CRC for Contamination Assessment and Remediation of the Environment

National Remediation Framework

Guideline on validation and closure

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.

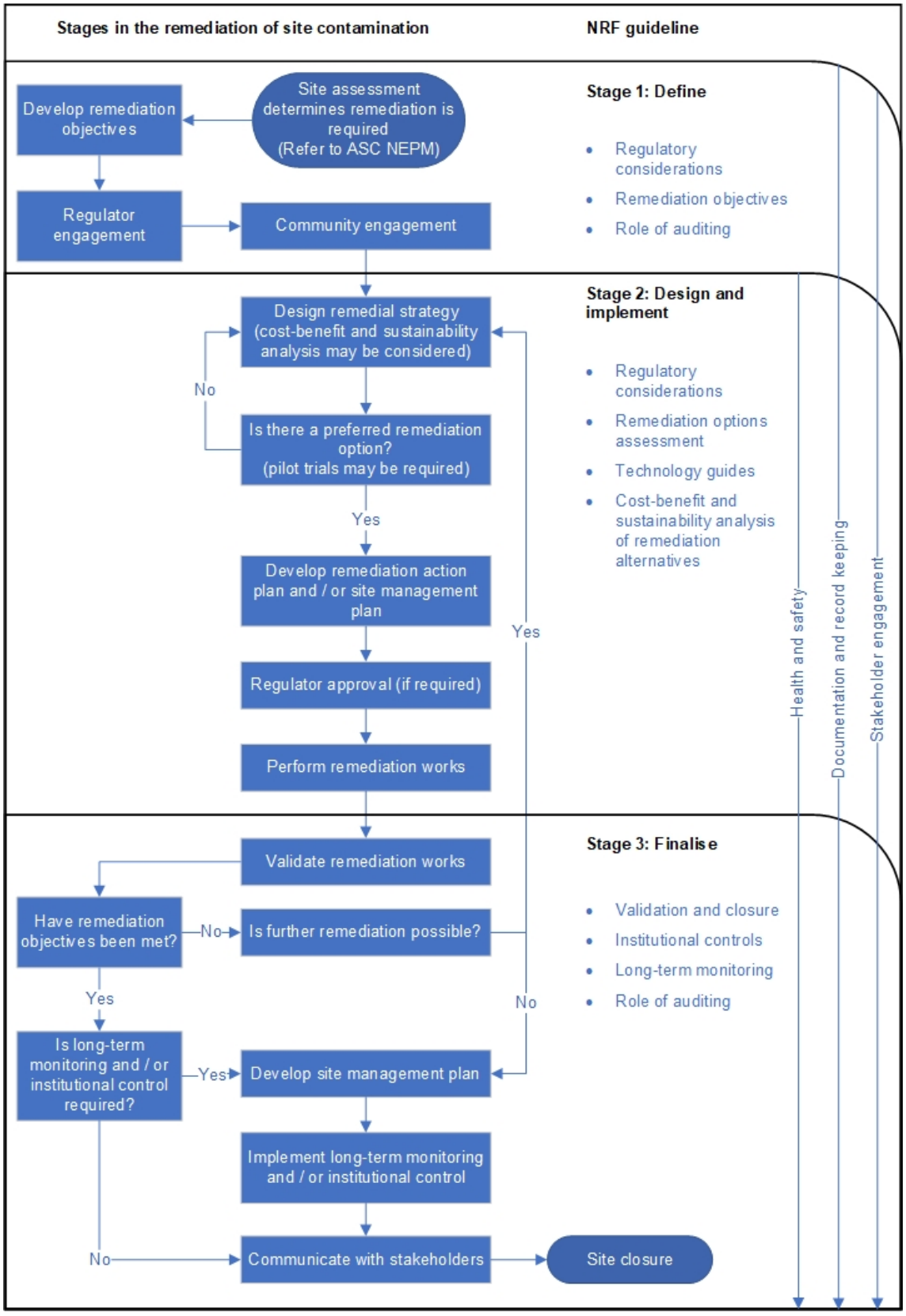
The NRF is intended to be consistent with local jurisdictional requirements, including State, Territory and Commonwealth legislation and existing guidance. To this end, the NRF is not prescriptive. It is important that practitioners are familiar with local legislation and regulations and note that **the 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
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
Yes
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
Health and safety
Documentation and record keeping
Stakeholder engagement

Executive summary

Where remediation is undertaken, works should be carried out to verify the effectiveness of the remediation methodology and to assess whether the remediation objectives have been achieved. This is referred to as validation. Validation should provide a scientifically defensible and statistically valid data set which characterise the site at the time of validation. Validation aims to confirm that unacceptable risks to human health and environmental receptors have been reduced to acceptable levels. When sufficient evidence is present to determine that remediation objectives have been met and it is approved by the regulator and potentially an auditor (where required), site closure may be achieved.

The validation strategy describes the overall goals of the validation, including the criteria which must be validated against, and the lines of evidence that will be used to demonstrate the remediation objectives have been met. The conceptual site model should be used to show which source-pathway-receptor linkages the remediation is targeting, and therefore which linkages must be shown through validation to be incomplete.

A line of evidence is a data set of a key parameter that support the agreed validation criteria to demonstrate the performance of remediation. It is widely accepted that using only one line of evidence, for example assessing the concentration of a contaminant in a few samples against a target concentration, may not be sufficient to determine that a remediation program has been successful and that the remediation objectives have been met. This is particularly relevant where complex remediation methodologies have been applied to sites where heterogeneous strata and/or difficult contaminants are present. This guideline describes several lines of evidence, including when they may be used and what information should be collected.

A contingency plan details the response to new or previously unidentified site conditions, and/or poor performance of a remediation system. It should anticipate risks and issues with the remediation plan and should be flexible to allow for adjustments due to new information gathered during the remediation process and validation monitoring. This guideline describes several contingency solutions.

Site closure is the process of obtaining approval by the regulator and/or auditor, if required, to cease remediation of a site because validation has demonstrated that the remediation objectives have been met. The conditions required to achieve site closure are highly site-specific. This guideline looks at achieving and reporting site closure.

Abbreviations

Abbreviation	Expansion
COC	Contaminant of Concern
CRC CARE	Cooperative Research Centre for Contamination Assessment and Remediation of the Environment
CSM	Conceptual Site Model
CUTEP	Cleanup to the Extent Practicable
DNAPL	Dense Non-Aqueous Phase Liquid
DO	Dissolved Oxygen
DQO	Data Quality Objectives
Eh	Oxidation Potential
EMP	Environmental Management Plan
LNAPL	Light Non-Aqueous Phase Liquid
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
SMP	Site Management Plant
TI	Technical Impracticability

Glossary

Anaerobic groundwater	Groundwater that contains less than about 0.5 mg/L of dissolved oxygen.
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.
Attenuation	The reduction in mass, toxicity, mobility, volume or concentration of contaminants by physical, chemical and biological processes
Auditor	Individuals accredited under state specific formal auditing schemes, to independently review site contamination consultants' activities to ensure the work complies with current regulations and guidelines and meets the standard appropriate for the proposed land use.
Beneficial use	A particular value or use of the environment or any element or segment of the environment which: · is important for a healthy ecosystem; · is conducive to public benefit, welfare, safety, health or aesthetic enjoyment which requires protection; or · is declared in state or territory environment protection policy to be a beneficial use. Definitions for 'beneficial use' or 'environmental value' may differ among jurisdictions (e.g. may include additional considerations for 'environmental harm' as defined in jurisdictional legislation See also "Environmental value"
Biodegradation	The transformation of a substance or chemical by micro- organisms such as bacteria or fungi, resulting in a change in chemical structure mass within the environment.
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.
Data quality objectives (DQOs)	Qualitative and quantitative statements that define the type, quality and quantity of data necessary to support decision- making within the resource constraints of a project.
Electron acceptor / donor	A chemical capable of accepting / donating electrons during oxidation-reduction reactions.
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.
Line of evidence	A data set of a key parameter that support the agreed validation criteria to demonstrate the performance of remediation.
Monitored natural attenuation (MNA)	A remedial method comprising the monitoring of naturally occurring physical, chemical and biological processes, or any combination of those processes to reduce the mass, toxicity, mobility, volume or concentration of polluting substances in groundwater. These processes must be sufficient to prevent contaminants from reaching identified receptors and minimise the expansion of plumes into currently uncontaminated groundwater.
Non-aqueous phase liquid (NAPL)	Non miscible organic fluids. Light NAPL (LNAPL) are less dense than water and as a result primarily float on the surface of groundwater, whilst dense NAPL (DNAPL) are more dense than water and primarily sink to the bottom of the water column.

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.
Reductive dechlorination	Reduction of a chlorine-containing organic compound (typically a solvent) by the replacement of chlorine with hydrogen in the compound.
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 objective	An objective established for a specific site to be met by the implementation of a Remediation Action Plan and, if appropriate, ongoing site management.
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.
Sediment pore water	The water occupying the spaces between sediment particles.
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.
Site audit	An independent review of site contamination by an accredited auditor to ensure that it complies with current regulations and guidelines and meets the standard appropriate for the proposed land use.
Validation criteria	Concentration of a contaminant in air, soil, water, or sediment that is demonstrated to be protective of human health and the environment under specific conditions, and must be achieved for a remedial action to be considered successful.
Validation report	A complete record of all remediation activities on site and data that characterises the site post-remediation, to support compliance with agreed remediation objectives and criteria

Chemical symbols, formulae and abbreviations

Ca	Calcium
CO_3^{2-}	Carbonate ion
Fe	Iron
HS^-	Bisulfide ion
K	Potassium
Mg	Magnesium
Mn	Manganese
Na	Sodium
NO_3^-	Nitrate ion
O_2	Oxygen
PO_4^{3-}	Phosphate ion
SO_4^{2-}	Sulfate ion

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1. Introduction

The objective of this guideline is to provide an overview of the best practice approaches for validation of remediation to achieve site closure by:

- Outlining the range of evidence that may be collected to demonstrate the effectiveness of remediation with a view to site closure;
- Provide an overview of the steps required to achieve site closure; and
- Describing contingency measures that may be employed if remediation objectives are not achieved within the scheduled timeframe.

This guideline presents Australian approaches pertaining to remediation validation and closure in order to inform the reader on how to incorporate validation into remedial planning for the purpose of achieving site closure. International guidance has been sought where gaps were identified in Australian guidance, most notably from the Environment Agency (England and Wales, UK) and the Interstate Technology and Regulatory Council (ITRC; USA). Familiarity with local legislation and regulations is necessary before proceeding with environmental investigations or remediation/ management.

Where remediation is undertaken, works should be carried out to verify the effectiveness of the remediation methodology and to assess whether the remediation objectives have been achieved. This is referred to as validation. Validation should provide a scientifically defensible and statistically valid data set which characterise the site at the time of validation. When sufficient evidence is present to determine that remediation objectives have been met and it is approved by the regulator and potentially an auditor (where required), site closure may be achieved.

The following definitions have been adopted for the NRF:

Validation is "the process of determining whether remediation objectives have been achieved"

Closure is "the final step in the remediation and validation process, when remediation objectives have been achieved and validation demonstrates that no further active remediation is required at a site, (although long-term monitoring may be identified as being required to achieve site closure).."

The key benefits to undertaking appropriate validation of the remediation of a site include the following:

- Demonstrates compliance with legal and contractual requirements;
- Evidence for corporate or government reporting purposes;

- Greater confidence for future owners and generations in the quality of remediated land;
- Evidence of successful (or otherwise) remediation;
- Enhanced understanding and increased confidence in the efficacy of innovative treatments; and
- Identification of unsuccessful remediation.

The purpose of validation sampling and reporting is to assess whether remediation has been completed in accordance with the remediation plan and if so, whether the remediation objectives have been met.

A validation monitoring program can consist of both compliance and performance monitoring programs. The objective of compliance monitoring is to demonstrate adherence to validation criteria at designated 'end points', usually at the end of remediation works with a view to achieving site closure. In most cases, remediation is ultimately considered successful when the contaminants of concern (COC) (and any potentially harmful by- products) have been sufficiently reduced to comply with the validation criteria.

Performance monitoring aims to verify the effectiveness and efficiency of the treatment during the remediation process and is therefore technology-specific. Performance monitoring is outside of the scope of this guideline, and readers are directed to the individual NRF technology guides for further information on performance monitoring. It is noted that performance monitoring may be long-term for structures retained on the site (e.g. for containment).

The deliverable produced following remediation and validation works is referred to as the validation report, which also serves the purpose of providing an accurate and permanent record of remediation and the standard it has achieved.

2. Validation strategy

The validation strategy describes the overall goals of the validation, including the criteria which must be validated against, and the lines of evidence that will be used to demonstrate the remediation objectives have been met. The remediation objectives are established prior to the commencement of remediation, in accordance with the conceptual site model (CSM) developed as part of the site assessment process.

The CSM is updated during remediation, and used in the development of data quality objectives (DQOs) for the validation works. The CSM and DQOs are then used to inform how resources will be applied during validation works, and documented in the validation plan. The CSM is useful in showing which source-pathway-receptor linkages the remediation is targeting, and therefore which linkages must be shown through validation to be incomplete.

Remediation works themselves may change the nature of the site, creating a potential for new source-pathway-receptor linkages to be created (e.g. the production of daughter products, or the placement of more permeable fill material). The CSM review must also anticipate these new linkages and show through validation that they too are incomplete. Final validation is dependent on all data that represents the final condition of the site, including the data collected to validate the site.

A summary of the development of a validation strategy is presented in Figure 1.

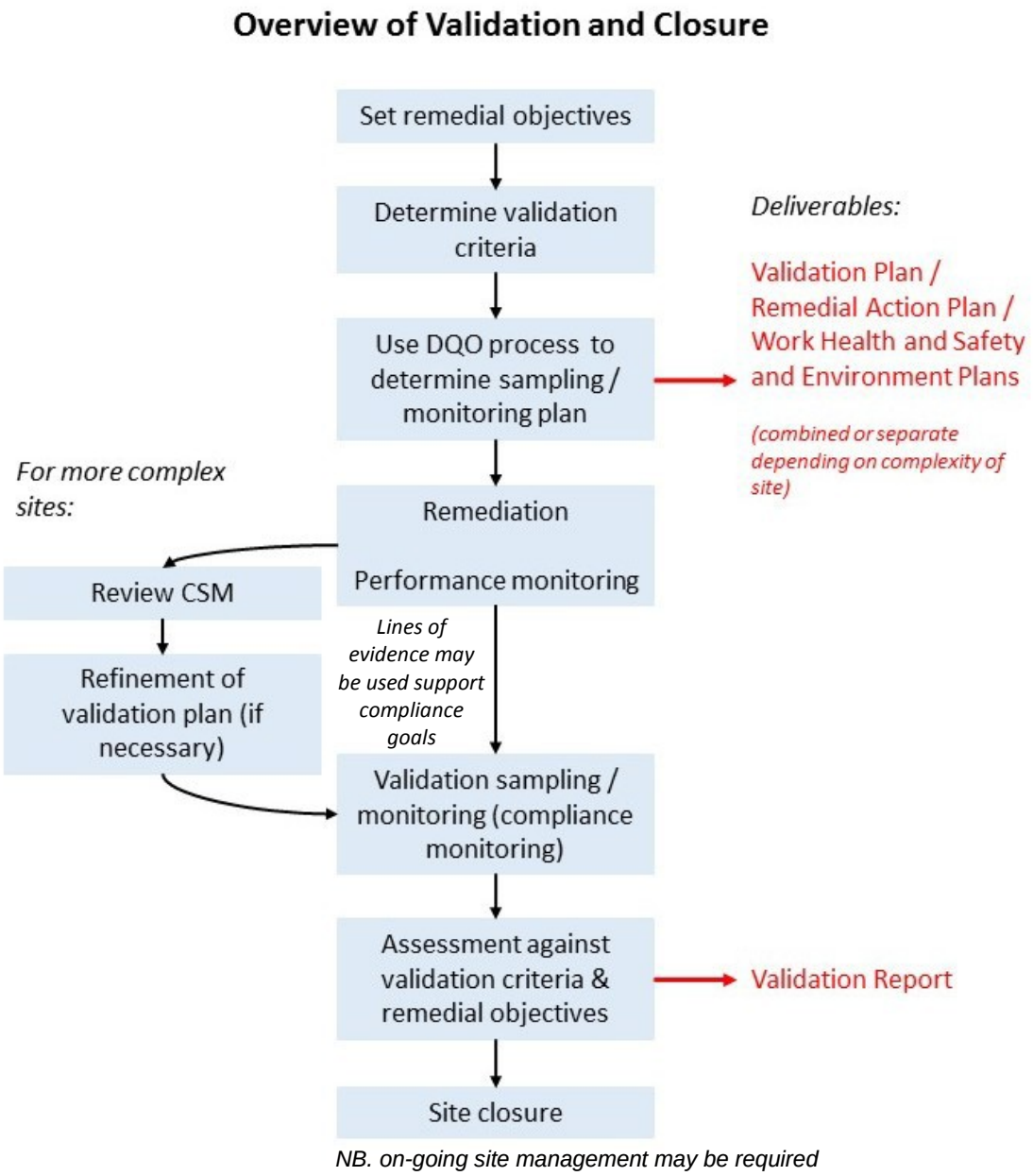

Figure 1. Typical steps in the development of a validation strategy.

2.1 Validation criteria

The remediation objectives are central to the development of the validation and closure strategy. In the majority of cases the remediation objectives are fixed and do not change during the validation and closure process. However, in some circumstances (particularly for large and/or complex sites, for which the initial assessment could not provide complete information as to the extent and nature of contamination present), it may be beneficial to have some flexibility in the remediation objectives, and thus the ability to respond to site-specific conditions and local property demands, and be able to adapt the validation and closure strategy accordingly.

In some situations, the remediation strategy adopted may not meet the remediation objectives. At this point, further remediation may be required, or the remediation objectives and/or remediation scope may need to be adjusted to manage unacceptable

risks to human health and the environment and address the residual contamination (or further validation may be required).

Numerical site-specific validation criteria should be developed in accordance with the remediation objectives. Meeting the remediation objectives may include meeting the validation criteria. While remediation objectives may be expressed in both numerical and non-numerical terms, validation criteria are typically numeric, against which the results of validation monitoring may be compared.

Validation criteria should be established at the commencement of remediation planning, when technology is being selected. The process of deciding which validation criteria are appropriate for the site should involve environmental practitioners, the proponent, regulators, the auditor (where applicable) and potentially other stakeholders, to avoid possible misunderstandings and delays when the data become available and decisions are made (ITRC 2004). Readers are directed to the NRF *Guideline on establishing remediation objectives* for guidance on setting remediation objectives, and to the NRF technology guides for specific guidance on validation considerations for specific remediation technologies.

2.2 Review of the conceptual site model (CSM)

The CSM should be appropriately scaled for the complexity of the site and should continue to evolve throughout the remediation and validation process. For large and complex sites, it is particularly important to routinely challenge and review the CSM and be aware of associated uncertainties (Environment Agency 2010). A review of the CSM as part of the validation works should consider the following (DECCW NSW 2010):

- the type and extent of remediation activities carried out at the site;
- the nature and extent of contamination removed or immobilised during remediation;
- the potential presence of degradation products;
- changes in proposed on-site or adjacent land uses and other sensitive receptors;
- changes in site layout following remediation;
- changes in soil or aquifer characteristics following remediation; and/or
- details of any failures, leaks, spills and incidents on site during remediation.

Significant updates to the CSM may not be required for all sites, e.g. if all contaminated media are excavated and disposed of off-site. The properties of contaminants must be carefully considered due to their impact upon mobility and potential migration pathways, and thus their effect upon the CSM and hence the validation strategy (Environment Agency 2010):

- solubility in water, and the potential for reversible immobilisation or solubilisation;
- miscibility with water, and the potential for NAPL to be present. NAPL can serve as a secondary source of contamination, and its presence is associated with distinct regulatory requirements;

- proportion that may be sorbed to soil, which is reversible and dependent upon factors such as pH and redox potential;
- volatility, and hence potential for phase transfer through volatilisation;
- potential for different oxidation states, which will impact the toxicity and mobility of the contaminant; and
- degradability, resulting in conversion to by-products.

2.3 Data quality objectives (DQOs)

Gathering data at sufficient density for effective and reliable validation has a financial and temporal cost. The use of resources in gathering such data should be weighed against other site constraints. In order to do this, in accordance with NEPM, the DQO process should be adopted such that an appropriate method with sufficient data density is used, and this requires professional judgement. The DQO process, drawing on the pre-established remediation objectives and the CSM (and associated data gaps), should be used to define the type, quantity and quality of data needed as part of site validation to support a potential decision in relation to site closure.

The development of a sampling program using the pre-determined DQO process provides a statistical basis for decision-making (DECCW NSW 2010a). This allows detailed planning to be undertaken to further support the development of the validation approach in the most resource effective manner. A sufficient portion of remediation project resources (as determined by the DQO process) should be devoted to validating the works, in terms of budget, planning, and available technical expertise (ITRC 2004).

It is essential that the selected validation methods meet the DQOs. The merit in gathering data where the limit of detection is equal to or greater than the validation criterion may be discussed with decision-makers (see Environment Agency 2010). Guidance on the DQO process can be found in AS4482.1, the NEPM and the US EPA DQO guidelines (2000, 2006).

2.4 Lines of evidence

A line of evidence is a data set of a key parameter that support the agreed validation criteria to demonstrate the performance of remediation (Environment Agency 2010). It is widely accepted that using only one line of evidence, for example assessing the concentration of a contaminant in a few samples against a target concentration, may not be sufficient to determine that a remediation program has been successful and that the remediation objectives have been met. This is particularly relevant where complex remediation methodologies have been applied to sites where heterogeneous strata and/or difficult contaminants are present.

This section provides detail on several commonly used lines of evidence. The lines of evidence should be reviewed regularly during remediation to ensure that they remain appropriate and sufficient to meet the remediation objectives.

Readers are directed to the individual NRF *Technology guides* for detailed information on validating different remediation technology options. Different lines of evidence may be applicable to each technology.

Details on validation sampling for different matrices (soil, groundwater, vapour, NAPL) are presented in **Appendix A.**

2.4.1 *Validation before or during remediation*

Some remediation technologies, such as pump and treat or soil vapour extraction, will provide validation data as the remediation progresses. The same metrics used to assess the performance of the remediation technology can be used as a line of evidence for the success, or completion, of remediation.

Similarly, portions of the site may be able to be validated prior to remediation works commencing. For example, soil samples can be collected from the anticipated base of an excavation using drilling methods, prior to breaking ground. Should the soils at the base conform to expected characteristics of uncontaminated soil during inspection, validation samples of the excavation may not be required. This methodology can be useful if site access or timeline restrictions apply.

2.4.2 *Pathway removal*

One method of remediation is to remove the pathway between the source and the receptor. For example:

- Placing contaminated soil underneath buildings;
- Placing contaminated soil at a depth where the risk is low and acceptable;
- Installing a hardstand or similar barrier to prevent contact; or
- Installing a vapour barrier to mitigate indoor vapour accumulation risks.

Validation involves demonstrating that the pathway has indeed been removed as intended. This can include such evidence as:

- Photographs, field notes and survey data as evidence the contaminated soil was placed / removed in accordance with the remediation plan;
- Photographs, field notes and survey data as evidence of the installation of a vapour barrier;

In some cases, this validation evidence should be supported by a documented reduction in contaminant concentration, described below.

2.4.3 *Documented reduction in contaminant concentration*

In most cases, the primary evidence for remediation performance will be a documented temporal reduction in contaminant concentrations in a given media (e.g. soil, sediment, groundwater, vapour or NAPL), towards agreed validation criteria.

Baseline data and validation data can be assessed in numerous ways, depending on the remediation objectives and the statistical approach adopted. Discrete data points can be compared directly to validation criteria established for the site or the data can be averaged geospatially to evaluate overall decreases in contaminant concentrations.

Whilst the aim is for contaminant concentrations to be reduced to comply with validation criteria, this may not be achievable at some sites due to the presence of more complex contaminants and geologies. At these sites, documented reduction in contaminant concentration from levels observed prior to remediation remains an important line of evidence to suggest that the remediation method has been successful in reducing the overall impacts and associated risks at the site as far as is practicable.

If initial site investigations indicate that migration of contaminated groundwater may pose an unacceptable risk to down-gradient receptors, sampling at intermediate points and at the receptor may also be required for regulatory purposes. This may comprise several rounds of testing of the water quality in nearby watercourses or groundwater bodies.

Soils subject to *ex-situ* treatment should be validated prior to reinstatement to verify that contaminant concentrations have reduced sufficiently to comply with validation criteria.

In addition to measuring the primary COC, it may also be necessary to measure degradation by-products (daughter products) to establish proof of principle that the COC are degrading. Additionally, the by-products of the primary COC may themselves pose an unacceptable risk to human health or the environment, and as such, need to be monitored. All toxic by-products should be carefully monitored so that they do not exceed a point of compliance. All toxic by-products should be carefully monitored so that they do not exceed a point of compliance. Evaluating trends and ratios of molar concentrations can often be more informative than evaluating changes in the parent / dechlorination product concentrations alone (see ITRC 2011).

Many jurisdictions allow for statistical analysis of data to demonstrate remediation objectives have been met. There are several ways of achieving this, including trend analysis, Mann-Kendal statistics or other statistical methods. In most cases the data set required for statistical methods must include sampling locations from the whole site, not just the validation samples. Thus, prior to writing the validation sampling plan, it is important to understand the data that has been collected so far, the data points that will remain post-remediation (if any) and the data that will be required. In addition, many jurisdictions also require a site-wide data set at a certain sampling density. This density must also be accounted for when planning the validation sampling locations.

2.4.4 *Contaminant mass flux and mass discharge*

As it considers transmissivity in combination with concentration data, groundwater mass flux and mass discharge estimates can be used to evaluate the strength of the groundwater contamination source and the ability for a contaminant to reach a receptor.

Mass flux and mass discharge can be used to estimate source strength and can be compared to the level of natural attenuation to determine whether an active remediation system can be potentially shut down, with subsequent reliance on natural attenuation to degrade residual impacts. This can be assessed using site-specific quantitative models. Mass flux measurements can be used to quantify natural attenuation rates. However, in applying this approach, field measurement and estimates of fluxes would need to be repeated some time apart (or through spatial separation) to confirm that the differences in flux result from attenuation, and not the movement of contaminants. These data should also be supported by various chemical measures of natural attenuation. In groundwater, it is important that storage within less transmissive zones within the aquifer is not misinterpreted as degradation, or conversely, back-diffusion of secondary sources into more transmissive areas is not misinterpreted as remediation underperformance.

If the remediation performance is not meeting the expected milestones, then mass flux measurements can additionally assist in understanding where contaminant reduction is less than expected, and where improvement can be directed.

Mass flux estimates have been applied in a variety of contexts, including:

- The assessment of groundwater plume changes over time;
- Contaminant flux from soil impacts to surrounding media;
- Vapour generation from soil and groundwater impacts; and
- The flux of contaminants from sediments, groundwater, or wastewater into surface water.

Readers are directed to the CRC CARE technical report 37: *Flux-based groundwater assessment and management* for further information.

2.4.5 *Geochemistry and biochemistry*

The analysis of geochemical and biochemical parameters assists in determining the environmental conditions that are present on a site. These parameters indicate the potential chemical and biological processes that may be occurring and how they may impact the identified COC and are therefore useful parameters in validating the site and the condition of the site prior to site closure.

Geochemical and biochemical parameters obtained in the field can be used to supplement laboratory data. When used with an appropriate sampling and analytical plan and in conjunction with laboratory analysis, field measurements have the following advantages (Environment Agency 2010):

- Access to real-time data, allowing real-time decisions to be made;
- Allows for greater sample density, improving data quality;
- Avoids potential for sample degradation during transport and storage, improving data quality (i.e. for dissolved oxygen, dissolved iron and redox potential); and
- Potential reduction in laboratory analysis, resulting in cost savings.

Groundwater multi-parameter probes can provide basic biochemical and geochemical data. Field measurements are often the most accurate way to measure parameters that are unstable, such as dissolved oxygen, oxygen-reduction potential (ORP or Eh) and hydrogen potential (pH).

The patterns and distribution of available electron acceptors in an aquifer provide an indication of the natural attenuation capacity of the system, which determines the mass of organic contaminants that can be degraded. Mass balance equations can therefore be used to estimate the attenuation capacity of an aquifer. For compounds that are oxidised during biodegradation, such as petroleum hydrocarbons, phenols and polycyclic aromatic hydrocarbons, data on redox potential and electron acceptors (e.g. O_2, NO_3^-, SO_4^{2-}) are informative. For compounds that are reduced, such as VOCs and polychlorinated biphenyls, data on ORP and the presence of electron donors (i.e. other degradable organic compounds than can be oxidised) are informative. A decrease in COC and change in electron acceptor/donor concentrations can typically be directly correlated to an increase in metabolic by- products.

A list of geochemical and biochemical parameters, which may be useful to monitor during validation monitoring, and the rationale for their inclusion are summarised in Table 1 below. It is noted that not all monitoring parameters may be necessary at all

sites, and the validation monitoring and sampling plan must therefore be specific to the site and the COCs requiring remediation.

Table 1: Useful parameters to measure during validation monitoring (adapted from ITRC 2011).

Parameter	**Rationale**
Dissolved oxygen (DO)	• Determines whether aerobic or anaerobic conditions exist. DO values <0.5 mg/L generally indicate that anaerobic pathways are likely.
Oxygen-reduction potential (ORP or Eh)	• Reflects the relative oxidising or reducing nature of the media and the treatment zone.
pH	• Provides an indication of the representativeness of groundwater samples. • Affects the fraction of metals that are sorbed vs dissolved in an aquifer and hence their mobility. • Affects aerobic and anaerobic processes.
Temperature	• Provides an indication of the representativeness of groundwater samples. • The rates of both biological and chemical reactions are temperature dependent.
Moisture content	• May affect chemical and biological processes that are required for remediation to be successful.
Conductivity	• Provides an indication of the representativeness of groundwater samples. • High conductivity may be an indication of high salinity, which may impact chemical precipitation or inhibit biological processes. Impacts the potential uses of an aquifer and the ability of superficial soils to support vegetative growth.
Electron receptors (oxygen, nitrate, manganese, iron, sulfate)	• Indicates which chemical and biological reactions are occurring and the natural attenuation capacity of the system. Determines microbial processes involved in biodegradation. • Measures either the production of reduced species (e.g. Mn(II) or Fe(II), the reduction of oxidised species (e.g. nitrate or sulfate), or the production of CH_4.
Major cations (Fe, Ca, Mg, Na, K	• Some metals may be more mobile under highly reducing conditions. May be required for compliance with secondary water-quality standards. May be used for geochemical modelling.
Major anions (HS-, NO_3^-, SO_4^{2-}, PO_4^{3-}, CO_3^{2-})	• May be used for geochemical modelling or to evaluate the potential for precipitation of minerals.

Parameter	Rationale
Sulfide	• By-product of sulfate reduction. Elevated concentrations of sulfide may inhibit dechlorinating microorganisms and may pose taste and odour problems.
Total organic carbon	• Indication of organic substrate available for biological metabolism.
Biological and chemical oxygen demand	• Secondary water-quality parameters that may also be used as an indication of substrate demand.
Nitrogen, phosphate and potassium	• Nutrients necessary for microbial growth, and biodegradation processes.
Ethane and ethene	• Presence indicates that reductive de-chlorination of chlorinated solvents are occurring.
Dissolved methane, dissolved CO2	• Indications of biological activity

2.4.6 *Assessment of micro-organisms*

Laboratory assays of micro-organisms can be used to assess the potential to transform the contaminants under expected site conditions and are likely to be an important validation tool for sites applying biodegradation or monitored natural attenuation techniques. The quantity of micro-_organisms is generally assessed through direct count methods or by culturing on specific growth media with or without selective enhancements. Species that proliferate when grown on the selected contaminant can be used to confirm the presence of suitable degraders (see Environment Agency 2010). However, this method is limited to organisms that can be cultured in a laboratory setting and is unlikely to represent the diversity of bacterial species that may be present in the soil / aquifer.

Advanced molecular techniques, such as quantitative polymerase chain reaction or phospholipid fatty acid analysis, have been developed more recently, allowing the extraction of molecular data from uncultured samples. This may provide insight into the diversity of micro-organisms present and their metabolic functionality in the contaminated media (see Environment Agency 2010).

It is noted that considerable uncertainty may arise from the wide range of pH and ORP found in groundwater systems and the resulting variety of micro- organisms that may be present. The representativeness of collected samples therefore needs to be assessed and uncertainties clearly understood before using the information to assess the natural attenuation capacity of the system. This line of evidence is therefore better suited to complement analytical and field measurements rather than as a sole means to justify natural attenuation processes at a site.

Field tests can also be used to assess biological activity at a site. For example, biochemical tests such as a field dehydrogenase test may be used to determine if aerobic bacteria capable of biodegrading petroleum hydrocarbons are present in the system and in sufficient quantities to do so.

Sampling methods to assess micro-organisms in groundwater are further detailed in the CRC CARE technical report 21: *Sampling Strategies for Biological Assessment of Groundwater Ecosystems* for further information.

2.4.7 *Geophysical survey data*

Geophysical surveying techniques (e.g. ground penetrating radar, electromagnetic terrain conductivity and seismic reflection) can identify changes in geology and hydrology, the depth to the water table, and the location of buried obstructions. The survey data are processed to produce an image of the subsurface, which can be used to reduce spatial uncertainty, although it is often affected by uncertainties in the relationship between the measured fields and physical parameters.

Applications for validation include:

- Delineation of a contaminant plume to determine whether it is shrinking;
- Confirmation of the effectiveness of a geomembrane barrier;
- Delineation of residual NAPL that potentially remains following the implementation of remediation systems;
- Verification that monitored natural attenuation is occurring (e.g. using electrical resistivity tomography); and
- Assessment of air saturation in groundwater during in-situ air sparging.

Geophysical surveys are considered better suited to assessing changes in the distribution of contaminants over time rather than determining absolute distribution, as matrix effects will not change (Environment Agency 2010).

2.5 When to discontinue validation monitoring

Validation monitoring can be discontinued when the validation criteria, and ultimately the remediation objectives, have been met. This can be demonstrated when the lines of evidence converge, i.e. when multiple lines of evidence collectively verify that the remediation method has been successful and that validation criteria have been met.

Statistical analysis of validation monitoring data is recommended to evaluate remediation performance and manage uncertainty. Statistical tools and models help in the determination of trends and will assist in evaluating whether validation criteria have been met and if the monitoring program can be discontinued. For instance, assessing the degree of change in contaminant levels between pre- and post-treatment may require a modelling procedure or established methods that can account for temporal and/or spatial data correlations (ITRC 2004).

Depending on the complexity of the site and extent of contamination, it may take several years for validation criteria to be met. Once validation criteria have been met, continued compliance monitoring may be required to ascertain that the levels are sustainable and are not subject to rebound (e.g. due to seasonal fluctuations). The duration of compliance monitoring should be agreed with stakeholders, and contaminant levels should remain below the end point for the duration (Beck & Mann

2010). Depending on the jurisdiction, the proponent may have to consult with the relevant environmental agency to confirm that they have approval to cease remediation.

3. Developing a validation plan

3.1 Overview

The validation plan documents both the validation strategy and the detailed methodology necessary to ensure adequate and appropriate sampling and analysis is undertaken so that demonstration of the remediation objectives can be justified. They are designed to characterise the post-remediation condition of a site in accordance with the site-specific DQOs. They differ from validation reports, which document the findings of the validation works, and are prepared following validation works.

Validation plans should be prepared in accordance with local jurisdictional requirements (where available). The validation plan should be scaled in accordance with the complexity of the site.

The validation plan should be developed once the DQOs have been established, and the plan should be endorsed by the regulator / auditor (as appropriate) prior to the commencement of remediation works. In many jurisdictions, the development of a validation plan occurs concurrently with the development of the RAP, and the validation plan may even be part of the RAP.

The validation plan is more likely to be a standalone document when:

- A third-party practitioner is engaged to carry out the works;
- The validation works are likely to change substantially because of the remediation works; or
- The project is large or complex.

The validation plan would typically comprise the following elements:

- Summary background information, i.e. site location, CSM and risk assessment findings prior to remediation;
- Overview of planned remediation works;
- Remediation objectives, DQOs and validation criteria;
- Roles and responsibilities;
- Validation monitoring methodology;
- Detail on the lines of evidence and compliance with validation criteria;
- Monitoring and sampling locations and the timeline of the validation program;
- Field and laboratory QA/QC procedures; and
- A contingency plan if remediation objectives are not met.

Although the NEPM does not specifically discuss validation, Schedule B2 should be referenced for guidance on the development of a sampling analysis and quality plan (SAQP).

3.2 Roles and responsibilities

The key parties involved in site contamination validation and closure are the proponents, environmental practitioners, regulators, auditors, and other stakeholders such as the community. The roles and responsibilities of each party are usually set out in the remediation plan. Accredited site auditors may be appointed to undertake an audit of the site to provide an independent opinion on whether remediation objectives have been met. The roles of auditors are stipulated by jurisdictions.

Roles and responsibilities may need to be revised, particularly on complex projects, should changes to the project occur after the approval of the remediation plan and before the implementation of validation processes. Validation sampling and/or monitoring should be carried out by the environmental practitioner or a qualified third party, and should demonstrate that the remediation technology used was adequate and the remediation objectives have been met (CSMWG 2000).

The proponent should be legally authorised to make decisions with regard to the site. The proponent may be the site owner or occupier, a representative of the site owner or occupier, a prospective purchaser, developer, planner or other person with written consent from the owner or occupier. It is typically the responsibility of the proponent to consider stakeholder interests and involve stakeholders as and when appropriate. It is also the proponent's responsibility to ensure compliance with conditions or restrictions placed on a site as part of the closure process.

The environmental practitioner developing the validation strategy should consult with the regulator (and/or auditor, if appropriate) regarding their expectations for the site, in order to make the process of achieving site closure more efficient and cost-effective. It is essential for the environmental practitioner to maintain communication with the proponent, auditor (where applicable) and regulator throughout the works. This is particularly important so that the progress of remediation and validation works, as well as potential changes to the initial remediation plan, are understood and approved prior to implementation. Practitioners should present the findings of the validation works in a validation report and demonstrate that remediation objectives have been met. If the practitioner considers that site closure is achievable, they should justify this and seek regulatory endorsement/approval.

The regulator will receive advice from the environmental practitioner and/or auditor (where applicable) in the form of a technical report and/or site audit statement or letter. The regulator (and/or auditor, where engaged) determines: when risks to the environment and human health are considered to be acceptable and therefore that it is appropriate to cease remediation; whether the presence of impacts such as non-aqueous phase liquids (NAPL) no longer pose a potentially unacceptable risk to receptors; and, where applicable (e.g. EPA Victoria), whether source removal or groundwater remediation has occurred to the extent practicable. The regulator will require all remediation works to be validated and documented in order to endorse discharging a planning condition or to confirm in the site classification that remediation has been successfully undertaken at the site.

For Commonwealth-owned airports, Airport Environment Officers will require a practitioner to complete validation works to verify that remediation objectives have been met. Consultation should be ongoing with the Airport Environment Officer during the remediation and validation process.

Stakeholders such as the general public, community and interest groups should be considered during validation and closure. In particular, the proponent should work closely with owners and occupiers of sites affected by off-site contamination. The scope and detail of stakeholder engagement will depend on the size of the project, its complexity, and the level of interest or concern expressed by the community (see WA DER 2014). Readers are directed to the NRF *Guideline for Stakeholder Engagement.*

Roles and responsibilities may change as the remediation project moves through different phases.

3.3 Validation monitoring and sampling

Validation monitoring and/or sampling should be undertaken:

- before remediation to establish a baseline;
- during remediation to assess whether milestones are being met (i.e. performance or remediation monitoring); and
- after remediation (i.e. compliance monitoring, endpoint validation monitoring/sampling) to assess whether remediation objectives have been met.

Technical and hydrogeological considerations often dictate the design of a validation plan (see ITRC 2004). Validation activities include:

- Target media;
- Target analytes;
- Monitoring / sampling locations:
  - Density;
  - Specific locations, including a site plan if required; and
  - Depths
- Suitable sampling methodology

Different source-receptor-pathway linkages may exist for the same contaminant in different phases, and all may need to be assessed to validate remediation works and achieve site closure. Details on validation sampling for different matrices (soil, groundwater, vapour, NAPL) are presented in **Appendix A**.

The rationale for the selection of sampling patterns, density, locations, depths, and samples selected for analysis should be provided in the validation plan, as well as the analytical methods and analytes chosen. The validation plan should include a detailed description of the sampling method, including sampling devices and equipment, sample handling and field screening protocols. The requirements for the frequency and duration of validation monitoring should be determined on a site-specific basis in accordance with the CSM, the remediation works undertaken and the requirements of the regulator and auditor (where applicable). The potential for contaminant rebound and other site-specific factors and seasonal effects should also be considered.

Regarding collection of samples the validation plan should identify the:

- Sampling and testing methods and equipment;
- Calibration procedures for field measurements;

- The number and type of quality assurance / quality control (QA/QC) samples to be collected and analysed; and
- Filtering, decontamination and preservation techniques.

The appropriate sampling method(s) and the rationale for its selection must be clearly specified in the validation plan.

Regarding laboratory analysis, the validation plan 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 validation plan.

The validation plan should be refined, if required, in accordance with the revised CSM following the remediation of the site. For more complex sites, numerous rounds of monitoring are typically required to establish seasonal trends and the nature and extent of contamination over time. A contingency sampling plan may be required to address alternative sampling and investigative techniques useful in addressing a situation where results are unexpected or the remediation method fails to meet compliance or performance criteria (see ITRC 2011).

Validation of simple remediation projects may comprise a single sampling round to demonstrate that all contaminated soil has been excavated or that redeposited soil meets site-specific assessment criteria.

The frequency of groundwater monitoring typically depends on contaminant type and properties, affected media and extent of contamination, local and regional hydrogeology, the sensitivity of identified receptors and the quality of existing background data. Sufficient monitoring rounds spanning seasonal variations should be conducted to characterise changes in the hydrogeological, geochemical and/or microbiological conditions.

It is emphasised that where any immediate hazards are considered to pose imminent risk (e.g. the presence of explosive vapours) at any time, these should be mitigated and validated as a priority.

The duration of validation works is contingent on the results from monitoring and sampling activities (see Beck & Mann 2010). Once validation criteria are met, or statistical analysis determines that identified impacts do not pose unacceptable risks, confirmation monitoring should continue for a period of time (as agreed by the stakeholders) to confirm and provide confidence that concentrations remain below the validation criteria. Site closure should be based on field data that demonstrate compliance with validation criteria. However, if there are sufficient robust monitoring data to complete predictive modelling, and trends indicate that it is acceptable in accordance with remediation objectives, then in some jurisdictions modelling may be applied to assess compliance with validation criteria.

If long-term monitoring is also planned at the site, it can be worthwhile to consider planning these components together, as validation activities can become the ‘baseline’ for long-term monitoring. For more information on long-term monitoring readers are directed to the NRF *Guideline on implementing long-term monitoring*.

3.3.1 *Uncertainty*

Validation sampling relies on the collection of single data points which are then analysed and perhaps modelled to demonstrate the remediation objectives have been met. 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 validation plan 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.

3.4 Quality assurance and quality control

All validation programs should incorporate robust field and laboratory QA/QC procedures, with sampling conducted to meet the parameters of precision, accuracy, representativeness, completeness and comparability, as detailed in the ASC NEPM Schedule B2 Appendix B. The following elements should be considered as part of a robust QA/QC program:

- Maintaining sample integrity through the application of correct field techniques and sample preservation through adherence to Australian Standards and industry best practice;
- Collecting intra-laboratory duplicates and inter-laboratory duplicates;
- Collecting representative samples;
- Collecting samples immediately after the excavated surface is exposed to minimise potential for the sample to degrade or volatilise;
- Using sterilised and appropriate sampling equipment, collection procedures, and containers for the type of sample and analysis to be undertaken;
- Using best practice decontamination procedures;
- Accurate sample identification and chain of custody documentation;
- Field instrument calibration;
- Appropriate storage of samples in transit; and
- Delivery and analysis within laboratory defined holding times.

QA/QC sample results should be reported and evaluated against the stated DQOs. The ASC NEPM, AS4482.2-1999 and AS4482.1-2005 should 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. These records provide evidence to justify decisions made during the site works). Readers are directed to the NRF *Guideline on documentation and record keeping* for further information.

3.5 Compliance monitoring

Lines of evidence are useful in demonstrating that the remediation objectives have been met. Section 2.4 describes several lines of evidence, including when they may be used and what information should be collected. Recommended lines of evidence to validate each of the remediation techniques are included in the NRF *Technology guides*. Section 2.5 discusses when to discontinue validation monitoring.

Approaches other than those presented in the NRF guidelines may be applied if they are adequately justified, or they are warranted due to site-specific conditions. The relevant environment agency may need to be consulted and/or provide regulatory approval prior to the implementation of these solutions.

It is noted that it is important to review the validation approach during the remediation and validation works, and periodically update relevant plans as new data come to light.

3.6 Safety and environmental management

Safety is always the priority in any remediation and validation program. The two principal health and safety factors to be considered during validation works are worker protection during site work and the safety of the general public.

There should be appropriate WHS measures in place for any personnel involved in the assessment and remediation of site contamination in accordance with applicable work health and safety legislation. Care should be taken to recognise all potential hazards before the initiation of any field work, and to prepare a health and safety plan to address and mitigate these hazards.

The NRF guideline entitled *'Guidance for Worker Health and Safety considerations'* provides further information regarding health and safety issues associated with site contamination remediation and validation.

Environmental management measures required to be implemented during the validation process should also be addressed. Potential risks to the environment (e.g. rainfall and surface water runoff causing erosion of soils, or waste management procedures), should be identified prior to validation works and mitigated appropriately.

3.7 Contingency plan

The validation plan should document the contingency plan or actions if the validation shows the remediation objectives have not been met. This should include:

- Alternatives, and how to choose between them.
- Triggers for enacting the need for a contingency; and
- Requirements of notifications to stakeholders.

A contingency plan details the response to address new or previously unidentified site conditions, and/or poor performance of a remediation system. It should anticipate risks and issues with the remediation plan and should be flexible to allow for adjustments due to new information gathered during the remediation process and validation monitoring.

The likelihood that the contingency plan will need to be implemented is minimised where appropriate and realistic remediation objectives have been developed and relevant remediation definition/treatability/feasibility studies have been carried out prior to commencing remediation. Contingency plans are more likely to be required for *in situ* remediation approaches with complex contaminants and/or geologies.

The contingency plan involves four steps:

1. Identification of risks and issues;
2. Details of triggers for the contingency;
3. Identification of solutions; and
4. Details of solution implementation.

There are two types of risk that apply to remediation; logistical risks and technology / contamination risks. Examples of both types of risks include:

- Technology / contamination risks
    - Remediation technology performs poorly
    - Contamination rebounds
    - Contamination is more widespread than anticipated
    - Validation samples do not meet validation criteria
- Logistical risks:
    - Permits are not granted
    - Specialist technology is not available
    - Specialist personnel are not available
    - Laboratory methods require an unrealistically low holding time
    - Site access is unavailable

The triggers for the contingency should be:

- Based on clear quantifiable thresholds or milestones, such as:
    - Volume of hydrocarbons extracted and treated per day
    - Indoor air COC concentrations
    - Volume of contaminated soil excavated
- Documented clearly so that site staff are aware of what parameters to be monitoring and who to notify if the thresholds are met.

Where validation indicates that remediation objectives are unlikely to be met, the remediation system may be modified, or alternatively additional remediation technologies may be implemented. Where it is considered that further remediation is impracticable, contingency plans such as long-term monitoring or institutional controls may be considered in order to achieve site closure. These scenarios are discussed in more detail below.

3.7.1 *Alternative or modified technology*

Most remediation approaches need to be progressively optimised throughout their operation. Remediation systems are installed based on the best knowledge and intentions at the outset of the remediation programme, and the initial set up may not turn out to be optimal after a period of operation. Ideally, the design and implementation of the remediation approach allows for some flexibility so that more than one approach can be utilised, as required. It is noted, however, that whilst contingency methods should be planned for and anticipated in the remediation design phase, the contingency measure(s) adopted will depend on the results of validation monitoring and the mechanism of failure, where relevant.

Unless the remediation approach has been optimised, it may be difficult to justify a claim that all technically practicable efforts have been applied to remediate the site. The remediation approach may be modified during remediation to achieve the remediation objectives, for example by:

- Targeting additional areas of a groundwater plume or other media that were not the target of initial remediation works (identified through validation monitoring);

- Varying operational modes such as periodic on/off phases to allow periods of contaminant rebound (see Lam & Moritz 2007);
- Augmenting natural attenuation processes through the manipulation of the groundwater chemistry (see Beck & Mann 2010);
- Enhancing bioremediation through the addition of nutrients, electron donors or micro-organisms; and
- Installation of a secondary barrier to capture any impacts that bypass a primary barrier.

Where remediation objectives have not been achieved, a secondary remediation approach may be required, referred to as a "step-wise remediation approach". For instance, where performance monitoring of a passive remediation method identifies that it is insufficient to achieve remediation objectives within an acceptable timeframe, an active remediation approach may need to be implemented at the site to more aggressively target identified impacts.

The implementation of a secondary remediation approach may also be useful towards the end of an initial productive phase of remediation, when returns for effort using the initial approach have decreased. Secondary remediation approaches through natural attenuation, groundwater extraction, or supplemental source treatment (such as enhanced bioremediation or in-situ chemical oxidation) may then be implemented to address any residual contamination that remains on the site (ITRC 2004). Where more than one approach is used, a series of asymptotes in the recovery rate are likely to be observed. By undertaking several attempts or approaches to achieve remediation objectives, multiple lines of evidence can be obtained to demonstrate that the practicable limit has been reached.

3.7.2 *Impracticability of further remediation*

Regulatory authorities generally recognise the difficulties involved in remediation at some sites. For example, it is rarely possible to remove all impacts from an aquifer during remediation works. This has led to concepts such as 'clean up to the extent practicable (CUTEP)', and 'technical impracticability' (TI), which acknowledge that remediation efforts need to be balanced by practical considerations and that complete removal of impacts such as NAPL are unlikely to be achieved (Johnston 2010).

Practicability encompasses the following considerations (EPA Vic 2014):

- Technical – physical ability to remove contamination within a reasonable timeframe, taking into consideration the chemical and physical properties of the COC, aquifer characteristics and the availability of technology that is capable of effectively removing the contamination from the aquifer;
- Financial – the cost of remediation, including equipment, installation, maintenance and waste treatment. Measures should be cost-effective and proportionate to the environmental issues being addressed; and
- Logistical – includes access to the site, availability of materials and infrastructure and the disposal of wastes.

EPA Victoria refers to 'a reasonable timeframe' in relation to the adequacy of interim measures to protect existing beneficial uses, whether remediation will be achieved

before contamination migrates off-site or affects beneficial uses and community views on timing and the extent of remediation.

Depending on the CSM, the sensitivity of the site, and requirements that may be imposed by the regulator, TI may be invoked following remediation pilot trials or following the implementation of a remediation strategy, when it is considered that the original remediation objectives cannot be achieved. A range of remediation approaches should be considered to determine which method(s) is most likely to achieve the remediation objectives. A regulator may require more than one remediation method to be implemented to demonstrate that remediation is not effective in the site-specific conditions. If an inappropriate method of remediation is chosen, its failure cannot be used as an indicator that clean up is not practicable. Where unacceptable risks to human health or the environment exist, these risks need to be managed and an impracticability approach is unlikely to be considered acceptable.

Additional principles that should be considered in the application of CUTEP or similar methodologies include:

- Intergenerational equity – degraded environments should not be passed down to future generations; and
- Precautionary principle – the lack of complete scientific certainty should not be used as a reason to postpone measures to prevent environmental degradation.

In consideration of the above principles regulators or auditors may, in some jurisdictions, require further remediation even though a site is not considered to pose an unacceptable risk to current receptors.

Where it has been concluded that further remediation is impracticable and the regulator and/or auditor are in agreement with this conclusion, MNA may be an appropriate approach to manage impacts that remain on the site. MNA can form part of the remediation approach prior to site validation and closure, or it can be introduced as a long-term monitoring strategy for the site following site closure. (In WA there is no site closure if long term monitoring is required – and will attract a 'remediated for restricted use' classification). Readers should refer to the NRF *Technology Guide* on MNA.

3.7.3 *Long-term monitoring*

On sites where it is considered that meeting remediation objectives is not feasible or the on-site containment of contamination is proposed, a long-term monitoring program should be considered as a contingency.

Readers are directed to the NRF *Guideline on implementing long-term monitoring* for more information.

3.7.4 *Institutional controls*

On sites where it is considered that meeting remediation objectives is not feasible or the on-site containment of contamination is proposed, the need for institutional controls should be considered as a contingency.

Readers are directed to the NRF *Guideline on implementing institutional controls* for more information.

4. Achieving and reporting site closure

Site closure is the process of obtaining approval by the regulator (and/or auditor, where applicable), if required, to cease remediation of a site because validation has demonstrated that the remediation objectives have been met. The conditions required to achieve site closure are highly site-specific.

To achieve site closure, the proponent must demonstrate to stakeholders that remediation objectives have been met. The environmental practitioner should therefore document the remediation approach, the remediation objectives and the validation program in a validation report, as well as an assessment of whether the remediated site complies with the remediation objectives for the site and any future monitoring requirements.

4.1 Demonstrating achievement of remediation objectives

The achievement of remediation objectives is often a contentious subject as it directly influences the cost of remediation. Elimination of the actual or potential risk is always the preferred option (i.e. removal of primary and/or secondary sources), however regulators and auditors recognise that some circumstances are challenging (section 3.7).

4.1.1 *Practicability*

The practicable limit of remediation is site- and jurisdiction- specific, and some key indicators which may be monitored to validate this approach and allow for site closure include the following (see Lam & Moritz 2007; CRC CARE 2015):

- Specific COC are reduced to a target value at a certain number of monitoring locations over a given period;
- An asymptotic cumulative recovery curve, which indicates that practical recovery limits are being approached;
- Declining recovery rates, demonstrated statistically, or recovery rates reduced to an established value;
- NAPL saturation at all points within the area of distribution have been reduced to levels below residual saturation, supported by at least two lines of evidence;
- Stability of a dissolved-phase plume based on a dissolved COC concentration threshold at a certain number of monitoring locations over a given period;
- A containment system meeting certain specifications has been installed and tested for integrity; and/or
- A final relative permeability value is attained.

The performance of a remediation approach needs to meet a desired target for reducing concerns associated with identified impacts.

Only the regulator, or parties with delegated authority (e.g. auditors), can determine whether remediation has been carried out to an appropriate level. Furthermore, depending on the sensitivity of the site, nature of contaminants and whether there has been off-site migration, stakeholders may need to be engaged to obtain agreement that remediation objectives have been met.

In Victoria, if the regulator and/or auditor consider it impracticable to remediate a site further, they will determine the required ongoing management measures (EPA Victoria 2014). Where an auditor determines CUTEP or an equivalent approach has been met, the auditor must notify the regulator with respect to the validation criteria used and provide an opinion as to the practicability of further remediation. Conditions restricting existing and potential future extractive uses of groundwater should be provided in the report submitted to the regulator.

4.1.2 *NAPL*

With regard to NAPL impacts, regulatory requirements vary across Australia in accordance with jurisdictional regulations:

- NSW – NAPL must be removed to the extent practicable. Where complete removal is considered impracticable, long-term monitoring and management is required as long as NAPL remains on the site (DEC NSW 2007);
- SA – NAPL must be removed to the extent practicable. An assessment of the practicability of NAPL remediation is often reliant on the outcomes of a site audit, with input from the regulator (EPA SA 2009);
- Tasmania – NAPL must be removed to the extent practicable, unless the regulator is satisfied that no unacceptable risks remain;
- Victoria – NAPL must be removed, unless the regulator is satisfied that no unacceptable risks remain to any environmental values associated with groundwater (EPA Victoria 2014a);
- WA – NAPL clean-up is required to endpoints set or agreed by the regulator, rather than to the extent practicable, to address unacceptable risks to human health, the environment and environmental values. At least two years of groundwater monitoring is required to determine whether remediation has been successful, with the regulator confirming the extent to which the remediation has been completed in the classification as ‘remediated for restricted use’ or ‘decontaminated’; and
- ACT, NT and QLD – no NAPL specific remediation requirements have been sighted.

In all Australian jurisdictions, the legislative framework for managing NAPL impacts are outcome-focused, therefore the protection of the environment is focused on remediation targets rather than prescribing what a proponent must do in order to achieve validation. The overall position is that regulators expect NAPL to be actively remediated at least to ‘the extent practicable’ (Lam & Moritz 2007). As noted previously, WA follows a more risk based approach.

4.1.3 *Ongoing site management*

Site closure may be contingent upon the development and adherence to a site management plan (SMP). An SMP documents necessary long-term site management procedures such as periodic maintenance and monitoring and procedures to be followed when carrying out intrusive works at the site (WA DER 2014, EPA Victoria 2014, QLD 2014, NSW DEC 2006). The regulator and/or auditor should be consulted in its preparation. The requirement for an SMP depends on site-specific conditions, the remediation approach utilised to remediate the site, and the regulatory

requirements in the relevant jurisdiction. In certain circumstances, residual impacts may be managed through the proposed site use, such as a requirement for a site to be fully sealed to prevent access to soils. It is noted that in some jurisdictions, if an SMP is required then the site cannot be fully closed out.

4.2 Regulatory Approval

4.2.1 *General requirements*

State regulators will typically only be involved in the site closure process where there is significant risk of harm or the site is very complex (an exception is WA, where the regulator should be involved in all site validation and closure decisions). Local governments will regulate sites that are changing zoning/land use via the development application or planning process, however in these situations an auditor will often be engaged to undertake the approval role via a planning condition.

Auditors are commonly engaged to 'sign-off' on sites to verify that investigation and remediation works have been undertaken in accordance with legislation and any residual impacts are not considered to pose an unacceptable risk to human health or the environment.

Typically, validation criteria must be met for the regulator to discharge any regulatory notices or conditions placed on a site. It is noted that some sites may require consideration by more than one regulatory agency, e.g. a large plume affecting potable quality groundwater may be of interest to both environmental protection and water resource regulators.

There are generally two ways in which to achieve site closure:

- the regulatory agency and/or auditor agrees that the site does not pose an unacceptable risk to human health and the environment and/or regulatory compliance has been met, and therefore site closure can be achieved in an absolute sense; or
- the remediation objectives have been met, however there is some ongoing or residual impact that requires attention and the site is placed in a long-term management program.

If remediation objectives have been met, the site closure process may go through a period of monitoring followed by decommissioning of the sampling well locations, where applicable. Decommissioned monitoring infrastructure must be properly sealed, to mitigate the potential for vertical migration and hence contamination of aquifers.

4.2.2 *Commonwealth owned airports*

For Commonwealth owned airports, if a Preliminary Site Investigation or monitoring indicates that the triggers in any of the Schedules of the Airports (Environment Protection) Regulations 1997 are exceeded, an Airport Environment Officer may require an Independent Assessor (Auditor) to be engaged. After a remediation plan has been approved the AEO will oversee the remediation process and be involved in the closure process. The AEO must be provided with biannual reports and an additional report prior to the occupant ceasing occupation.

4.3 Reporting

The sections and general content which are recommended to be included within a validation report are presented in **Table 3**.

Table 2: Recommended content for a validation report

Report section	Content
Background	• site identification, including the address, lot number and geographic coordinates of the site and a current site layout plan • a summary of the site history, including relevant former contaminative land uses • a summary of the site condition and surrounds, including local topography, geology, hydrogeology, presence of waste material and fill, presence of any sensitive environmental receptors and flood potential • summary of previous investigations and results, with site plans depicting sample locations and exceedances of criteria (depending on state-specific guidance, one may be able to refer to the remediation plan)
Remediation scope	• clear statement of the scope of work • reasons and objectives for undertaking remediation • a summary of the remediation plan, including an evaluation of remediation options and rational for selected option • remediation objectives and criteria • site contamination audit details, where applicable • sequence of activities during the remediation program, including any deviations from the plan. Works must be documented in detail, i.e. volumes and characteristics of material or liquid waste treated or disposed, design of encapsulations or permanent treatment installations, etc. • plans showing areas remediated, any areas of residual contamination or subsurface structures, as well as photographic records • documentation of compliance with regulatory requirements set by the regulatory authority and local government • health and safety issues

Report section	Content
Validation strategy and results	• rationale and justification for the validation strategy • a sampling and analysis plan and sampling methodology, including the DQOs used • field and laboratory QA/QC procedures • figures depicting monitoring locations, borelogs and site photographs, where applicable • assessment criteria including rationale and assumptions • validation sampling and monitoring results, details of statistical analysis of results and assessment against validation criteria
Final site conditions	• description of site conditions at the completion of remediation works, with an updated CSM for the site • data set of the entire site, including all data collected for media that remains on site, both from site assessment and validation. • implications of final site condition on the future use of the site • assessment of the extent to which remediation objectives have been met
Regulatory conditions and permits, where relevant / applicable	• verification that regulatory conditions (eg licence) and permits applying to the site have been adhered to. • location and volume of treated materials and evidence of conformance to requirements of discharge consents and abstraction licences • disposal of soil off-site is in accordance with the remediation plan, such as copies of consignment and waste carrier notes for materials being taken to landfill • Results of nuisance monitoring at site boundaries and other agreed locations (e.g. dust, noise, odour)
Recommendations	• Make suggestions in relation to any conditions to be placed on the site and any ongoing monitoring requirements, where applicable, including details of the parties responsible and ongoing site and equipment maintenance. • Where groundwater impacts are present (on- and off-site), impacts upon potential future land uses should be discussed.

Further information on reporting is presented in the *NRF Guidelines for Documentation, record keeping, and reporting.*

Appendix A – Validation sampling for each matrix

Soil

The soil validation program will typically comprise soil sampling, analysis and a statistical assessment against adopted validation criteria. Validation soil sampling may also be undertaken to:

- Derive estimates of in-situ contaminant mass to compare the total mass before and after remediation;
- Estimate rates of reaction or degradation; or
- Validate the quality of soils imported to a site.

Soil sampling programs should identify and delineate the lateral and vertical extent of any contamination with a statistically valid data set. The soil sampling strategy will be driven by the:

- Identified COC;
- Potential source(s) and pathway(s), including:
  - Secondary source zones;
  - Sub-surface utilities;
  - Permeable media installed during remediation works
- Remediation objectives;
- Validation criteria; and
- Statistical method used to assess the data.

The soil sampling strategy should define the:

- Sampling pattern – grid sampling (random, stratified, systematic) and/or judgemental sampling;
- Sampling method – discrete or composite samples; and
- Timing of soil sampling, including intervals where more than one round of sampling is proposed.

Table 4 below provides additional information to consider when preparing a soil validation strategy

Table 3: Information to consider when preparing a soil validation strategy

Consideration	Information
Number of samples to collect	In determining the number of soil samples to be collected, consideration should be given to the: • Heterogeneity of the material; • Reliability in terms of QA/QC measures; • Density of sampling required for statistical methods; • Density of sampling required to meet regulations.
Discrete or composite sampling	Composite sampling is not suitable for: • Clay or fine-grained soils as it is difficult to mix the subsamples adequately; • Volatile COC It is noted that for composite sample results, validation criteria need to be divided by the number of composites taken to avoid the potential for elevated concentrations in some samples being diluted by low concentrations in others.
Method	• Shallow soil samples are generally obtained from test pits and trenches or from augers, whilst deeper soil samples are generally obtained using a range of drilling methods. • Direct-push methods are frequently used to sample soils as they provide largely undisturbed samples. Segments of the borehole can be cased off to protect uncontaminated zones by driving larger diameter surface casing to the necessary depth. • Wash rigs and mud rotary methods may displace potential impacts ahead of the drill bit due to the delivery and recirculation of drilling fluids through the stem. • The use of air to evacuate cuttings from around the drill bit will result in the loss of vapours at sites where the COC are volatile. • Sonic drill rigs are an alternative method for continuous sampling and provide a large volume of core for sampling. It should be noted that soils are sometimes compacted vertically whilst drilling and may therefore result in a vertically averaged (and perhaps lower) concentration.

Consideration	Information
Repeatability	• Soil sampling is inherently destructive, and once a sample is obtained from a location, subsequent sampling must be made in a new location (that may or may not be impacted in the same way). • If the goal is to assess performance of a remediation technology, it is difficult to obtain a direct comparison of conditions before and after treatment. Therefore, the validation plan should consider that observed changes in contaminant concentrations may be attributable to the redistribution of mass during the remediation process rather than the treatment itself, and account for this in the DQO process.
Underground storage tanks	When underground storage tanks are decommissioned, abandoned or removed, regulations typically require validation works to establish that the site is suitable for continued use. • The tank pit can be validated through the collection of soil samples from the walls and base of the tank pit once the tank has been decommissioned and removed. • Validation of the tank pit alone, however, may not comply with regulations, as the area potentially influenced by contamination may extend across a site and even off site. As a result, validation should consider preferential pathways such as cracks and fissures, and pathways where the hydrocarbon acts as a solvent, as well as other potentially contaminating factors beyond the tank pit, including leaking pipework and workshop activities. • For tanks decommissioned in situ, for instance when their removal is impractical or will affect other structures, validation sampling should be carried out in the surrounding soils as close to the tank pit as practicable whilst adhering to safe working practices. In these instances, validation reporting should include a site drawing with the size and location of all equipment and associated infrastructure remaining on the site, so that this information is readily available to current and future owners or occupiers of the site.
Volatile COC	The loss of volatiles should be minimised through: • Collecting samples with minimal headspace; • Leaving the core intact and sealing it to send directly to the laboratory or using ‘Encore’ type samplers. Further information on the sampling of volatile contaminants can be found in ‘AS4482.2-1999: Guide to the Sampling and Investigation of Potentially Contaminated Soil, Part 2 – Volatile Substances’.

Groundwater

The validation of groundwater typically requires monitoring at locations within and around a contaminant plume to determine changes to contaminant concentrations and/or plume extent over time.

The objectives of groundwater monitoring for site validation purposes are typically to:

- Delineate the extent of remaining impacts;
- Understand the life cycle of remaining impacts; and
- Collect the required evidence to demonstrate compliance with validation criteria.

A groundwater sampling and monitoring program for validation purposes typically aims to demonstrate one or more of the following:

- Concentrations of COCs are below the nominated validation criteria and/or a reduction in mass flux/mass discharge has been demonstrated;
- The remaining impacts do not pose an unacceptable risk to human health or the environment;
- Clean up to the extent practicable has occurred (in jurisdictions where this approach is followed); and/or
- The mass of dissolved phase contaminants is degrading, demonstrated through monitored natural attenuation.

Table 5 below provides additional information to consider when preparing a soil validation strategy.

Table 4: Information to consider when preparing a groundwater validation strategy

Consideration	Information
GWMW network	The groundwater monitoring well network should allow for the three-dimensional delineation of impacts in groundwater. Whilst the number of monitoring wells required to achieve this are site-specific, a larger number of wells are typically required in heterogeneous anisotropic groundwater systems than in homogeneous isotropic groundwater systems. Monitoring wells within the source zone can be used to demonstrate its depletion because of remediation activities and to estimate the quantity of residual source mass that remains following remediation. Wells may also be installed at compliance points (i.e. near receptors or the site boundary), as appropriate for the CSM and the defined validation criteria. Groundwater samples should be collected up-gradient and down-gradient of the remediation system, where applicable, to understand background conditions and evaluate the impacts of the system. If DNAPL is present at the site groundwater sample locations should also consider potential impermeable strata dip directions that may affect the direction of DNAPL migration.
GWMW design	Groundwater monitoring well design, including the depth and length of the screened interval, should be carefully selected and requires a detailed understanding of the CSM and an appreciation of the DQOs and specific monitoring needs of the validation works. Generally, screen lengths should not exceed 3m. Shorter well screens are generally preferred as they allow sampling of discrete portions of a formation and reduce the excessive dilution of samples that may occur when using longer screens.
Frequency of monitoring	Groundwater monitoring may be required on a quarterly basis for several years to evaluate seasonal variation, which may decrease to annual monitoring once the variation is understood. Monitoring should additionally account for the potential 'rebound' of contaminants following the temporary shut-down of pump and treat and soil vapour extraction technologies.

Consideration	Information
Sampling methodology	Monitoring wells should be purged prior to sample collection so that the collected samples are representative of in-situ groundwater conditions that exist in the portion of the aquifer being sampled. To minimise changes to geochemistry and the physical properties of the sample (such as turbidity), low-flow submersible or positive-displacement pumps that can control flow rates are recommended for purging and sampling. Groundwater elevation should be measured in each well in each monitoring round to enable the determination of the groundwater flow direction and rate.

Vapour

The vapour validation program will typically comprise vapour sampling, analysis and an assessment against adopted validation criteria. Vapour validation needs to demonstrate, where applicable, that:

- Concentrations of the COCs are below the nominated validation criteria; and/or
- Concentrations of the COCs do not pose an unacceptable risk to human health or the environment.

Table 6 below provides additional information to consider when preparing a vapour validation strategy:

Table 5: Information to consider when preparing a vapour validation strategy

Consideration	Information
Location	Vapour monitoring for validation purposes will typically comprise the monitoring of one or more of the following locations: • Vadose zone of the subsurface through the installation of temporary or permanent vapour wells; • Sub-slab monitoring through drilling a core through the slab of the building and installing a temporary or permanent probe; or • Indoor air or crawl space monitoring. It should be noted that indoor air and crawl space monitoring can be contentious due to the presence of confounding factors such as cleaning products, cigarette smoke, paints, air fresheners and other products which emit VOCs. At sites with hydrocarbon impacts, crawlspace and indoor air sampling should occur near the centre of the slab, where less oxygen will be present in underlying soils and hence biodegradation will be less active. When an indoor air or crawl space sample is collected, it is important to simultaneously collect a background air sample outdoors in the near vicinity for comparison purposes.
Passive or active	Vapour sampling can be active or passive. Active sampling involves the use of summa canisters, thermal desorption tubes or tedlar bags, and should be preceded by a leak test and purging of the probe and sample train. Individual connectors and tubing should be dedicated to each sample to prevent cross-contamination. Passive sampling typically comprises the diffusion of a contaminant into a sampler and onto an adsorbent, with analysis yielding a mass rather than a concentration as the amount of gas that passed through the sampler is unknown. Indoor air sampling can additionally occur with passive samplers that are hung within the breathing zone (1.2 m - 1.8 m in height) and operate through diffusion or through more novel technologies such as the dynamic active flux chamber.

Consideration	**Information**
Active monitoring point construction	Vapour wells should be installed in boreholes with a diameter ranging from 2.5 cm to 20 cm, created with hand-augers, direct-push methods or rotary drill-rigs. Depths of at least 1 m are recommended so that samples are not affected by ambient air. Thick- walled Teflon or nylon tubing should be used to avoid leakage over time, and a competent seal should be installed to prevent ambient air from infiltrating into the soil vapour sample.
Laboratory analytical suite	In addition to the COCs, vapour validation sampling should consider the following analytes as they indicate the likelihood of the hydrocarbon-derived vapours biodegrading amongst other factors: • Oxygen; • Carbon dioxide • Methane; • Hydrogen sulphide; and • Sulfur dioxide levels.
Daughter products	In addition to considering the volatility of primary COC, potential by-products that may be formed because of remediation activities should be accounted for and monitored where there is potential for vapour generation. For example, at sites with chlorinated solvents their dechlorination results to daughter by-products that are more soluble and potentially pose a greater risk to human health and the environment than the primary COC. Vapour monitoring of these constituents may be a necessary component of validation.
Rebound	Rebound of source contamination may occur following or during remediation, and this rebound may not be immediate depending on the geology and the nature of the contamination. This rebound may also occur in vapour concentrations, so validation must show that either rebound has not occurred, or that rebound has occurred and been remediated. Where the remediation solution comprises a barrier or venting system to prevent soil vapours from entering a property, validation should clearly comprise an assessment of the integrity of this system (and potentially indoor air concentrations) rather than soil vapours.

Consideration	**Information**
Modelling	A site-specific vapour model such as the Johnson & Ettinger model or BioVapor can be used to estimate the likely maximum concentrations of vapour that a receptor may be exposed to. It is noted that a limitation with vapour data analysis is the high variability, both temporally and spatially, in in-situ vapour concentrations. Additionally, changes may not be the result of remediation efforts, rather they may be attributable to rate-limited processes and dilution effects.

NAPL

Remediation of sites with NAPL can be extremely challenging, from a technical, logistical, financial, and an environmental perspective.

Technical challenges to NAPL removal arise due to the:

- Specific behaviour and distribution of NAPL in porous materials;
- Heterogeneity of soils and aquifers; and
- Difficulties of measuring the distribution of NAPL in the subsurface.

As mobile NAPL is recovered it becomes increasingly difficult to recover the remaining mobile NAPL. As it is extremely difficult to remove all NAPL contamination from a site, approaches such as CUTEP and similar have been developed.

Depending on site conditions and regulatory requirements, NAPL validation sampling and monitoring need to demonstrate that:

- NAPL are no longer present or have been cleaned up to the extent practicable; and
- The NAPL plume is no longer expanding.

LNAPL

The state of residual LNAPL contamination and the performance of the remediation technology can be validated through several means, some of which are outlined in Table 7 below. Reader are directed to refer to CRC CARE technical report 34: *A practitioner's guide for the analysis, management and remediation of LNAPL*. One of these measures alone is unlikely to be sufficient for validation purposes; they are included here as performance indicators which, combined with other factors may be used to demonstrate compliance with remediation objectives.

Table 6: Measurement techniques to validate LNAPL remediation performance

Metric	Performance Indicator	Measurement technique
LNAPL saturation	• Spatial distribution in LNAPL saturation	• Aquifer sampling; • Partitioning tracer tests
LNAPL mobility	LNAPL • Flow rates; • Pressure gradients; • Transmissivity; • Viscosity; and • interconnectedness	• Bail-down tests; • Pressure gradients: • Thickness in monitoring wells; • Tracer tests; • Sampling and analysis .
Presence of LNAPL and composition	• Presence of immobile or entrapped LNAPL; • Concentrations of COCs.	• Aquifer sampling; • Partitioning tracer tests; • Sampling and analysis.
LNAPL flux	• Change in LNAPL and constituent mass flux	• Measurements from recovery pumps and operating units

Metric	Performance Indicator	Measurement technique
LNAPL volume	• LNAPL volume in a given area	• Aquifer sampling; • Partitioning tracer tests; • Thickness in monitoring wells
LNAPL properties	Changes to • Density; • Viscosity; or • Interfacial tensions	• Sampling and analysis.
Dissolved constituents	• Concentration and mass flux of constituents dissolved in groundwater	• Sampling and analysis.
VOCs originating from LNAPL	• Vadose zone VOC concentrations and fluxes	• Soil vapour sampling and analysis

The natural endpoint for LNAPL remediation is typically for the LNAPL to be reduced to residual and entrapped saturations in the aquifer. At this stage, LNAPL would typically be absent from wells screened across the water table, however some remediation objectives may allow LNAPL to continue to appear in screened wells when there is limited transmissivity or potential to spread.

Whilst the presence and thickness of LNAPL in monitoring wells provides useful information in validating remediation works, it is noted that this information is often interpreted incorrectly. For example, the absence of LNAPL in a monitoring well does not necessarily mean that LNAPL is not present at that location, as the thickness and presence of LNAPL is dependent upon changes in water table elevation and whether impacts are captured within the depth range of the well screen. During high water tables, there is potential for no LNAPL to be observed in a well, therefore a decrease in the measured LNAPL thickness does not necessarily indicate that the remediation methodology is working. Similarly, an increase in the thickness of LNAPL in a well can also be related to changes in water table elevation and does not necessarily indicate that the remediation technology is not working. Moreover, the thickness of LNAPL measured in a well is not necessarily proportional to the recoverable quantity of LNAPL, as the product may be in areas of lower hydraulic conductivity (i.e. silts and clays with low transmissivity). It is therefore important to interpret LNAPL thickness changes in time relative to fluctuating water table elevations and other confounding factors. Where LNAPL is associated with an unconfined aquifer, it is generally accepted that the best indication of the spatial distribution of LNAPL is during the lowest water table conditions (when the greatest thicknesses of NAPL would be measured in the well). It is noted that the absence of a sheen is not sufficient to indicate the complete removal of NAPL, as residual saturation NAPL may remain in the subsurface.

DNAPL

DNAPL impacts are generally considered more difficult to remediate and to monitor for validation purposes. As detecting DNAPL at a site is often difficult, validation will most

often comprise the monitoring of groundwater, vapour and/or soil. High concentrations of dissolved phase constituents (typically taken to be equal to aqueous concentrations >1% of the DNAPL solubility are generally used to indicate DNAPL presence. Moreover, the validation process may assess the following:

- Soil, groundwater and/or vapour concentrations in collected samples to assess whether validation criteria have been met (as applicable);
- The mass of DNAPL, vapour, and groundwater extracted;
- The mass of DNAPL degraded in-situ, through the measurement of appropriate indicators and the increase of by-products;
- The mass of DNAPL remaining, through the analysis of soil cores and tracer tests;
- Decrease in toxicity, through contaminant analysis of soil cores and groundwater samples;
- Decrease in mobility, with DNAPL saturation demonstrated through soil core analysis and tracer tests; and/or
- Decrease in plume loading, by measuring mass flux. Contaminant mass remaining within a DNAPL source zone is typically calculated from soil core data by multiplying the contaminant concentration in a soil sample by the density of the soil and the source zone volume. Contaminant mass reduction is then estimated by comparing the baseline mass with that estimated after remediation. The method assumes that the volume and density of the media is known and that these properties are homogeneous throughout the source zone. Interpretation in fractured media may be difficult as the NAPL will be concentrated in small volumes of fractures, typically not evenly distributed in the core.

Appendix B – References

ALTENBOCKUM & KRAFT, 2001, *Site specific validation of soil vapour extraction: Experiences and new strategies in Germany*, Presented at NATO/CCMS pilot study meeting: Evaluation of demonstrated and emerging technologies for the treatment of contaminated land and groundwater, Liege, Belgium.

ASTM, 1998, *Standard guide for remediation of ground water by natural attenuation at petroleum release sites*, E1943-98, American Society of Testing and Materials, West Conshohocken, PA.

CANADA CSMWG, 1999, *A Federal approach to contaminated sites*, Government of Canada, Contaminated Sites Management Working Group, Ottawa, Canada.

CCME, 1994, *Subsurface assessment handbook for contaminated sites*, Report no. CCME EPC-NCSRP-48E, Canadian Council of Ministers of the Environment, Canada.

CRC CARE, 2010, *The Australian experience: A comparative analysis of the effects of contamination and its remediation on individuals and communities at two Australian sites*, CRC CARE Technical Report no 17, CRC for Contamination Assessment and Remediation of the Environment, Adelaide.

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.

CRC CARE, 2012, *Developing a national guidance framework for Australian remediation and management of site contamination: Review of Australian and international frameworks for remediation*, CRC CARE Technical Report no 22, CRC for Contamination Assessment and Remediation of the Environment, Adelaide.

CRC CARE, 2012, *Sampling strategies for biological assessment of groundwater ecosystems*, CRC CARE Technical Report no 21, CRC for Contamination Assessment and Remediation of the Environment, Adelaide.

CRC CARE, 2013, *Petroleum hydrocarbon vapour intrusion assessment: Australian guidance*, CRC CARE Technical Report no 23, CRC for Contamination Assessment and Remediation of the Environment, Adelaide.

CRC CARE, 2015, *A practitioner's guide for the analysis, management and remediation of LNAPL*, CRC CARE Technical Report no 34, CRC for Contamination Assessment and Remediation of the Environment, Adelaide, Australia.

CRC CARE, 2016, *Flux-based groundwater assessment and management*, CRC CARE Technical Report no 37, CRC for Contamination Assessment and Remediation of the Environment, Newcastle.

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.

EPA VICTORIA, 2016, *The cleanup and management of polluted groundwater*, Publication 840.2, Victoria Environment Protection Authority, Carlton.

HIRSCH & HELSEL, 2002, *Statistical methods in water resources; Techniques of water*

resources investigations, United States Geological Survey, Available at: https://pubs.usgs.gov/twri/twri4a3/.

ITRC, 2004, *Strategies for monitoring the performance of DNAPL source zone remedies*, Report no. DNAPL-5, United States Interstate Technology and Regulatory Council, Dense Nonaqueous-Phase Liquids 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, 2009, *Evaluating LNAPL remedial technologies for achieving project goals*, LNAPL-2, United States Interstate Technology Regulatory Council, LNAPL Team, Washington, DC.

ITRC, 2011, *Development of performance specifications for solidification/stabilisation*, Report number S/S-1, Interstate Technology and Regulatory Council, Solidification/Stabilisation Team, Washington, D.C.

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

ITRC, 2011, *Permeable reactive barrier: Technology update (PRB-5)*, Interstate Technology and Regulatory Council, PRB: technology update team, Washington, D.C.

LOPEZ-MESA, CARRABRANTS, VAN DER SLOOT & KOSSON, 2008, Comparison of the release of consituents from granular materials under batch and column testing, *Journal of Waste Management,* Vol. 28(10)**,** pp 1853-1867.

NSW DEC, 2007, *Contaminated sites: Guidelines for the assessment and management of groundwater contamination*, DEC 2007/144, New South Wales Department of Environment and Conservation, Sydney.

NSW DECCW, 2010, *UPSS technical note: Decommissioning, abandonment and removal of UPSS*, New South Wales Department of Environment, Climate Change and Water, Sydney.

NSW DECCW, 2010, *UPSS technical note: Site validation reporting*, New South Wales Department of Environment, CLimate Change and Water, Sydney.

NSW EPA, 2014, *Best practice note: Landfarming*, New South Wales Environment Protection Authority, Sydney.

NSW EPA, 2014, *Technical note: Investigation of service station sites*, New South Wales Environment Protection Authority, Sydney.

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

OSWER, 2002, *Elements for effective management of operating pump and treat systems*, EPA/542/R-02/009. OSWER 9355.4-27FS-A, United States Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C.

OSWER, 2013, *Introduction to in situ bioremediation of groundwater*, EPA/542/R-13/018, United States Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C.

QLD DEHP, 2014, *Contaminated land assessment guideline*, Queensland Department of Environment Heritage and Protection, Brisbane.

SA EPA, 2014, *Guidelines for the assessment and remediation of site contamination*, 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, 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, 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.

UK EA, 2012, *Treating waste by thermal desorption: An addendum to S5.06*, 382_12 - Guidance, United Kingdom Environment Agency, Bristol.

US ACE, 2014, *Environmental quality design: In situ thermal remediation*, Engineer Manual EM 200-1-21, United States Army Corps of Engineers, Washington, DC.

US DOD, 2013, *United Facilities Guide Specification: Soil washing through separation/solubilization*, UFGS-02-54-23, United States Department of Defence, Washington, DC.

US EPA, 1999, *Monitored natural attenuation of chlorinated solvents*, EPA 600/F-98/022, United States Environmental Protection Agency, Washington, D.C.

US EPA, 2000, *Data quality objectives process for hazardous waste site investigations. EPA QA/G-4HW*, EPA 600/R-00/007, United States Environmental Protection Agency, Washington, D.C.

US EPA, 2002, *Guidance on choosing a sampling design for environmental data collection, for use in developing a quality assurance project plan. EPA QA/G-5S*, EPA 240/R-02/005, United States Environmental Protection Agency, Washington, D.C.

US EPA, 2006, *Guidance on systematic planning using the data quality objectives process. EPA QA/G-4*, EPA 240/B-06/001, United States Environmental Protection Agency, Washington, D.C.

US EPA, 2009, *Statistical analysis of groundwater monitoring data at RCRA facilities*, EPA530-R-09-007, United States Environmental Protection Agency, Washington, D.C.

VAN DER SLOOT & DIJKSTRA, 2004, *Development of horizontally standardised leaching tests for construction materials: A material based or release based approach? Identical leaching mechanisms for different materials*, ECN-C-04-060, Dutch Ministry of Housing, Spatial Planning and the Environment, The Netherlands.

WA DEC, 2009, *Contaminated sites management series - Contaminated sites auditors: Guidelines for accreditation, conduct and reporting*, Western Australia Department of Environment and Conservation, Perth.

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.

WA DOH, 2009, *Guidelines for the assessment, remediation and management of asbestos-contaminated sites in Western Australia*, Western Australia Department of Health, Perth.