CRC for Contamination Assessment and Remediation of the Environment

National Remediation Framework

# Guideline on implementing long-term monitoring

Version 0.1: August 2018

# National Remediation Framework

The following guideline is one component of the National Remediation Framework (NRF). The NRF was developed by the Cooperative Research Centre for Contamination Assessment and Remediation of the Environment (CRC CARE) to enable a nationally consistent approach to the remediation and management of contaminated sites. The NRF is compatible with the *National Environment Protection (Assessment of Site Contamination) Measure* (ASC NEPM).

The NRF has been designed to assist the contaminated land practitioner undertaking a remediation project, and assumes the reader has a basic understanding of site contamination assessment and remediation principles. The NRF provides the underlying context, philosophy and principles for the remediation and management of contaminated sites in Australia. Importantly it provides general guidance based on best practice, as well as links to further information to assist with remediation planning, implementation, review, and long-term management.

This guidance is intended to be utilised by stakeholders within the contaminated sites industry, including site owners, proponents of works, contaminated land professionals, local councils, regulators, and the community.

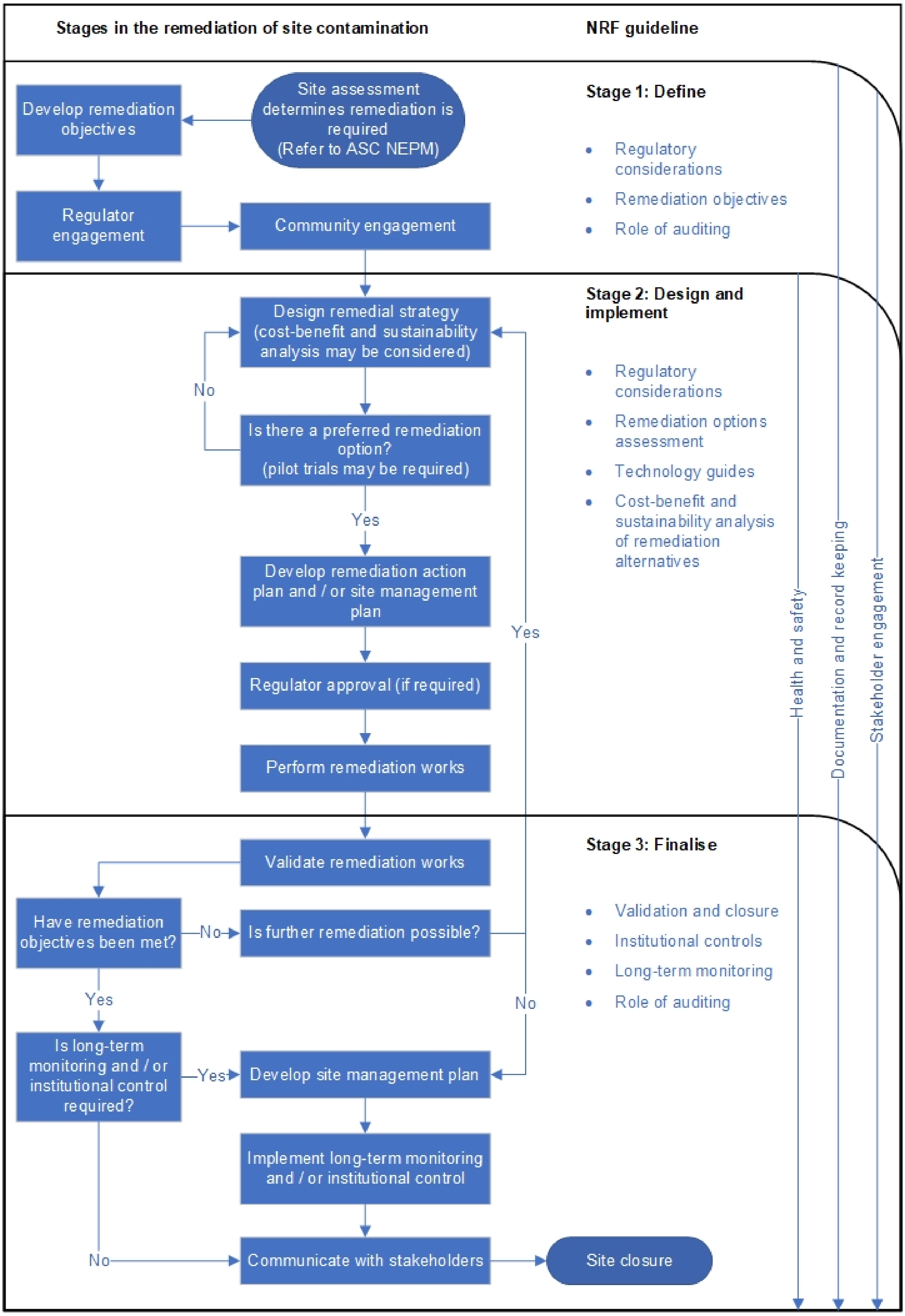
The NRF is intended to be consistent with local jurisdictional requirements, including State, Territory and Commonwealth legislation and existing guidance. To this end, the NRF is not prescriptive. It is important that practitioners are familiar with local legislation and regulations and note that **the NRF does not supersede regulatory requirements**.

The NRF has three main components that represent the general stages of a remediation project, noting that the remediation steps may often require an iterative approach. The stages are:

- Define;
- Design and implement; and
- Finalise.

The flowchart overleaf provides an indication of how the various NRF guidelines fit within the stages outlined above, and also indicates that some guidelines are relevant throughout the remediation and management process.

It is assumed that the reader is familiar with the ASC NEPM and will consult other CRC CARE guidelines included within the NRF. This guideline is not intended to provide the sole or primary source of information.



Stages in the remediation of site contamination
NRF guideline
Site assessment determines remediation is required (Refer to ASC NEPM)
Develop remediation objectives
Regulator engagement
Community engagement
Stage 1: Define
Regulatory considerations
Remediation objectives
Role of auditing
Design remedial strategy (cost-benefit and sustainability analysis may be considered)
No
Is there a preferred remediation option? (pilot trials may be required)
Yes
Develop remediation action plan and / or site management plan
Yes
Regulator approval (if required)
Perform remediation works
Stage 2: Design and implement
Regulatory considerations
Remediation options assessment
Technology guides
Cost-benefit and sustainability analysis of remediation alternatives
Health and safety
Documentation and record keeping
Stakeholder engagement
Validate remediation works
Have remediation objectives been met?
No
Is further remediation possible?
Yes
No
Is long-term monitoring and / or institutional control required?
Yes
Develop site management plan
Implement long-term monitoring and / or institutional control
No
Communicate with stakeholders
Site closure
Stage 3: Finalise
Validation and closure
Institutional controls
Long-term monitoring
Role of auditing

# Executive summary

Long-term monitoring is conducted after some active, passive, or containment remedy has been selected and put in place and is used to evaluate the degree to which the remedial measure achieves its objectives.

As it is often impractical to completely remove contamination within a groundwater resource groundwater sampling is the most common form of LTM employed at remediated sites. It typically comprises the monitoring of an existing groundwater monitoring well network, and the analysis and statistical assessment of samples against adopted remedial criteria.

Some common triggers for LTM include:

- Uncertainty with remediation technology;
- As a requirement of an environment management plan or site management plan;
- On-site treatment of contamination (e.g. solidification/stabilisation) is used;
- A long-term remedial approach (e.g. monitored natural attenuation or a permeable reactive barrier) will be implemented; or
- A remedial approach (e.g. source removal or pump and treat) will leave residual contamination.

While LTM forms a valuable part of relevant remedial scenarios, there are many situations where the adoption of LTM is not appropriate. LTM is not relevant and does not need to be considered when:

- A site assessment indicates the current site use does not pose an unacceptable risk to human health or the environment;
- A site assessment indicates that further investigation of a site is required to determine whether a site is suitable for a proposed use;
- A site assessment/validation indicates that further remediation is required to make a site suitable for its proposed use; and/or
- As a requirement of ongoing site management.

# Abbreviations

| | |
|---|---|
| AS | Australian Standards |
| COC | Contaminant of Concern |
| CRC CARE | Cooperative Research Centre for Contamination Assessment and Remediation of the Environment |
| CSM | Conceptual Site Model |
| DQO | Data Quality Objectives |
| EMP | Environment Management Plan |
| EPA | Environmental Protection Agency / Authority |
| GIS | Global Information Systems |
| GWMW | Groundwater monitoring well |
| LTM | Long Term Monitoring |
| LTMO | Long Term Monitoring Optimisation |
| LTMP | Long Term Monitoring Plan |
| MNA | Monitored Natural Attenuation |
| NAPL | Non-Aqueous Phase Liquid |
| NEPM | National Environment Protection (Assessment of Site contamination) Measure 1999 (amended 2013) |
| NRF | National Remediation Framework |
| QA/QC | Quality Assurance / Quality Control |
| RAP | Remediation Action Plan |
| SMP | Site Management Plan |
| SVOC | Semi-Volatile Organic Compounds |
| VOC | Volatile Organic Compounds |

# Glossary

| | |
|---|---|
| Advection | Mass transport caused by the bulk movement of a fluid media. This applies to both molecules dissolved in groundwater, and to vapour molecules present in air. |
| Aquifer | An underground layer comprising bedrock, unconsolidated natural material, or fill, that is capable of being permeated permanently or intermittently with groundwater, and that allows the free passage of groundwater through its pore spaces. |
| Background | The condition of soil and/or water in the vicinity of a site which is the sum of the ambient and natural background (ASC NEPM 2013). Jurisdictional definitions may vary |
| Baseline conditions | The condition of the site before an activity begins. Depending on the context, 'activity' could mean a particular site use, site development, change in site use, or remediation. |
| Biofouling | Accumulation of living matter on a wet surface. For example, algae growing inside groundwater monitoring wells or tubing. |
| Closure | Completion of remediation activities to the satisfaction of the relevant authorities, including monitoring and reporting to stakeholders. |
| Concentration | The amount of material or agent dissolved or contained in unit quantity in a given medium or system. |
| Conceptual site model | A representation of site-related information including the environmental setting, geological, hydrogeological and soil characteristics together with the nature and distribution of contaminants. Contamination sources, exposure pathways and potentially affected receptors are identified. Presentation is usually graphical or tabular with accompanying explanatory text. |
| Contaminant | Any chemical existing in the environment above background levels and representing, or potentially representing, an adverse health or environment risk. |
| Contaminated site | A site that is affected by substances that occur at concentrations above background or local levels and which are likely to pose an immediate or long-term risk to human health and/or the environment. It is not necessary for the boundaries of the contaminated site to correspond to the legal ownership boundaries. |
| Contamination | The presence of a substance at a concentration above background or local levels that represents, or potentially |

| | |
|---|---|
| | represents, a risk to human health and/or the environment. |
| Daughter products | The chemicals that result from the stepwise dechlorination of chlorinated hydrocarbons. Each separate dechlorination step has a separate daughter product. |
| Dispersion | The breaking apart of a solid or mass, usually to be held in suspension in a liquid. |
| Environment(al) protection authority / agency | The government agency in each state or territory that has responsibility for the enforcement of various jurisdictional environmental legislation, including some regulation of contaminated land. |
| Ex-situ | A Latin phrase that translates literally to "off site" or "out of position". It refers to remediation that is performed on the contamination following removal, ususally the excavation of soil. |
| Groundwater | Water stored in the pores and crevices of the material below the land surface, including soil, rock and fill material. |
| In-situ | A Latin phrase that translates literally to "on site" or "in position". It refers to remediation that is performed on the contamination while it is in place, without excavating soil. |
| Long-term monitoring | Monitoring once a site has had a remediation plan enacted on it, in order to evaluate the degree to which the remedial measure is meeting its objectives. |
| Long-term monitoring optimisation | The evaluation of a well-established long term monitoring program in order to detect and respond to changes in performance. |
| Plume | A zone of dissolved contaminants in groundwater. A plume usually originates from the source and extends in the direction of groundwater flow. |
| Practitioner | Those in the private sector professionally engaged in the assessment, remediation or management of site contamination. |
| Proponent | A person who is legally authorised to make decisions about a site. The proponent may be a site owner or occupier or their representative. |
| Remediation | An action designed to deliberately break the source-pathway-receptor linkage in order to reduce the risk to human health and/or the environment to an acceptable level. |
| Remediation criteria | Targets (preferably numerical values) that need to be achieved to demonstrate that remediation has been |

| | |
|---|---|
| | effective. Also known as technology or remediation end-points or remediation clean-up criteria. A multiple lines of evidence approach may be used to demonstrate the effectiveness of remediation. |
| Remediation objective | A site-specific objective that relates solely to the reduction or control of unacceptable risks associated with one or more pollutant linkage. |
| Residual contamination | Concentrations of the contaminants of concern remaining following completion of remediation. |
| Risk | The probability that in a certain timeframe an adverse outcome will occur in a person, a group of people, plants, animals and/or the ecology of a specified area that is exposed to a particular dose or concentration of a specified substance, i.e. it depends on both the level of toxicity of the substance and the level of exposure. 'Risk' differs from 'hazard' primarily because risk considers probability. |
| Site | A parcel of land (including ground and surface water) being assessed for contamination, as identified on a map by parameters including Lot and Plan number(s) and street address. It is not necessary for the site boundary to correspond to the Lot and Plan boundary, however it commonly does. |

# Table of contents

# 1. Introduction

The objective of this guideline is to provide national guidance for long-term monitoring (LTM) for remediated sites with residual contamination. LTM may be identified:

- when developing the remedial objectives for the site;
- during the implementation of a remediation plan or validation plan, or
- post-remediation if required as part of ongoing site management.

The guideline does not specifically address long term monitoring of landfill sites, instead readers are referred to environmental regulations for guidance on monitoring of landfill sites. The guideline also does not address performance monitoring of remediation systems. Readers are referred to the individual technology guidelines within the NRF document set for information related to performance monitoring of remedial systems.

Similarly, this guideline does not specifically address long-term monitoring of surface water, instead readers are referred to the National Water Quality Management Strategy for guidance on surface water monitoring.

This guideline is intended to be utilised by stakeholders within the contaminated sites industry, including site owners, proponents of works, contaminated land practitioners, and regulators.

It is assumed that the reader is familiar with ASC NEPM and will refer to other CRC CARE guidelines included within the NRF. This guideline and the methods presented within are not intended to provide the sole or primary source of information regarding long-term monitoring.

This document does not supersede regulatory requirements, and familiarity with local legislation and regulations is necessary before proceeding with environmental investigations or remediation/management.

## 1.1 Definition of long-term monitoring

Remediation is driven by the presence of unacceptable risks to human health and/or the environment and is followed by validation to demonstrate that the remedial objectives have been met. LTM is usually implemented at sites where the complete remediation of contamination is not feasible, or where on-site containment of contamination is proposed. As the nature and extent of contamination can change through time, if there is residual contamination present following remediation then LTM may be utilised to demonstrate that long-term remedial goals are being met and that risks to human health and the environment remain low and acceptable.

This guideline adopts the definition of LTM provided within US EPA (2005):

***Monitoring conducted after some active, passive, or containment remedy has been selected and put in place and is used to evaluate the degree to which the remedial measure achieves its objectives***

## 1.2 Other types of monitoring

A key point of difference between LTM and validation monitoring is that LTM is primarily concerned with residual contamination at a site, whereas validation monitoring is utilised to demonstrate that remedial objectives at a site have been met following remediation, and closure can be achieved. Readers are directed to the NRF *Guideline on establishing remediation objectives* and the *Guideline on validation and closur*e.

Performance monitoring of remediation systems is an important phase of long-term management. In particular, performance monitoring relates to measuring the long-term effectiveness of the remedial system itself to ensure it is still operating within optimal parameters. Performance monitoring involves the collection of data relating explicitly to the remedial system (for example biofouling of a permeable reactive barrier by monitoring the type and nature of surface precipitates, or inspecting a cap and contain remediation system). It does not provide an indication of the degree to which the remedial measure has achieved its objectives. Performance monitoring of long-term remedial systems is outside the scope of this guidance document.

LTM optimisation (LTMO) relates to the evaluation of a well-established LTM program to detect and respond to changes in performance. The US EPA Federal Remediation Technologies Roundtable (FDTR) indicates that LTMO offers benefits such as enhanced protectiveness, reduced cost, shortened clean-up times, and the increased likelihood of site closeout.

A major difference between optimisation and this guidance is the period of reference. This document is designed to guide practitioners and regulators in the preliminary stages of designing and implementing a LTM strategy, whereas optimisation should be considered following the establishment of physical monitoring systems and the collection of several iterations of data - refer to **Section 8.**

## 1.3 When is LTM utilised

In the event that validation indicates that remediation was not complete, revised remedial goals and long-term objectives should be documented in the subsequent validation report. Further, in the event that on-site containment of contamination is proposed as the remedial option, the remediation plan should document the remedial goals and long-term objectives to be achieved by the implementation of the specific technology. LTM can demonstrate that long-term remedial goals are being met and that risks to human health and the environment remain low and acceptable (see UK EA, 2010).

LTM is most often associated with groundwater contamination. This is because it is often impractical to completely remove contamination within a groundwater resource (in particular, groundwater remediation can experience ‘contaminant rebound’) necessitating monitoring over the long-term. LTM typically comprises the monitoring of an existing groundwater monitoring well network, and the analysis and statistical assessment of samples against adopted remedial criteria.

A flow-chart showing where LTM sits within the typical site remediation process is presented below in **Figure 1**.

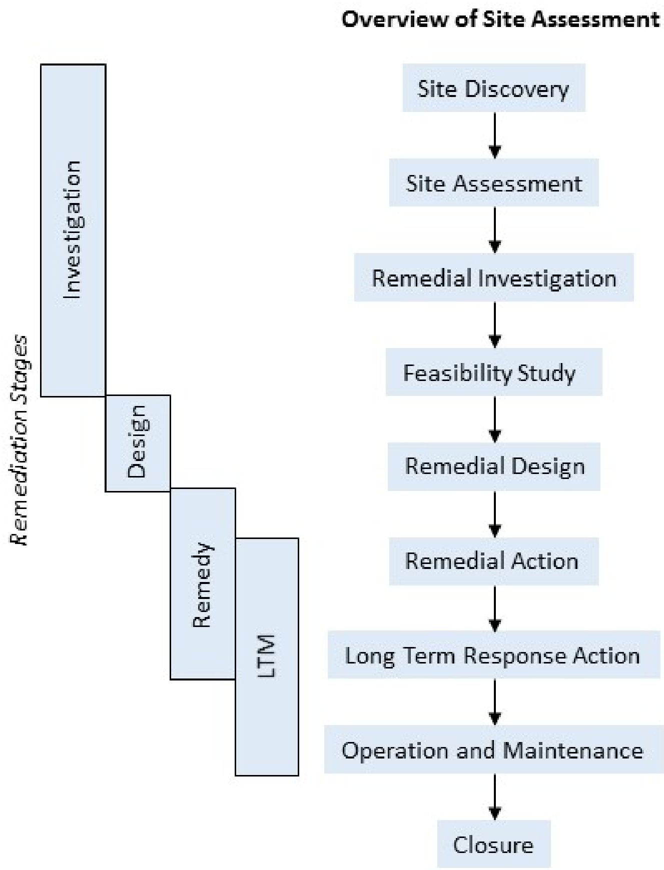



**Figure 1: Typical steps in site remediation**

Some common triggers for LTM include:

- Uncertainty with remediation technology;
- On-site treatment of contamination (e.g. solidification/stabilisation) is used;
- A long-term remedial approach (e.g. monitored natural attenuation or a permeable reactive barrier) will be implemented; or
- A remedial approach (e.g. source removal or pump and treat) will leave residual contamination.
- As a requirement of ongoing site management;

Whilst it is preferable that the requirement for LTM is documented in a remediation or validation report, in many jurisdictions the regulator can require LTM as part of regulatory approval or in a notice. When a regulatory requirement exists for LTM, the relevant notice should be referred to for any stipulated requirements, however the scope of monitoring would still require formalisation in an LTM plan (see **Section 3**).

## 1.4 When is LTM not utilised

While LTM forms a valuable part of relevant remedial scenarios, there are many situations where the adoption of LTM is not appropriate. LTM is not relevant and does not need to be considered when:

- A site assessment indicates the current site use does not pose an unacceptable risk to human health or the environment;

- A site assessment indicates that further investigation of a site is required to determine whether a site is suitable for a proposed use;
- A site assessment/validation indicates that further remediation is required to make a site suitable for its proposed use; and/or
- validation of a site indicates that contamination has been remediated to an acceptable level.

## 1.5 Regulatory context

LTM is not an explicitly legislated requirement in any Australian jurisdiction, however its use is covered in several jurisdictional publications. At the time of publication, the following guidance documents referred to jurisdictional approaches to LTM:

- ACT EPA (2015);
- EPA Victoria (2015);
- NSW OEH (2011);
- Qld DEHP (2014);
- SA EPA (2008); and
- WA DER (2014).

Practitioners should refer to the jurisdictional documentation relevant to the site.

For example, in New South Wales (NSW), under the *Contaminated Land Management Act 1997* the NSW EPA can issue a management order or ongoing maintenance order in relation to management of the site. Any LTM requirements for a site will be stipulated in those orders, and must then be documented in an EMP. Alternatively, LTM requirements may be contained within an institutional control, or within reporting obligations. Alternatively, a person may submit a voluntary management proposal, which facilitates the future management and monitoring at a site, to the NSW EPA for approval.

In Victoria, LTM requirements for a site are documented in the conditions of a Statement of Environmental Audit or in a notice from the EPA.

In WA, the site would likely be classified as 'contaminated-remediation required' or 'remediated for restricted use' and the requirement for LTM would be specified in the site classification.

Further information on management orders and institutional controls can be found in the NRF *Guideline on implementing institutional controls*.

# 2. Monitoring strategy

Following the identification of the need for LTM at a site an LTM strategy should be formulated. The strategy will be different for each site, and be dependent on:

- Objectives of the LTM;
- Site conditions;
- Remediation already deployed;
- Regulatory requirements, including orders or notices;
- Sensitivity of potential receptors; and
- Uncertainty (e.g. seasonal fluctuations, limits of reporting, new remediation techniques)

The LTM strategy should also be informed by a conceptual site model (CSM) consistent with the site assessment and remediation phases and updated to include the remediation that has occurred at the site. It is important that the scale of the monitoring approach be commensurate with the complexity of the site and remedial technology being monitored. Through reviewing and challenging the CSM, the source-pathway-receptor linkages that may be associated with residual contamination can be identified, and related uncertainties reduced. Changes in the site conditions can be identified more easily by using a CSM consistent with the site assessment and remediation phases. For example, information regarding varying concentrations in a monitoring well can be indicative of source depletion, rebound or other important processes affecting assessment of remedial performance.

If LTM is planned to be part of remediation from the start of remedial design, it may be practical to design both the remediation action plan (RAP) and the LTM strategy either simultaneously or iteratively. This is particularly true if there is a high level of uncertainty around the chosen remedial technology.

## 2.1 Monitoring locations and methodology

Part of the power of LTM comes from the ability to compare data through time. As such consistency in monitoring locations and methodology is vital to successful implementation of LTM. Along with using the updated CSM to choose monitoring locations based on the source-pathway- receptor linkages, it is recommended that monitoring locations be selected that will be accessible through the duration of the LTM.

It is recommended that the monitoring methodology utilised during validation be used again during LTM if possible. This way the validation sampling becomes the 'baseline' to which other measurements are compared.

It is also useful to contemplate site restrictions when deciding on the methodology. Perhaps a technique that involves expensive capital costs, but inexpensive operating costs is worthwhile to implement for validation if it can be used again for LTM. Or perhaps an inexpensive methodology is impractical if it requires a complicated and costly site shutdown on a regular basis. For more information on optimising resources readers are directed to the NRF *Guideline on cost-benefit and sustainability analysis of remedial options*.

## 2.2 Monitoring frequency

There are many factors that influence how frequently monitoring should occur, including:

- Nature of the contamination;
- Site characteristics;
- Seasonal fluctuations in conditions;
- Regulatory requirements; and
- Stakeholder perception of risk (including community perspectives).

Some of these factors may not be understood at the commencement of the LTM, and so consideration should be given to a staged approach to monitoring frequency. A staged approach involves frequent monitoring in the early stages of the LTM to assist in characterising seasonal or other variations, with subsequent monitoring occurring at intervals which have been shown to be statistically significant with regard to any contaminant fluctuations.

## 2.3 Monitoring analytes and parameters

As with the monitoring locations and methods, it is recommended that the analytes and analytical methods be consistent with those employed in the validation phase.

Target analytes and parameters will typically include:

- Analytes identified as contaminants of concern during the remedial phase;
- Analytes identified as potential contaminants of concern based on the CSM update following validation;
- Parameters which provide information regarding hydrogeological or geochemical conditions affecting the fate of identified contaminants of concern (eg oxidation/reduction potential, soil pH); and
- Parameters which provide information regarding environmental change (e.g. groundwater levels, temperature).

Further details regarding analytes and parameters are provided in individual media **Sections 4, 5, 6, and 7.**

## 2.4 Closure

A key part of formulating the LTM strategy is to identify whether site closure is likely to be achievable (e.g. the remedial objectives are forecast to be met after a period of time) or whether the site will require monitoring in perpetuity (eg a coastal containment cell).

If appropriately achievable goals are established, they can be developed to contain suitable metrics to meet “SMART” requirements (ie specific, measurable, attainable, relevant, and time-bound). Readers are directed to the NRF *guideline on validation and closure* for the parameters and reporting to justify site closure. If the LTM strategy will be required to facilitate monitoring in perpetuity it is recommended to include routine optimisation (see **Section 8**), as advances occur in monitoring technology, risk assessment and regulatory approaches.

# 3. Long-term monitoring plan

The long-term monitoring plan (LTMP) documents both the LTM strategy and the detailed methodology necessary to ensure adequate and appropriate sampling and analysis is undertaken so that demonstration of the LTM objectives can be justified. In many jurisdictions, the development of a LTMP occurs concurrently with the development of an EMP (or equivalent) or a validation report which may stipulate LTM requirements. In other cases, it may be appropriate to develop the LTMP concurrently with the RAP.

An example table of contents for an LTMP is:

- Introduction;
- Background;
- Conceptual site model;
- Roles and responsibilities;
- Monitoring activities;
- Quality control / quality assurance;
- Maintenance activities;
- Contingency planning;
- Reporting;
- Closure; and
- Uncertainty.

Further details on each of these components is provided in the sections below.

## 3.1 Background

To provide context for the LTMP, and sufficient information for third parties who may review the LTMP, the following background information may be included:

- Executive summary;
- Scope of work;
- Site identification;
- Site history;
- Site condition;
- Summary of previous investigations;
- Conceptual site model;
- Data quality objectives.

Where information has likely been detailed within previous reports a summary of pertinent information may suffice.

## 3.2 Roles and responsibilities

The LTMP should include the roles and responsibilities of people involved with carrying out the LTM strategy. This may include:

- Site owner;
- Site occupier;
- Regulator;
- Auditor (if relevant);
- Practitioner; and
- Community liaison.

The LTMP should also identify the party responsible for ensuring that the LTM objectives are achieved. In most cases this will be the site owner, but it may be their representative or tenant. The responsible party must provide the LTMP to the regulator along with other pertinent information such as the RAP, validation reports or risk assessments prior to the works commencing.

## 3.3 Site access

As the LTM may continue for many years, the LTMP may be implemented by different personnel within a company or by different companies. As such it is important that the LTMP include details on accessing the site to conduct monitoring. This may include:

- Notice to relevant onsite person to:
  - Arrange a mutually agreeable date and time, particularly if monitoring involves disruption to the site;
  - Arrange maintenance (e.g. mowing grass around monitoring sites for easier access);
  - Ensure inductions are relevant and current;
  - Ensure the monitoring locations are still present;
- Logistical / infrastructure constraints including third party access;
- Notice to regulators or Auditors if they are required to be present or informed;
- Notice to community groups or leaders if this is part of the stakeholder consultation plan;
- Details of permits required to undertake the monitoring (if any); and
- Health and safety considerations, including such things as traffic control or specific personal protective equipment that may have a lead-time or an expiry date;

## 3.4 Monitoring activities

The LTMP should document the decisions made in formulating the LTM strategy (discussed in **Section 2**).

Regarding monitoring, the LTMP should:

- Identify target media;

- Identify target analytes;
- Identify monitoring locations;
- Determine sampling frequency at each location;
- Select suitable sampling methodology; and
- Meet data quality objectives.

Sometimes it may be necessary to deploy a sampling procedure or analytical method that does not comply with relevant jurisdictional guidelines. In these cases the method(s) used and the rationale for their deviation from the jurisdictional guidelines, must be clearly specified in the LMTP.

Regarding collection of samples the LTMP should identify the:

- Sampling and testing methods and equipment;
- Calibration procedures for field measurements;
- The number and type of QA/QC samples to be collected and analysed; and
- Filtering, decontamination and preservation techniques.

Regarding laboratory analysis, the LTMP should document the:

- Proposed analytical suite, including specific analytes;
- Analytical methods, and
- Limits of reporting.

If a site is large or complex in some way it may be useful to have a sampling analysis and quality plan as a subsection of the LTMP.

## 3.5 Quality assurance and quality control

All LTM programs should incorporate robust field and laboratory quality assurance / quality control (QA/QC) procedures in accordance with ASC NEPM. QA/QC sample results should be presented and evaluated against the stated data quality objectives (DQOs). ASC NEPM, AS4482.2-1999 and AS4482.1-2005 can be consulted for further information on sample collection, preservation, health and safety, decontamination, and quality assurance procedures.

Field work should be documented by an experienced environmental practitioner using notes written at the time, supplemented by photographs or videos to record field observations and activities. Readers are directed to the NRF *guideline on documentation, record keeping and reporting* for further information on this topic.

## 3.6 Maintenance activities

A key component of LTM is the use of existing sampling points to retrieve environmental samples. Due to the timescales involved for LTM, the monitoring infrastructure may require maintenance to ensure its longevity and the reliability of collected data. For example, groundwater monitoring wells where the well casing stands above ground level may be damaged by the movement of plant or mowing of grass. Wells may need redevelopment due to silting. The LTMP should therefore make provision for maintenance of existing sampling points and their replacement if necessary to meet the DQOs.

For sites with a long time between monitoring events it may be prudent to arrange an inspection of the monitoring locations prior to mobilising for sampling, so that maintenance requirements can be identified and implemented.

## 3.7 Contingency planning

A contingency plan in the LTMP will ensure that human health and the environment are protected if source-pathway-receptor linkages change over time. This may occur because of residual contamination behaving in an unexpected manner or because of a change in land use.

The contingency plan should include trigger levels for the indicator parameters that are important in protecting human health, the environment, and the environmental values of the site, which if exceeded necessitate implementation of the contingency plan. Such triggers may include, but are not limited to, evidence:

- of increased contaminant concentrations;
- of changing contamination extent or migration;
- of new contaminants being released from the source, contaminant rebound, or a new primary source;
- that remediation has ceased, or is occurring at a reduced rate;
- that contaminant concentrations are not decreasing at a sufficient rate to achieve the remedial objectives within a reasonable timeframe; and
- of changes in land, groundwater, or land resource utilisation that could adversely affect the remediation.

In establishing the contingency triggers for the LTM, temporal and spatial variations in the existing dataset should be considered. For example, seasonal variations in groundwater are a common variance at sites, and the contingency triggers should take this into account, utilising long-term trends to avoid action on a short-term variance.

The contingency plan should be initiated when trigger levels are exceeded on a consistent basis, at which stage an increased level of monitoring should be undertaken to ascertain the nature of the exceedance in greater detail. Additionally, it is recommended that the contingency plan provides for a tiered response to consider the level of seriousness of the trigger exceedance(s). Further, it should be possible to incorporate new information regarding the site characteristics and remedial technology into the contingency response.

In the event there are isolated/inconsistent exceedances, an exception report detailing the exceedances in the context of the CSM may be an appropriate response. The exception report should address the exceedance and outline any further action. The purpose of documentation in an exception report is to document the rationale surrounding the response (i.e. why it is or is not a significant issue). As noted above, a tiered response based on the significance is recommended.

## 3.8 Reporting

Reporting requirements will differ between each site, depending on regulatory or legislative requirements, or proponent or community expectations. As monitoring events are likely to be spaced apart in time it is important to document each monitoring event as it occurs so as not to lose or forget important information.

Following each monitoring event, a report should be prepared that provides the detail listed in Table 1 below. This report does not have to be large or onerous; and should be tailored to the requirements of the site. On some sites it may be appropriate to issue a memorandum with the results and recommendations throughout the year and then provide one larger report once a year. The practitioner, proponent and regulator should work together to find a reporting regime that suits the situation.

**Table 1: Suggested content for an LTM report, from UK EA (2004).**

| Report Section | General Content |
|---|---|
| Monitoring Scope | • Scope of the monitoring work covered by the report<br>• Reasons and objectives for undertaking the monitoring.<br>• Summary of the works undertaken to date, including the remediation and validation, and subsequent monitoring.<br>• LTM objectives and criteria.<br>• Updated CSM<br>• Plan or figure showing the extent of remediation, areas of residual contamination, subsurface structures (if present), and monitoring locations. |
| Monitoring Results | • Schedule of monitoring activities carried out since the previous monitoring report.<br>• Report on the visual inspection, monitoring and test results.<br>• Assessment of compliance against the adopted criteria.<br>• Field and laboratory QA/QC procedures.<br>• Figures depicting monitoring locations, borelogs and site photographs, where applicable. |
| Actions | • Report on any actions taken in response to exceedances. |
| Recommendations | • Assessment of the extent to which remedial objectives have been met.<br>• Recommendations for future monitoring and any variations to the LTMP such as optimisation. |
| Attachments | Supporting information, including sampling, analytical and quality assurance procedures, type of equipment, calibration records, location and construction of monitoring points, laboratory analytical data, and field documentation. |

As part of the reporting the data obtained during each round of LTM should be compared against the CSM, and the CSM updated to incorporate the new data. This can assist in identifying critical data gaps, including the significance of the data gap relative to the relevant source-pathway-receptor linkages.

## 3.9 Uncertainty

Groundwater sampling in an LTM context relies on the collection of single data points which are then analysed and often modelled in the context of the LTM program. As such, there is a level of uncertainty in the collection of this data. It is acknowledged that a sampling plan cannot be perfect but should address the uncertainly posed by certain scenarios and aim to minimise the uncertainty in the sampling. Sources of uncertainty which should be addressed in the DQOs of the LTMP include:

- Monitoring location and sample collection – it needs to be acknowledged that GWMWs offer a point information source, and groundwater chemical properties can change because of sampling, all of which contribute to the uncertainty in contaminant spatial and temporal distribution;
- Field and laboratory quality assurance and quality control – QA/QC measurements are also point measurements, and can produce spatial distribution variations because of the point nature of the data;
- CSM – the formulation of a CSM and any resulting modelling incorporates significant uncertainty, particularly as the CSM is a simplified description of the actual aquifer system; and
- Modelling inputs, software selection, and predictive uncertainty – in undertaking modelling of groundwater, there is introduced uncertainty in the data inputs due to the uncertainties outlined above, the limitations of the chosen software, and the differences between outputs of different models.

# 4. Groundwater LTM

Groundwater sampling is the most common form of LTM employed at remediated sites and may be employed to monitor the effectiveness of prior remediation, as a standalone remediation strategy in the form of monitored natural attenuation (MNA), or as a combination of the two.

The objectives of performing LTM of groundwater are to:

- Demonstrate that the remedial objectives are continuing to be met;
- Determine the plume status (i.e. stable, shrinking or expanding);
- Identify changes to the groundwater flow;
- Identify potentially toxic breakdown products;
- Detect new releases of contaminants;
- Identify changes in the groundwater conditions; and
- Demonstrate that there is no down-gradient impact.

The methodology for the LTM of groundwater is dependent on factors such as the data required, number and placement of wells, nature of contaminants, and cost constraints. When undertaking groundwater sampling it is imperative that the sampling methodology results in the collection of samples which are representative of the aquifer conditions.

ASC NEPM provides references for guidance on the sampling of groundwater, including:

- Victoria EPA (2000);
- SA EPA (2007); and
- AS/NZS 5667.12 (1999)

In addition to the above Australian guidance, the following international guidance is also available:

- UK EA (2000);
- ITRC (2005);
- ITRC (2010).

Guidance for MNA has been developed nationally and by various jurisdictions including:

- CRC CARE (2010);
- SA EPA (2007);
- EPA Victoria (2000); and
- WA DEC (2004).

The following sections provide detail on the different aspects of conducting groundwater LTM.

## 4.1 Monitoring locations

An appropriately designed groundwater LTM network will include groundwater monitoring wells (GWMWs) placed strategically throughout the contaminant source and plume, to monitor changes in contaminant concentrations near residual contaminant sources and in down-gradient locations, and to assess the potential migration to the receptor locations.

The following factors should be considered in the identification of appropriate sampling locations:

- Location of monitoring points relative to the residual contamination source(s), contaminant plume(s), and potential receptors;
- Contaminant concentration trends;
- Relative contaminant concentrations (as compared with other locations within, and surrounding the plume);
- Vertical hydraulic gradients;
- Presence of multiple discrete hydrogeologic zones;
- Relative plume size;
- Plume shape; and
- Local ambient groundwater quality and use.

The presence or absence of potential receptors at contaminant exposure points should be considered when designing the groundwater LTM network. For example, a groundwater plume that underlies or is adjacent to populated areas where residents could potentially be exposed to contaminants (eg via contaminant migration to potable groundwater wells) will require a more rigorous LTM program than a groundwater plume at great distances from potential receptors. Thus the latter scenario may have a large down gradient well spacing sufficient to meet LTM objectives, but the residential scenario may require a greater number of down-gradient wells, spaced more closely together, to monitor protectiveness.

The following locations should be considered when planning the groundwater LTM network:

- *background/up-gradient* – one or more GWMWs located up-gradient of the source zone to establish background groundwater chemistry and potential attenuation capacity, as well as the hydrogeological setting and hydrogeochemical dynamics of the aquifer;
- *lateral* – one or more GWMWs located across the source zone (generally perpendicular to the groundwater flow direction) to establish the maximum potential width of the plume and to assess variability in the hydrogeology and hydrochemistry of the aquifer;
- *source zone* – one or more GWMWs within the source zone to assess changes in the mass loading and changes in the plume constituents;
- *plume centreline* – one or more GWMWs along the middle of the plume in the direction of groundwater flow at varying distances to assess changes in the plume down-gradient from the source;

- *leading edge* – one or more GWMWs that are installed on the down-gradient plume to delineate the plume length and provide an early warning if the plume geometry changes and extends down-gradient;
- *sentinel/compliance* – GWMWs that are installed at designated compliance points such as adjacent to sensitive receptors or the site boundary to help quantify the potential risk to receptors; and
- *vertical delineation* – GWMWs nested in tandem with existing wells as above to assess whether the plume is sinking or rising.

The following figures provide a graphical representation of these hydrogeological concepts, showing the positioning of the different types of GWMWs listed above.

**Figure 1: Groundwater monitoring network and types of GWMWs (plan view of a CSM), from CRC CARE (2010b)**

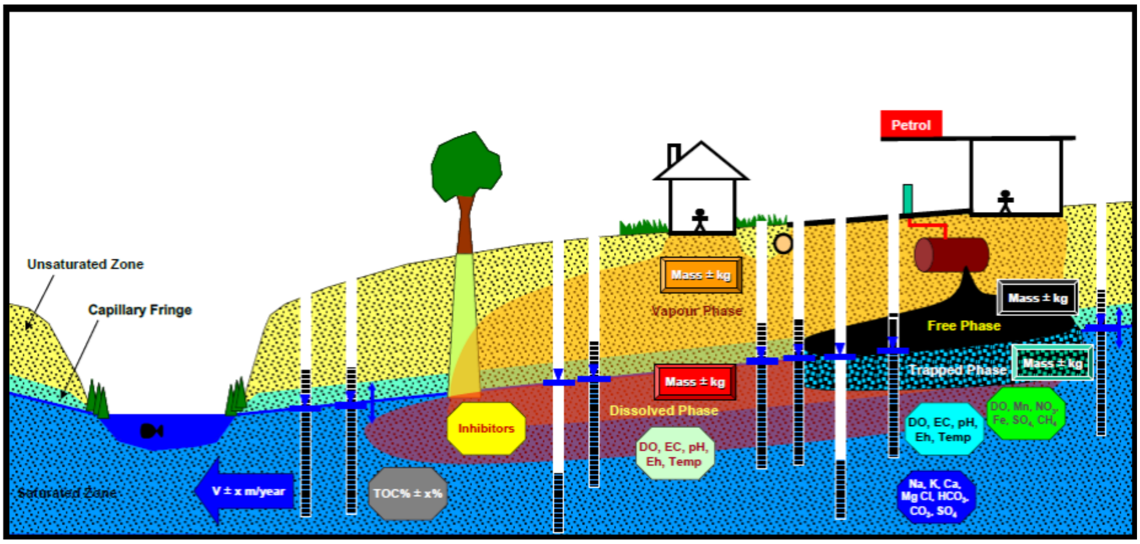



**Figure 2: CSM elevation view, from CRC CARE (2010b)**

The groundwater LTM network can be adapted as the requirements of the LTM program evolve. For example, at the initiation of the groundwater LTM program, those GWMWs previously designated as down-gradient or compliance GWMWs can be used as sentinel GWMWs to verify that contaminants are not migrating beyond a specific boundary. As the plume matures and recedes, these GWMWs may be too far down-gradient to serve a purpose, and (some) may therefore be decommissioned. Former leading edge GWMWs may now be located appropriately to fulfil the role of sentinel GWMWs, and may be reclassified as down-gradient GWMWs, whilst plume GWMWs may be reclassified as leading edge GWMWs. By carefully considering the CSM when planning the groundwater LTM network, the design can allow for the progressive reassignment of GWMWs within the network as conditions change over time.

The location and description of each sampling location should be included in the LTMP, including unique location identifiers and geographical co-ordinates. On large sites it can be helpful to incorporate this information into a robust geographical information system (GIS) database for the site to allow collation of monitoring location data (including past and present locations) with relevant analytical results from previous monitoring events, environmental parameters, and physical parameters (such as groundwater level).

## 4.2 Monitoring frequency

The sampling frequency will be dependent on:

- Hydrogeological conditions;
- Nature of the contaminant migration pathway;
- Sensitivity of receptors;
- Natural attenuation rates;
- Regulatory requirements

It is recommended that the sampling frequency be specified to occur at periods no greater than the minimum length of time that would be required for a dissolved contaminant to move in groundwater from a location where contaminants are known to be present to the monitoring point under consideration, including accounting for natural attenuation rates. For example, if the distance between a leading edge well and a down-gradient well is 100m, and if the maximum contaminant migration velocity is 200m/year, then approximately six months would be required for a dissolved contaminant to migrate from the leading edge of the plume to the down-gradient well location (not including natural attenuation). Therefore, a semi-annual (twice per year) sampling frequency would be necessary to monitor conditions at the leading edge of the plume. Information generated by sampling at a frequency greater than semi-annually would be of limited value, because it is unlikely that contaminants will migrate to a down-gradient well at a rate greater than the maximum contaminant migration velocity, particularly as it does not account for natural attenuation. Given that LTM programs are generally only appropriate for plumes that are stable or receding, the sampling frequency should be designed such that there is little concern that a contaminant migrating from the leading edge of a plume will reach a down-gradient GWMW. If there is the potential for preferential pathways to exist, and sensitive receptors are present, then a higher frequency of monitoring may be necessary.

## 4.3 Analytes and parameters

Groundwater sampling should be undertaken in line with the requirements of the LTM strategy to obtain contaminant concentrations and data relevant for determining plume and groundwater characteristics.

Chemical data collected in relation to groundwater primarily provides information on the concentration of residual contamination in the groundwater. Additionally, such data can provide information on the change in concentrations of parent and daughter contaminant and co-contaminants.

Geochemical data collected in relation to groundwater can provide information regarding hydraulic conductivity, hydraulic gradient, mineralogy and temperature, which affect the fate and transport of contaminants in an aquifer. Indicators of an aerobic or anaerobic environment, and information on indicators of biological degradation should be considered during the development of the LTM strategy.

Biological parameters collected in relation to groundwater provide information on the biodegradation of contaminants in the groundwater. The ecological health of aquatic biota (including microbial counts/biomass) should be considered during the development of the LTMP.

In addition to the collection of specific groundwater data relating to the remedial approach and contaminant characteristics, there are minimum requirements for groundwater monitoring in each jurisdiction that must be met. The utilisation of surrogate parameters, such as water levels, dissolved oxygen, temperature and pH data, should also be considered. These typically low-cost methods can be useful indicators of remedial system effectiveness, if used appropriately in the context of the CSM.

Consideration should be given to the seasonal dynamic nature of groundwater including:

- Groundwater table elevation – where not previously defined data should be collected over multiple initial events to define seasonal fluctuations in the groundwater elevation, flow direction and contaminant concentrations, as well as identifying potential trends;
- Biodegradation indicators; and
- Aquifer chemistry.

Once the seasonal fluctuations have been determined, the ongoing monitoring frequency should be specified taking these variations into consideration

Sampling dates and/or times should consider site specific conditions such as tidal fluctuations or climatic conditions to ensure that relevant scenarios with contaminant behaviour under varying conditions have been considered. Longer term climate variations should be accounted for in the selection and density of monitoring locations, particularly with respect to the potential for groundwater flow to change and/or reverse direction.

## 4.4 Contaminant concentration trends

Identification of long-term trends in contaminant concentrations at each sampling location is an important consideration when developing an LTM program. Temporal data can be examined to evaluate dissolved-contaminant plume stability, either graphically, or using statistical tests. If removal of contaminant mass is occurring in the subsurface because of attenuation processes or operation of a remediation system, mass removal will be apparent as a decrease in contaminant concentrations through time at specific sampling location(s), as a decrease in contaminant concentrations with increasing distance from chemical source areas, and/or as a change in the suite of chemicals through time or with increasing migration distance.

Temporal chemical-concentration data can be evaluated by plotting contaminant concentrations through time for individual sample points, or by plotting contaminant concentrations against down-gradient distance from the contaminant source for several monitoring points, over several monitoring events. Plotting temporal concentration data is recommended for any analysis of plume stability (Wiedemeier et al. 2000). However, visual identification of trends in plotted data may be a subjective process, particularly if (as is likely) the concentration data do not exhibit a uniform trend but are variable through time.

The possibility of arriving at incorrect conclusions regarding plume stability based on visual examination of temporal concentration data can be reduced by examining temporal trends in chemical concentrations using various statistical procedures, including regression analyses and the Mann-Kendall test for trends. The Mann-Kendall nonparametric test (Gibbons, 1994) is well-suited for evaluation of environmental data because the sample size can be small (as few as four data points), no assumptions are made regarding the underlying statistical distribution of the data, and the test can be adapted to account for seasonal variations in the data. The Mann-Kendall test statistic can be calculated at a specified level of confidence to evaluate whether a temporal trend is exhibited by contaminant concentrations detected through time in samples from an individual GWMW. If a trend is identified, a nonparametric slope of the trend line (change in concentration per unit time) also can be estimated using the test procedure. A negative slope (indicating decreasing contaminant concentrations through time) or a positive slope (increasing concentrations through time) provides statistical confirmation of temporal trends that may have been identified visually from plotted data. Whatever technique is applied to identify temporal trends in concentration data, care must be exercised when evaluating the results of applying these tools, to ensure that spurious “trends” do not occur because of changes in analytical methods or detection limits.

The relative value of information obtained from periodic monitoring at a sample point can be evaluated by considering the location of the sample point with respect to residual contaminant sources, the contaminant plume, and potential receptor exposure points, while also considering the presence or absence of temporal trends in contaminant concentrations in samples. The degree to which the amount and quality of information that can be obtained at a monitoring point serves the two primary (i.e. temporal and spatial) objectives of monitoring must be considered in this evaluation. For example, for a monitoring location to provide information about temporal trends in contaminant concentration, it must lie along a flow path between a contaminant source and a potential receptor exposure point, otherwise one can expect continued non-detection of the target contaminant at that location. Thus, a sampling location having a history of contaminant concentrations below detection limits provides little or no useful information.

## 4.5 Relative contaminant concentrations

Fewer monitoring locations are typically required for contaminant plumes in which the concentrations of COCs pose a low risk to receptors. Conversely, for contaminant plumes in which concentrations of COCs potentially pose a high risk to receptors, more sampling points may be necessary. Again, decisions regarding the numbers and locations of sampling points to be included in the LTM program also should consider the location of the sampling location with respect to residual contaminant sources, the contaminant plume, and potential receptor exposure points as informed by the updated CSM.

## 4.6 Vertical hydraulic gradients

Vertical hydraulic gradients in groundwater are created when differences in piezometric head/groundwater elevation occur.

In situations where the total head of groundwater is higher at greater depths, groundwater will move vertically upward, if the intervening lithology are sufficiently permeable. Conversely, in situations where the total head is lower at greater depths, groundwater will move vertically downward (again, within the constraints of permeability). Since contaminant migration usually is controlled by groundwater advective and dispersive processes, vertical gradients (directed upward or downward) can strongly influence the nature of contaminant migration, and therefore should be considered when selecting wells to include in the groundwater LTM network. For example, if a contaminant plume is migrating down-gradient in a formation that has a downward-directed vertical gradient, it is recommended that the groundwater LTM network design include GWMWs with completion intervals at progressively greater depths as the distance from the contaminant source area increases, and conversely, GWMWs near the contaminant source area may be completed at shallower depths. Detail of this nature should be informed by the updated CSM.

## 4.7 Presence of multiple discrete hydrogeologic zones

In some situations, contaminants may be present in groundwater within multiple discrete hydrogeologic zones or intervals, and this may show up as significant variations in concentration with depth. For a given location it may be necessary to monitor such discrete zones using multiple GWMWs, each monitoring the groundwater at different depths. The information of greatest value will be provided by monitoring those zones that are identified as preferential pathways for contaminant migration.

## 4.8 Relative plume size

Generally, the greater the lateral and vertical extent of contaminants in the subsurface, the greater the number of monitoring locations that will be required to achieve the objectives of the groundwater LTM program. This should be informed by the updated CSM, contaminant migration pathways and receptor sensitivity.

## 4.9 Plume shape

Plumes are traditionally depicted as lobes of dissolved constituents that emanate from a well-defined source area and extend some distance down-gradient in a regular elongated oval shape. In practice, contaminant plumes can be found in a variety of shapes, which are influenced by several factors, including:

- Co-mingling of plumes from different source areas;
- Changing hydraulic gradients (which can have a tidal, seasonal or long-term climatic influence, causing groundwater flow to change direction over time);
- Processes that control contaminant migration (advection, dispersion, diffusion, sorption, degradation, volatilisation);
- Subsurface geology and hydrogeology (e.g. groundwater divides, preferential migration pathways);
- Source-release mechanisms (e.g. "instantaneous" release, long-term continuing source); and
- Installation/operation of engineered systems (e.g. groundwater extraction systems, permeable reactive barriers, underground utility corridors).

An appropriately designed groundwater LTM network will include sampling points that can be monitored routinely to assess the extent of contaminants in the subsurface, while considering factors that may influence contaminant fate and transport. For example, contaminant plumes which originated at multiple source areas may become co-mingled at some distance down-gradient from the source areas; in this situation, it may be appropriate to include multiple up-gradient wells in the groundwater LTM network to monitor groundwater conditions up-gradient from each of the separate source areas. In conditions where groundwater hydraulic gradients are extremely low, it may be necessary to surround the distal plume edges with monitoring points, as minor changes in hydraulic gradient can cause changes in the direction(s) of groundwater movement, so that the down-gradient sense of movement may in fact be defined radially rather than linearly. Professional judgment is required when considering these factors when developing LTM networks.

## 4.10 Local groundwater quality and use

The quality of the ambient groundwater may limit the beneficial uses of the groundwater, and this will in turn influence the objectives (and therefore the design) of a groundwater LTM strategy, as will the nature, density and location of receptors. There may be many users of non-potable water, e.g. some residential areas of Perth have a high density of bores which are used for garden irrigation and other non-potable uses; conversely groundwater used for stock water in a regional area would typically have a much lower density of bores. Thus, for non-potable groundwater, which excludes humans as a possible receptor, larger spacing between LTM locations may be appropriate depending on the ecological sensitivity of groundwater and the density of bores for non-potable uses. As each state and territory has different requirements regarding groundwater, this may affect the LTM design.

## 4.11 Contingency triggers

In establishing the contingency triggers for a groundwater LTM strategy, temporal and spatial variations in the existing dataset should be considered. For example, seasonal variations in groundwater are a common variance at sites, and the contingency triggers should take this into account, utilising long-term trends to avoid action on a short-term variance.

It is recommended that practitioners consider the following for inclusion as contingency triggers of groundwater LTM:

- Increased contaminant concentrations in the source area;
- Plume expansion or migration to a down- or cross-gradient GWMW;
- New contaminants being released from the source, contaminant rebound, or a new primary source;
- Evidence that remediation has ceased, or is occurring at an unexpectedly reduced rate;
- Contaminant concentrations are not decreasing at a sufficient rate to achieve the remedial objectives within a reasonable timeframe; and
- Changes in land, groundwater, or land resource utilisation that could adversely affect the remediation.

# 5. Soil LTM

LTM of soils is predominantly applicable to sites with non-aqueous phase liquid (NAPL) contamination in soil, when considering contaminant rebound following in-situ treatment or source removal. Soil LTM will typically comprise the collection of passive non-destructive data, targeted samples, laboratory analysis, and statistical assessment against applicable criteria.

The locations of soil samples, both laterally and vertically, should be decided based upon site conditions and the updated CSM, considering site characteristics such as:

- Depth to potential residual contamination;
- Heterogeneity of the impacted media; and
- Lateral characterisation of the source area.

Soil sampling methodology should be sufficient to facilitate the collection of representative samples of the sub-surface for analysis, and it is recommended that the same methods used during validation be employed during LTM if possible. Focus should be given to the retrieval of undisturbed samples to minimise the potential loss of volatile contaminants. Practitioners should refer to the methodologies presented in the ASC NEPM, along with AS 4482.1-2005, AS 4482.2-1999 and AS 1726-1993 for detailed guidance on the retrieval of soil samples.

It is recommended that the laboratory analytical suite consider:

- Contaminant(s) identified in the updated CSM;
- Potential daughter or sequestration products generated as a result of active or passive remediation;
- Daughter and sequestration products because of the particular remediation technology;

Biological data, such as vegetative surveys, can also be monitored to give an indication of ecological health.

Field screening using non-destructive methods can be utilised either on their own or in conjunction with destructive soil sampling to provide real-time information on the concentration and distribution of contaminants. These typically low-cost methods can be useful indicators of remedial system effectiveness, if used appropriately in the context of the CSM. Use of the following field tests, where applicable to the contaminants of concern, can be useful:

- Gas detector tubes – to provide information on volatile gases;
- Colorimetric test kits – to provide fast indicative information on the presence of contaminants such as benzene, toluene, ethylene and xylene; polyaromatic hydrocarbons; polychlorinated biphenyls; and chlorinated hydrocarbons;
- Photo-ionisation detectors/flame ionisation detectors – to provide information on the presence of volatile and semi-volatile organic compounds;
- Portable x-ray fluorescence – to provide a measurement of heavy metal concentrations in soil;

- Field gas chromatography – to provide an analysis of volatile and semi-volatile compounds; and
- Laser-induced fluorescence;
- Membrane interface probe;
- Geophysical methods (e.g. ground penetrating radar or electromagnetic conductivity surveys); and
- Surrogate parameters (e.g. photo-ionisation detector data and pH).

# 6. Soil Vapour LTM

The accumulation of vapours within buildings poses a significant potential risk to human health. If residual groundwater, soil or NAPL impacts remain following remediation, they have the potential to be a source of volatile organic compounds (VOCs) impacting on the vadose soil zone and overlying enclosed structures.

At sites where soil vapour has previously been identified as an issue an existing soil vapour monitoring network should be present, which may be suitable to re-purpose for LTM, otherwise a new soil vapour monitoring network may be required. The suitability of the existing soil vapour monitoring network to meet the requirements of the LTM strategy should be evaluated in conjunction with the updated CSM. Data gaps can be addressed through the installation of additional sample points, and redundant sample points decommissioned. The soil vapour LTM strategy should consider:

- Nature and extent of residual impacts;
- Generation of daughter products;
- Contaminant migration pathways (including inhalation);
- Variability through time and space;
- Regulatory requirements;
- Sensitivity of receptors; and
- Stakeholder relations (including community consultation and risk perception).

Soil vapour sample point construction methods should be consistent with those employed during validation to allow for comparison with historical data. Further high-level guidance on soil vapour sampling methodology is provided in ASC NEPM, CRC CARE (2010b), and ITRC (2007).

Soil vapour sampling may be carried out by passive or active sampling techniques or flux chambers. The analytical suite should be tailored to the site based on the updated CSM and the potential for both parent and daughter products to be present. In addition to collecting volatile contaminant concentrations, levels of fixed gases such as oxygen, carbon dioxide and methane (depending on vapour source) can be obtained to aid in the interpretation of the results about vapour attenuation and biodegradation.

It is recommended that the soil vapour LTM strategy considers all the parameters monitored during validation to assist in deriving statistically significant conclusions relating to vapour concentrations over time. High level guidance on the specific data required is provided in ASC NEPM, CRC CARE (2009), and ITRC (2007).

The largest sources of uncertainty in soil vapour sampling stem from the variable nature of soil vapour pathways and maintaining sampling consistency, and in the distance of sampling points from the receptor(s). Measurements can be taken as close as possible to the relevant receptor to decrease the level of uncertainty.

# 7. Sediment LTM

Sediment is often overlooked in sampling programs where at sites where sediment remediation was not the objective. However, where they occur, sediments are the repository for many water-borne contaminants and can therefore be important for LTM.

For sites where sediment is a concern, the LTM strategy should be based on site-specific data and clearly defined, with respect to:

- The updated CSM;
- The role of the site in the watershed context (including other potential contaminant sources);
- Key issues within the watershed; and
- Current and reasonable anticipated or desired future uses of the water body and adjacent land.

The ASC NEPM refers to AS/NZS 5667.12-1999 and Simpson et al. (2005) about Australian guidance on the sampling of sediments. International guidance on sediments is available in OSWER (2002).

The methodology for sediment sampling is dependent on the data required for the monitoring event and the composition of the sediment. Physical data primarily concerns the structure, texture and later formation of the sediment, and sampling apparatus should be used which minimises disturbance to these properties. Chemical data primarily concerns substances that have adsorbed to the sediment and which have dissolved in residual pore water, and sampling apparatus should be used that minimise the potential for oxidation, abrasion, reaction with sampling equipment and loss of pore water. Biological data primarily concerns the classification of the species and numbers of flora and/or fauna present, sampling should be undertaken in a manner that results in representative sample(s) being obtained.

Examples of sampling methodology are provided below (and further guidance is provided in AS/NZS 5667.12-1999 and Simpson et al. (2005)):

- Grab sampling – suitable for sediment comprising silt and/or sand and gravel. There are a multitude of grab samples available for use, including the scissor grab (Van Veenhapper), Ponar and Birge-Ekman. Grab sampling can provide a relatively undisturbed representative sample of surface media, but it is ineffective for sampling deeper horizons. It can be utilised for obtaining physical, chemical and biological data; and
- Corer systems – suitable for sediment comprising clay and soft peat. It involves driving a hollow tube into the sediment which is then removed with the sediment inside the tube. Tubes may be driven in manually utilising rods or by means of its weight or a vibration mechanism. As with grab sampling, there are many corer systems available for use, such as a piston drill, beeker core sampler or vibro corer. Corer systems provide a relatively undisturbed sample with the added benefit of being able to define strata. They can be utilised for both physical, chemical, and some biological data.

Sediment sampling should consider the updated CSM and the LTM objectives. An appropriate combination of biological, physical and chemical data relating to the sediment should be obtained.

Chemical data are preferred for assessing the risk to human health. Biological data provide a more detailed measurement of the changes in ecological risk. For example, a bioassay performed at a site over a defined timeframe can identify changes in bioavailable concentrations of many contaminants, whilst collection of fish and tissue analysis can address both human health and ecological responses of the system. Additionally, pore water quality provides a good indicator of ecological risk with respect to residual sediment contamination.

Chemical data for sediments (both the upper biological surficial zone and/or deeper sediment) can provide information regarding biodegradation, contaminant partitioning to the pore water, and concentrations of total organic carbon. Sampling for vertical profile chemistry, contaminant chemistry, and the sediment-water interface should be considered during the development of the LTM strategy.

Physical data for sediments can provide information regarding erosion and/or deposition of sediment, groundwater advective flow, particle size, surface water flow rates, and sediment homogeneity/heterogeneity. Fate and transport, contaminant bioavailability, and sediment stability data should be considered during the development of the LTM strategy.

Biological data for sediments can provide data regarding ecological toxicity, changes in the biological assemblages at the site, and determining toxicant bioaccumulation and food chain effect. Biota monitoring and toxicity assessments should be considered during the development of the LTM strategy. The utilisation of surrogate parameters, such as water levels, dissolved oxygen, and pH, should also be considered. These typically low-cost methods can be useful indicators of remedial system effectiveness, if used appropriately in the context of the CSM.

The effect that poor sediment sample collection and handling procedures can have on test outcomes are generally not well described in assessment protocols. Research has demonstrated that inadequate handling, storage and manipulations during testing procedures may lead to changes in sediment chemistry that affect the bioavailability and toxicity of sediments (e.g. the oxidation of Fe(II) and associated decreases in pore water pH may increase metal concentrations in the pore water and increase toxicity). As such, the level of uncertainty in sediment sampling can be significantly reduced by following established sampling protocols to ensure that the chemistry in sediment samples is consistent with naturally occurring sediments.

# 8. Long-term Monitoring Optimisation

Long-term Monitoring Optimisation (LTMO) is an approach taken at sites with well-established LTM programs to:

- Detect and respond to changes in performance;
- Ensure that the correct remedial decisions are being made;
- Streamline data collection and management requirements;
- Ensure the continued collection of representative (and cost effective) data appropriate to the decision making required.

LTMO offers benefits such as enhanced protectiveness, reduced cost, shortened remediation times, and the increased likelihood of site closure.

Although the focus of LTMO is often the frequency of sampling and the sampling network, as optimisation of these yields the greatest cost, time and data benefits, other aspects of an LTM program can be evaluated for optimisation, including:

- The analytical suite (for example elimination of redundant analyses or inclusion of a more robust suite);
- Sampling method(s) (for example installation of no-flow groundwater sampling rather than low-flow for a large groundwater network);
- Analytical methods; and
- Data management tools and reporting (for example implementation of a more intuitive database for storing the site data).

Typically, LTMO comprises the following steps:

1. Define and document the current monitoring program;
2. Examine the existing data;
3. Determine the type of evaluation;
4. Select the LTMO methods/tools;
5. Perform the optimisation; and
6. Assess and implement the results.

The following sections provide detail on each of these seven steps.

The decision on whether to evaluate a site for the potential of LTMO, the approach to take with the evaluation, and the degree of regulatory involvement in the optimisation relies on several site-specific factors, including:

- Projected level of effort required to complete the evaluation;
- Available resources to undertake the evaluation;
- Anticipated degree of difficulty in implementing the LTMO recommendations;
- Potential benefits/cost savings that could be realised from the LTMO; and
- Perceived problems with the current LTM program.

It is recommended that LTMO is considered at sites where the LTMP is based on monitoring points and frequencies established during site characterisation, or for sites where it appears excessive sampling is undertaken. LTMO can also be considered periodically as monitoring parameters and trends change over time.

LTMO is most beneficial when site conditions are relatively stable and show a consistent trend, in addition to no major changes to the site or remediation infrastructure planned in the near-term. Recommended minimum requirements are:

- Results from four to six monitoring events (for temporal trends);
- Results from six to 15 monitoring points across the monitoring events (for spatial trends); and
- An appropriately updated CSM which describes site specific conditions in detail.
- The level of detail proposed for the evaluation has been selected;
- The appropriate tool and/or guidance document has been identified; and
- Relevant stakeholders have agreed to the objectives of the LTMO, the data to be used, and the approach to be followed.

In determining if a site can be considered for LTMO, reference should be made to the CSM for the site. The CSM should be utilised to define the extent of residual contamination remaining at the site and temporal and spatial variations across the site. The LTMO process enables refinement of the relevant CSM, which can then be used to assess remedial performance metrics.

## 8.1 Define and document the current monitoring program

It is necessary for the primary elements of the existing LTM to be clearly defined and documented prior to implementing LTMO or undertaking an LTMO evaluation of the program.

The first step of LTMO is therefore to define the monitoring objectives, parameters being monitored, analytical suite, sampling and analytical methods, frequency and location of the sampling, and the monitoring program costs.

## 8.2 Examine the existing data

The existing data drives the type of optimisation and level of detail that is feasible in an LTMO, including both a baseline and an end to the optimisation. Thus, to successfully apply LTMO, a site-specific evaluation of the available data is required.

It is recognised that the identification of appropriate data and transferring them to a useable format can be time-consuming and labour-intensive. LTMO is a data driven process, and considerable up-front effort is required to accomplish the optimisation.

The recommended data, potential data sources, and the associated purpose(s) of the data required for LTMO is presented in Table 2 below.

**Table 2: Recommended long-term monitoring optimisation inputs**

| Data Required | Potential Data Source(s) | Purpose of Data |
|---|---|---|
| Current monitoring program | • LTMP<br>• Recent monitoring report | Establish the baseline site conditions, the purpose of the LTM, rationale for sample location, and the sampling and analytical methodology utilised at the site. |
| Sample locations (coordinates) | • Sample database<br>• Site maps<br>• Previous investigation reports | Determine the spatial distribution of sample locations. |
| Sampling results | • Sample database<br>• Recent monitoring report(s)<br>• Previous investigation reports | Define the spatial and temporal concentrations of contaminants<br>Confirm the contaminants of concern<br>Verify data quality |
| Potentiometric groundwater contours | • Recent monitoring report(s)<br>• Previous investigation reports<br>• Sample database | Evaluate the direction and rate of groundwater movement and contaminant migration. |
| Subsurface conditions | • Conceptual site model<br>• Hydrogeologic testing results<br>• Previous investigation reports | Identify geologic or other controls on groundwater |
| Well screening intervals and aquifer water bearing zones | • Sample database<br>• Well construction logs<br>• Drilling logs | Determine the depth of sample collection in the aquifer and identify the site stratigraphy. |
| Validation criteria and regulatory limits | • Validation Report<br>• LTMP | Establish the validation criteria and areas of concern requiring monitoring. |
| Potential receptors and compliance points | • LTPM<br>• Site map<br>• Site inspection | Identify areas or contamination pathways of concern |

Table 3 provides additional inputs that may be relevant, depending on the site conditions and contamination status.

**Table 3: Additional long-term monitoring inputs**

| Data Recommended | Potential Data Source(s) | Purpose of Data |
|---|---|---|
| Logistics and policy considerations | • Site personnel<br>• Stakeholders | Identify regulatory/public priorities and the potential for alternative program implementation. |
| Site features | • Site map<br>• Site inspection | Create the spatial context of the LTM.<br>Develop a base map for the LTMO reporting |
| Historical site features | • Previous investigation reports<br>• Sample database | Identify dry/redundant wells/sample locations<br>Evaluate seasonal effects at the site. |
| Geochemical data | • Sample database<br>• Previous investigation reports | Identify natural attenuation factors. |
| Presence of NAPL | • Previous investigation reports<br>• Sample database | Identify data which can potentially be excluded from the LTMO |
| Current program costs | • Laboratory invoices<br>• Project budget/schedule/projections<br>• Site personnel<br>• Professional judgement | Establishes a baseline for the LTM at the site and quantifies potential cost savings based on the LTMO. |

## 8.3 Type of evaluation

Evaluations may be qualitative, quantitative, or a combination of the two. LTM programs are traditionally qualitative, as spatial and temporal variability are difficult to capture using quantitative techniques. However, there are multiple factors to be taken into consideration with either a qualitative or quantitative approach.

In determining the type of LTMO to undertake at a site, practitioners should evaluate whether a stand-alone qualitative evaluation, or a qualitative evaluation with supporting quantitative temporal and/or spatial analysis, is appropriate for the site. It is broadly recommended that a combined approach consisting of a qualitative evaluation of site analytical data and conditions, and a quantitative statistical evaluation of the analytical data be implemented to obtain a robust outcome.

### 8.3.1 *Qualitative evaluation*

In a qualitative evaluation, the numbers and location of sample points and frequency of sample collection are examined in the context of site-specific conditions. This is done to ensure that the LTMO program can generate information regarding contaminant migration and changes in chemical concentrations through time, and to ensure that the objectives of the program are being met. Additional considerations such as the analytes, sampling methods, analytical methods, data management, and reporting can also be assessed during the qualitative evaluation. The relative performance of the monitoring program is assessed from estimations and judgements made without the use of quantitative methods. Sample locations can be evaluated through the consideration of contaminant behaviour and hydrogeological (and other) conditions within and at locations surrounding the source. The optimal configuration of a monitoring program, including the sample locations and sampling frequency, is subject to:

- The properties and behaviours of the system;
- The ways in which these properties influence the fate and transport mechanisms, with resultant contaminant distributions; and
- What constitutes the 'optimal' monitoring program, considering the LTM objectives and source-pathway-receptor linkages.

Every monitoring location is assessed as part of the LTMO. The locations are assessed against optimisation criteria, and the resultant recommendations may include additional monitoring, cessation of monitoring or continued monitoring at a lower or higher frequency. There are multiple factors to be considered in developing the optimisation criteria including:

- Is the sampling location required to further characterise the site/monitor changes in contaminant changes through time or does it provide spatially redundant information with a neighbouring location?
- Is the sampling location required to laterally or vertically delineate the extent of contamination or does the sampling location not provide relevant data?
- Is the sampling location a compliance or receptor exposure location or are concentrations of contaminants consistently below the relevant criteria?
- Is the sampling location a background point?
- Does the sampling frequency need to be varied to account for high or low groundwater velocity?
- Would altering the sampling frequency continue to provide information at a rate high enough to alter decision making?
- Does the sampling frequency need to be varied to take into account the proximity of the monitoring location to the source?
- Do the concentrations and/or concentration trends indicate that sampling frequency should be increased/decreased?

A qualitative evaluation is considered complete when recommendations for the retention or removal of each individual monitoring point with respect to the overall monitoring program have been assessed and documented. Qualitative approaches range from simple to complex and are subjective. The degree to which the LTM program satisfies the spatial and temporal objectives of the program may not be easily evaluated by qualitative methods, and therefore a quantitative evaluation can also be considered.

### 8.3.2 *Quantitative evaluation*

A quantitative evaluation can consider temporal data such as chemical concentrations measured at different sampling locations over time to provide a means of quantitatively assessing the site conditions and evaluating the performance of the associated monitoring program. The identification of trends in contaminant concentrations through observing fluctuations or estimating long-term averages can be used to satisfy the temporal objective of LTM. Concentration trends are subsequently evaluated using statistical methods and the outputs can then be utilised to determine the frequency of sampling necessary to achieve the temporal objective of monitoring. A quantitative evaluation of temporal chemical concentrations can be utilised to make decisions on the sampling frequency at a site. In order to make decisions on sampling frequency a simulation or rule-based approach is followed.

In a simulation approach, modelling is undertaken to simulate contaminant trends and identify the optimal frequency of sampling to measure the modelled trend. Simulation, geostatistical, and analytical approaches can all be applied to the design and evaluation of monitoring networks. Simulation uses historical data in a computer model to simulate the evolution of a contaminant plume. Geostatistical and analytical approaches use historical data to interpolate contaminant concentrations for an area of interest. Once a plume model has been created, it can be incorporated into an optimisation algorithm to derive an optimal network configuration.

In a rule-based approach, a decision rule is established by the practitioner in association with the results of the trend evaluation to establish the sampling frequency for sample locations. For example, a decision rule may be made to increase the sample frequency if an increasing contaminant concentration trend is observed at a sampling location adjacent to a sensitive receptor.

Alternatively, ranking methods can be used to select monitoring configurations by a ‘rule-of-thumb’ approach over formal optimisation. A quantitative evaluation of the spatial monitoring network can indicate monitoring locations which contribute relatively little information (and which can be removed), and areas which exhibit significant uncertainty (and which are candidates for additional sampling locations).

## 8.4 Select the LTMO methods / tools

There are multiple LTMO tools available which may be applied to an individual site. Table 2.5.1 of US EPA (2005) provides information on recommended optimisation tools/approaches including an overview, frequency of the methodology, data requirements and the appropriate site size. US EPA (2005) identifies the two primary guidance documents in use in the United States at the time of publishing:

- NAVFAC (2000); and
- US AFCEE (1997).

NAVFAC (2000) includes information on the design of new monitoring programs and the optimisation of existing programs. It also covers a broad range of issues from physical program optimisation (frequency and location of sampling), analytical and field methodology, and data management and reporting. US AFCEE (1997) includes information on the development of the LTMP, the documentation of the existing LTM program, optimisation strategies, and an evaluation of cost savings.

Rather than reproducing that content here, readers are encouraged to refer to those documents to select the LTMO method or tool.

## 8.5 Assess and implement the results

The outcome of LTMO evaluation is a series of recommendations or refinements, which may include:

- A refined CSM;
- Refinement or clarification of program objectives;
- Changes in the number and location of sampling points;
- An increase/decrease in the sampling frequency of each sampling point in the program;
- Change to the sampling and/or analytical methodology; and
- Change to the data handling, management or reporting methods.

These outcomes should be documented within a suitable report distributed to the relevant stakeholders, including regulators and Auditors if applicable.

The LTMP should be updated to include the aspects of the LTMO that are adopted.

# Appendix A – LTM Optimisation case study

The case study illustrates LTM optimisation. For the purposes of illustration, selected summary data only are presented, and it can be assumed that raw data have been evaluated in accordance with the relevant guidance, and that the data have been assessed as being accurate and representative of each respective site.

**Case study – Chlorinated hydrocarbon impacted groundwater**

An industrial installation used for the storage, shipping, and packaging of general supplies, and the maintenance of equipment, is located in an environmentally sensitive area. The use and storage of petroleum fuels and a variety of industrial chemicals, including solvents, at the installation has led to inadvertent releases which have contaminated soil, soil vapour and groundwater. The primary concern and driver of remediation at the installation was the presence of co-mingled VOC plumes in groundwater, with trichloroethylene and tetrachloroethylene representing most VOCs exceeding the criteria in the plumes. Groundwater remediation established since 1987 comprises a groundwater extraction well network with an associated air-stripper system and groundwater treatment plant, with treated groundwater disposed of off-site. At the current stage of remediation, the groundwater extraction system is containing the migration of the co-mingled plumes and effectively removing VOC mass from the groundwater.

LTM of the remediation system consists of sample collection from numerous GWMWs and from various locations in the groundwater remediation system, for the purpose of monitoring groundwater contaminant conditions to evaluate progress towards meeting the remedial objectives. Since the 1980s, hundreds of GWMWs have been installed for site characterisation, remedial design, and remediation implementation requirements. Over time, the monitoring network has grown to include many of the GWMWs that were installed during previous site characterisation, investigation and remedial works. The groundwater well network comprises 217 GWMWs, 36 groundwater extraction wells (of which only 15 are operational), 10 injection wells (which are not in use), six injection observation wells (which are not in use), and 40 piezometers. Additionally, there are approximately 50 potable and industrial water supply wells on- and off-site, of which 37 are included in the LTM program. The variety of wells were sampled on a monthly, bi-annual or annual basis.

The objective of the LTM was to monitor contaminants to protect human health and the environment and evaluate the performance of the remediation. The LTMO objective was to reduce the spatial and temporal redundancy of sampling to improve cost effectiveness without loss of information.

The GWMW network as identified above is an aggregation of GWMWs installed for various purposes rather than a network developed solely for LTM purposes. GWMWs installed as part of the site characterisation were likely retained in the LTM network because they were available, rather than because they addressed the LTM objectives.

Due to the large and complex network of GWMWs utilised in the LTM network, LTMO was undertaken using optimisation software. This organised, evaluated and presented the monitoring data using trend analysis to evaluate plume stability, with the objective of reducing the spatial and temporal redundancy of sampling for cost effectiveness.

Application of the optimisation software generated recommendations regarding potentially redundant monitoring locations.

The results of the temporal-trend analyses completed during the software optimisation evaluation were retained and used in a subsequent evaluation involving several hydrogeologists reviewing the data to construct an updated LTM program. The hydrogeologists collated the GWMW information into a GIS database containing historical sampling to identify the locations and enable trend analysis by location. The maximum concentrations of each contaminant of concern were then digitised to enable plume maps to be generated to identify optimum GWMW locations. Source area maps were then consulted to evaluate the plume migration direction. The plumes were shown to be stable, however groundwater flow direction was shown to vary which influenced the direction of contaminant migration. Following this evaluation, potential vertical migration paths were considered and GWMWs screening deeper hydrogeological zones were considered for inclusion in the LTM program. Additionally, recommendations were made for the installation of GWMWs in some areas currently without them. Finally, groundwater flow velocity was utilised to refine the sampling frequency with sampling optimised at annual or bi-annual intervals.

Using the above rationale, the installation saw a 75% reduction in the number of GWMWs being sampled each year with an 88% reduction in the total number of samples collected and analysed per year. It was comprehensively shown that the cost-benefit of undertaking the LTMO of the installation presented a significant cost and time saving for the LTM program.

# Appendix B – References

ACT EPA, 2015, *Policy on institutional controls and enforcement of site management plans required for contaminated sites*, Australian Capital Territory Environment Protection Authority, Canberra.

ANZECC, 1999, *Guidelines for the assessment of on-site containment of contaminated soil*, Australian and New Zealand Environment and Conservation Council, Canberra.

ASC NEPM, 1999, *National Environment Protection (Assessment of Site Contamination) Measure 1999, as varied,* National Environment Protection Council, Australia.

ASTM, 2014, *Standard guide for developing conceptual site models for contaminated sites*, E1689-95, American Society of Testing and Materials, West Conshohocken, PA.

CIRIA, 2009, *The VOCs handbook: Investigating, assessing and managing risks from inhalation of volatile organic compounds (VOCs) at land affected by contamination*, United Kingdom Construction Industry Research and Information Association, London.

CRC CARE, 2010, *Selecting and assessing strategies for remediating LNAPL in soils and aquifers*, CRC CARE Technical Report no 18, CRC for Contamination Assessment and Remediation of the Environment, Adelaide.

CRC CARE, 2010, *Technical guidance for demonstration of monitored natural attenuation of petroleum hydrocarbons in groundwater*, CRC CARE Technical Report no 15, CRC for Contamination Assessment and Remediation of the Environment, Adelaide.

EPA VICTORIA, 2000, *Groundwater sampling guidelines*, Publication 669, Victoria Environment Protection Authority, Carlton.

EPA VICTORIA, 2015, *Environment auditor (contaminated land): Guidelines for issue of certificates and statements of environmental audit*, Publication 759.3, Victoria Environment Protection Authority, Carlton.

GIBBONS, BHAUMIK & ARYAL, 2009, *Statistical methods for groundwater monitoring, 2nd ed,* Wiley, New York, NY.

ITRC, 2006, *Technology overview of passive sample technologies*, Report no. DSP-4, United States Interstate Technology and Regulatory Council, Authoring Team, Washington, DC.

ITRC, 2007, *Vapor intrusion pathway: A practical guideline*, Report no. VI-1, United States Interstate Technology and Regulatory Council, Vapor Intrusion Team, Washington, DC.

ITRC, 2008, *In situ bioremediation of chlorinated ethene: DNAPL source zones*, Report no. BioDNAPL-2, United States Interstate Technology and Regulatory Council, Bioremediation of DNAPLs Team, Washington, DC.

ITRC, 2010, *A decision framework for applying monitored natural attenuation processes to metals and radionuclides in groundwater*, APMR-1, Interstate Technology and Regulatory Council, Attenuation Processes for Metals and Radionuclides Team, Washington, DC.

ITRC, 2011, *Integrated DNAPL site strategy*, Report no. IDSS-1, United States Interstate Technology and Regulatory Council, Integrated DNAPL Site Strategy Team, Washington, DC.

NAVFAC, 2000, *Guide to optimal groundwater monitoring*, United States Naval

Facilities Engineering Service Centre, Port Hueneme, CA.

NSW DEC, 2006, *Contaminated sites: Guidelines for the NSW site auditor scheme (2nd edition)*, New South Wales Department of Environment and Conservation, Sydney.

NSW DECCW, 2010, *Vapour intrusion: Technical practice note*, New South Wales Department of Environment, Climate Change and Water, Sydney.

NSW DIPNR, 2004, *Guideline to preparing environmental management plans*, New South Wales Department of Infrastructure, Planning and Natural Resources, Sydney.

NSW OEH, 2011, *Guidelines for consultants reporting on contaminated sites*, New South Wales Office of Environment and Heritage, Sydney.

OSWER, 2002, *Principles for managing contaminated sediment risks at hazardous waste sites*, Report no. 9285.6-08, United States Environmental Protection Agency, Office of Policy, Office of Solid Waste and Emergency Response, Washington, DC.

QLD DEHP, 2006, *Guideline for contaminated land professionals*, Queensland Department of Environment Heritage and Protection, Brisbane.

SA EPA, 2007, *Regulatory monitoring and testing: Groundwater sampling*, South Australia Environment Protection Authority, Adelaide.

SA EPA, 2008, *Guidelines for environmental management of on-site remediation*, South Australia Environment Protection Authority, Adelaide.

SA EPA, 2013, *Regulatory monitoring and testing: Monitoring plan requirements*, South Australia Environment Protection Authority, Adelaide.

SIMPSON, BATLEY, CHARITON, STAUBER, KING, CHAPMAN, HYNE, GALE, ROACH & MAHER, 2005, *Handbook for sediment quality assessment*, Commonwealth Scientific and Industrial Research Organisation, Centre for Environmental Contaminants Research, Bangor, NSW.

STANDARDS AUSTRALIA, 1993, *Geotechnical site investigations, AS 1726-1993,* Standards Association of Australia, NSW.

STANDARDS AUSTRALIA, 2005, *Guide to the investigation and sampling of sites with potentially contaminated soil. Part 1: Non-volatile and semi-volatile compounds, AS 4482.1-2005,* Standards Association of Australia, NSW.

STANDARDS AUSTRALIA, 2005, *Guide to the investigation and sampling of sites with potentially contaminated soil. Part 2: Volatile substances, AS 4482.2-2005,* Standards Association of Australia, NSW.

STANDARDS AUSTRALIA & STANDARDS NEW ZEALAND, 1999, *Water quality - sampling. Part 12: Guidance on sampling of bottom sediments, AS/NZS 5667.12:1999,* Standards Australia

Standards New Zealand, NSW.

UK EA, 2000, *Guidance on the assessment and monitoring of natural attenuation of contaminants in groundwater*, R&D Publication no 95, United Kingdom Environment Agency, Bristol.

UK EA, 2004, *Model procedures for the management of land contamination*, Contaminated land report 11, United Kingdom Environment Agency, Bristol.

UK EA, 2010, *Verification of remediation of land contamination*, Report no. SC030114/R1, United Kingdom Environment Agency, Bristol.

US AFCEE, 1997, *AFCEE long term monitoring optimization guide, ver1.1*, United States Air Force Center for Environmental Excellence, Brooks AFB, Brooks

City, TX.

US AFCEE, 2000, *Designing monitoring programs to effectively evaluate the performance of natural attenuation*, United States Air Force Center for Environmental Excellence, Brooks AFB, Brooks City, TX.

US EPA, 2005, *Roadmap to long-term monitoring optimization*, EPA/542/R-05/003, United States Environmental Protection Agency, Washington, DC.

WA DEP, 2004, *Use of monitored natural attenuation for groundwater remediation*, Western Australia Department of Environment Protection, Environmental Regulation Division, Land and Water Quality Branch, Perth.

WA DER, 2014, *Contaminated sites guideline: Assessment and management of contaminated sites*, Western Australia Department of Environment Regulation, Perth.