeological, geochemical and geophysical techniques which are currently available.

1 INTRODUCTION

1.1 Scope and definitions

This paper discusses the techniques available for investigation and monitoring of soil, groundwater and vapour at sites which have been contaminated by past industrial or waste disposal practices and sites which are being considered for future waste disposal uses. The emphasis of this paper is on field techniques specifically related to contamination assessment and potential contaminant behaviour; for this reason desk techniques such as mathematical modelling (discussed by other authors at this conference), and geotechnical considerations related to contaminated site redevelopment are not addressed.

Although assessment of contaminated sites and assessment of potential waste disposal sites have differences of emphasis, they have many things in common; in particular, many of the field techniques used are applicable, with modifications, to both types of study. Assessment of both contaminated sites and sites being considered for waste disposal requires a multi-disciplinary approach. In this paper, geological, hydrogeological,

geochemical and geophysical techniques are described, but such investigations will also frequently require inputs from other specialists: toxicologists, biologists, agriculturalists, engineers, planners and architects are frequently involved, not to mention the ubiquitous economists and accountants. Such considerations are really beyond the scope of this paper, but it should not be forgotten that the scope of an investigation, and the relative feasibility of alternative solutions to the problems posed by contaminated land and waste disposal sites, are determined as much by the availability of financial resources and the social acceptability of the solutions as by scientific and engineering considerations.

Whilst there is no universal definition of what constitutes a "contaminated site" (nor is it likely or indeed desirable that there will ever be one), a number of working definitions have been presented in recent Australian literature. Examples are: "a site where hazardous substances occur at concentrations above background levels" (Australia and New Zealand Environment and Conservation Council / National Health and Medical Research Council [ANZECC / NHMRC] 1992); "the presence of hazardous

substances(s) above response level(s)" (Langley, 1991); "land, which because of previous or present uses at or near the site, contains materials that give rise either directly or indirectly to long-term adverse effects on human health or the environment" (NHMRC 1991). Whilst the NHMRC definition is quite all-embracing, its application requires the use of risk assessment techniques and a good deal of judgement. While perhaps desirable, this approach has not been common, particularly for relatively small-scale investigations and, for practical purposes, the definition of Langley is used, with the response levels being those defined by the ANZECC/NHMRC document (NSW and Victoria) or local equivalents which take precedence in other states. (eg Queensland). The key element in any definition of contaminated land is that is not just the presence of hazardous materials which is important, but also their concentration and mobility.

Definition of "waste disposal sites" is easier. For the purposes of this paper, such sites are restricted to areas proposed for municipal solid waste (MSW) landfill, hazardous waste landfill, and the disposal of liquid waste (including saline water) by subsurface injection.

1.2 Objectives

Investigation of contaminated sites and waste disposal sites may have a variety of objectives depending on the circumstances of a specific project. However, there are two key objectives which are central to such investigations. These are risk limitation through an improved understanding of the conditions which exist at a particular site and the provision of the data necessary to design remedial or control measures.

As examples of risk limitation: The prospective purchaser of a block of land wishes to limit exposure to the financial risk of purchasing land which has been contaminated by a previous owner, and must be cleaned up at the expense of the purchaser. The EPA, the Health Department and local councils wish to reduce the health risks and financial risks incurred by building houses on land which is

contaminated, and the community at large wishes to reduce the risks to water resources and the environment in general caused by inappropriate siting of waste disposal facilities.

As examples of provision of design data: Remediation of contaminated soil and groundwater requires sound information on the nature, concentration and distribution of contaminants, while design and management of waste disposal facilities requires hard information concerning the hydrogeological characteristics of the site.

1.3 Framework

Limitation of risk is the key objective of both contaminated site assessment and investigation of potential waste disposal sites. In the United States, formal Risk Assessment has become an integral part of the process of investigation and remediation of contaminated land, and of the planning and approval process for waste disposal activities. (USEPA 1989a, Paustenbach et al 1990). The formalised risk assessment process described by the USEPA (Op. Cit) has been criticised for being overly conservative in its handling of the uncertainty inherent in predicting both exposure factors and toxicological effects, but more sophisticated, less conservative, models are becoming available, and it is likely that in the future, the emphasis on risk assessment will increase.

The current Australian and New Zealand Guidelines for the Assessment and Management of Contaminated Sites (ANZECC / NHMRC 1992) also stress the importance of the risk assessment process, and a major formal Risk Assessment has recently been undertaken for the largest single area of urban contaminated land in NSW, and probably Australia, the Homebush Bay site currently being redeveloped for the Sydney 2000 Olympics bid.

It is desirable that, whether or not a formal Risk Assessment is undertaken, planning and execution of contaminated land assessments and investigations of potential waste disposal sites are carried out within a risk assessment framework. The value of this approach is that it structures the investigation to provide the

specific information required to make the decisions on site development options. Risk Assessment frameworks for the investigation of contaminated sites and waste disposal sites are shown in Figures 1 and 2.

1.4 Protocols

A number of protocols for the assessment and management of contaminated sites have been developed during the past few years. Prominent among them at the International level is "Guidance for Conducting Remedial Investigations and Feasibility Studies under CERCLA" (USEPA 1989b) and the British Standards Institution draft "Code of Practice for the Identification of Potentially Contaminated Land and its Investigation" (BSI 1988). In Australia a series of draft and eventually final guidelines for the assessment and management of contaminated sites have been produced at both the National and State levels. Prominent among them are the series of draft guidelines produced jointly and separately by the NHMRC and ANZECC in 1989, 1990 and 1991, culminating in the current "Australian and New Zealand Guidelines for the Assessment and Management of Contaminated Sites 1992" which has been referenced above. At the State level, draft guidelines were produced by the State Pollution Control Commission in NSW, the Environment Protection Authority (EPA) in Victoria and the South Australian Health Commission (these states have now endorsed the ANZECC / NHMRC guidelines), and by the Chemical Hazards and Emergency Management (CHEM) Unit in Queensland (Queensland has now produced its own final guidelines). A recent joint meeting of state and national regulatory agencies in Adelaide produced the "Protocol for the Health Risk Assessment and Management of Contaminated Sites" (Langley and El Saadi, 1991).

It should be clear that these protocols are guidelines, not sets of instructions. Nevertheless, they do have considerable importance in that they are the standards against which the adequacy or otherwise of investigation programs is judged.

1.5 Format of paper

Sections 2 and 3 of this paper discuss the particular requirements of investigations of contaminated sites and potential waste disposal sites respectively. Section 4 discusses the preliminary or scoping studies which, though specifically directed towards contaminated land assessment, also have relevance for the investigation of potential waste disposal sites. Section 5 describes field techniques relevant to both types of investigation. Some concluding remarks are given in Section 6.

2 ASSESSMENT OF CONTAMINATED SITES

Assessment of contaminated sites involves a number of aspects which while not specific to this type of investigation, are universal within it. These are:

- the decision as to whether an investigation is appropriate
- the staging of the investigation
- direction towards design of a remedial strategy

2.1 When to investigate

Given the primary objective of risk limitation, the question arises - when should potentially contaminated land be investigated? - indeed what are the grounds indicating that a site may be potentially contaminated?

In practice, there are a number of "triggers" for contaminated land assessments. In approximate order of frequency these are:

- sale of the land (investigation may be carried out on behalf of either vendor or purchaser)
- rezoning or redevelopment of the land (investigation is usually carried out on behalf of the owner, but is mandated by the planning authority)
- internal review of status of assets - of increasing frequency, generally involving large corporations and Commonwealth or State government instrumentalities and

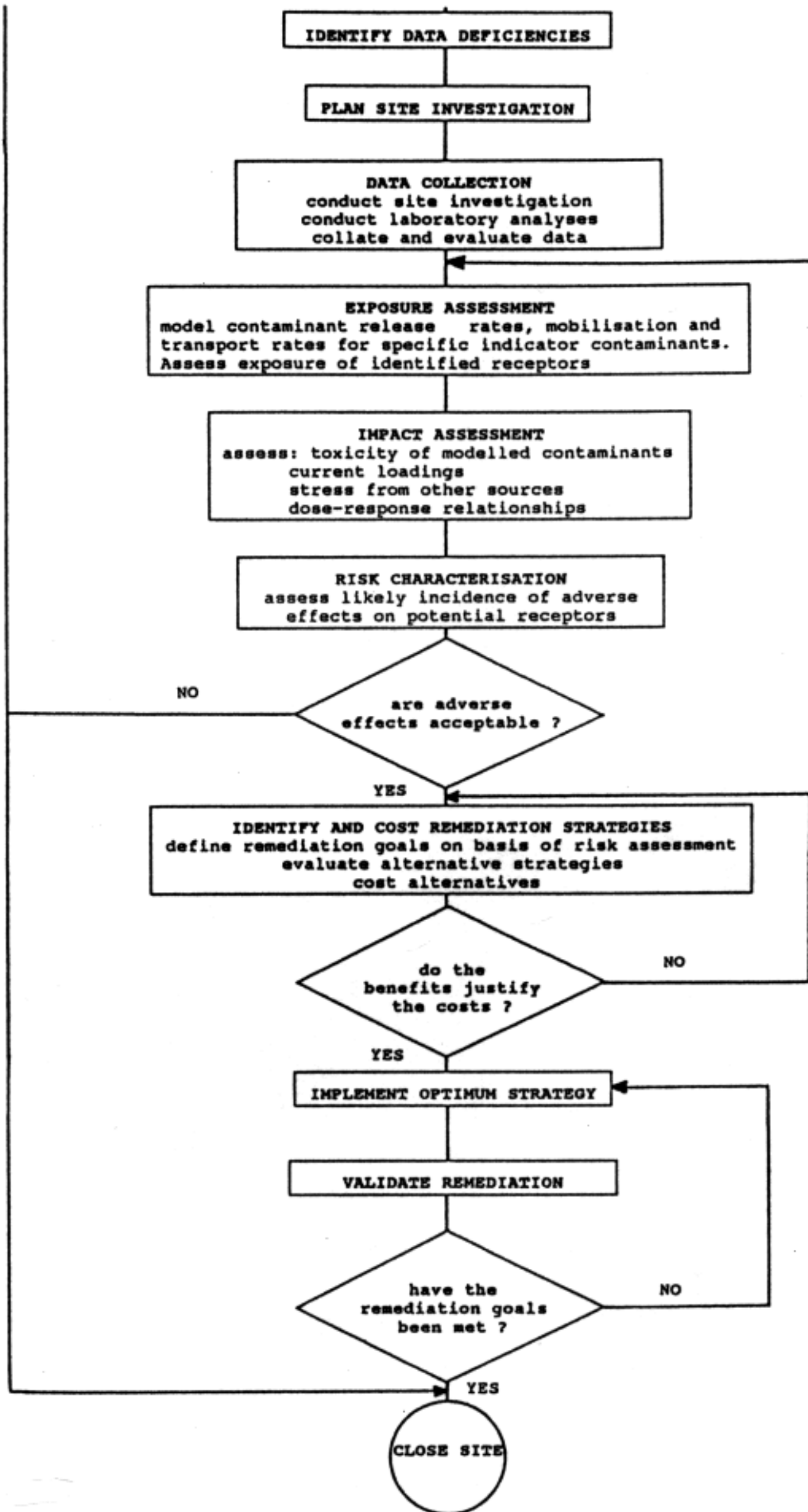


Figure 1 Risk analysis framework for investigation of a potentially contaminated site.
(continued)

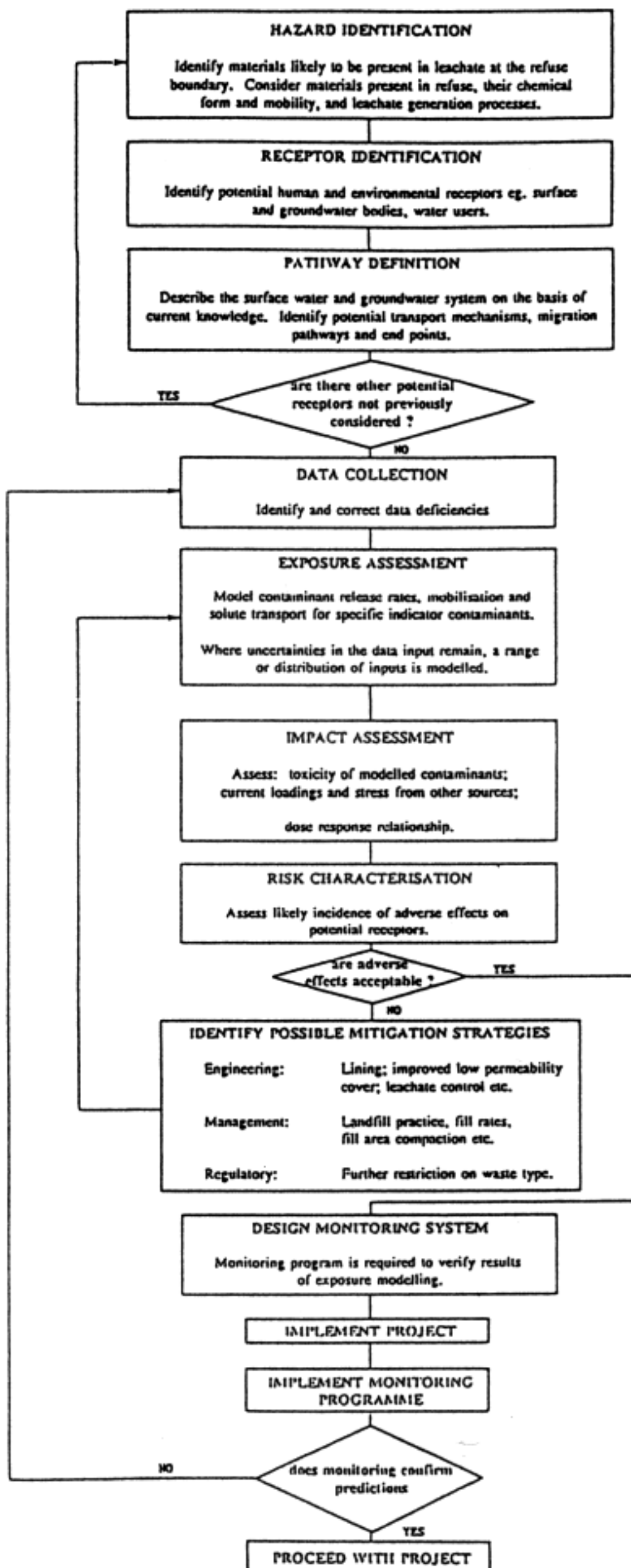


Figure 2 Risk analysis framework for site investigation for a major waste disposal operation.

- possibly linked to long-term, but undisclosed, policies for asset disposal
- investigation of known or strongly suspected contaminated sites where there is concern among the public or the authorities that contamination may be migrating beyond the site boundaries.- in fact quite a rare occurrence without the additional trigger of proposed development on the land itself or on adjacent property.

It is generally acknowledged that an investigation is desirable whenever there is a proposed change from a less risk-sensitive use to a more risk-sensitive one. A hierarchy of risk sensitivity must be subjective, but most would agree that the following order would be generally applicable.

Most sensitive	low density residential schools medium density residential high density residential public open spaces commercial with public access general commercial agricultural light industrial permanent pavement
Least sensitive	heavy industrial

2.2 The staged approach

A staged approach to investigation of contaminated sites is appropriate, cost effective and universally recommended, by the protocols referenced in Section 1.4. A typical staged approach would comprise:

Stage 1 A preliminary or "scoping" study - primarily a desk study, but generally incorporating at least a visual inspection of the site. The primary objective of such a preliminary study is to establish whether further investigation is warranted. If this does prove to be the case, then the scoping study should establish the nature and likely distribution of potential contaminants on the site.

In a few situations, scoping studies are not routinely carried out because the likelihood of

contamination and the nature of the contaminants has been well established by previous experience on similar sites. An example of this is the investigation of petrol service stations. It is known that effectively all such sites are contaminated to some extent, and the nature of the contaminants - petroleum hydrocarbons and lead - is also well known. In such cases there is a tendency to move straight to the planning phase.

Stage 2 Planning of the field investigation. In the planning stage the data acquired during the scoping study is used to plan an appropriate sampling and analytical program. Frequently this follows directly on from the scoping study, and forms part of the same report. An interim report at this stage is a good policy - it provides an opportunity to order priorities, a chance for the regulatory authorities to review the proposed field program, and justification for the substantial expenditure frequently required.

Stage 3 The on-site sampling and testing program and laboratory analysis of samples. Frequently an iterative process - as initial results prompt more sampling and testing. The techniques appropriate to this stage are discussed in section 5.

Stage 4 Interpretation and Assessment of results.

Stage 5 Design of a Remedial Action Program.

3 ASSESSMENT OF POTENTIAL WASTE DISPOSAL SITES

As indicated in Section 1, "waste disposal" for the purpose of this paper includes MSW and Hazardous Waste landfill, and disposal of liquid waste by subsurface injection. The latter practice, though quite extensively used overseas, has seen relatively little use in Australia. Recently, however, major schemes for the disposal of saline waste waters by this method have been proposed.

In NSW and most other states, landfill

operations are designated developments requiring the preparation of an Environmental Impact Statement (EIS). The subsurface injection proposals of which the authors are aware have generally been associated with mining operations, and for that reason are also encompassed by the EIS process. EIS are required to be comprehensive documents considering all aspects of a proposed development's impact on the environment. However, in Australia as elsewhere, one aspect tends to dominate waste disposal EIS; that aspect is the hydrogeological impact of the development, and specifically the potential for contaminant migration from the site through groundwater. Thus hydrogeological characterisation of potential waste disposal sites is paramount.

Hydrogeological characterisation of such sites would normally comprise:

- a basic assessment of the regional and local geology, including stratigraphy, structure and main lithotypes, weathering characteristics and superficial deposits
- a basic assessment of local surface hydrology, including hydrometeorological water balance, major and tributary drainage, flood levels, groundwater contribution to base flow
- identification of the main hydrogeological units - (aquifers, aquitards) - present
- assessment of likely groundwater flow mechanisms, and in particular, whether intergranular or fracture flow is likely to be dominant
- identification of local structural features which may control groundwater flow
- measurement of groundwater levels and calculation of the local hydraulic gradient
- measurement of the hydraulic conductivity of the main hydrogeological units identified
- assessment of the attenuation characteristics of the materials present in both vadose and phreatic zones
- analysis of natural groundwater chemistry
- identification of any present or potential beneficial use of groundwater
- identification of potential groundwater and surface water receptors of contamination.

The requirements of the investigation are basically similar for all three types of waste disposal activity, as are the field techniques which may be employed (discussed in Section 5). If a risk assessment approach is used, then the criteria against which a site is judged to be acceptable, or not, are likely to be much more stringent for operations involving hazardous waste.

The results of the hydrogeological investigation form the input into the modelling studies which will be used to assess the suitability of the site for its intended purpose, and the design studies required to determine the nature of the engineering control measures which are required to provide containment with the required degree of security.

A number of "standardised systems" for evaluating potential waste disposal sites have been developed. Prominent among them are the LeGrand system (LeGrand 1980) which was adopted in modified form in Victoria, and DRASTIC (Aller et al 1987), a "standardised system for evaluating ground water pollution potential using hydrogeologic settings".

The LeGrand system is quite general in its applicability, and by reducing the many factors involved in site evaluation to a simple number, has some merit for initial comparison of alternative sites. One disadvantage is that particular factors assessed by the system as being highly unfavourable - such as a high water table, will strongly down-weight the ranking of a site when, in other respects, it may be quite an adequate site. Thus, to use a local example, shale sites on the Cumberland Plain west of Sydney may be unfavourably compared with sites on the sandstone plateaux, when hydrogeological judgement, and the results of extensive investigations, indicate otherwise. Like all such systems, it needs to be used with care and judgement, and the results treated with a healthy degree of scepticism.

DRASTIC has been specifically developed for the United States. However, with the application of a little hydrogeological judgement, its principles could be adapted to other areas. It is really rather doubtful if such effort is worthwhile - the work would be better expended on site specific evaluation.

4.0 PRELIMINARY OR SCOPING STUDIES

As they are primarily desks studies, preliminary investigations involve the collation and review of existing information on the site, usually supplemented by at least a visual inspection of the site, and often by some preliminary field screening. A wide range of current and historical information should be considered to evaluate:

- the local geological setting
- the local hydrogeological regime, including groundwater, surface water and water abstraction sources
- the activities (past and present) carried out on or near the site
- the location of those activities
- the possible contaminants released by those activities
- the potential for contaminant migration off-site
- the potential for contaminant migration into the site
- the existence of any previous remediation measures, such as capping, at the site.

(Lord 1987, European Technical Committee 8 (ETC 8) 1991, NHMRC, 1991 ANZECC/NHMRC 1992). Sources of information for the preliminary investigation include:

- local geological and topographical maps
- atlases and maps of mineral deposits
- meteorological data
- site maps
- site surveys
- available borehole data
- site records, including discharge permits and licences
- past environmental, health or agricultural inspection reports
- existing and historical aerial, ground and/or space photographs (black and white, colour, infra-red)
- trade and street directories
- local literature, including local history and newspapers
- technical literature including engineering plans, building plans and alterations
- local knowledge of residents and current or previous site personnel

- complaints history
- present and past owners of site
- present and past owners of nearby land.

(Dumbleton 1979, Business Council of Australia (BCA) 1991, Burgess 1991, NHMRC 1991, ETC 8 (1991))

4.1 Site history

The review of the site history should attempt to document a chronological history of all site activities including:

- production
- storage of chemicals
- processes
- reactions
- chemicals used
- disposal practices
- regulatory compliance
- site uses
- site alterations
- tank and storage areas
- distribution pipelines
- inventory of potential hazards
- contaminant release history.

The aims are:

- to establish which materials may be present on the site
- to establish the locations where such materials are most likely to be present.

Undoubtedly, records of actual chemical usage, site layout plans, and the knowledge of personnel who worked on the site are the most useful sources of information. In their absence, knowledge of the nature of various industrial processes and indirect information such as that provided by aerial photographs, supplemented by observations during a site reconnaissance, must suffice.

4.2 Site reconnaissance

During site reconnaissance, the following should be observed:

- the present state of the site and its topography
- the location of present buildings and clues indicating the location of previous

buildings

- the locations of storage tanks, water ponds, tailings, drums, electrical transformers and capacitors
- the general nature of visible soil and site fill
- the presence of odours
- the presence/absence of vegetation
- the relationship to nearby sites, drainage watercourses, etc
- site hazards
- asbestos
- loading, unloading and storage areas
- adjacent land use.

The site reconnaissance may be greatly assisted by on-site interviews with site personnel, and persons such as former employees and local residents who are knowledgeable of the site history.

The NHMRC (1991) and ANZECC / NHMRC (1992) give the following as useful indicators of possible site contamination:

- vegetation; the absence or poor growth of vegetation may suggest the presence of phytotoxic substances such as oil, sulphates, copper, nickel, zinc and methane
- surface colouration; unusual colours may suggest the presence of chemical wastes and residues. Dark staining due to the presence of oils is frequently apparent
- unusual land contours, including surface depressions and piles of soil or wastes
- abandoned wells and vent pipes in the ground
- fumes and odours
- abandoned containers of chemicals
- flooring and pavement in poor condition.

It is valuable to make a detailed photographic record of the original condition of the site, since once site activities begin, it is often difficult to recall the undisturbed state.

During site reconnaissance, limited sampling for chemical analysis may be desirable, together with precursory on-site measurements, particularly for gas (Lord 1987). Hand-held photoionisation detectors are particularly useful in this respect.

If the preliminary investigation suggests that

the site may be contaminated, then an on-site investigation will be required.

4.3 Planning the on-site investigation

A complete investigation of a contaminated site must be concerned not only with the contamination, but also the geology, hydrology, hydrogeology and engineering properties of the site (Smith 1990). The latter will be essential if the site is to be developed, and may also be required if remediation is to be carried out at the site. Clearly, a multi-disciplinary approach to site investigation is needed, as the range and complexity of the issues is such that no single scientific discipline or profession can deal with them all.

Planning must be based on the need to satisfy the study objectives, as discussed in Section 1, and must take into account budgetary and practical constraints.

4.3.1 Initial planning

At the initial planning stage, it should be possible to formulate broadly the extent of the analytical program in terms of deciding "what to look for". In general, a comprehensive analytical program is likely to include three components (Smith 1991):

- ubiquitous contaminants such as lead, zinc, cadmium, copper, chromium, mineral oils
- contaminants characteristic of the land use(s)
- adventitious or not easily predicted contaminants.

Some contaminants such as the heavy metals are so frequently present on former industrial sites that it is advisable to search for such contaminants regardless of the site history. Indeed there is increasing evidence that in urban and industrial area, atmospheric deposition may cause soil concentration of these materials to exceed threshold levels. In addition, mineral oils and other petroleum products are commonly present on many sites, as are refuse and other gas producing combustible materials. Smith (1991) also cautions that hazardous materials, such as

solvents, degreasing agents and lubricants, are also more commonly present than is usually expected.

Potential contaminants characteristic of the land use can be identified using data from the preliminary investigation, and experience at sites of similar type.

The presence of adventitious contaminants may be revealed by "broad spectrum" or "surrogate" screening techniques (Smith 1991), or by the fairly broad ranging GC-MS priority pollutant scans favoured by the USEPA. The employment of such techniques during laboratory analysis is likely to invoke additional expense. However, this expense will be justified if the analysis reveals high concentration of unusual, but highly toxic materials. Observations of the unexpected during field or laboratory testing might be used as a trigger for such a search.

When there are a large number of potential contaminants at a site, it may be appropriate to group contaminants on the basis of their mobility, persistence and toxicity. The initial investigation could then concentrate on a limited number of representative indicator contaminants (Burgess 1991).

4.3.2 Detailed planning

The detailed planning stage is concerned with developing a broad sampling and analysis plan for the site and also the requisite quality assurance/quality control and Health and Safety Plans. It should be stressed that the plan produced at this stage should not be regarded as definitive.

The broad sampling and analysis plan should attempt to specify (Burgess 1991, Smith 1991):

- the number of sampling stages
- the pattern of sampling and the number of sampling points or locations
- the depth of sampling
- the size and type of samples required
- the methodology for sample collection and preservation
- the methodology for on-site and off-site chemical analysis
- the handling/transport of samples for off-site analysis.

The sampling and analysis plan needs to be formulated for each of the sampling sub-programs. In general, sub-programs will include sampling for gases, soils, water and vegetation.

4.3.3 Sampling stages

It is generally desirable, particularly if the history of a site is not well defined, to allow adequate time and resources for a multi-stage sampling program.

Unforeseen conditions on site, such as the discovery of underground storage areas, building foundations etc., are likely to prompt modifications to the initial sampling strategy. In addition, the strategy may require modification in response to site observations of strata, odour, appearance of deposits etc (NHMRC 1991). Further modification may also be required when analytical data on the site samples becomes available.

Ideally, the first stage of sampling and analysis should be regarded as an exploratory investigation, that may need to be followed up by a more detailed subsequent stage (or stages).

4.3.4 Sampling patterns and numbers

The sample pattern and frequency of sampling will depend upon the size and topography of the site, the likely distribution of contaminants, and the degree of confidence required (Smith 1990). In some cases it may be permissible to relate the latter to the "sensitivity" of the site.

A number of sampling patterns can be adopted. Those most frequently cited in the literature include composite sampling, random sampling, strategic sampling, grid sampling and network design. Discussion of these sampling patterns is given below.

However, it must be emphasised that many considerations may influence the design of a sampling program. In particular:

- whichever method of grid design is chosen, the design should make use of the information obtained from the preliminary investigation regarding location of contaminant sources, contaminant

mobility, direction of hydraulic gradient, and other transport mechanisms.

- there may be a requirement to relate sampling pattern to proposed end use - for example the requirement (not always logical) to sample from each lot of a proposed residential subdivision.
- budgetary constraints are paramount. Whoever is paying for an investigation, they will not want to spend more money than is absolutely necessary, and it is frequently necessary to trade off the number of sampling points against the breadth of the analytical suite. It must be recognised that most investigations of contaminated sites are carried out by consultants chosen on a competitive basis and that cost is a major consideration in the choice of consultants, therefore the consultant who can devise, and justify a more economical sampling program is likely to win the project.

4.3.5 Composite sampling

Composite sampling is widely used in agricultural land investigation. The technique assumes a homogeneous distribution of substances, and involves the bulking of spot samples taken along the outline of a figure 'W' or 'X' (Lord 1987). The bulking of spot samples has the disadvantage of obscuring high levels of contamination. Composite sampling is thus of limited value for the majority of contaminated site assessments. In fact, its only really useful application lies in sampling stockpiles of excavated soil or other material which is already "ex-situ". Compositing of samples has been effectively used in a number of applications, most notably in the mining industry and in sampling from bulk materials such as shipments and stockpiles. In these applications, sophisticated sample preparation methods, including drying, fine crushing and sieving, riffle splitting and mechanical mixing may be used to ensure that the composite is representative of its parts. These techniques are not appropriate to environmental samples, as substantial loss of volatile analytes (even some of the more volatile metals such as arsenic and mercury) may occur.

If environmental samples are composited, then the conventional approach to interpretation of the analytical results is to compare the analyses of the composites with figures obtained by dividing the investigation thresholds for particular analytes by a factor equal to the number of sub-samples in a composite. Take, for example, lead which has an investigation threshold in soils of 300 mg/kg. (ANZECC / NHMRC 1992) If six sub-samples are included in a composite, then the investigation threshold for the composite becomes $300/6$ or 50 mg/kg. If this value is exceeded, all sub-samples in the composite should be individually analysed, as the worst case of one sub-sample at 300 mg/kg and five at zero must be assumed for regulatory purposes.

4.3.6 Random sampling

The simplest random sampling methods involve gridding an area, assigning sequential numbers to points, and selecting sampling points from a table of random numbers covering the range of grid points (Burgess 1991). The probability of locating 'hot-spots' through random sampling can be estimated using binomial/hypergeometric sampling theory. The probability of locating contaminated areas of various sizes from binomial distribution theory is given in Table 1 below.

Thus, if 5% of the total site area is contaminated, then the use of 30 sampling

TABLE 1
(Bell, Gildon and Parry in Lord 1987)
PROBABILITY OF LOCATING
CONTAMINATED AREA

Contaminated area as % of total site area	Sample numbers		
	10	30	50
1	0.10	0.26	0.39
5	0.40	0.79	0.92
10	0.65	0.96	0.99
25	0.94	1.00	1.00

points will enable a 79% chance of locating that contamination.

The disadvantages of truly random sampling are: (i) it ignores the data from the preliminary investigation; (ii) in practice the technique tends to produce "clumping" of sample points, thus leaving significant areas of the site unsampled; and (iii) it allows for no alteration of the sampling strategy based on experience or observation (Lord 1987).

The problem of sample clumping can be overcome by stratified random sampling, where the site is divided into "strata" or cells, and a number of sampling points chosen at random within each strata. This procedure ensures a more even covering of the site, while still allowing a valid estimate to be made of the sampling error.

When an area is known to be contaminated, but little data is available on the location of probable 'hot-spots', random sampling may be appropriate to determine the statistics of the concentration of indicator contaminants (Burgess 1991).

4.3.7 Judgemental (strategic) sampling

Judgemental sampling involves the collection of samples from areas associated with known historical activities and events (NHMRC 1991). Data assembled during the preliminary survey can be used to ascertain the most appropriate locations for judgemental sampling. This technique is most likely to be of use during a preliminary sampling program carried out during site reconnaissance, or before development of the main program.

4.3.8 Grid sampling

Grid sampling involves mapping sampling points by imposing a regular, rectilinear (or, more efficiently, triangular) grid on the site. The NHMRC (1991) state that grid sampling is the preferred strategy, and Burgess (1991) cites it as the appropriate method for locating "hot-spots" within a known area. Smith (1990) asserts that grid sampling is generally the most useful approach in practice, and states that this approach can be shown, theoretically, as most likely to detect an area of contamination.

The probability of locating a target is a function of grid spacing and the geometrical configuration of the contaminant plume.

Based on experience and research, several authors have correlated the grid density required to the site area alone. Table 2 below presents two such examples of this correlation.

TABLE 2
GRID SIZE VERSUS SITE AREA

Site area (Ha)	Grid size (m)	
	Waterhouse (1980)	British Standard DD 175 (1988)
0.5	10	14-18
1.0	-	17-20
5.0	20	22-25
16	30	-

An alternative approach is to relate the grid size to both the site area and the percentage contamination of the site area. Bell, Gildon and Parry (in Lord 1987) have related the statistical basis of random sampling to rectangular grid sampling. Bell et al. postulate that a random sampling density at a high confidence level dispersed over a rectangular grid would neither increase nor decrease the probability of locating contamination. The probabilities for random sampling presented in Table 1 are therefore also assumed to apply to grid sampling. Accordingly, for 95% confidence in locating an area of contamination, the grid sizes shown in Table 3 would be appropriate (Lord 1987). Thus, if 10% of a 5 hectare site is contaminated, a grid size of around 41m would be required to give 95% confidence of locating the contaminated area.

In practice, for large sites with poorly defined contamination (and therefore extensive analytical suites) grid sampling can prove prohibitively expensive. In these circumstances, a combination of judgemental and stratified random sampling is preferred.

TABLE 3
GRID SIZE TO FACILITATE
LOCATION WITH 95% CONFIDENCE

Site area (Ha)	Grid spacing (m)	
	5% Site Contamination	10% Site Contamination
0.5	9	13
1.0	13	18
1.5	16	22
2.0	18	26
2.5	20	29
3.0	23	31
4.0	26	36
5.0	29	41
6.0	32	45
7.0	34	48
8.0	37	52
9.0	39	55
10.0	41	58
11.0	43	61
12.0	45	65

4.3.9 Network design

Network design involves the determination of an optimum sampling plan for a site under conditions of uncertainty. Due to the complexities of monitoring subsurface contamination, the field of network design is a developing one (Loaiciga 1989).

A detailed description of network design is beyond the scope of this paper. Accordingly, only a brief introduction to the technique is given below.

Network design normally couples simulation of contaminant distribution with variance reduction analysis or an optimisation model. Parameter uncertainty is usually taken into account using the Monte Carlo technique (de Marsily, 1986). Multiple synthetic distributions of contamination are typically generated by treating hydraulic conductivity as a random field. The synthetic distributions are then used to assess the performance of a given sampling network.

The variance reduction approach is an iterative technique that involves a methodical

search for the number of locations of sampling sites that minimise the variance of estimation error of pollutant concentration (Rouhani 1985). Sampling sites are added, one at a time, to a network, until the variance of estimation error cannot be further reduced, or until the additional gain in statistical accuracy is outweighed by other constraints, e.g, the cost of sampling (Loaiciga 1989).

Optimisation models locate a given number of sample sites to maximise coverage, where coverage is a weighted function of distance (Meyer and Brill 1988). The weights can be interpreted as the probability of any distinct plume occurring, or alternatively as the perceived value of detecting any distinct plume. The pattern of sample sites is indirectly determined by a specified areal coverage.

Network design requires adequate field data to characterise the flow properties of the system. In addition, the technique can be computationally intensive, and is liable to require the services of an expert. As with other non-judgemental techniques, it ignores pre-existing data on the site. Perhaps for these reasons, the authors are not aware of any practical applications of this technique on major contaminated land assessments in Australia.

4.3.10 Conclusions

To conclude this discussion of planning and sampling program design, it is worth remembering that all such sampling programs generate point data. Contaminated sites tend by their nature to be highly heterogeneous, and thus "broader brush" techniques which are able to assess changes across the site as a whole are a valuable supplement to sample data, and used as initial screening tools, may help direct a judgemental sampling program in the most effective way. In the following sections, some of the field techniques available for investigation of both contaminated sites and potential waste disposal sites will be described. The order of description is from the broader to the more point-specific techniques, which is also generally from least to the most invasive with regard to the site.

5 GEOLOGICAL AND GEOPHYSICAL TECHNIQUES

5.1 Geological mapping and photogeological interpretation

Geological mapping to assess lithology, stratigraphy and structure should not be neglected as a basic tool in the assessment of both types of sites. Its utility is sometimes limited by lack of exposure: conversely, if a potential waste disposal site happens to be located in a quarry, exposure can be nearly perfect.

Air-photo interpretation can often indicate the presence of structural features which are not obvious on the ground; such features may be related to preferred groundwater movement pathways. This technique is of well established utility in groundwater resource hydrogeology, particularly in hard-rock terrains; it can be of equal utility in contaminant hydrogeology.

Stereographic plotting of structural features is also a well established technique from other geological applications which can be utilised with benefit in this area.

5.2 Geophysical techniques - general comments

Geophysics can assist site characterisation through non-intrusive, surface measurement techniques. In contaminated site investigations, geophysical methods can be used in the following applications (Bates 1991) (Whiteley and Jewell 1992):

- Investigating soil types, stratigraphy, depth to bedrock etc.
- Assessment of lateral and vertical changes in bedrock properties
- Investigating hydrogeological conditions (e.g. depth to groundwater)
- Locating lateral and vertical boundaries of old landfill sites
- Estimating the general composition of landfill
- Mapping of leachate and contaminant plumes
- Detecting cavities (e.g. mine shafts)

- Locating buried drums, underground storage tanks and pipelines.

The information provided by a geophysical survey can lead to more efficient use of more expensive techniques such as drilling. This can sometimes translate into a significant cost saving.

The more frequently used geophysical techniques for environmental applications are summarised in Table 4 below.

It should be noted that for these methods to give useful results, meaningful contrasts in the dependent physical property must exist in the subsurface. For example, if the resistivity of a contaminant is not significantly different from that of natural groundwater, a geoelectrical survey will not give useful results (Stollar and Roux 1975).

Taking into account the typical problems in contaminated landfill assessment and the range of expected physical properties a simple tabulation of the expected applicability of the various geophysical techniques can be made and is shown in Table 5 (Whiteley and Jewell 1992). The techniques are listed in increasing cost from left to right.

It can be seen from Table 5 that EM and resistivity could be expected to have quite general application and that the other techniques can be used in specific problems or to support these techniques. It must be emphasised that an indication in Table 5 that a technique is suitable for a specific task does not mean that it will be suitable for that task in all circumstances. Geological and geophysical conditions at individual sites will determine the most useful technique for a particular task at that location.

5.2 Electrical and electromagnetic Techniques

All electrical and electromagnetic techniques attempt to measure ground conductivity. Electrical resistivity is the reciprocal of conductivity; thus the terms resistivity and conductivity describe an equivalent physical property. It has been traditional to describe direct contact electrode methods by the term "resistivity", while "conductivity" has been used for the same property measured by

TABLE 4

GEOPHYSICAL METHODS FREQUENTLY USED IN ENVIRONMENTAL SITE ASSESSMENT

Method	Dependent physical property	Major applications
Resistivity	Electrical Conductivity	Soil type, stratigraphy, depth to bedrock; Degree of saturation; Contaminant mapping; cavity detection.
Frequency Domain Electromagnetic (EM) Techniques	Electrical Conductivity	Soil type, stratigraphy; Degree of saturation; Landfill investigations; Contaminant mapping; Cavity detection; Location of buried objects.
Transient Electromagnetic (TEM) Techniques	Electrical Conductivity	Faults, shear zones; Contaminant mapping; Soil type, stratigraphy, depth to bedrock;
Ground Penetrating Radar (GPR)	Dielectric Permittivity	Location of water table; Contaminant mapping; Cavity detection; Location of buried objects.
Seismic Refraction	Elastic Moduli	Bedrock lithology and profiling; Overburden characteristics; Degree of saturation; Location of landfill boundaries.
Vertical Seismic Profiling (Surface-to-downhole)	Elastic Moduli	Vertical and lateral changes in bedrock properties; Anisotropy due to linear features such as faults and joints.
Magnetometry	Magnetic susceptibility	Fault location, bedrock lithology, cavity detection location of buried objects.

APPLICABILITY OF GEOPHYSICAL TECHNIQUES

19

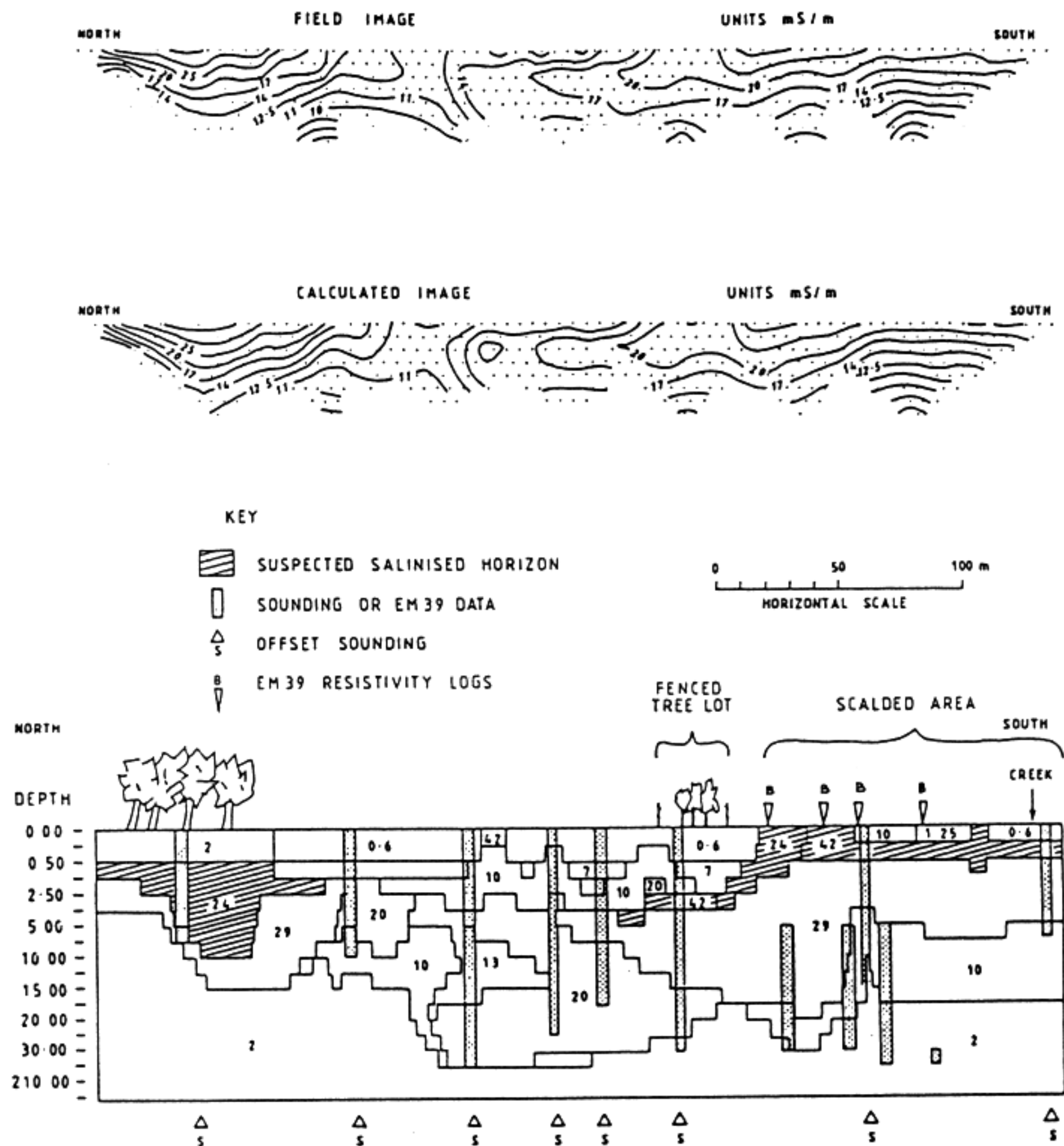


Figure 3 Field image data, calculated image data and electrical conductivity model built up for a section using multiple passes along a 390m electrode line. The profile is modelled to generate a calculated image, which is compared to the field image. The model is then modified and the process repeated until a good fit is obtained. The final model incorporates any available control from borehole and wireline log data. (Acworth et al 1990)

homogeneous isotropic plane layers of constant thickness. It has now been largely superseded by computer-based 1- and 2-dimensional modelling techniques.

Cases where electrical resistivity methods have been successfully used in field investigations of groundwater pollution are presented by, for example, Stollar and Roux (1975), Urish (1983), Schoepke and Thomsen (1991) and Barber et al. (1991). For the method to be productive, the contrast in conductivity due to contamination must exceed a threshold value related to the natural scatter in resistivity variations at the site (Klefsatd et al. 1975). In general, most authors report limited success at sites where either (i) the lateral variations in superficial geology are high, (ii) the contrast between the conductivities of the contaminated and natural poor fluid are low, (iii) the depth to the water table or contaminant plume is large, or (iv) the thickness of the contaminant plume is small.

More recently a 3-dimensional profiling method using computer-controlled electrode arrays has become available (Griffiths and Turnbull 1985). With this technique, a line of electrodes is connected to a central computer controlled switch-box by a multi-cored cable. A 3-dimensional image of the earth is built up by multiple passes along the line of electrodes at progressively increasing separation. This is illustrated in Figure 3. The method has been successfully used in the investigation of dryland salinity problems (Acworth et al 1990), and has potential application to the investigation of complex groundwater contaminant plumes.

As discussed in Section 5.1, the electrical resistivity method remains a core technique in the geophysical investigation of contaminated sites.

5.2.2 Electromagnetic (EM) methods

EM methods involve measurement of earth responses to time varying fields most often transmitted through closed loops of insulated wire (the so-called induction EM methods) or from antenna, the so-called Ground-Penetrating-Radar (GPR) technique. In conventional application there are two distinct

types of method depending on the type of source and the frequency of signal. If a continuous wave is transmitted and the response is measured at the same frequency then the method is called Frequency Domain EM (FEM). If the primary field is a pulse and measurements are made in the off-period the method is called pulse or Time Domain EM (TEM).

These techniques have the advantage of not requiring electrical contact with the ground surface. This reduces the sensitivity of the instrument to near surface variations, and allows surveys to be conducted over rocky ground or paved areas (Jansen 1991).

5.2.3 Frequency domain EM

EM conductivity meters generate electrical fields indirectly by energising a transmitter coil with an alternating current at a fixed frequency. This produces a primary magnetic field that induces very small electrical eddy currents in the subsurface. These currents generate a secondary magnetic field that is sensed, together with the primary field, at a receiver coil (Jordan et al. 1991). By comparing the magnitude (in-phase component) and phase lag (quadrature component) of the secondary field relative to the primary field, the conductivity of the subsurface can be determined.

At low frequencies and low conductivities the in-phase response is essentially zero, and the quadrature response is linear with conductivity (McNeil 1981). The in-phase magnetic component of the secondary field is not directly related to ground conductivity, but is very responsive to highly conductive objects, such as buried metals. By using in-phase readings in conjunction with quadrature phase readings, both ground conductivity and the presence or absence of buried metal objects may be inferred (McQuown et al. 1991 and Saunders et al. 1991).

The transmitter to receiver spacing (coil separation) determines the maximum depth of penetration and the relative response of the instrument to materials at different depths. The actual depth of investigation is controlled by the frequency of the transmitted EM field

and the ground conductivity. High frequency EM fields are adsorbed faster in the ground and do not penetrate to the depth of low frequency fields. In addition, the EM energy is adsorbed faster in high conductivity materials. Thus, the greatest penetration is achieved by low frequency EM fields in low conductivity materials. Effective investigation depths of between 1.5 and 100m are reported in the literature.

Several highly successful case histories involving electromagnetic investigations of contaminated sites are presented by, for example; Slaine and Greenhouse (1982), Lawrence and Boutwell (1990), and Brooks et al. (1991). These case histories confirm that, if conditions are conducive to performing an EM survey, the method can be used to delineate the horizontal extent of landfilled materials, the presence of ionic and organic contaminant plumes, and the whereabouts of buried metallic objects, such as waste drums, storage tanks and metal pipelines.

The change in ground conductivity with depth can be determined by altering the coil spacing at a constant frequency (geometric sounding), or by changing transmitter frequencies at a fixed coil spacing (parametric sounding). In general, the latter method is more convenient. However, these instruments have inherently poor vertical resolution and a limited range of operational frequencies and in practice are generally combined with resistivity sounding for depth information. The results of the survey can be presented as profiles, areal iso-conductivity maps or isometric projections of both the quadrature and in-phase data. Anomalous areas of conductivity, in comparison to natural or background conditions, are used to identify possible areas of ionic and/or organic contamination, and the location of buried conductive material.

5.2.4 Transient electromagnetic techniques

TEM techniques use the interaction of a transient electromagnetic wave with the earth to determine the electrical conductivity of the ground).

TEM conductivity meters generate transient electromagnetic fields by abruptly switching

off a current in a large transmitter loop laid out on the earth's surface. When the current is switched off, the induced magnetic field collapses and provokes eddy currents in the ground. The decaying magnetic field of these eddy currents is detected with the loop, or with a smaller multi-turn receiver coil on the surface (Buselli et al. 1986).

Apparent ground conductivity is calculated as a function of the time after the current is removed. At greater times, the induced fields penetrate further, and are thus representative of greater depths. The measurement of TEM response therefore offers the possibility of rapidly obtaining a vertical EM sounding.

TEM induction equipment such as SIROTEM (MCI Pty. Ltd.) and the PROTEM (EM47 - Geonics Ltd.) have also been used for contaminated land assessment (Buselli et al. 1989). There are interpretational advantages, particularly for the resolution of thin contaminated layers, in combining the results of both TEM and resistivity soundings through the process of joint inversion. These methods tend to compensate for each others weaknesses with the EM methods highly sensitive to conductive layers while the resistivity method gives more accurate values for resistive layers (Whiteley, 1983).

A disadvantage of TEM systems, which otherwise seem to have many advantages for contaminated land assessment is that they currently have a significant limitation which is their minimum depth of investigation. This is controlled by the time at which the first measurement can be taken after the primary current in the loop has ceased flowing. The significance of this limitation will vary dependant upon geophysical conditions at a specific site, and has been reduced in recent equipment such as the PROTEM.

5.2.5 Radiowave electromagnetic techniques

The radiowave electromagnetic technique was developed in the former Soviet Union and has recently been introduced into Australia (Whiteley 1992). It operates at a frequency of 1.5MHz, responds to changes in both dielectric constant and electrical conductivity to a depth of about 25m, and is able to operate in areas

where interference from surrounding metals or magnetic fields would make conventional EM systems inoperable. It would seem to have great potential in work of this type.

5.2.6 *Ground penetrating radar*

Ground penetrating radar (GPR) is a rapidly developing technique at present (Reynolds 1991). Short impulses of electromagnetic energy, at frequencies in the range of 10 MHz to 1000 MHz, are transmitted into the ground and signals are returned to the surface from reflecting interfaces. These reflecting interfaces are provided by changes in the geoelectrical properties of the ground. By measuring the time taken from the electromagnetic waves to leave a transmitting antenna, propagate through the ground, and return to a receiving antenna, a radar profile can be obtained.

Modern GPR equipment is portable and relatively easy to use. The antenna may be towed behind a vehicle, and some systems may be moved manually.

The depth of signal penetration and the quality of the reflected signal are influenced by the characteristics of the subsurface. If the substrate does not attenuate the signal, the depth of penetration is limited by how far the signal can travel and return in the maximum scanning time. Under these circumstances the signal depth is controlled by the propagation velocity, which is inversely related to dielectric constant (or relative permittivity) of the soil system (Truman et al. 1988). Because the mineral components of many soils have low dielectric constants in comparison to most pore fluids, the system dielectric constant is strongly dependent on the volumetric fluid content of the soil and the dielectric constant of the pore fluid.

Signals are reflected when there is an abrupt change in geoelectrical properties at some depth in the profile. Thus, a strong reflection will occur when a horizon has a dielectric constant that differs sharply from that of the horizon above. This can occur because of a sudden change in the dielectric constant of the substrate, or because of the presence of a buried object.

Beres and Haeni (1991) describe the use of GPR in hydrogeological mapping studies, and indicate that in the right environment continuous, high resolution, profiles which show the depth of the water table and position of lithological changes may be produced.

When the GPR signal encounters a highly conductive object in the near surface "ringing" occurs. A portion of the radar wave is reflected back towards the receiving antenna, while the other portion continues to greater depths. The reflected portion of the wave, which has high energy, continues to reflect back and forth throughout the GPR record, thereby obscuring any deeper reflections.

The "ringing" effect enables GPR to accurately delineate the location, dimensions and burial depths of highly conductive objects, such as underground storage tanks (USTs) and pipes. For example, Hager et al. (1991) report detecting the size and orientation of more than 60 USTs through examination of some 30,000m of GPR profile. However, the technique is not limited to detecting the whereabouts of highly conductive objects. Asmussen et al. 1986) report the successful location and sizing of PVC drainage pipes using GPR.

Use of GPR to identify contaminant plumes caused by both conductive (ionic) contaminants and non-conductive (dense non-aqueous phase liquid - DNAPL) contaminants has been reported (Annan et al. 1991, 1992, Brewster et al 1992, Redman et al. 1991). The work carried out by these authors on an experimental spill of tetrachloroethylene (PCE) at a site in Borden, Ontario, has demonstrated the usefulness of GPR in the detection of organic contaminants which form a distinct DNAPL layer.

A major limitation on the usefulness of GPR in some environments is attenuation of the signal. Signal attenuation increases as ground conductivity increases, and while in favourable, low conductivity environments GPR sounding can be made to depths of up to 40m (Davies and Annan 1989), once conductivity increases above 5 mS/m the range of GPR is drastically reduced.

For this reason, a GPR survey would not normally be undertaken without first carrying

out a resistivity or EM survey of the site to establish that GPR would have a useful range of penetration.

5.3 Seismic refraction

Seismic refraction is another technique with a long and proven record in mineral exploration, hydrogeology and geotechnical engineering. Its principal use in the assessment of contaminated sites lies in delineating the boundaries of filled and natural ground, based on the substantial contrasts in seismic velocity which frequently exist between fill and bedrock. This contrast is particularly well marked in the Sydney area, where the Hawkesbury sandstone has velocities ranging from 2400 to 3600 m/s, compared with 370 m/s to 1000 m/s for MSW. (Whiteley and Jewell 1992).

In the assessment of potential waste disposal sites, the utility of the refraction technique is mainly in stratigraphic mapping. Control in the form of borehole data or another geophysical technique is generally required.

During recent investigations for the proposed extension to the Lucas Heights landfill (Douglas / Coffey 1992), seismic refraction was used in conjunction with vertical seismic profiling and interactive ray-trace modelling to delineate vertical and lateral changes in velocity associated with fracturing in the Hawkesbury sandstone. In this application an array of geophones was emplaced vertically in boreholes, and surface - to - downhole measurements made utilising both percussive and explosive sources.

5.4 Magnetometry

Geomagnetic surveys involve measurements of the Earth's magnetic field. Buried ferromagnetic materials, such as drums or tanks, will distort the addition, some landfill boundaries (oriented E-W), can also be mapped using magnetic methods (Reynolds 1991).

Magnetic mapping is usually used as a reconnaissance method to locate anomalous ground. Magnetometry instruments are highly portable and can be operated by one person. In a typical survey, measurements of the

Earth's total field strength are made over a grid. Field data are then used to construct a map of magnetic anomalies (Applied Geology 1991).

The interpretation of magnetic data is qualitative, and the technique is often used in conjunction with complementary geophysical techniques, such as EM surveying. For example, Schutts and Nicholas (1991) report that a combination of magnetometer and EM profiles precisely located over 5,000 m of pipeline and 100 USTs during an environmental audit.

In general, the technique (like seismic refraction) is most useful for detecting geological features that influence contaminant transport, rather than mapping the contaminants themselves (Bates 1991).

5.5 Conclusions

In summary, it can be concluded that while geophysical techniques have much to offer in the fields of contaminated land and waste disposal site assessments, they also have severe limitations. Best results will always be obtained by using geophysics in conjunction with other techniques such as drilling and geochemical testing, or by using two geophysical techniques in combination, for example, seismic refraction and resistivity sounding, EM and resistivity, TEM and resistivity sounding, or GPR and either EM or resistivity.

6.0 INVASIVE SAMPLING TECHNIQUES

Despite the rapid advances being made in the application of geophysical techniques to the investigation of contaminated land, obtaining and analysing samples of soil and groundwater remains, and will remain for the foreseeable future, an essential part of most investigations. Sampling on sites which may be contaminated with a variety of toxic materials poses particular problems with regard to worker health and safety, and requirements to ensuring that the quality of the results obtained will stand legal scrutiny. These issues are discussed in the following sections, followed

by descriptions of some of the available sampling techniques.

6.1 *Health and safety*

Assessment of contaminated sites may pose particular hazards to the personnel involved in site work, which is one excellent reason for favouring the least invasive techniques. However, in most investigations, some sampling is required, and the need to protect personnel working on hazardous waste and contaminated land assessments from injury or long-term health damage by the materials present on these sites is obvious. Less obvious is the need to protect personnel against hazards which can occur equally on any drilling or construction site - head injuries, foot injuries, falls, heat exhaustion etc, but which are more likely to occur when individuals are encumbered by protective clothing.

Heat exhaustion is of particular concern as temperatures during the summer months in Australia are high and, besides being dangerous to health in its own right, heat stress exacerbates the risk of physical injury due to other causes. It is thus necessary to strike a balance between the need to protect personnel from chemical hazards, and the need to avoid unnecessary imposition of heat stress and its related risks.

Levine and Martin (1985) and the US Department of Health and Human Services (1985) give sound general guidelines for the protection of workers on hazardous waste sites, but local conditions and legislation must also be taken into account. Health and Safety legislation is a State responsibility but the federal body WorkSafe Australia has an advisory role in framing guidance notes, standards and national model regulations and codes of practice which states are encouraged to incorporate in their own legislation.

Existing Health and Safety legislation in most states generally refers to chemical hazards as they affect workers in the chemical manufacturing and distribution industries, and general chemical use in industry. Other applicable legislation relates primarily to safety on construction sites.

6.2 *Quality Assurance and Quality Control*

A Quality Assurance (QA) /Quality Control (QC) program is necessary to during investigations of contaminated sites to ensure that all data generated during the project is scientifically valid, defensible, and of known precision and accuracy. The data must be of sufficient known quality to withstand scientific scrutiny and legal challenges relative to the intended future use of the site. This data includes that obtained in the field during sampling and in the laboratory during analysis. The conclusions of a study cannot be credible unless the sampling and analytical procedures are performed properly and this performance documented.

QA refers to the design and management aspects of the program while QC relates to the specific procedural steps. Proper identification and organisation of program goals is the first essential for program success; this must be supplemented by detailed procedures to define and document the flow of materials, samples and information from the field to the laboratory and project management, and from the laboratory back to the project management.

Specific measures are also required to monitor and document the efficacy of field procedures for equipment decontamination and preservation of sample integrity, and to monitor the accuracy and precision of laboratory analyses. Publications by the USEPA (1986 and 1989c) provide good general guidance on QA/QC procedures.

Intra- and inter-laboratory duplicate samples, obtained from the same locations and at the same time as the primary samples, are used to monitor the precision of laboratory analyses.

Control samples "spiked" with known concentrations of the analytes of interest are used to monitor laboratory accuracy.

Field blanks - samples of analyte-free media - are used to monitor the integrity of the sampling and sample-transport process.

Equipment blanks - samples of wash-water obtained during equipment decontamination, are used to monitor the efficiency of the decontamination process, and ensure that cross contamination of samples does not occur.

6.3 Resistivity and Gas Cone Testing

The use of electric friction (Dutch) cone probing in geotechnical investigations is well established. Modifications to the basic equipment allow the electrical resistivity of the formation fluid (an indication of salinity) to be read directly (Robertson and Woeller 1991), and allow gas samples to be withdrawn for analysis, either on-site using portable photoionisation detectors and/or gas chromatographs, or in the laboratory (Campanella and Weemeees 1990).

A more sophisticated use of the cone technique for hydrochemical sampling and piezometric measurement is the BAT technique (Envirotech AB 1988) which utilises a porous filter tip permanently installed using cone equipment. Samples are obtained using an evacuated vial which is temporarily connected to the filter cone-tip using a double-ended hollow needle, then retrieved.

Cone equipment has particular utility in unconsolidated formations, especially sands, and sands with clay and peat interbeds. To be used effectively to significant depths, the technique requires heavy, purpose-built cone rigs. It is, however, also being used at shallow depths using much lighter, utility-mounted equipment.

6.4 Drilling

Despite the development of less invasive techniques, drilling remains one of the primary tools used during waste disposal and contaminated land investigations. In this type of work, drilling is used for three basic purposes, namely:

- obtaining stratigraphical and lithological data
- obtaining soil samples for chemical analysis
- installing monitoring wells for groundwater sampling and hydraulic testing

Frequently all three purposes must be served with the same borehole.

The options available for borehole drilling

include auguring (solid and hollow-stem), rotary drilling with a variety of flush media, and percussion (cable tool) drilling.

It is a general requirement of drilling for both soil sampling and groundwater monitoring that the method chosen should have minimal impact on the natural system and, in particular, should minimise the risk of transfer of contaminants between soil horizons, from soils to aquifers or between different aquifers. Conventional (direct circulation) rotary drilling, regardless of the flush medium, does not fulfil this requirement. The flush medium, whether bentonite or polymer mud, air-foam emulsion or water, is a conduit for potential contaminant transfer; removal of residual flush medium following drilling is particularly difficult in low-permeability formations.

The preferred drilling techniques are thus:

- hollow-stem auguring (relatively shallow unindurated formations); and
- cable-tool drilling or twin-tube reverse circulation drilling (deeper and/or indurated formations).

These techniques all provide temporary mechanical support for the borehole during drilling, and allow permanent casing and screen to be installed inside this support without contacting the formation - thus reducing the risk of carrying contamination down from upper layers. Generally permanent casing would be steam-cleaned prior to installation.

These methods are, however, slower than conventional rotary drilling, which necessarily imposes a cost penalty. This must be borne if high standards for data validity and defensibility are to be met. A further problem is that relatively few drilling contractors have the necessary equipment - thus premium rates are charged, and mobilisation costs are also frequently required.

Solid-flight auguring is extensively used for soil sampling during geotechnical investigations; used in conjunction with tube sampling, in relatively cohesive formations, the technique can provide soil samples of adequate integrity for chemical analysis. However, the

method has severe limitations for groundwater monitoring borehole construction.

Of necessity, conventional-circulation rotary coring, using water as the flush medium, has been used for monitoring borehole construction in shales and sandstones on a number of recent contaminated land investigations (for example, Homebush Bay - Coffey 1990) and waste disposal site investigations (for example Lucas Heights (Douglas/Coffey 1992).

In these instances, cost and logistic considerations dictated the choice of drilling method. The compromise was recognised, and additional development and purging procedures were adopted to compensate, but it was still necessary to qualify the initial sampling results.

6.5 Sampling

6.5.1 Soils

The primary requirement of soil sampling for environmental investigations is to obtain samples which are as chemically representative as possible of the bulk medium from which they were taken. This applies whether soil samples are obtained during drilling operations, or using mechanical equipment such as backhoes and excavators, or by hand, using hand-augers or simple trowels.

When sampling for many non-labile analytes, such as heavy metals or mineral fibres, grabs samples obtained by trowel, hand auger or from the backhoe bucket are adequate. When samples are obtained from deeper boreholes using drilling equipment, the use of either thin-wall tubes (normally U50's) for cohesive soils, split-spoon samplers for uncohesive soils and piston samplers for 'sloppy' sediments is preferred, as this reduces the risk of cross-contamination by more highly contaminated horizons uphole. Sampling equipment which actually contacts the sample must be cleaned between samples; generally steam cleaning and/or scrubbing with a laboratory grade detergent, for example DECON 90 or equivalent, is employed. In the case of equipment such as tubes and split-spoons, it is generally more convenient to pre-clean sufficient equipment for the job in hand, and

take it into the field suitably wrapped, where it is used once only before being returned for re-cleaning. Samples are usually transferred from the sampling device to a clean glass jar in the field.

In some circumstances, sampling direct from auger flights is permissible, although it must be emphasised that the risk of cross-contamination is greatly increased by this technique.

Greater problems arise when sampling soils for volatile components, for example the lighter aliphatic petroleum hydrocarbons, monocyclic aromatic hydrocarbons and chlorinated hydrocarbons. In these cases, the risk of loss of a significant proportion of the analyte of interest either during sampling, or during transfer between sample containers in the field or laboratory is high. Options available to reduce this risk include zero-headspace sample and crimp devices for shallow sampling, the use of sample tubes pre-chilled in dry ice for deeper sampling, and retaining the sample within the sampling tube until it is removed for analysis. Samples for volatile analysis are cooled in the field as soon as they are taken, and are transported under cold-chain conditions.

6.5.2 Groundwater

Over the past 10 years, the development of techniques for sampling groundwater has probably received more attention than has been given to any other medium. The key issues are:

- construction methods and materials for monitoring boreholes
- purging requirements
- sampling equipment
- on-site analysis
- sample treatment and preservation

The prime requirement for monitoring borehole construction is that this construction should enable samples which are representative of the aquifer horizon of interest to be obtained, without the risk of cross contamination from overlying or underlying aquifers. In general, this is achieved by

drilling to fully penetrate the aquifer of interest, screening (and usually gravel packing) this aquifer, and then casing and grouting off the overlying horizons.

Where samples are required from more than one aquifer, the conventional approach is to drill separate monitoring boreholes for each aquifer. This approach is costly, and two alternatives are available - dedicated samplers and multi-port casing systems.

During the 1970's, much work was carried out on the development of gas-operated in-situ or dedicated samplers (for example, Naylor et al 1978). Such samplers are permanently installed in an unlined borehole, which is then backfilled with a granular medium around the sampler, and a suitable grout placed between the samplers. These devices were used successfully in landfill studies and in a major investigation of the vertical distribution of nitrates in the extensive Triassic Sandstone and Chalk aquifers of southern England. The main disadvantages of samplers of this type is that, once installed, they cannot be retrieved for maintenance, and use of the borehole for other purposes is precluded.

Multi-port sampling systems were developed in Canada, the best known are the Waterloo (Pickens et al 1978) system and its commercial (Westbay) derivative (Figure 4). In this system, a single, relatively large diameter casing is installed, gravel packed over the aquifer horizons of interest and grouted between them. Evacuated tubes are used to obtain samples from a series of ports in the outer casing which are located at the various aquifer horizons. The ports can also be used for piezometric measurements. While sophisticated, the system has few moving parts to require maintenance. These systems have been successfully used in a variety of applications in North America (Raythane and Patton 1982), but, though proposed for a number of projects, expense has so far precluded their use in Australia.

The choice of materials for screen and casing during monitoring borehole construction has been a matter of considerable controversy. uPVC (unplasticised polyvinylchloride) is generally the material of choice for well casing and screen. This material is widely used for

groundwater monitoring borehole construction on account of its durability and low cost. However, a number of authorities advised against the use of this material when monitoring of organic contamination (particularly volatile halocarbons) is the primary objective.

For example, Barcelona et al (1985) recommended uPVC only for limited monitoring situations where inorganic contaminants only are of interest. The RCRA Ground Water Monitoring Technical Enforcement Guidance Document (USEPA / NWWA 1986) also recommends only Teflon or stainless steel where volatile organics are to be determined. A study by Reynolds and Gillham (1985) found that sorption of some organics (specifically 1,1,2,2-tetrachloroethane, 1,1,1-trichloroethane, bromoform and tetrachloroethene) could be a source of bias. Parker and Jenkins (1986) found a statistically significant loss of the explosives TNT and HMX from groundwater in contact with uPVC casing, but believed that this loss was due to enhanced biodegradation rather than sorption, and concluded that uPVC was a suitable material for this use. Later work by Gillham et al (1988), Reynolds et al (1990) and Hewitt (1992) has concluded that uPVC is generally a suitable material for monitoring borehole construction, being in fact superior to many more expensive materials. It should go without saying that, when used for monitoring borehole construction, no solvents or chemical cements must be used for joining PVC sections.

Purging is required to ensure that samples obtained from open boreholes are representative of the water in the aquifer, not the water column in the borehole. Three approaches to purging are common. These are:

- specification of the number of "well volumes" to be purged (the USEPA [1986], suggest 5 volumes) which has the advantage of simplicity and uniformity, but may impose unnecessary costs, and in some circumstances result in loss of the analytes of interest (Gibs and Imbrigiotta 1990),

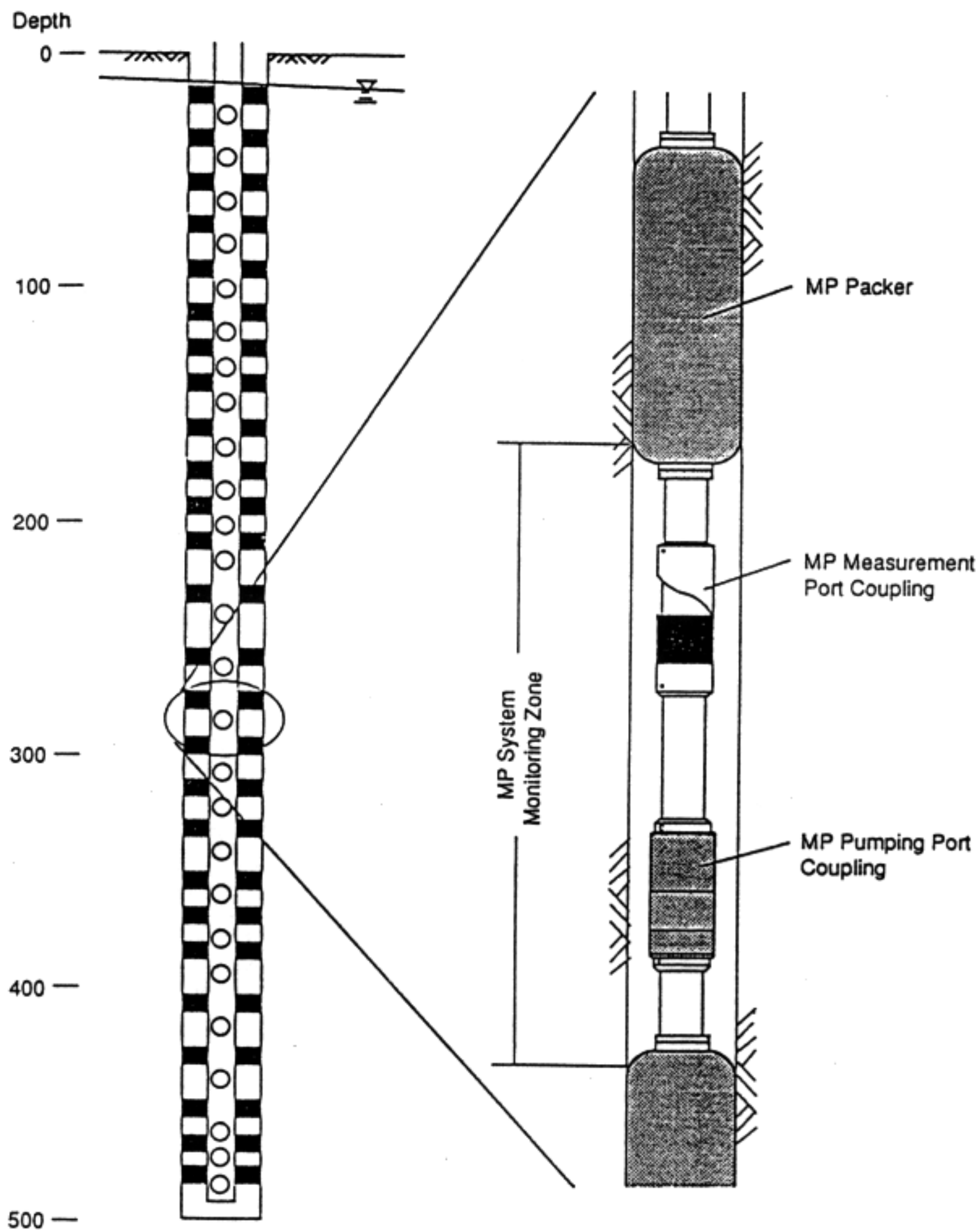


Figure 4 Multi-port sampling system installation with monitoring zones isolated by packers (Westbay Instruments Inc).

- a site specific approach, as recommended by Barcelona et al (1985) and Barber & Davis (1987) which calculates the volume of purging required from the well storage theory of Papadopoulos & Cooper (1987), and
- monitoring of field measurable parameters such as pH and conductivity, followed by sampling when these parameters have stabilised. The disadvantage of this approach is that these parameters may have little relationship to the analytes of primary interest, such as trace organic determinands.

In some circumstances, sampling of the "first flush" of water from the borehole at the start of purging may be advisable in addition to sampling at the end of purging.

A wide variety of sampling and pumping systems are available for environmental sampling of groundwater from conventional monitoring boreholes. These include, in approximate order of frequency of use:

- bailers - generally bottom-loading, check-valve systems of stainless steel or Teflon construction
- small-diameter stainless-steel submersible pumps with variable discharge, designed specifically for groundwater monitoring. The Grundfos MP1 is a fine example. The main advantages of such pumps are that the variable discharge rate allows rapid purging followed by more gentle sampling, they are capable of pumping against high total heads, and sufficient pressure is available for direct field filtration if required.
- gas-operated bladder-type pumps, again designed specifically for environmental sampling, which exclude contact between the working gas and the sample, and are also generally of stainless steel and Teflon construction. Whilst bladder pumps have a number of theoretical advantages, in practice they are limited by slow discharge rates, difficulties in decontamination, and

relative unreliability.

- inertial pumps - simple, cheap and effective (Rannie and Nadon, 1988)
- vacuum-operated down-hole grab samplers (similar to the BAT cone-sampler), in which a hollow needle is used to pierce a membrane on an evacuated container once the device has been lowered to the required depth (Pankow et al 1984)

As with soil sampling, decontamination of sampling equipment between samples is desirable in groundwater sampling. Bailers may be decontaminated with laboratory-grade detergent, followed by distilled water rinsing, but in the case of pumping equipment, involving many metres of small-diameter tubing, decontamination is problematic, and it is common to rely on the purging process at the next borehole to complete decontamination. Equipment blanks taken as part of a field quality assurance / quality control program provide assurance that decontamination of equipment has been adequate.

Vadose zone sampling is an important consideration in some investigations, as the vadose zone may provide many years of retention before contaminants reach the saturated zone. A variety of lysimeter-type devices are commercially available for this purpose. Lysimeters have a number of limitations (Everett et al 1984), including loss of volatiles by degassing under suction, slow sample collection and a tendency to bias the sample disproportionately from the larger pores. However, the only real alternative is extraction of pore water by centrifugation from cored samples, which also has problems of volatile loss and sample contamination.

On-site analysis of a large number of determinands is now possible. However, unless logistical reasons dictate otherwise, analysis carried out in the field is generally restricted to two main groups:

- field screening to reduce the cost of laboratory analysis
- analysis of labile analytes

Temperature, pH, redox potential and dissolved oxygen are labile, and may be measured instrumentally in the field, generally using a flow-cell which excludes air access to the sample prior to measurement. The usefulness of measurements of redox potential is a matter of some dispute. Good equipment and great care are required to obtain meaningful measurements, and interpretation of the results is not straightforward. While redox measurements may have value in a research context, routine measurement during investigations of groundwater contamination is probably not worthwhile.

Conductivity is easily measured, and is a useful screen.

Carbonate, bicarbonate and dissolved carbon dioxide may be labile in some conditions, and can be measured titrimetrically in the field relatively simply.

Volatile organic compounds may be analysed using the headspace technique, either integrated (using a photoionisation detector, or discretely with a portable gas chromatograph.

Groundwater samples are generally more prone to alteration during storage and transport than other samples, as profound differences in temperature, pressure, and redox conditions may occur between the sample source at depth in the aquifer, and the surface. Field preservation techniques are commonly applied to overcome this problem, and may include:

- filtration and acidification for metals
- zero-headspace vials for volatiles
- acidification for phenolics, TKN and ammonia
- alkali treatment for cyanides
- cold-chain transport and storage for all samples.

6.5.3 Gases

Soil vapour analysis is a useful screening tool in environmental site assessments. The technique is particularly valuable in the assessment of leakage from underground storage tanks, and the investigation of former landfill sites.

A relatively shallow (generally 1-2m) probe, either temporary or permanent, is installed in

the vadose zone, and samples of soil vapour are withdrawn for field analysis using a photoionisation detector, combustible gas detector or gas chromatograph, or are collected in gas-bags for subsequent laboratory analysis. As volatile organic compounds partition favourably between the soil vapour phase and the dissolved and adsorbed phases, the concentration of such materials in soil vapour is an excellent indicator of their presence and location as soil and groundwater contaminants. Other papers presented at this conference discuss soil vapour and headspace screening techniques in more detail.

An alternative technique for soil vapour screening (Malley et al 1985, Danahy et al 1990) makes use of tubes containing a curie point ferromagnetic wire filament with an absorptive coating which are placed in contact with the soil surface and left for several days. The absorptive coating is able to collect vapour diffusing from the soil, and is then collected for laboratory analysis by curie point desorption mass spectrometry.

6.6 Analytical considerations

Laboratory analysis is generally beyond the scope of this paper. It must be emphasised, however, that choice of laboratory, and an appropriate analytical suite and analytical methodology for the job in hand form a vital part of the project planning process., which must be integrated with the choice of sampling and field measurement techniques. Both USEPA (USEPA 1986) and APHA (APHA/AWWA/WEF 1992) analytical and QA/QC protocols are commonly used in Australia.

6.7 Hydraulic conductivity measurement

In many instances, on both chemically contaminated sites and on potential waste disposal sites, contaminant transport in groundwater forms the primary pathway for migration of contaminants from the site, and consequent exposure of human populations and the environment. The hydraulic characteristics, particularly hydraulic conductivity, of the aquifer materials will

govern the rate of such transport, and their assessment is therefore an important objective in most investigations. A wide range of techniques are available for measurement of hydraulic conductivity and a full discussion is beyond the scope of this paper, but in the authors' experience, a relatively small subset of these are commonly employed in investigations of this type. These are:

- pumping tests - (high conductivity formations)
- injection (packer) tests - low conductivity and fractured formations)
- rising and falling head piezometer (slug) tests
- laboratory measurements at defined effective stress (limited in this context to measurements on landfill lining materials)
- infiltrometer / lysimeter tests (limited to measurements on landfill lining materials)

7 CONCLUSIONS

Geological techniques for investigation of contaminated sites and potential waste disposal sites include mapping, photogeological interpretation and drilling; these well-established techniques still have a key role in contaminated site assessment. Hydrogeological techniques include both traditional and innovative techniques for the measurement of hydraulic characteristics. Geochemical techniques have advanced considerably in recent years; sampling and on-site analysis of soil vapour is both a valuable tool in its own right and an useful screen prior to sampling soils and groundwaters, and much research has been devoted to securing defensible samples of groundwater from monitoring boreholes - whilst standard purging and sampling strategies for this activity have been established, sound hydrogeological judgement is still required in the choice of the most appropriate technique for a particular situation. Sound techniques for reducing the risk of cross contamination during sampling of soils and other unconsolidated geological materials are also available, however, sampling of consolidated materials remains problematic. Geophysical techniques

form a useful adjunct to geological and geochemical methods, particularly in an initial, broader, look at the site, and are sometimes able to extend the reach of other methods in a cost effective manner. As in most other areas of application, however, geophysical techniques cannot stand alone, and high quality sampling remains an essential part of the investigation process.

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