NATIONAL REMEDIATION FRAMEWORK

Technology Guide
Groundwater

Barrier systems

August 2019

A safer, cleaner environmental future

Cooperative Research Centre for Contamination Assessment and Remediation of the Environment, National Remediation Framework

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Note on the National Remediation Framework
This document is one component of the National Remediation Framework (NRF). The NRF was developed by CRC CARE to enable a nationally consistent approach to the remediation and management of contaminated sites. The NRF is intended to be compatible with the National Environment Protection (Assessment of Site Contamination) Measure.

Acknowledgements
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CRC for Contamination Assessment and Remediation of the Environment

National Remediation Framework

Technology guide: Barrier systems

Version 1.0: August 2019

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 site contamination 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 site contamination industry, including site owners, proponents of works, site contamination practitioners, local councils, regulators, and the community.

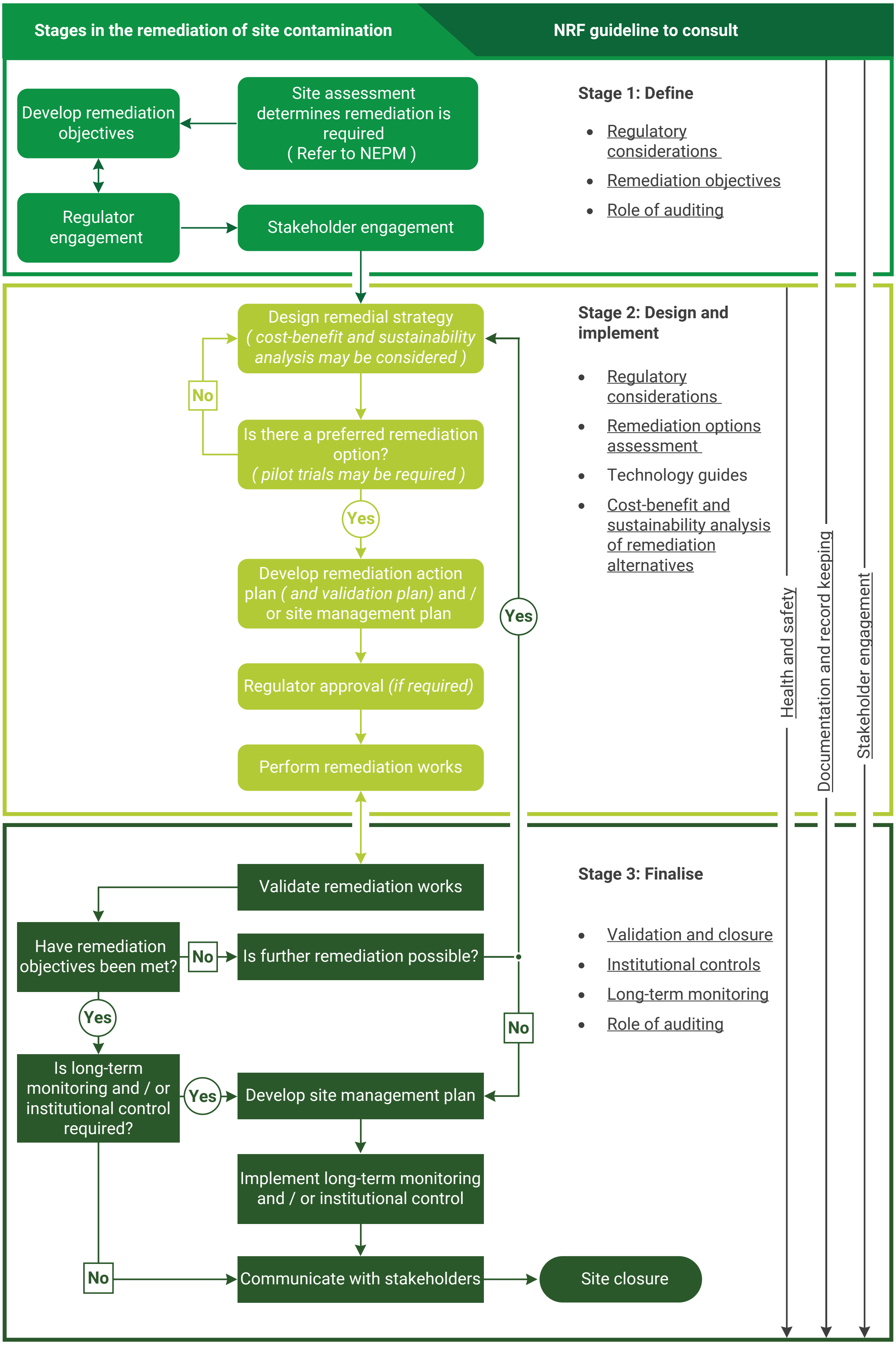
The NRF is intended to be consistent with local jurisdictional requirements, including state, territory and Commonwealth legislation and existing guidance. To this end, the NRF is not prescriptive. It is important that practitioners are familiar with local legislation and regulations and note that **the 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 to consult
Develop remediation objectives
Site assessment determines remediation is required (Refer to NEPM)
Regulator engagement
Stakeholder 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 validation 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

Barrier systems aim to either treat contaminants as groundwater passes through a reactive barrier or to contain groundwater to prevent the down gradient migration of contaminants.

There are two main types of barriers discussed in this guideline:

- reactive barriers, including:
  - permeable reactive barriers (PRBs)
  - funnel and gate reactive barriers
  - continuous reactive barriers, and
- cut off walls.

PRBs treat contaminants as groundwater passes through a reactive barrier installed in the subsurface in the direction of groundwater flow, enabling contaminated groundwater to passively flow through the treatment zone (the reactive barrier). PRBs can treat contaminants that are dissolved in groundwater, including for example volatile and semi volatile organic compounds, petroleum hydrocarbons, explosives and metals.

Funnel and gate systems contain impermeable barriers such as slurry walls to direct the contaminated groundwater to a permeable gate containing reactive media where the contamination is treated.

Continuous systems comprise a fully permeable reactive barrier (without an impermeable barrier) installed in the subsurface to treat the contaminated groundwater as it flows through the reactive media.

Cut off walls are impermeable walls installed in the subsurface to contain contaminated groundwater and prevent migration of contaminants beyond the wall. Cut off walls can be used to contain any contaminant, although the construction materials may degrade over time and could be attacked by some contaminants, which should be considered at the design stage.

The viability of installing a barrier system as a potential remediation solution will often depend on the following site-specific considerations:

- whether the depth and length of the barrier/cut off walls required to contain the contaminant plume, and nature of the geology and hydrogeology, does lead to other alternatives such as hydraulic containment and/or source treatment being favoured, and
- whether the risk posed by contaminant source (if the source is not treated) is acceptable.

In addition, the viability of installing a reactive barrier as a remediation solution may also depend on:

- whether the length of time the barrier will be effective satisfies the requirements for remediation, and the requirement and cost for renewal is acceptable
- whether the contaminant-groundwater-barrier interactions/reactions are sufficiently well understood to predict the effectiveness and life of the barrier, and

- whether groundwater will flow through the barrier rather than around the barrier (i.e. relative permeability of the local geology to that of the barrier, considering any reduction in permeability through the life of the barrier).

In the case of a permeable reactive barrier, treatability studies are likely to be required to:

- confirm the performance that could be achieved
- determining the key design requirements, and
- estimate the costs of implementation.

Abbreviations

Cr(III)	Chromium oxide, Cr_2O_3
Cr(VI)	Hexavalent chromium
CRC CARE	Cooperative Research Centre for Contamination Assessment and Remediation of the Environment
mbgl	Metres below ground level
NAPL	Non-aqueous phase liquid
NRF	National Remediation Framework
PPE	Personal protective equipment
PRB	Permeable reactive barrier
RAP	Remediation action plan
Redox potential	Reduction/oxidation potential

Glossary

Adsorption	The adhesion of molecules to surfaces of solids.
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.
Concentration	The amount of material or agent dissolved or contained in unit quantity in a given medium or system.
Conceptual site model (CSM)	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 risk to human health and/or environment, and/or any other environmental value.
Contaminated site or land	A generic term referring to any land (including soil, surface water, groundwater and soil vapour) that is affected by substances that occur at concentrations above background or local levels and which represent, or potentially represent, a risk to human health and/or the environment, and/or any other environmental value. It is not necessary for the boundaries of the site contamination to correspond to the legal ownership boundaries.
Cut-off wall	An impermeable structure designed to restrict or direct the flow of either surface or ground water.
Dehalogenated	A chemical reaction with a halogenated hydrocarbon that results in one or more halogen ions being removed from the original molecule to form a new hydrocarbon molecule with less, or no, halogens.
Desorption	The release of molecules from surfaces of solids.
Environment(al) protection authority/agency (EPA)	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.
Groundwater	Water stored in the pores and crevices of the material below the land surface, including soil, rock and fill material.

Halogen	The group in the period table of the elements that includes fluorine, chlorine, bromine, iodine and astatine. Halogenated molecules have one or more of these atoms in their structure.
Impermeable	A substance or device that does not allow water to pass through it.
Leachate	Water that has percolated through a solid and leached out some of the constituents, including contamination.
Medium	A general term for the physical solid containing the PRB reagent.
Permeable	A substance or device that easily allows water to pass through it.
Permeable reactive barrier	A reactive barrier installed in the subsurface in the direction of groundwater flow, through which contaminated groundwater flows and is remediated.
Permeable treatment zone	The portion of the subsurface where remediation is occurring due to groundwater flow through a permeable reactive barrier.
Plume	A zone of dissolved contaminants in groundwater. A plume usually originates from the source and extends in the direction of groundwater flow.
Practitioner	Those in the private sector professionally engaged in the assessment, remediation or management of site contamination.
Proponent	A person who is legally authorised to make decisions about a site. The proponent may be a site owner or occupier or their representative.
Redox potential	An expression of the oxidising or reducing power of a solution relative to a reference potential. This potential is dependent on the nature of the substances dissolved in the water, as well as on the proportion of their oxidised and reduced components.
Remediation	Remediation is taking steps towards remedying something, in particular of reversing or stopping environmental damage. It may be 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.
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.
Source area	The location of the origin of the contamination on a site.
Treatability studies	A series of tests designed to ascertain the suitability of the treatment for the contaminants under the site conditions
Trigger level	The concentration of a contaminant above which the contingency plan must be implemented.

Table of contents

1. Introduction

The purpose of this guideline is to provide information on barrier systems as a treatment technology for the remediation of contaminated sites to assist with selection of remediation options. The document contains information to inform remediation planning and aid compilation of a remediation action plan (RAP).

This guidance is primarily intended to be used by remediation practitioners and those reviewing practitioner's work, however it can be used by other stakeholders within the contaminated sites industry, including site owners, proponents of works, and the community.

Barrier systems are one of many technologies available for contamination remediation, and other technologies may be more appropriate. It is assumed that the information presented within will be used in a remediation options assessment to identify and select the preferred technologies for more detailed evaluation. This guideline provides information for both initial options screening and more detailed technology evaluation. This guideline does not provide detailed information on the design of barrier systems as this is a complex undertaking and should be carried out by appropriately qualified and experienced practitioners. Readers are directed to the NRF Guideline on performing remediation options assessment for detailed advice on assessing remediation options. In addition, the remediation objectives, particularly the required quality of the soil after treatment, are a critical matter and it is assumed that these have been determined and considered in the remediation options assessment and selection process. Readers are directed to the NRF Guideline on establishing remediation objectives for more detailed advice.

References to case studies are provided in **appendix A.**

A number of sources of information were reviewed during the formulation of this document to compile information on potential technologies. These are listed in references and provide an important resource to readers.

2. Technology description and application

Barrier systems aim to either treat contaminants as groundwater passes through a reactive barrier or to contain groundwater to prevent the down gradient migration of contaminants. There are two main types of barriers discussed in this guideline:

- reactive barriers, including:
  - permeable reactive barriers (PRBs)
  - funnel and gate reactive barriers
  - continuous reactive barriers, and
- cut off walls.

Reactive barrier systems involve the installation of treatment zones perpendicular to the direction of the groundwater flow which allows the groundwater in a contamination plume to passively move through the permeable treatment zone (reactive barrier) while the contaminant is transformed to a less toxic or non-toxic form or changed in form so that the contaminant becomes immobilised.

Cut off walls, also referred to as vertical or physical barriers, comprise impermeable walls installed in the sub surface to contain groundwater and prevent the migration of contaminants beyond the wall. They can also serve to control and alter the groundwater flow direction to prevent contaminant migration, or to direct groundwater flow to a treatment zone.

The advantages and disadvantages of each type are presented in table 1.

2.1 Permeable reactive barriers

A PRB is an engineered treatment zone comprising a reactive material that is placed into the aquifer to treat contaminated groundwater arising from a source area as it flows through the barrier. A PRB does not treat the source of contamination. The source may naturally reduce to an acceptable level over the life of the PRB, or the source may need to be treated as a separate undertaking.

The permeability of the reactive zone within either type of PRB needs to be equal to or greater than the aquifer permeability so as to not restrict the groundwater flow and cause the contaminated groundwater to flow around the reactive barrier.

PRBs are generally installed at relatively shallow depths to facilitate installation, although there are cases where they have been installed at significant depths.

Table 1: Advantages and disadvantages of barrier systems.

Type	Advantage	Disadvantage
Reactive barriers	• May be a sustainable remediation solution (using passive processes without chemicals e.g. via sorption or precipitation, power, water or wastewater). • Can potentially treat a wide range of contaminants. • Installed below ground, may allow use of the land surface. • Can function for several years and possibly for decades without requiring maintenance. • Can be combined with other remediation technologies.	• Does not treat the source of contamination. • Long-term, regular monitoring required to demonstrate that the barrier remains effective at meeting the remediation criteria. • If the treatment material becomes exhausted or blocked, the barrier may need to be rebuilt and the exhausted medium disposed of. • Constituents of the groundwater (other than the contaminants of concern) may react with the treatment medium and limit the life of the reactive medium. • Difficult to reliably predict the long-term performance and life of the reactive medium. • Building foundations and services can prevent installation in the required area. • May not be viable for deep contamination plumes due to construction issues and costs. • May sterilise footprint for some forms of development. • Groundwater flow may be difficult to manage in certain geological conditions such as fractured rock. • It can be difficult and expensive to install a barrier that intersects the correct portion of the aquifer.
Cut-off wall	• Can be used on any contaminant group. • Can be combined with other remediation technologies.	• Does not treat the source of contamination. • Long-term monitoring can be required to confirm that containment is maintained. • Large volume of ground disturbance required. • Construction materials may degrade over time or be subject to attack by the contaminants (e.g. acid corrosion).

2.2 Funnel and gate reactive barriers

Funnel and gate systems contain impermeable barriers such as slurry walls or sheet piles which prevent groundwater flow and redirect it to permeable gates containing the treatment for the groundwater and remediate it as it flows through the gate. A funnel and gate system schematic is presented in figure 1.

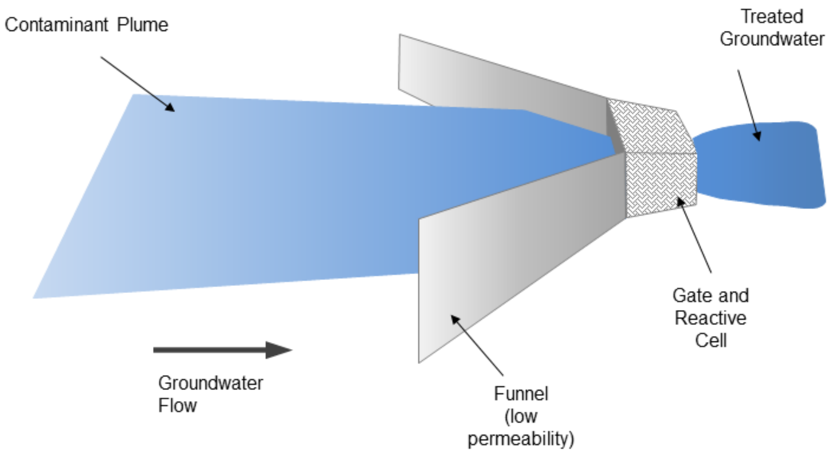


Figure 1: Funnel and gate reactive barrier.

2.3 Continuous reactive barriers

Continuous systems consist of a fully permeable barrier (e.g. a trench filled with permeable material combined with a reagent) installed in the subsurface, perpendicular to the direction of the flow of contaminated groundwater, which treats the groundwater as it flows through. A continuous system schematic is presented in figure 2.

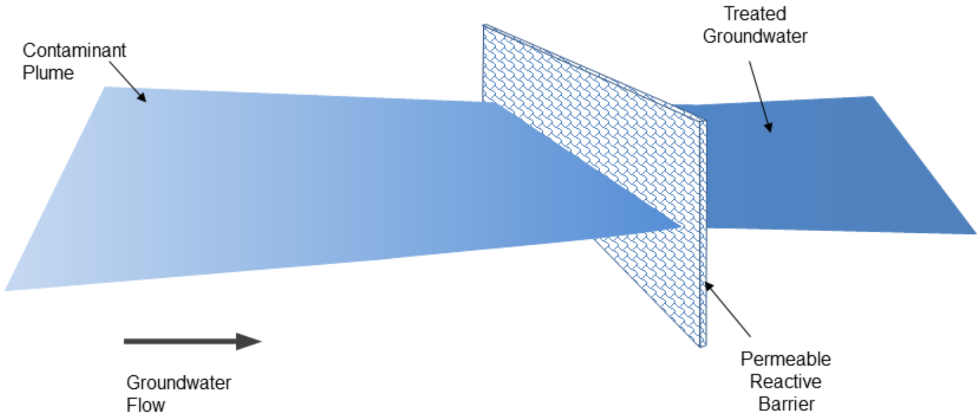


Figure 2: Continuous permeable reactive barrier.

2.4 Cut-off walls

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.

2.5 Monitoring

In addition to the installation of the physical barrier system, a groundwater monitoring well (GWMW) network will be required to assess the effectiveness of the system and to monitor performance.

Typically, monitoring consists of GWMWs positioned down-gradient of the barrier, and possibly up-gradient to monitor ambient groundwater concentrations. Well locations and sampling depths need to take into account the hydrogeology of the area. Regular sampling events will need to be undertaken to measure the contaminants of concern (both the primary contaminants and any break down products) in the groundwater,

Products of the reaction as the plume moves through the barrier should also be included in the analytical suite of the down-gradient samples to determine whether the reaction has occurred. Where required, the continual supply of barrier chemicals (reactive media) should also be monitored. If the treatment process within a reactive barrier is non-destructive, such as adsorption, the monitoring results should indicate whether the system might be failing, and whether desorption might be occurring.

3. Feasibility assessment

The viability of installing a barrier system as a potential remediation solution will often depend on the following site-specific considerations:

- whether the depth and length of the barrier/cut off walls required to contain the contaminant plume, and nature of the geology and hydrogeology, does lead to other alternatives such as hydraulic containment and/or source treatment being favoured, and
- whether the risk posed by contaminant source (if the source is not treated) is acceptable.

In addition, the viability of installing a reactive barrier as a remediation solution may also depend on:

- whether the length of time the barrier will be effective satisfies the requirements for remediation, and the requirement and cost for renewal is acceptable
- whether the contaminant-groundwater-barrier interactions/reactions are sufficiently well understood to predict the effectiveness and life of the barrier, and
- whether groundwater will flow through the barrier rather than around the barrier (i.e. relative permeability of the local geology to that of the barrier, considering any reduction in permeability through the life of the barrier).

If a barrier system is likely to be feasible, other issues will need to be considered to determine if it is likely to be an appropriate remediation solution for the site. These include:

- Is the risk associated with the barrier system likely to be acceptable to all stakeholders? In particular, is the risk that the system might fail at some time in the future acceptable?
- Will the relevant regulatory agencies accept the PRB as a viable means of remediation, or the cut off wall as a containment method? Are specific approvals required by council or other jurisdictions for the proposed works?
- Is it likely that other stakeholders (such as local government or the public) will accept the use of the remediation method, particularly those stakeholders that can have a significant bearing on whether the technology is applied at the site?
- Has the source of contamination been treated or will it continue to be a source of contamination?
- How long must the system operate for, and is there reasonable confidence that the system will operate for this period?
- Is the groundwater composition, and the ability to treat or contain the contaminants, sufficiently well known to be able to design a reliable system?
- What is the composition of the groundwater after it passes through the PRB? Could there be breakdown products of the parent compound/s that need to be assessed?

- What happens after the design life of the system – will the PRB require removal, or the contained contamination treated? Can exhausted or blocked PRB medium be treated or disposed of?
- Are there engineering aspects to a new development that could impact on the proposed remediation program (e.g. deep basement requiring dewatering that could influence groundwater flow)?
- What are the receptors to groundwater contamination (abstraction bores, rivers etc)? Are there sensitive sites or groundwater users nearby that would not be compatible with the proposed remediation plan?
- Is there a time constraint for implementation and proving of the system, and can the barrier system meet this constraint?
- Is the expected order of cost of remediation acceptable?

In evaluating applications for remediation via barrier systems, regulators may require that one or more contingency measures be incorporated in the design to prevent contaminant migration. Where a barrier is installed, design measures may include extending the length of the barrier to ensure capture of the plume or installing a second barrier down-gradient. The implementation of additional approaches such as a pump and treat system may be required if contaminant breakthrough or bypass of the barrier occurs.

3.1 Data requirements

Successful implementation and design of a barrier system, whichever approach is used, is likely to be dependent on the:

- geological conditions
- hydrogeological conditions, and
- chemical properties and concentrations of contaminants.

3.1.1 Geological and hydrogeological conditions

The physical characteristics of the aquifer and groundwater to be treated need to be well characterised. Important factors include:

- depth to groundwater table
- aquifer lithology and properties (e.g. is it multi layered or dual porosity?)
- groundwater flow – rate, direction and mechanism (e.g. is groundwater flowing through granular/porous media or fractures in rock?)
- groundwater velocity (hydraulic conductivity, gradient and porosity)
- background groundwater quality, and
- interconnection with surface or marine waterways.

3.1.2 Contaminant chemistry and concentrations

The groundwater contamination needs to be well characterised. Important factors include:

- The location and composition of the contaminant source, and whether this will have been treated or not.
- The distribution and phase of contaminants in the groundwater (e.g. dissolved, non-aqueous phase liquid, adsorbed, vapour).
- Identification and understanding of contaminant source (historical or ongoing).
- Organic and inorganic constituents that could affect the performance of a reactive barrier, including for example:
  - pH
  - alkalinity
  - electrical conductivity
  - redox potential
  - iron
  - manganese
  - major anions and cations
  - dissolved oxygen, and
  - natural organic matter.

Reactions that can take place in a PRB include:

- Chlorinated hydrocarbons can be reductively dehalogenated (e.g. trichloroethylene can be reduced to ethene). It is possible that only partial dehalogenation may occur meaning breakdown products may remain that will require consideration and potential treatment, such as vinyl chloride or dichloroethene.
- Hydrocarbons can be adsorbed onto an adsorbent (e.g. activated carbon), where natural degradation can take place.
- Metals can be converted to an insoluble form (e.g. soluble chromium (VI) can be reduced to insoluble chromium (III) hydroxides).

3.2 Treatable contaminants

Reactive barrier systems can be used to treat:

- volatile organic compounds
- semi-volatile organic compounds
- petroleum hydrocarbons, and
- heavy metals (dissolved and present in low concentrations).

Cut-off walls can be used to physically contain any contaminant (as it is a containment method rather than a treatment technology), though the construction material used for the walls needs to be selected so that it will not degrade over time and fail. For example, acidic or highly saline groundwater may attack certain cementitious and clay construction materials, and organic solvents particularly if present as a non-aqueous phase liquid (NAPL) may attack synthetic liner systems.

4. Treatability studies

In the case of a cut-off wall, it is unlikely that treatability studies will be required, and it is more likely that reference will be made to published information on the long-term performance of particular materials and construction techniques for the geological and hydrogeological conditions, composition of the groundwater and nature and form of the contaminants.

In the case of a permeable reactive barrier, treatability studies are likely to be required to:

- confirm the performance that could be achieved
- determining the key design requirements, and
- estimate the costs of implementation.

This section is focussed on the requirements for treatability studies for a PRB. Readers are also directed to US EPA (1998) for further detail on conducting PRB treatability studies.

Designing the treatability study may require input from several technical specialists including environmental scientists/engineers, chemical engineers, mechanical engineers, microbiologists, hydrogeologists and air quality specialists to ensure that the study is designed to obtain the data required to enable the most appropriate implementation strategy to be developed.

The nature of the information that is required should be determined through reference to the literature for the specific contaminants involved, and through an assessment of the treatment that can be expected to be achieved based on the groundwater composition and the reactive material. If the particular material has been widely applied to treat the contaminants involved, it may be possible to extrapolate information (such as removal rates for a PRB) from previous case studies and published rate data (as in the cases of trichloroethylene or chromate in granular iron) to avoid duplication and the need for treatability studies, and thereby reduce project costs.

In general, treatability studies for the implementation of a PRB are likely to be necessary where:

- there is a mixture of contaminants to be remediated
- there is little available information on the use of barrier systems to treat the specific contaminants of concern, or
- there is little available information on the specific reactive agents being considered to treat the contamination.

In the first instance, the treatability studies may involve bench testing. The objectives of such work should be established prior to undertaking the work. Usually the objective will be to provide sufficient information to enable:

- comparison of reactivity and longevity of reactive materials to the range of contaminant and natural constituent concentrations expected to be present in the groundwater
- estimation of the half-life and residence time for treatment of the contaminants of concern, and

- assessment of the effect of temperature to the reaction/treatment rates (if any).

The bench tests should be carried out using contaminated groundwater extracted from the plume to be remediated and ideally site soils to best represent the relevant ground conditions for the barrier system to be installed in. Batch studies will usually first be undertaken, followed by column studies if additional data is needed.

4.1 Batch studies

Batch treatability studies are often used to obtain performance data relating to the proposed reactive material to install in the PRB. They are lower cost and simpler than column studies but can provide a rapid comparison of test parameters. Although this information is useful, caution is recommended when using laboratory data to inform design of the field remediation system (to avoid over or under designing the system).

The tests are carried out using tubes or bottles containing the contaminated groundwater to be treated (extracted from the site) with the various reactive agents that are under consideration and also using site-sourced geological material (ideally). The mixtures are agitated and the resulting contaminant concentrations measured to determine which reactive agent is most effective.

The data from batch studies, together with published data in case studies, may be sufficient to determine the design of the barrier system and enable preparation of a RAP. Tests of this type will provide information on the contaminant concentration that will result on equilibration with the reactive medium, but it may be difficult to determine from this what the result will be when the contaminant flows through the medium. To determine this is likely to require column studies.

4.2 Column studies

Column studies are likely to provide a more representative indication of field performance compared with batch tests. The tests are undertaken in the laboratory in columns with a number of sampling points along the length of the column to enable the collection of water samples to assess the treatment efficiency (resulting contaminant concentration) and the number of bed volumes of groundwater that are able to be treated before the reactive medium is exhausted. Information may also be provided on whether the medium is likely to become blocked (e.g. by a precipitate or biomass). The tests are conducted using contaminated groundwater and soils from the site which is inserted into the test columns at a constant flow rate (representing site flow conditions).

The column study data can assist in determining the required residence time for the groundwater in the reactive zone of a PRB and hence calculation of the thickness of the reactive zone and the volume of reactive medium required for the site conditions.

5. Validation

The following information describes the specific validation appropriate for barrier systems, to assist validation planning within the RAP. Readers are directed to the NRF Guideline on validation and closure, which among other things, provides further information on each of the lines of evidence.

The primary lines of evidence for the validation of a PRB are:

- reduction in contaminant concentration through the reactive zone
- analysis of geochemical and biochemical parameters
- mass flus or mass discharge from treated materials, and
- groundwater monitoring to assess whether the plume is diverting around or beneath the system.

Reported data from up-gradient monitoring wells can be compared with groundwater samples collected immediately down-gradient of the PRB to assess whether contaminants are captured/modified in accordance with remedial objectives. As noted in section 2.5, products of the reaction as the plume moves through the barrier should also be included in the analytical suite of the down-gradient samples to determine whether the reaction has occurred. Where required, the continual supply of barrier chemicals (reactive media) should also be monitored.

A major compliance challenge at many PRB installations is the length of time (up to several years) it may take for a perceptible improvement in the down-gradient groundwater quality to appear. Thus, the validation approach must account for:

- rate of groundwater flow
- rate of diffusion of contaminants from less accessible pores in the down-gradient aquifer
- smearing of low-permeability materials across the face of the PRB during construction, and
- development of vertical gradients and stagnant zones in the PRB and in the down-gradient aquifer.

Numerical modelling of the laboratory results may be useful to predict the potential behaviour of the system over long periods of time.

6. Health and safety

Barrier system remediation projects can expose site workers to health and safety hazards, such as:

- exposure to the agents used in the PRB
- exposure to the contaminants in the soil and/or groundwater
- slip/trip hazards associated with deep excavations when installing the PRB or cut off wall, and
- exposure to risks associated with the drilling and/or other hazardous trench installation techniques.

The site-specific risks associated with the remediation implementation should be assessed as part of the RAP.

Common health and safety hazards associated with barrier system installation and monitoring are highlighted in table 2, along with possible control methods. The identified hazards are intended to serve as a general list, with variations from site to site. A detailed hazard assessment should be undertaken at every site where barrier systems are intended to be implemented, which should be documented in the RAP. Many of these matters will be subject to regulatory control measures, and relevant national and state regulations should be referred to.

Readers are directed to the NRF Guideline on health and safety for further information on health and safety on remediation sites, including risk assessment, the hierarchy of controls and suggested documentation.

Table 2: Common barrier systems hazards and controls.

Hazard	Sources of hazard	Control method
Site contaminants	• Excavation of soils during installation of barrier system (sub surface).	• All site workers should use PPE (relevant PPE to be determined based on nature of contaminants present and concentrations, e.g. volatility etc). • Odour control enclosures, ventilation and emissions control systems to contain dust and capture odours and harmful contaminants. • Odour suppressants for nuisance odours.
Chemicals/agents in PRB	• Handling, storage and mixing of chemicals/agents.	• Ensure workers use proper PPE, including gloves. • Store chemicals in locked area to minimise potential for unrestricted contact.
Mechanical	• Contacting or becoming entangled in moving/ unguarded equipment, such as an excavator. • Working on any of this moving equipment without isolating the energy source.	• Train workers on hazards. • Ensure use of lockout procedures for maintenance. • Use of guards, who may remove guards, and how to remove guards.
Flying particles and falling material	• Disturbance of the ground from moving equipment or from high winds, leading to dust generation.	• Ensure workers use proper PPE. • Use of dust suppressants as necessary
Slips, trips and falls	• Storing construction materials or other unnecessary items on walkways and in work areas. • Creating and/or using uneven terrain in and around work areas.	• Keep walking and working areas free of debris, tools, electrical cords, etc. • Keep walking and working areas as clean and dry as possible. • Train workers on fall hazards.

Hazard	Sources of hazard	Control method
Moving vehicles	• Moving and stockpiling excavated contaminated material either on-site or at an offsite facility using earth moving equipment. • Receiving and transferring chemicals/agents and other materials from commercial vehicles.	• Train affected employees on limitations of equipment and drivers. • Train equipment and vehicle operators in safe operation. • Set acceptable speed limits and traffic patterns. • Do routine maintenance.

References and recommended reading

Banasiak, L & Indraratna, B 2012, *Permeable reactive barrier (PRB) technology: An innovative solution for the remediation of acidic groundwater from acid sulphate soil (ASS) terrain*, presented at GeoCongress 2012, Oakland, CA, USA.

Carey, MA, Fretwell, BA, Mosley, NG & Smith, WN 2002, *Guidance on the use of permeable reactive barriers for remediating contaminated groundwater. Report NC/01/51*, National Groundwater and Contaminated Land Centre, Environment Agency, Bristol, UK.

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US Environmental Protection Agency (EPA) 1998, *Permeable reactive barrier technologies for contaminant remediation*, EPA/600/R-98/125, United States Environmental Protection Agency, Washington, DC, USA.

Appendix A – Case studies

Australian barrier systems remediation case studies:

- *Permeable reactive barrier (PRB) technology: an innovative solution for the remediation of acidic groundwater from acid sulphate soil (ASS) terrain*, Banasiak, L & Indraratna, B (2012)[1].
- Bellevue, WA – permeable reactive barriers, Menard Bachy[2,3].
- *Use of permeable reactive barriers for the remediation of diffuse groundwater nutrient pollution: A review of the Mills Street groundwater treatment trial*, Donn, M and Baron, O (CSIRO 2010)[4].
- *Hunter River: installation of one of the world's deepest continuous soil bentonite barrier walls, Mayfield, NSW* (Douglas Partners 2010)[5].

[1] ro.uow.edu.au/cgi/viewcontent.cgi?article=7522&context=engpapers
[2] menardoceania.com.au/wp-content/uploads/2018/01//Bellevue-Permeable-Reactive-Barriers_Menard.pdf
[3] www.der.wa.gov.au/our-work/community-updates/64-bellevue-former-waste-control-site
[4] www.clw.csiro.au/publications/waterforahealthycountry/2010/wfhc-permeable-reactive-barriers.pdf
[5] https://www.douglaspartners.com.au/knowledge/deep-soil-bentonite-barrier-wall

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