CRC for Contamination Assessment and Remediation of the Environment

National Remediation Framework

Guideline on performing remediation options assessment

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.

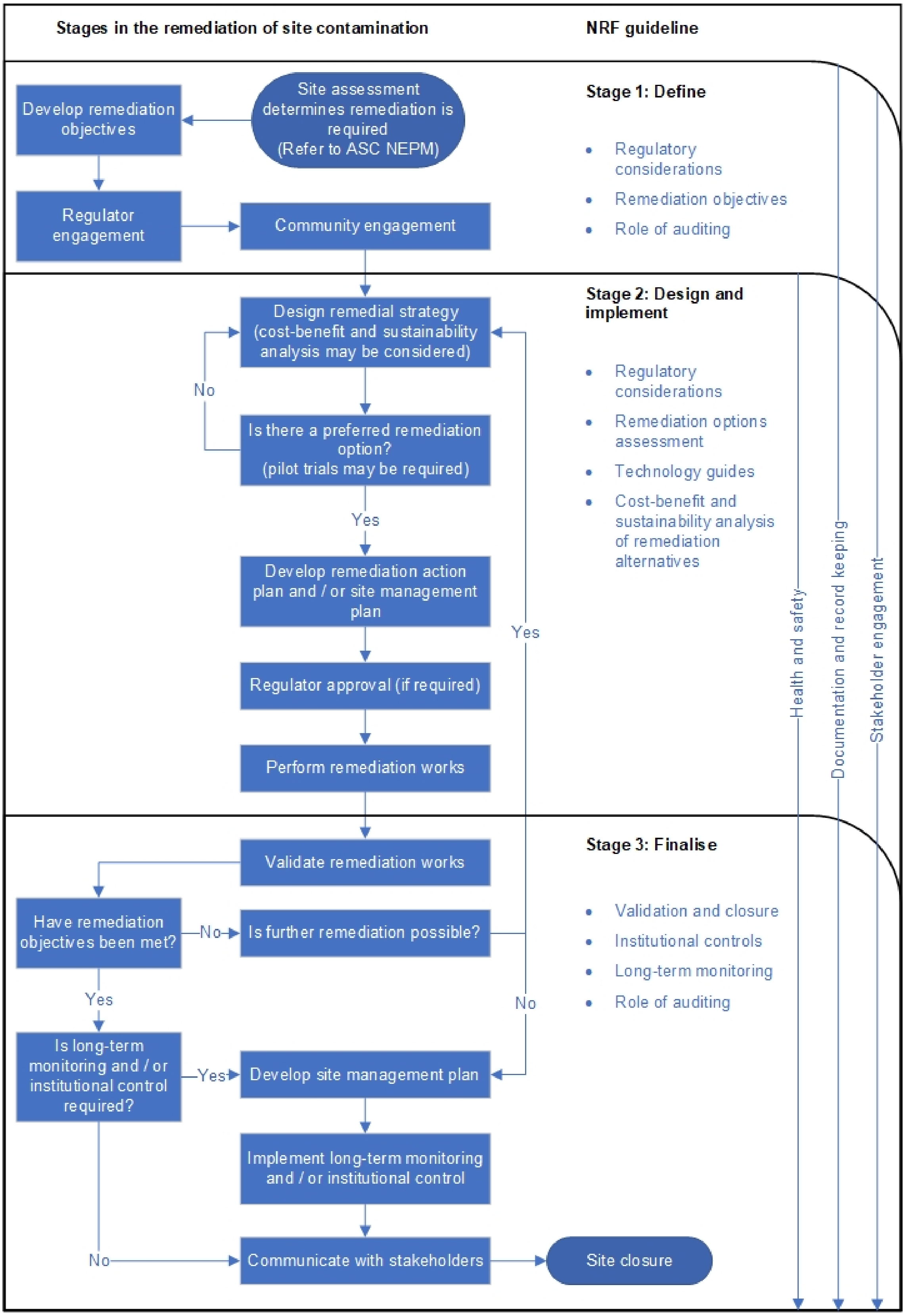
The NRF is intended to be consistent with local jurisdictional requirements, including State, Territory and Commonwealth legislation and existing guidance. To this end, the NRF is not prescriptive. It is important that practitioners are familiar with local legislation and regulations and note that **the 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
Develop remediation objectives
Site assessment determines remediation is required (Refer to ASC NEPM)
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
Yes
Stage 2: Design and implement
Regulatory considerations
Remediation options assessment
Technology guides
Cost-benefit and sustainability analysis of remediation alternatives
Health and safety
Documentation and record keeping
Stakeholder engagement
Validate remediation works
Have remediation objectives been met?
No
Is further remediation possible?
Yes
No
Is long-term monitoring and / or institutional control required?
Yes
Develop site management plan
Implement long-term monitoring and / or institutional control
No
Communicate with stakeholders
Site closure
Stage 3: Finalise
Validation and closure
Institutional controls
Long-term monitoring
Role of auditing

Executive summary

The selection of remediation technology is important to the success of the remediation project. Remediation will be required where a risk assessment has concluded that contamination poses an unacceptable risk to a receptor. All valid source-pathway-receptor link should be clearly illustrated in a conceptual site model.

The remediation technologies considered in this document are listed below, although the principles apply to other technologies and management strategies:

Soil:

- Containment
- Chemical immobilisation and solidification
- Bioremediation
- Soil washing
- Thermal desorption
- Excavation (and disposal)
- Soil vapour remediation

Groundwater:

- In Situ Air Sparging
- In Situ Chemical Oxidation (and surfactant enhanced in situ chemical oxidation)
- Skimming systems
- Monitored natural attenuation
- Barrier systems (permeable reactive barriers and cut off walls)
- Pump and treat

The first stage of developing a remediation strategy and remediation action plan is to establish clear and measurable remediation objectives and remediation criteria (clean up levels); these will form the requirements against which remediation options are assessed.

The next stage of the remediation options appraisal is to select technology and management options, or combinations of options, that have the potential to reduce contaminant concentrations and apply management controls as necessary so that the remediation objectives are achieved and no unacceptable risk is posed by the contamination in the context of the proposed site use. If there is only one viable option to meet the remediation objectives, it may be possible to formulate the RAP on completion of the preliminary options appraisal, though additional assessment of the components of the option taking into account site-specific data is often required to enable the design of the remediation program.

Where several viable options have been identified, a detailed appraisal of each of the options will be required to determine which option will most adequately and sustainably meet the remediation objectives.

Abbreviations

ASC NEPM	National Environment Protection (Assessment of Site contamination) Measure 1999 (amended 2013)
CB&SA	Cost-Benefit and Sustainability Analysis
CBA	Cost-Benefit Analysis
CRC CARE	Cooperative Research Centre for Contamination Assessment and Remediation of the Environment
MCA	Multi-Criteria Analysis
NRF	National Remediation Framework
ROA	Remedial Options Assessment
SMART	Specific, Measurable, Achievable, Relevant, Timebound

Glossary

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.
Cost-Benefit Analysis (CBA)	An economic evaluation technique used to estimate the net worth to society of a project, program or policy involving evaluating the costs and benefits in dollar terms. That is, costs and benefits are expressed as far as possible in money terms and hence are directly comparable with one another.
Cost-Benefit and Sustainability Analysis (CB&SA)	An economic evaluation technique that combines elements of CBA and MCA evaluation. Impacts that can be readily monetised are assessed as part of a standard CBA, while those impacts that can only be quantified are assessed as part of a standard MCA. The results of the CBA and MCA are then combined and assessed to allow for the identification of the most economically and sustainably preferred option.
Decision-maker	A specific person who has decision making power for one or more aspects of the remediation project. For example a financial manager who approves the budget, a regulator who approves a particular methodology, or a community representative that accepts a risk mitigation strategy. All decision makers are

	stakeholders, but not all stakeholders are decision makers.
Environment(al) protection authority / agency	The government agency in each state or territory that has responsibility for the enforcement of various jurisdictional environmental legislation, including some regulation of contaminated land.
Ex-situ	A Latin phrase that translates literally to "off site" or "out of position". It refers to remediation that is performed on the contamination following removal, usually the excavation of soil.
Groundwater	Water stored in the pores and crevices of the material below the land surface, including soil, rock and fill material.
In-situ	A Latin phrase that translates literally to "on site" or "in position". It refers to remediation that is performed on the contamination while it is in place, without excavating soil.
Off-site	Physical area outside of the site boundary. Includes air, soil, water and groundwater, both above and below ground.
On-site	Physical area inside the site boundary. Includes air, soil, water and groundwater, both above and below ground.
Practitioner	Those in the private sector professionally engaged in the assessment, remediation or management of site contamination.
Proponent	A person who is legally authorised to make decisions about a site. The proponent may be a site owner or occupier or their representative.
Remediation	An action designed to deliberately break the source-pathway-receptor linkage in order to reduce the risk to human health and/or the environment to an acceptable level.
Remediation objective	A site-specific objective that relates solely to the reduction or control of unacceptable risks associated with one or more pollutant linkage.
Risk	The probability that in a certain timeframe an adverse outcome will occur in a person, a group of people, plants, animals and/or the ecology of a specified area that is exposed to a particular dose or concentration of a specified substance, i.e. it depends on both the level of toxicity of the substance and the level of exposure. ‘Risk’ differs from ‘hazard’ primarily because risk considers probability.

Site	A parcel of land (including ground and surface water) being assessed for contamination, as identified on a map by parameters including Lot and Plan number(s) and street address. It is not necessary for the site boundary to correspond to the Lot and Plan boundary, however it commonly does.
Stakeholder	An individual, group, organisation or other entity that may be interested in, or affected by, the remediation and management of a contaminated site. Depending on specific site circumstances, stakeholders may include residents, site owners, public health officials, government regulatory authorities, media, businesses working on site, and environmental or other action/interest groups, as well as site owners and people working on the project. Stakeholders may or may not be directly involved in the project but do include all those who may have knowledge of or views about the project. Not all stakeholders are necessarily decision makers.
Sustainability	Generally, refers to achieving a balance between meeting the needs of the present without compromising the ability of future generations to meet their own needs. In specific reference to the remediation of site contamination, sustainability refers to achieving an acceptable balance between the impacts of undertaking remediation activities and the benefits those activities will deliver in terms of the environmental, economic and social indicators relevant to the site.
Treatability studies	A series of tests designed to ascertain the suitability of the treatment for the contaminants under the site conditions

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1. Introduction

Remediation options assessment (ROA) is important to the success of the remediation project. This document provides guidance to assist remediation practitioners and regulators with the preliminary remediation options appraisal process to select technologies that may be suitable for the remediation of particular contaminated sites.

This guideline is intended to assist the reader with conducting a preliminary remediation options appraisal and identifying remediation technologies (or management solutions) that could potentially treat the contaminants of concern or break identified pollutant linkages at the site under investigation. This builds on the approach outlined in the NRF *Guideline on establishing remediation objectives* and provides advice on the identification and selection of remediation options that will meet the objectives, and in formulating a remediation action plan (RAP). The terminology adopted for these plans varies across each jurisdiction, but the overall process is consistent. Jurisdiction-specific terminologies for RAP include: environmental management Plan (EMP) or site remediation plan (SRP).

Once options are identified and a preliminary screening has been carried out, a detailed appraisal of the feasible remediation options will need to be carried out. This guideline also provides information relevant to the detailed remediation options appraisal stage. The NRF *Guideline on cost-benefit and sustainability analysis* (CB&SA) provide detailed appraisal steps for selecting remediation options, which may further assist decision-making. Detailed decision-making and application information on each technology is presented within the individual NRF *Technology guides*.

The detailed options appraisal will lead to the selection of a preferred option (or options) that can be expected to achieve the management and remediation objectives. Treatability and/or feasibility studies may be required at this stage to further assess the applicability of the technologies, reduce uncertainties, and to confirm the preferred option. A series of remediation application guides are available to assist in this process. This process will lead to the point where there is sufficient information and certainty to design the remediation program, and for the RAP to be completed.

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

This guideline assumes the reader has set the remediation objectives and established the regulatory requirements prior to commencing the ROA process.

It is assumed that the reader is familiar with the ASC NEPM and will refer to other CRC CARE guidelines included within the NRF. This document does not supersede regulatory requirements, and familiarity with local legislation and regulations is necessary before proceeding with environmental investigations or remediation/management.

2. Developing a remediation strategy

This document is intended to provide guidance on identifying remediation options that are likely to achieve the objectives for the site and warrant more detailed consideration, and to screen out options that are unlikely to be successful. In general, it can be expected that an investigation and assessment will have been carried out to identify contamination that poses an unacceptable risk to a receptor, and the requirements for management or remediation will have been determined.

Note that this guidance document is limited to the preliminary identification of remedial options that may be suitable to manage or treat contaminants that have been identified in soil, groundwater or vapour. This document does not include a detailed appraisal of particular options; information on the more detailed appraisal of particular remediation options and technologies is the subject of other guidance documents that are included in the NRF.

In general, the appraisal of remediation options will be carried out after a conceptual site model (CSM) has been prepared which sets out the contamination sources, pathways and potentially affected receptors at the site under investigation, and a contamination risk assessment has been carried out to determine the risks that need to be addressed. The person undertaking the remediation options appraisal should have a clear understanding of the CSM and the source-pathway-receptor linkages that potentially can give rise to unacceptable risks, so that the available treatment options can be reviewed as to their ability to reduce the risks to an acceptable level.

2.1 Remediation criteria

The remediation criteria will need to be known at the outset of the options appraisal so it can be determined whether particular technologies will be able to reduce the risk from contamination sufficiently to meet the remediation criteria.

Determining clear and measurable objectives for remediation at the outset prior to options appraisal enables criteria to be set, against which to determine whether particular treatment options are viable. Readers are directed to the NRF *Guideline on establishing remediation objectives* for more detailed information. Remediation objectives should provide a clear indication of what is to be achieved by the remediation process. The fundamental basis for any remediation is the protection of human health and the environment - this requirement may be framed in terms of protecting particular environmental values or beneficial uses.

Readers are directed to the NRF *Guideline on validation and closure* for more detailed information on validation strategies to achieve site closure.

2.2 Preferred hierarchy

In accordance with the ASC NEPM, the preferred hierarchy of options for site clean-up and management of soil contamination is:

i) On-site treatment of soil contamination, so that the risk associated with the contaminant is reduced to an acceptable level.
ii) Off-site treatment of excavated soil, so that the risk associated with the contaminant is reduced to an acceptable level, after which it is returned to the site.

If it is not possible for either of the above options to be implemented, then other options for consideration can include, for example:

i) Removal of contaminated soil to an approved site or facility, and replacement with clean fill where necessary.
ii) Containment of the contamination on-site either in-situ with appropriate controls that reduce the risk to an acceptable level, or in an appropriately designed and managed containment facility.
iii) Adoption of a less sensitive land use or controls on site activities that will reduce the need for remedial works.

The remediation hierarchy for groundwater is:

- In-situ treatment or monitored natural attenuation be adopted where this is feasible and can achieve an acceptable level of risk within an acceptable timeframe;
- Extraction followed by disposal or treatment and disposal may be preferred where feasible and the timeframe is acceptable; and
- Where the risks and timeframe are such that a reduction in ‘down-gradient’ risk is required, options such as hydraulic containment, interception, or the application of a barrier system may be preferred.

As part of the identification and selection of remediation options, consideration should be given to the hierarchy above so that remedial options are selected that provide a permanent solution without the need for ongoing control, where feasible.

Some jurisdictions vary from the above in terms of preferred hierarchy of options.

2.3 Project objectives

It is important that the key decision makers of the remediation project are identified as early as possible and are engaged throughout the life of the project and decision-making process. The project objectives will likely be wider than simply the remediation objectives. In defining the project objectives, it is essential to consider the constraints or key assumptions that may impact the achievement of overall project success in conjunction with decision makers to gain their input and feedback. The ability to effectively communicate and engage with decision makers and receive their direction and input is critical to the overall success of the ROA process. Readers are directed to the NRF *Guideline on stakeholder engagement* for more detailed information on liaising with decision makers.

The Contaminated Land Report (CLR) 11 (Environment Agency, 2004) contains advice on specific parameters to be considered when selecting remediation options. For complex sites, an iterative process for determining remediation objectives may be required, as the viable remediation options may limit the outcome that is able to be achieved. In some cases a re-evaluation may be needed of the potential future land use(s) for the site (and possibly the environmental values that are to be protected). This may lead to the outcome that contamination may remain and may require long term monitoring and/or institutional controls. Readers are directed to the NRF *Guideline on implementing long-term monitoring* and *Guideline on Institutional Controls* for more detailed information on liaising with decision makers.

The Contaminated Land Report suggests specific parameters for consideration in relation to developing a remediation strategy; these include:

- **Level of risk**: that needs to be achieved by the remediation and the level of risk reduction that is necessary in order to do so
- **Long term outcomes:** will be maintainable and acceptable in the long term.
- **Legal requirements:** it is essential to satisfy legal requirements, particularly those relating to environmental protection and planning, as well as other issues such as occupational health and safety
- **Benefits:** beyond reducing or controlling the unacceptable risks on site
- **Cost:** of the remediation program.
- **Sustainability:** remediation strategy will provide an acceptable level of risk and a balance in terms of environmental, financial and social considerations.
- **Practicability:** ability to implement the remediation system and carry out necessary maintenance
- **Duration:** of the remediation program.
- **Stakeholders:** views are considered and remediation strategy will achieve an acceptable outcome on essential matters.
- **Risks**: all risks that need to be controlled during remediation

Each of these parameters should be considered and a distinction made between those that are essential, and those which are desirable (but not essential). The costs, benefits and sustainability outcomes may be better understood using the guidance and tool in the NRF *Guideline on cost-benefit and sustainability analysis.*

2.4 Identifying treatment options

Once the remediation objectives have been set and the remediation criteria are known, the next stage is to identify remediation technologies or management options, and an overall remediation strategy that has the potential to satisfy the essential objectives of the remediation. The preferred method for remediation will be to remove or treat the contaminant source; however, in some cases other methods involving containment or control may be able to satisfy the remediation objectives and can be included as options for consideration.

The next stage would be to compile a list of remediation technologies that have the potential to deal with the contamination and reduce the risks identified in the CSM to an acceptable level. In this, consideration should be given to the overall remediation strategy and whether combinations of technologies or other options will achieve an acceptable outcome and should be included for consideration.

A number of sources of information were reviewed during the formulation of this document to establish the guidance available nationally and internationally to assist with conducting preliminary remediation options appraisals and selecting potential technologies. These are listed in references, and provide an important resource to readers.

3. Remediation options

The process of assessing each of the identified options requires thought from the practitioner regarding the consequences or impacts of each option, and how each option may achieve the stated objectives of the project.

3.1 Remediation technologies

It is important to identify all the potential remediation options that could be implemented that would meet remediation objectives.

To avoid overlooking a promising or innovative remedial or site use option, it is best for practitioners to consider the widest range of realistic options as practical. This should range from traditional, well-known options for the site to those with which the practitioner is not necessarily familiar, including less popular or emerging technologies Otherwise, potentially innovative and preferred options may be dismissed before they can be adequately considered.

One option that should always be considered by the practitioner is the base case of "maintaining the status quo”. This represents the situation that will arise if the current scenario, land use or approach is maintained. The base case should always be considered as an option, so that the chosen option does not lead to worse or less desirable outcomes than expected by maintaining the current situation. The base case should not imply "spending nothing" or “do nothing”. It may become the "minimum essential expenditure option" or “minimum regulatory requirement”. This may, for example, involve ongoing monitoring and reporting of a contaminated site.

An overview of common remediation technologies is provided in **Appendix A**, each of which has a corresponding *Technology guide* as part of the NRF:

- Soil
    - Containment.
    - Chemical immobilisation and solidification (CIS).
    - Bioremediation (including bioventing, biopiles/windrows, phytoremediation, composting, enhanced bioremediation, land farming and slurry phase biological treatment).
    - Soil washing.
    - Thermal desorption.
    - Excavation.
    - Soil vapour extraction.
- Groundwater
    - In Situ Air Sparging.
    - In-situ chemical oxidation (ISCO), including surfactant-enhanced ISCO (SISCO).
    - Skimming systems.
    - Monitored natural attenuation (MNA).
    - Barrier systems, including permeable reactive barriers and cut off walls.
    - Pump and treat.

This list is not exhaustive, and the set of NRF guidance documents may be expanded in the future to include other technologies

The remediation technologies have been divided into two groups – those that are generally applicable to address soil contamination, and those that are generally applicable to groundwater contamination. In some cases, the technologies may be applicable to other media, such as sludge, sediments or vapour arising from soil or groundwater contamination.

Each NRF *Technology Guide* includes important information on:

- Technology description and application
- Feasibility assessment
- Treatability studies
- Validation
- Health and safety
- Case studies

A matrix showing what site characteristics are suited to which technology is provided in **Appendix B**.

When considering the remediation options for the active exposure pathways in the conceptual site model, various remediation options can be considered to achieve the following:

- Treat the source – to remove the contaminant, either fully or partially;
- Break the pathway – to mitigate the risk to the receptor(s) from source(s); or
- Control the receptor to avoid exposure – to mitigate the potential for the exposure scenario to occur.

Where the remediation options being considered do not address all the risks or it will take time to address the risks, consideration should be given to the inclusion of additional interim management controls and responses that need to be taken to reduce the risks to an acceptable level.

3.2 Treatments for multiple media or mixed contamination

Often, contamination is present in multiple media (e.g. soil and groundwater contamination) or is comprised of more than one type of chemical (e.g. hydrocarbons and heavy metal contamination). In some circumstances one remediation technology may be suitable for multiple media or mixed contamination, however it is more common that multiple remediation technologies are implemented to achieve the remediation objectives.

If applying multiple technologies, it is important that either the remediation technologies are compatible to occur simultaneously, or that the remediation can be staged to implement them separately. This complexity can be simplified using a matrix to find intersections of applicability. All the options available to treat each type of contamination in each media can be identified and placed in a matrix. The individual options that are compatible can be combined and considered as part of the preliminary screening. An example is provided in Box 2.1 below.

	Groundwater Remedial Options		
Soil Remedial Options	In-situ containment and treatment gate	In-situ thermal	Multi-phase extraction
Ex-situ Bioremediation	X	X	X
Thermal desorption			
Soil washing			
Offsite disposal	X		X
Soil vapour extraction			
In-situ thermal		X	X
X = soil and groundwater remedial technologies can be used together			

Based on the above assessment, the following eight potential site remedial options were identified for further analysis:

- Option 1: In-situ containment and treatment gate for groundwater and ex-situ bioremediation of soil,
- Option 2: In-situ containment and treatment gate for groundwater and offsite disposal of soil,
- Option 3: In-situ thermal treatment of groundwater and ex-situ bioremediation of soil,
- Option 4: In-situ thermal treatment for both soil and groundwater,
- Option 5: Multi phase extraction of groundwater and ex-situ bioremediation of soil,
- Option 6: Multi phase extraction of groundwater and offsite disposal of soil,
- Option 7: Multi phase extraction of groundwater and in-situ thermal treatment of soil, and
- Option 8: Base Case. The site continues with the current land use, with periodic monitoring of groundwater.

Box 2-1: Example of combining technologies into single options for consideration

3.3 Preliminary screening of options

A screening exercise should be undertaken to assess what contaminants particular technologies can treat, and what medium they are effective in (i.e. soil, groundwater) to assemble a list of potential treatment options. Preliminary screening allows multiple remediation options to be appraised, and efficiently discounts those which are clearly not viable for the site, or will not meet the established remediation objectives.

The matrix outlined in **Appendix B** can assist in the technology identification process, and will yield an initial set of options that can be assessed further for applicability as part of the next stage of the detailed assessment.

Documenting the process used to short-list options can be important in the final reporting of the ROA process, particularly for stakeholder engagement. Transparency in the consideration of options is one of the key components of a robust ROA, and the removal of each option must be justifiable.

A simple approach to undertaking a preliminary review of options is to conduct a qualitative assessment (i.e. yes, no or maybe) of whether the identified options clearly meet remediation requirements. Those options that are deemed to not meet remediation requirements can then be eliminated from the list of options. If there is uncertainty if an option will meet requirements, the option should be retained for further analysis.

There may be one or more potentially viable remedial options to treat the contamination. If there is only one viable option to meet the objectives of the remediation work then the remediation strategy may be able to be formulated at this stage (to form the basis for the RAP), defining the objectives, remediation criteria and selected technology (along with the justification for this decision). Further, more detailed assessment of the technology considering site-specific data is likely to be required to enable the remediation action plan and design to be developed and finalised.

If there are several potentially viable remediation options, an appraisal of each of the options should be undertaken to assess which option(s) will most effectively meet the remediation objectives.

Information that will be useful for the appraisal of each of the selected remediation options is provided in separate Application Guides for each technology.

For further information relevant to the assessment of each of the selected remediation options readers are directed to the individual NRF *technology guides*.

Practitioners will need to apply their judgment as to whether the level of uncertainty surrounding an option warrants it being short-listed for further evaluation or eliminated from the ROA.

3.4 Detailed assessment of options

Following the preliminary screening, a detailed evaluation of the feasible options is required. This should apply more rigour to the assessment, achieving greater certainty regarding the preferred remediation strategy, and determining whether further evaluation should be carried out to resolve uncertainties and fill information gaps. Treatability and/or feasibility studies may be required at this stage to further assess the applicability of the technologies, reduce uncertainties, and to confirm the preferred option.

There are several approaches to carrying out a detailed options assessment, particularly for complex and or large sites; including the generic approaches of cost-benefit analysis (CBA) and multi-criteria analysis (MCA). Further, the method of cost-benefit and sustainability analysis (CB&SA) combines CBA with MCA and has been developed specifically for the remediation industry.

An alternative approach to decision making is to adopt a linear sequential decision making strategy. There are recognised decision processes that adopt this strategy, including commercially available packages (eg Kepner Tregoe 2017). The sequential decision making process can provide an efficient method.

3.4.1 *Linear sequential decision making strategy*

When screening options for remediation, the following steps adopting a linear decision making approach, are typically involved:

- Review the CSM, with the objective of ensuring that the contamination source-pathway-receptor linkages are understood, and the impacts that can occur have been identified. It is essential that all possible impacts are identified, the remediation objectives are fully defined, and the remediation criteria established.
- Review the remediation options that could meet the remediation criteria and achieve the remediation objectives, and determine whether the options selected for consideration are comprehensive in their ability to achieve the objectives, or whether additional technologies or combinations of technologies or management strategies should be included for consideration. Each source-pathway-receptor linkage identified in the CSM should be considered individually to identify options that might treat the source of contamination, break the pathway between the source and the receptor, or control the receptor to avoid exposure. There may be multiple impacts that need to be addressed, such as soil contamination (protecting human health, protecting ecosystems), groundwater contamination (restoring and protecting uses of groundwater and avoiding effects that may occur through volatilisation of contaminants from groundwater), sediment contamination and surface water contamination. Thus there may need to be remedial options for soil, and different options for groundwater.
- Identify the objectives and remediation criteria that are essential requirements; consider them first to make sure they are satisfied, and only then consider matters that are not essential. Often the most important factor that should be considered first will be whether the technology will really achieve all of the key objectives of the remediation. Those technologies that will not or are not likely to achieve the key objectives can be eliminated from further consideration, and only those technologies where there is confidence that they will be able to achieve the required outcome retained for consideration.
- Where the options being considered will not address all of the risks or it will take time to address the risks, consideration should be given to the interim management controls and responses that need to be taken to reduce the risks to an acceptable level.
- The need for certainty should also be considered - whether innovative and developing technologies with higher uncertainty are acceptable, or whether technologies should be commercially available and proven.
- Often the next most important factor will be whether the risk is, or is likely to be, acceptable to stakeholders. There are two important areas of risk: the risks associated with undertaking the remediation works (such as vapours, dust, truck traffic), and the risks associated with the final condition of the site. Consideration of the risks (and the management of those risks

including monitoring and response if the monitoring indicates problems), in consultation with stakeholders, will determine which options are acceptable and which options are not acceptable.

In these considerations:

- This process will place a focus on the remediation objectives, and it may be that these will be adjusted to reflect alternative outcomes that are considered to be acceptable (such as remediation to a level that allows institutional controls to be applied that will give an acceptable outcome with a lesser level of remediation).
- Alternative remediation strategies may evolve, with combinations of technologies being identified as necessary to achieve all of the objectives. This is appropriate, as combinations of technologies may well offer a better solution.
- There may well be uncertainty as to whether a technology will achieve the objectives, and further investigation (such as treatability trials) will be required to resolve the uncertainty. Generally the approach should be to retain only technologies for which there is a reasonable prospect of success, and to note the requirement for further work.
- There may well be uncertainty as to whether stakeholders will consider a particular option to be acceptable; consultation with stakeholders should seek to resolve this. It may be that there will be trade-offs and other considerations that need to be taken into account; this may lead to a more comprehensive assessment following the principles of sustainability.

Options that pass this screening process can then be further screened against other essential requirements (e.g. cost-prohibitive options might be eliminated, or perhaps options that take too long).

Once a set of options has been selected for which there is a reasonable degree of confidence that they will achieve all of the essential requirements (albeit some further work might be required to confirm this), then the ‘nice to have’ factors, trade-offs and other distinguishing matters can be considered.

3.4.2 *Cost-benefit analysis*

CBA is a set of procedures for defining and comparing the benefits and costs (economic, social and environmental) associated with decisions to implement a project or to undertake an investment. The benefits and costs are expressed in monetary (i.e. dollar value) terms and hence are directly comparable with one another.

The CBA method provides a framework for analysing data in a logical and consistent way. It involves the systematic identification and quantification of the economic, social and environmental benefits and costs of each option.

3.4.3 *Multi-criteria analysis*

MCA is a structured approach to determine overall preferences among options, where the options accomplish several objectives. It provides a robust, transparent and repeatable decision-making structure, making explicit the key considerations and the values attributed to them, and providing opportunities for stakeholder and community participation.

MCA is most useful when there is a clear basis for scoring project options against a set of performance indicators and where this evaluation framework is agreed upon and documented before the analysis has commenced. However, unlike CBA, MCA cannot guide the decision-maker on whether individual projects, programs or policies provide a positive community benefit. Rather, it provides a process for organising and evaluating the impacts that are not included in the CBA to support the decision-maker in making the necessary trade-offs between economic, environmental and social objectives to reach and defend a decision.

While multi-criteria analysis is widely used in the industry to assess different remediation strategies, it averages across a range of factors, and factors that are important may be obscured. This can be overcome using a weighting system when rating performance indicators, thereby giving a higher weighting to more important factors.

3.4.4 *Cost-benefit and sustainability analysis*

CB&SA involves the integration of results of the CBA with the results of the MCA, to produce a combined cost-benefit and sustainability analysis. This enables a robust consideration of the relevant economic and sustainability impacts of the various options.

The key benefits and strengths of undertaking an integrated CB&SA include:

- Enables consideration of impacts or issues that a traditional CBA cannot sufficiently measure;
- Handles complex decision-making processes where major impacts and considerations cannot be readily or reliably monetised;
- Supports sustainability principles by determining the value of the proposal to the community, environment or the next generation;
- Applicable at every stage of the decision-making process;
- Provides a quantitative measure of the benefits of an investment, allowing direct comparisons between dissimilar projects;
- Presents results provided by the CBA or MCA in a transparent and repeatable fashion to facilitate meaningful, transparent and robust comparisons between competing options;
- Encourages clear thinking about the estimated worth of a proposal relative to what would happen in the absence of a proposal (i.e. no change to current site conditions);
- Helps to undertake legislative and regulatory requirements; and
- Enables an iterative assessment over the whole decision-making life cycle.

Detailed instructions on conducting a CB&SA, along with an Excel-based tool to aid with the calculations, are presented within the NRF *Guideline on performing cost-benefit and sustainability analysis of remediation options*.

Appendix A – Technology overview

The remediation technologies have been divided into two groups – those that are generally applicable to address soil contamination, presented in Table 1, and those that are generally applicable to groundwater contamination, presented in Table 2. In some cases, the technologies may be applicable to other media, such as sludge, sediments or vapour arising from soil or groundwater contamination. The technology guides should be referred to for such information.

Table 1: Soil remediation technologies

Remediation technology	Description
Bioremediation	Bioremediation techniques aim to remove contaminants through microorganisms that use the contamination as a food and energy source for development and growth. They involve adjusting the soil conditions (particularly oxygen, moisture, nutrients, temperature and pH) to favour the growth and activity of microorganisms that will degrade the contaminants. Bioremediation is usually carried out ex-situ but can also be applied in-situ. Phytoremediation entails the use of plants to encourage degradation of contaminants in the soil, or to remove contaminants from the soil via uptake through the plant roots and transfer of the contaminants to the body and leaves of the plant. Phytoremediation is usually carried out on soil that remains in place on site.
Chemical immobilisation and solidification	Chemical immobilisation and solidification is a treatment technology that involves mixing reagents into the contaminated soil to alter its physicochemical properties by stimulating sorption, precipitation or incorporation into crystal lattices, or by physically encapsulating the contaminants. These induced alterations serve to reduce the rate of contaminant migration via leaching (dissolution). Immobilisation involves adding reagents to a contaminated soil to chemically immobilise hazardous materials or reduce their solubility, resulting in a reduction of their leachability and toxicity. Solidification comprises the addition of cementitious reagents to contaminated soil to encapsulate the waste materials within the matrix and change its physical properties. The surface area exposed to leaching is reduced and the permeability of the material is reduced, minimising contaminant migration to clean soils and/or groundwater outside of the treated medium.

Remediation technology	Description
Containment	Containment of contaminated soil or sediments involves the use of covering material (such as soil) or a structure (such as paving or a building) to prevent exposure to the contaminated media. Engineered solutions can be used to isolate contaminated soils and prevent exposure; these can include for example the construction of an on-site containment cell or repository to contain the contaminated material. The containment cell can be located above or below ground. Containment can also include other engineered pathway controls, such as hardstand surface / car parks in ‘dirty’ areas, and sensitive land-uses in ‘clean’ areas of the site.
Excavation and removal	Removal of the contaminated soil from site does not constitute a treatment technology but breaks a exposure pathway linkage by removing the source. The excavated soil can be either retained on site within a containment cell, or disposed of off-site, usually to a waste disposal facility. Treatment either on site or off site may also be required before the soil can be either contained or disposed of.
Soil vapour extraction	Soil vapour extraction involves the separation and removal of volatile contaminants from the subsurface by application of vacuum. For example, this can strip the volatile fraction of light non-aqueous phase liquids or adsorbed phase hydrocarbons and transfer them to an above ground treatment system.
Soil washing	Soil washing uses a liquid (e.g. water or a non-aqueous solvent) to remove adsorbed contaminants from soil, usually by separating particles that have a higher concentration of contaminants (such as fine silt or clay particles that have a larger surface area per unit mass). Soil washing involves screens or other separation devices to separate the fine fraction with higher contaminant concentration from the coarse fraction that has a relatively low contaminant concentration, with the objective of allowing the coarse fraction to remain on the site (assuming it complies with the requirements). To be cost effective the volume of the fine material that contains the bulk of the contamination should be small relative to the clean coarse material. The concentrated fine material will require treatment if necessary, and disposal. The fine material will generally be in the form of a slurry that will need to be dewatered and, in some cases, treated, for disposal or for recovery of the contaminants.
Thermal desorption	Thermal desorption is a process that uses either direct or indirect heat exchange to heat organic contaminants to a temperature high enough to volatilise and separate them from a contaminated soil medium. Air, combustion gas or an inert gas is used as the transfer medium for the volatilised components. This process is most usually applied ex-situ (the material is excavated and treated), although it can also be applied in-situ.

Table 2: Groundwater remediation technologies

Remediation technology	Description
In situ air sparging/injection	Air sparging is an in-situ remedial treatment comprising the injection of air into a contaminated aquifer to strip dissolved phase contaminants from the water and to transfer the contaminants into the vapour phase. The vapour, in the overlying unsaturated zone, is then recovered via an extraction system. Air sparging can also raise the dissolved oxygen levels and stimulate biodegradation, although this is typically a minor process compared to stripping.
In-situ chemical oxidation	Chemical oxidation is used to oxidise (or mineralise) contaminants into less hazardous forms or components. The most commonly applied oxidising agents are hydrogen peroxide, permanganate and persulphate, however there are numerous other emerging oxidants (e.g. percarbonates) which may also be used. Often these oxidants are activated (or made to act more strongly) by addition of heat, sodium hydroxide, acids, or metals, etc.
Monitored natural attenuation	This involves relying on and monitoring of the effects of naturally occurring physical, chemical, and biological processes or any combination of these processes to reduce the load, concentration, flux or toxicity of polluting substances in groundwater.
Barrier systems	This involves constructing a barrier in the subsurface (extending into the saturated zone) which contains reactive chemicals or bioremediation agents that will treat groundwater as it passes through the barrier. PRBs are typically aligned perpendicular to the groundwater flow direction and may be coupled with impervious barriers to direct the contaminated groundwater to the permeable barrier. The barriers are commonly used with chemical reduction to reduce a contaminant valency to a less hazardous form (e.g. chromium IV to chromium III). Reduction often involves the use of chemical amendments to the aquifer to facilitate enabling biological or chemical changes to occur to the contaminant mass. Cut off walls usually incorporate impermeable barriers from the top to the bottom of the wall to fully contain contaminated groundwater. They are also often used in conjunction with other remediation methods, such as pump and treat to extract the contaminated groundwater from the containment area and treat it using an appropriate technology. Cut off walls can be used to contain a source of contamination, and hence can apply to a source area, or to the plume that results from a source area.

Remediation technology	**Description**
Pump and treat	Pump and treat (P&T) is one of the most widely used groundwater remediation technologies. Conventional P&T methods involve pumping contaminated water to the surface for treatment, however the NRF uses term P&T in a broader sense to include any system where withdrawal of groundwater is part of a remediation strategy (whether this be contaminant mass removal or containment). Variations and enhancements of conventional P&T include hydraulic fracturing as well as chemical and biological enhancements. Once contaminated groundwater has been extracted, it typically must be treated prior to discharge / disposal. There are two broad categories of treatment, including biological and physical / chemical. Regulatory requirements likely apply to both aquifer recharge and disposal of contaminated groundwater, even following treatment.
Skimming	Skimming is a tool for mass recovery of light non-aqueous phase liquids (LNAPLs) and occasionally dense non-aqueous phase liquids (DNAPLs). Skimming uses a pump or hydrophobic belt to extract LNAPL from a well at the air/LNAPL interface and is effective for confined, unconfined and perched LNAPL. Mass recovery technologies, such as skimming, are the most frequently used technologies for LNAPL remediation and, as such, the appropriate design and implementation of such systems is commonplace, and the costs and technical limits are generally well understood. Skimming is often used during emergency or short-term remedial actions to effect immediate mass recovery of LNAPL.

Appendix B – Technology application matrix

Table 3 below provides a summary of the types of chemical contamination that each featured remediation technology is suited to. Further detail is available in the individual NRF technology guides, along with the US Federal Remediation Technology Roundtable website at: https://frtr.gov/matrix2/section3/table3_2.pdf

Table 3: Technology summary

Media	Technology	Inorganics (including metals)	Petroleum hydrocarbons	Volatile organic compounds	Semi volatile organic compounds	PAHs
Soil	Bioremediation	?	Y	Y	Y	?
Soil	Chemical immobilisation and solidification	Y	?	?	?	?
Soil	Containment	Y	Y	Y	Y	Y
Soil	Excavation	Y	Y	Y	Y	Y
Soil	Soil vapour extraction	N	Y	Y	?	?
Soil	Soil washing	?	?	?	?	?
Soil	Thermal desorption	N	Y	Y	Y	Y
Groundwater	Barrier systems	Y	Y	Y	Y	?
Groundwater	In-situ air sparging	N	Y	Y	Y	Y
Groundwater	In-situ chemical oxidation	N	Y	Y	Y	?
Groundwater	Monitored Natural Attenuation	?	Y	Y	?	Y
Groundwater	Pump and treat	Y	Y	Y	Y	Y
Groundwater	Skimming	N	Y	Y	N	N

Legend:
Y - Viable remediation option
? - Potentially viable remediation option (less common or demonstrated)
N - Not viable remediation option (or not known / demonstrated)

Appendix C – References

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