CRC for Contamination Assessment and Remediation of the Environment

National Remediation Framework

Technology guide: Pump and treat

Version 0.1: August 2018

National Remediation Framework

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

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

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

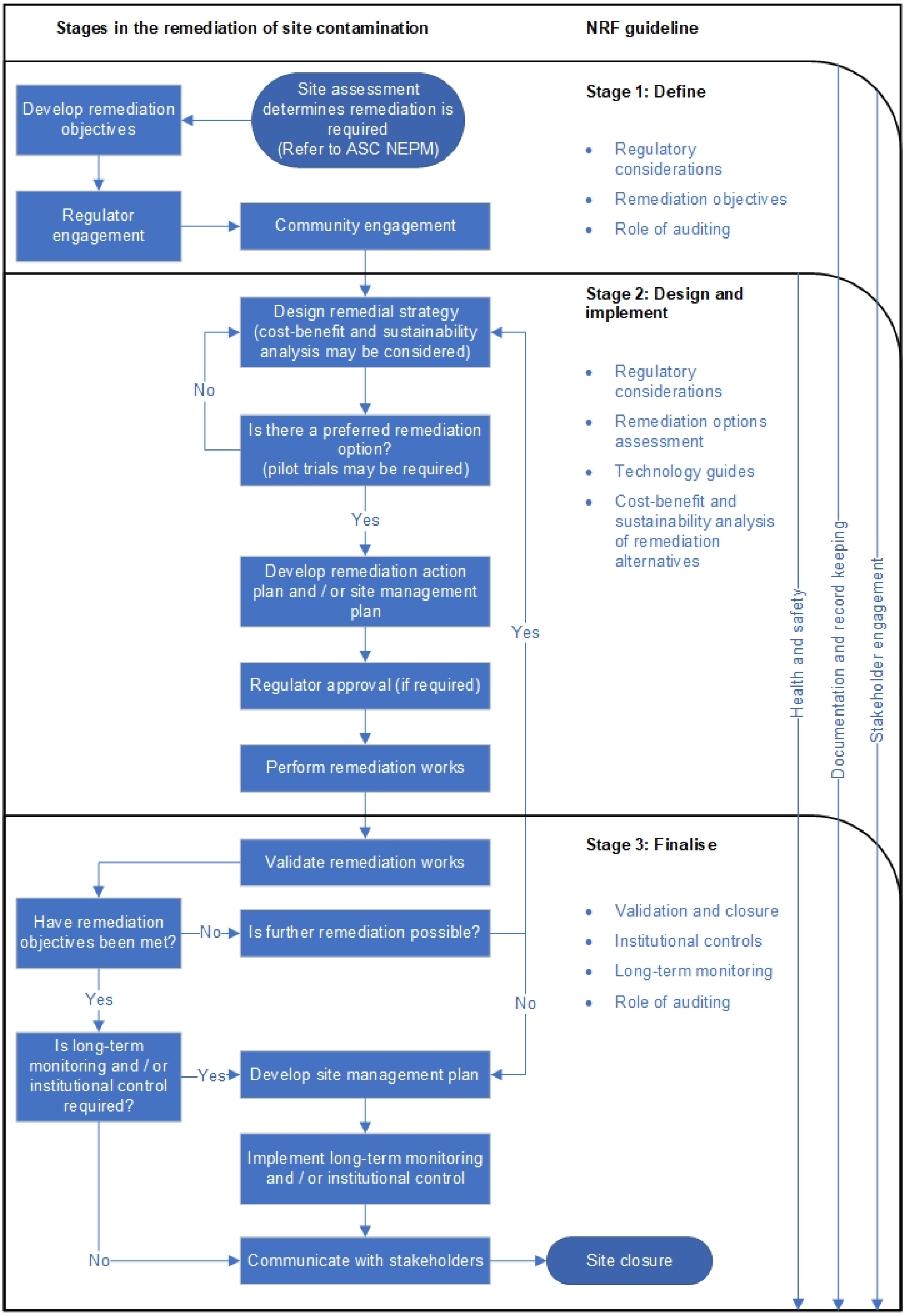
The NRF is intended to be consistent with local jurisdictional requirements, including State, Territory and Commonwealth legislation and existing guidance. To this end, the NRF is not prescriptive. It is important that practitioners are familiar with local legislation and regulations and note that **the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

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

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

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

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


Stages in the remediation of site contamination
NRF guideline
Site assessment determines remediation is required (Refer to ASC NEPM)
Develop remediation objectives
Regulator engagement
Community engagement
Stage 1: Define
Regulatory considerations
Remediation objectives
Role of auditing
Design remedial strategy (cost-benefit and sustainability analysis may be considered)
No
Is there a preferred remediation option? (pilot trials may be required)
Yes
Develop remediation action plan and / or site management plan
Regulator approval (if required)
Perform remediation works
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

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. This guide uses the 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.

P&T is an applicable component of many remedial systems. However, such a system may not be appropriate depending on the hydrogeological and contaminant properties, such as where there is a significant volume of light and/or dense non-aqueous phase liquid (LNAPL/DNAPL) trapped at or below the water table.

Strategies for managing groundwater contamination using P&T technology include:

- Hydraulic/physical containment.
- Groundwater quality restoration.
- Mixed techniques.

Several innovative technologies such as air sparging, engineered bioremediation and permeable treatment walls can be used in conjunction with P&T to address the groundwater remediation objectives. At some sites, natural attenuation processes may limit the need for P&T. The management strategy selected depends on-site specific hydrogeological and contaminant conditions and the remediation objectives.

Although hydraulic containment and aquifer restoration can represent separate remediation objectives, both are often undertaken simultaneously. For example, if restoration is not feasible, the primary objective might be containment.

Treatability studies are typically focussed on hydrogeological investigations into the feasibility of groundwater extraction and the ex-situ treatment of the dissolved contaminants. There are numerous techniques and methods for treating extracted groundwater which are summarised according to type and chemical treated. A methodology for monitoring and demonstrating site closure is also provided.

Abbreviations

COCs	Contaminant Of Concern
CRC CARE	Cooperative Research Centre for Contamination Assessment and Remediation of the Environment
DNAPL	Dense Non-Aqueous Phase Liquid
GAC	Granular Activated Carbon
LNAPL	Light Non-Aqueous Phase Liquids
MNA	Monitored Natural Attenuation
NAPL	Non-Aqueous Phase Liquid
O&M	Operation and Maintenance
P&T	Pump and Treat
pH	Power of Hydrogen
Redox potential	Reduction/Oxidation Potential
SVOC	Semi-Volatile Organic Compounds
VOC	Volatile Organic Compounds

Glossary

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	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.
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.
Groundwater	Water stored in the pores and crevices of the material below the land surface, including soil, rock and fill material.
Hydraulic containment	The deliberate control of movement of contaminated ground water, typically to prevent the continued expansion or migration of a dissolved phase plume of contamination
Influent concentrations	The concentration of contaminants entering a treatment system

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.
Pump and treat	A remediation method involving the extracting the contaminated groundwater and treating the contamination above ground. Treated water is then either disposed of offsite or reinjected.
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.
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.
Treatability studies	A series of tests designed to ascertain the suitability of the treatment for the contaminants under the site conditions

Measurements

Unit or symbol	Expansion
cm/s	Centimetres per second
L/min	Litres per minute

Chemical symbols, formulae and abbreviations

Symbol or abbreviation	Meaning or expansion
Fe	Iron
Mn	Manganese

Table of contents

1. Introduction

The purpose of this guideline is to provide information on pump and treat (P&T) 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).

P&T is often coupled with hydraulic control and treated groundwater is sometimes reinjected, therefore the scope of this guideline includes hydraulic control and reinjection.

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

P&T is 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 P&T 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

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. This guide uses the term P&T in a broader sense to include any system where extraction of groundwater is part of a remediation strategy (whether this be contaminant mass removal or containment), and reinjection where this is part of the P&T strategy. Variations and enhancements of conventional P&T include hydraulic fracturing as well as chemical and biological enhancements.

Although the effectiveness of P&T systems has been questioned (residual source material remaining in the formation and rebound of contaminants is a common problem), it remains a necessary component of many groundwater remediation efforts and can be applied as a remedial method. It may also include hydraulic control and reinjection to enhance the remediation process.

Reviews presented in US EPA (1992) found that:

- In most of the cases studied (15 of the 24 sites), the groundwater extraction systems were able to achieve hydraulic containment of the dissolved phase contaminant plume;
- Extraction systems were often able to remove a substantial mass of contamination from the aquifer; and
- When extraction systems were started up, contaminant concentrations usually showed a rapid initial decrease, but then tended to level off or decrease at a greatly reduced rate.

P&T is an applicable component of many remedial systems. However, such a system may not be appropriate depending on the hydrogeological and contaminant properties, such as where significant volumes of light and/or dense non aqueous phase liquids (LNAPLs/DNAPLs) are trapped at or below the water table.

2.1 Types of P&T

Strategies for managing groundwater contamination using P&T technology include:

- Hydraulic/physical containment;
- Aquifer restoration; and
- Mixed objective strategies.

For sites where the contaminant source has been removed or contained, it may be possible to remediate the dissolved plume using P&T. Systems designed for aquifer restoration generally combine hydraulic containment with more aggressive manipulation of groundwater (e.g. higher pumping rates, chemical enhancement) to meet the remediation criteria. Aquifer restoration is typically much more difficult to achieve than hydraulic containment.

Several innovative technologies, such as air sparging, engineered bioremediation and permeable treatment walls, can be used in conjunction with P&T (or alone) to achieve the remediation objectives.

2.1.1 *Hydraulic containment*

Hydraulic containment refers to the control of movement of contaminated groundwater, typically to prevent the continued expansion or migration of a dissolved phase plume but can also apply to source containment.

Figure 1 illustrates three major configurations for accomplishing hydraulic containment, in plan and section:

- A pumping well alone (a).
- A subsurface drain combined with a pumping well (b).
- A pumping well within a barrier wall system (c).

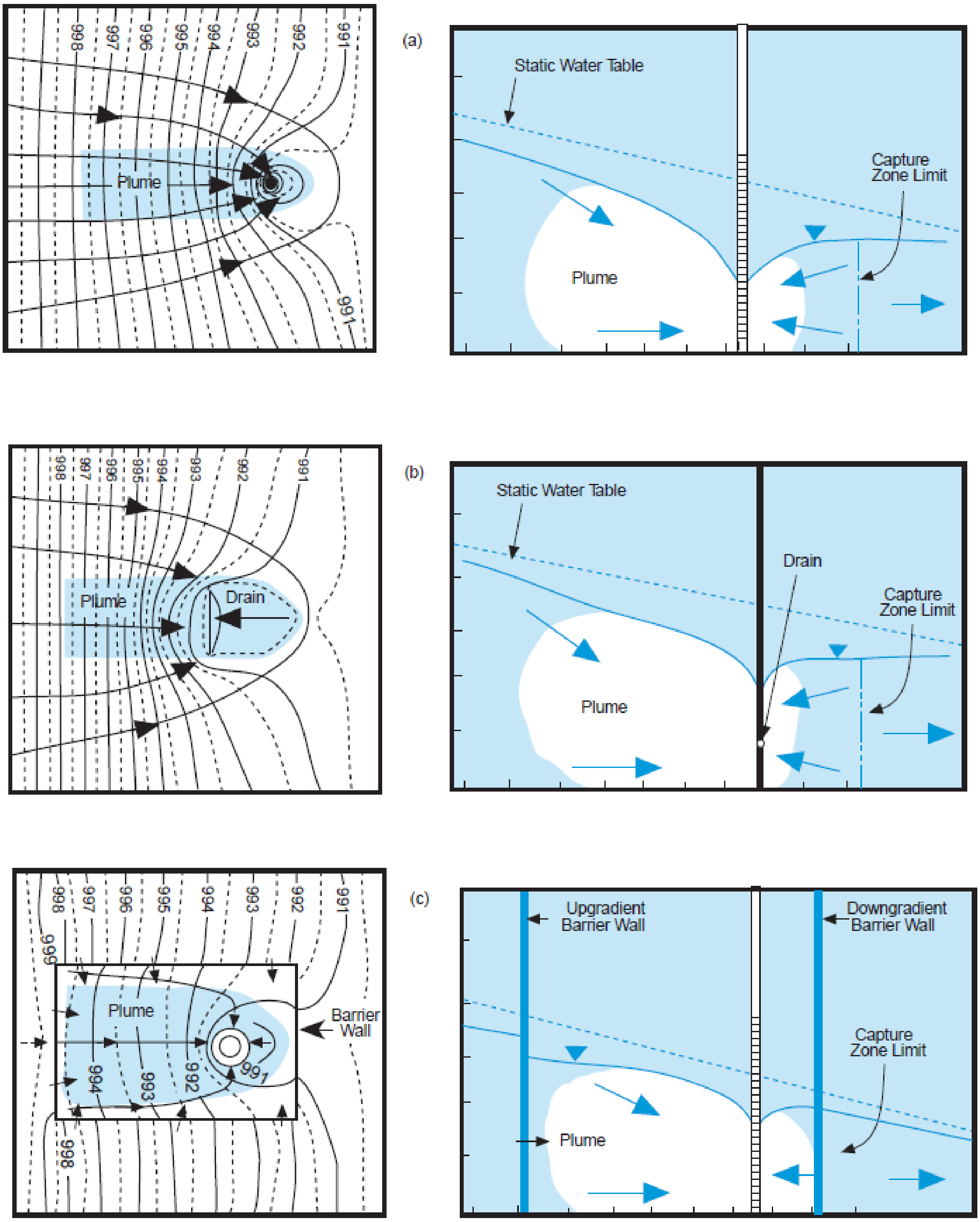


Figure 1 Examples of hydraulic containment from US EPA (2002)

It is also possible to intercept clean, up gradient groundwater to prevent or minimise the flow of groundwater through the contaminated source zone and to minimise the off-site migration of the contaminant plume.

2.1.2 *Aquifer restoration*

Aquifer restoration refers to P&T systems that can be used to reduce the dissolved contaminant concentrations in groundwater sufficiently to comply with the remediation criteria or to reach sufficiently low contaminant concentrations that allow other more cost-effective methods (such as chemical or biological enhancement, or monitored natural attenuation) to be applied. Aquifer restoration systems can also provide treated water that is suitable for reuse.

2.2 Potential limitations to P&T

Contaminant concentrations in groundwater at P&T sites often undergo what is referred to as ‘tailing’ and ‘rebound’ over the course of the P&T implementation, which can limit the effectiveness of the technology.

‘Tailing’ refers to the progressively slower rate of dissolved contaminant concentration observed with continued operation of a P&T system, with the contaminant concentration that will be achieved in the long term often exceeding the designated remediation criteria.

At sites where most of the contaminant mass is present in a form or location where it is not readily extracted, such as NAPL, an adsorbed-phase, or in a material with low permeability (such as clay), the rate of mass transfer of contaminants into the more readily extractable groundwater will be slow and this can result in a prolonged remediation effort. Often the aquifer will be heterogeneous and there will be complex pathways involving low and high permeability, and in this situation the slow diffusion of contaminants from low permeability zones during P&T will result in tailing and rebound.

‘Rebound’ comprises the return of the dissolved contaminant concentrations to or near to pre-pumping levels if pumping is discontinued after temporarily attaining the remediation criteria.

3. Feasibility assessment

Key considerations that will often determine the feasibility of applying P&T as a potential remediation option include:

- Whether the reduction in contaminant concentration and mass with time is sufficiently well characterised, and the required time to achieve an acceptable outcome is consistent with pump and treat providing a practicable solution; and
- Whether pump and treat offers benefits other than providing a final solution to the contamination problem, such as providing hydraulic containment or a reduction in mass flux or mass.

3.1 Data requirements

The physical composition of the aquifer to be treated needs to be well characterised. Important factors are described in Table 1 below.

Table 1 Hydrogeological and hydraulic parameters important to P&T performance

Parameter	Affects the following P&T performance mechanisms	Source of Information
Hydraulic Conductivity	Ease with which water can move through a formation, the rate at which groundwater can be pumped for treatment, and the total flow rate of the system.	• Groundwater pumping tests. • Rising and falling head permeability tests.
Permeability	Rate at which groundwater can travel in the subsurface (thus affecting pumping rates and volume of groundwater that can be extracted for treatment).	• Soil texture classification. • Bore logs.
Hydraulic Gradient	Direction of contaminant movement based on the elevation and pressure differences.	• Groundwater elevation contour plans.
Transmissivity	Rate at which groundwater can be pumped; total flow rate of the system.	• Pumping tests • Rising and falling head permeability tests.
Groundwater Velocity	• Direction and velocity of dissolved contaminant movement. • Important when designing a containment system.	• Hydraulic conductivity. • Hydraulic gradient. • Effective porosity.

Parameter	Affects the following P&T performance mechanisms	Source of Information
Porosity	Volume of water and mass of contaminants stored in pores; hydraulic conductivity. Fate of the contaminants due to various physical, chemical, and biological processes that take place in the saturated zone.	• Soil texture classification. • Sieve analysis.
Effective Porosity	Groundwater velocity.	• Soil texture classification. • Sieve analysis.
Storage Coefficient	Quantity of groundwater that can be obtained by pumping.	Groundwater pumping tests, with observation bores.
Specific Yield	• Fraction of total pore volume released as water by gravity drainage during pumping of an unconfined aquifer. • Quantity of groundwater that can be obtained by pumping.	Groundwater pumping tests, with observation bores.
Contaminant Mass Flux	Mass of contaminant flowing off-site	Hydrogeological parameters and analysis

3.2 Treatable contaminants

Hydrogeological and contaminant conditions favourable to P&T (e.g. degradable dissolved contaminants in homogenous, permeable media) are summarised in Table 2 below. These can also be used as a basis for an initial screening assessment of P&T feasibility.

Table 2: Summary of favourable conditions for P&T

	Contaminant and hydrogeological characteristics	Generalised restoration difficulty scale *Increasing difficulty* →
Site use	Nature of release	Small volume → Large volume
		Short duration → Long duration
		Slug release → Continuous
Contaminant properties	Biotic/abiotic decay potential	High → Low
	Volatility	High → Low
	Sorption potential	Low → High
	Contaminant phase	Aqueous → LNAPL → DNAPL

Contaminant distribution	Volume / mass	Small → Large
	Depth	Shallow → Deep
Geological conditions	Stratigraphy	Simple → Complex
	Porous media type	Coarse → Fine
	Heterogeneity	Low → High
Hydrogeological conditions	Hydraulic conductivity	High → Low (>0.01 cm/s) (<0.0001 cm/s)
	Temporal variation	Small → Large
	Vertical flow	Small → Large

P&T is designed to remediate contaminants which are dissolved in groundwater and which can be removed via groundwater extraction. Table 3 provides some parameters and sources of information to characterise the contamination.

Table 3: Parameters and information sources for P&T

Parameter	Description	Sources of information
Are the contaminants of concern (COCs) organics?	The suite of treatment technologies applicable to organics includes various separation and destruction techniques, both biological and physical/chemical.	Laboratory analysis
If organic, are they chlorinated?	The presence of chlorinated organics suggests that aerobic biological treatment process may not be applicable.	Laboratory analysis
If organic, are they highly water soluble?	Water-soluble organics (such as alcohols and ketones) are difficult to remove using common separation technologies (i.e. carbon adsorption or air stripping); however, they can be amenable to biological or chemical techniques.	Literature, laboratory analysis
If organic, are they extremely insoluble?	The presence of extremely insoluble organics (such as PCBs or multi-ring PAHs) in groundwater, at concentrations above their solubility limit, suggests that the organics are adsorbed to colloidal solids, and that colloidal solids removal will be required.	Literature, laboratory analysis

Parameter	Description	Sources of information
Are the COCs inorganic?	The suite of technologies applicable to inorganics is generally limited to physical/chemical separation techniques. Some non-metals (i.e. nitrates, ammonia) can be treated biologically.	Laboratory analysis
Are both organics and inorganics present?	Separate treatment technologies may have to be incorporated in the treatment train, with consideration to the preferred order of treatment.	Laboratory analysis
Is the contaminant present as a NAPL?	Priority should be given to remove the separate phase contaminants (either as LNAPL or DNAPL) to minimise the continuous solubilisation of contaminants into the aqueous phase.	Laboratory analysis. If NAPL present, analyse for viscosity, density, weathering

4. Treatability studies

There are generally two types of treatability studies which need to be completed prior to P&T implementation:

- Characterising the hydrogeological limitations on extracting groundwater; and
- Exploring treatment of the extracted groundwater so that it may be managed or disposed of appropriately.

4.1 Aquifer testing

Long-term aquifer tests and phased system installations are often cost-effective means of acquiring field scale hydrogeological and P&T design data. Aquifer tests should be conducted to acquire field scale measurements of hydrogeological properties, such as formation permeability, transmissivity and storage coefficient, that are critical to P&T system design. Test results can be used to:

- Determine well pumping rates and drawdowns.
- Assess well locations and pumping rates needed for full-scale operation.
- Evaluate the design of well and treatment system components.
- Estimate capital and operation and maintenance (O&M) costs.

Readers are referred to Driscoll (1986) and US EPA (1990) for more information on procedures for conducting and analysing aquifer tests. The number and duration of tests required to obtain sufficient data to design a P&T system depends on many factors including plume size, the distribution of hydrogeological units, their hydraulic properties, and hydrogeological boundary conditions. In order to calculate basic aquifer properties, pumping tests should be run until steady state conditions are reached.

In general, multiple tests will be warranted at large and complex sites. Test design parameters (including specification of observation well locations, test duration, and pumping rate) can be assessed using groundwater monitoring well (GWMW) hydraulics solutions, groundwater flow models, and/or by conducting short-term step tests. Observation GWMWs should be located close enough to the pumping GWMW to ensure adequate responses to pumping stress. Drawdowns will depend on site specific aquifer hydraulic properties that influence groundwater elevations during the test.

GWMWs should also be located so that data may be used to evaluate heterogeneity and anisotropy, if warranted. Although reasonable estimates of formation transmissivity can generally be obtained using data acquired during the first several hours of pumping (if observation GWMWs are close to the pumping GWMWs), it may be advisable to extend aquifer tests to days or weeks to evaluate capture zones, boundary conditions and groundwater treatability issues. Rising and falling head permeability tests can also be used to augment aquifer test results. However, short term aquifer, and rising and falling head permeability tests, generally are not as reliable indicators of system performance as long term aquifer tests.

Disposal options for aquifer test water are subject to site conditions and regulations but may include discharge to a storm or sanitary sewer, discharge to ground, discharge to surface water, reinjection to the subsurface, or transport to an off-site disposal facility. Regulatory agencies should be contacted to determine disposal requirements.

Characterising groundwater flow and contaminant transport is particularly challenging in heterogeneous media, especially where contaminants have migrated into fractured rock. Methods for characterising fractured rock settings include drilling/coring, aquifer tests, packer tests, tracer tests, surface and borehole geophysical surveys, borehole flow meter surveys, and air photograph fracture trace analysis.

At the scale of many contaminated sites, complete characterisation of fractured rock (and other heterogeneous media) may be economically infeasible, and unnecessary to design an effective P&T system. The appropriate characterisation methods and level-of-effort must be determined on a site-specific basis.

4.2 Potential for fluid injection

Artificial fluid injection/recharge can be used to:

- Achieve or improve hydraulic control;
- Flush contamination zones;
- Deliver amendments (e.g. nutrients, bacteria); and
- Minimise screen clogging.

Effluent from the groundwater treatment plant may be able to be disposed of by recharge, injected above or below the water table via wells, trenches, drains, or surface application (sprinkler, furrow, or basin infiltration). Recharge is typically controlled by maintaining the water level in injection wells or drains or by pumping at specified rates. Regulatory agencies should be contacted to determine injection permit requirements.

Aspects of site characterisation important to fluid injection design include determination of:

- Site stratigraphy and permeability distribution;
- Hydrogeological boundary conditions;
- Possible injection rates and resulting hydraulic head and groundwater flow patterns; and
- The potential for well and formation clogging due to injection.

Potential problems with the use of injection include undesired horizontal or vertical contaminant migration due to the increased hydraulic gradients. Sites where injection is to be used should be carefully characterised and monitored to ensure that contamination issues are not exacerbated.

Hydraulic parameters estimated from analysis of standard aquifer tests are often used to design injection systems. Constant head, constant-rate, and stepped rate or head injection tests can also be conducted to evaluate hydraulic properties and injection potential using standard aquifer test procedures. More discrete techniques (e.g. packer tests, borehole flow meter surveys) may be desirable to identify high permeability zones. Hydraulic heads and groundwater flow patterns resulting from injection can be examined and predicted using well or drain hydraulics equations and groundwater flow models.

Such analysis can also be used to determine potential injection rates, durations and monitoring locations for injection tests. In addition to helping estimate formation hydraulic properties, injection tests provide information on clogging issues that can be critical to injection design.

The most common problem associated with fluid injection is permeability reduction due to clogging of screen openings. This causes a decline in injection rates. Clogging can result from physical filtration of solids suspended in injected water, chemical precipitation of dissolved solids, or the excessive growth of microorganisms (also known as bio-fouling).

In general, the injection capacity of a system is often overdesigned by a significant factor (e.g. 1.5 to 2) to account for loss of capacity under operating conditions due to such problems as permeability reduction and the temporary loss of capacity during GWMW maintenance. The optimal degree of overdesign is site specific and will depend on such factors as the rate at which clogging occurs and the cost of maintenance.

The potential for GWMW clogging and correction measures can be examined by analysis of the injected fluid and bench scale testing. In general, injection water should contain:

- No suspended solids to minimise clogging;
- Little or no dissolved oxygen, nutrients, and microbes to minimise bio-fouling; and
- Low concentrations of constituents that may precipitate with changes in pH, redox, pressure, and temperature conditions (e.g. iron and manganese).

Column permeation tests can be conducted to examine changes in hydraulic conductivity resulting from injection. Due to the potential significance of many hydrogeological, physical, and chemical factors, however, fluid injection is best evaluated by conducting extended injection tests during which injection rates and hydraulic heads are monitored carefully. Results of field tests help define formation hydraulic properties, potential injection rates, injection well spacing, mounding response and clogging potential. Dissolved or suspended solids may need to be removed from water by aeration, flocculation, and filtration prior to injection. Similarly, nutrients and/or dissolved oxygen may need to be removed to prevent bio-fouling. Water should be injected below the water table through a pipe to prevent its aeration in the well.

Injecting warm water can also promote bio-fouling. Clogging problems can be minimised by overdesigning injection capacity (e.g. by installing more GWMWs, longer screens, etc.) and implementing a regular GWMW maintenance program. Extraction and injection rate monitoring and GWMW inspection, using a downhole video camera or other means, can help identify GWMWs in need of treatment or replacement. Periodic rehabilitation of GWMWs or drains (by surging, jetting, chlorination, or acid treatment) may be required to restore declining injection rates. Chemical incrustation can be addressed by acid treatment, backwashing, mechanical agitation (with a wire brush or surge block), and pumping. Strong oxidising agents, such as a chlorine solution, can be used in conjunction with backwashing, mechanical agitation, and pumping to treat wells damaged by slime-producing bacteria. Acidification and chlorination, however, may interfere with interpretation of groundwater chemistry data. Fine particles can be removed (to some extent) using standard GWMW development techniques. Experienced well drillers should be contacted for advice on rehabilitation methods. These potential problems need to be considered when projecting P&T costs. Significant maintenance may be required at many sites to retain desired injection capacity. Readers are directed to Pyne (1995) for more detailed discussions of the engineering aspects of water injection.

4.3 Chemical enhancement

Chemical enhancement of P&T systems can accelerate aquifer remediation, however there are many aspects of chemical enhancement that need to be known before these techniques can be successfully implemented.

The reactive agents may be chosen to:

- Increase adsorption capability;
- Change the redox state of the contaminant;
- Act as a surfactant;
- Oxidise or ionise the contaminant; or
- Substitute the contaminant in a precipitate.

If the reactive agents are chosen on the basis of incorrectly identified limiting processes, there is a risk that the reactive agents will provide no net benefit and may even prolong remediation.

When a reactive agent is found that specifically addresses the limiting chemical process, other considerations must be investigated to assure successful implementation. The key areas of concern in any chemical enhancement method are the:

- Delivery of the reactive agent to those areas of the aquifer where it is needed;
- Enhanced removal of the target contaminants by the reactive agent;
- Removal of the reactive agent from subsurface; and
- Impact of the reactive agent on the treatment of the target contaminant and the volume of sludge to be disposed of.

Figure 2 is a schematic of how chemical enhancement can be used as a supplement to P&T systems

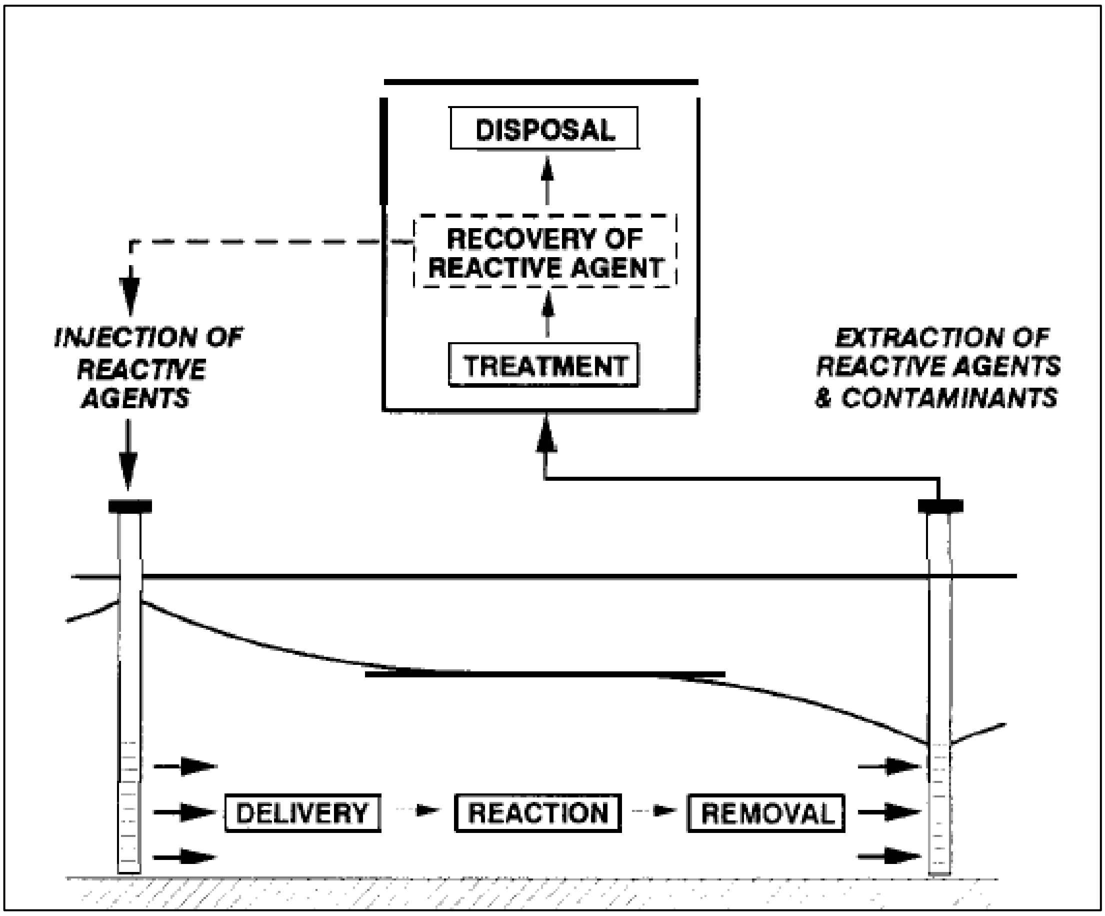


Figure 2: Schematic of using chemical enhancement to supplement P&T systems

4.4 Treatment technologies

Once contaminated groundwater has been extracted, it typically must be treated prior to discharge / disposal. As such, treatability studies for P&T systems typically involve assessing which above ground treatment technique(s) is/are the most appropriate.

Treatability data needed for design of groundwater treatment systems generally should be acquired by conducting chemical analyses and treatability studies on contaminated groundwater extracted during aquifer tests. Analysis of water samples obtained at different times during an aquifer test often will provide data regarding the initial range of contaminant concentrations in influent water to the treatment plant.

Bench tests and pilot trials are valuable means for evaluating the feasibility of different processes for treating contaminated groundwater. Bench tests use small quantities of extracted groundwater to provide:

- Preliminary data on various treatment processes;
- Pre-treatment requirements; and
- Estimates of costs.

During pilot scale tests, skid-mounted or mobile pilot equipment is operated to study the effect of varying system parameters (e.g. flow rate) on treatment results and to identify potential problems, such as chemical precipitation of dissolved iron and manganese in an air stripper.

Air stripping and granular activated carbon (GAC) units may be used to remove organic compounds from groundwater during aquifer tests and ion exchange/adsorption can be used to remove most metals. Air stripping is generally more cost-effective than GAC for treating volatile organic compounds when flow rates exceed approximately 15 L/min, but may require additional vapour phase treatment.

Treatment methods for P&T systems generally fall into two main categories, biological and physical/chemical. A description of these is presented in Table 4.

Table 4: Description of treatment methods

Category	Description	Type
Biological	Uses micro-organisms to degrade organic compounds and materials into inorganic products. These methods may be applicable for treatment of organic compounds if concentrations are low and the biological processes are not inhibited	• Activated sludge systems • A sequencing batch reactor • Powdered activated carbon in activated sludge (biophysical system) • Rotating biological contactors • An aerobic fluidised bed biological reactor
Physical / Chemical	Physical, chemical, or a combination of physical and chemical methods can be used to remove contaminants from groundwater	• Air stripping • Granular activated carbon (GAC) • Ion exchange • Reverse osmosis • Chemical precipitation of metals • Chemical oxidation • Chemically assisted clarification • Filtration • Ultraviolet (UV) radiation oxidation

Table 5 provides a summary of key aspects of treatment technologies commonly used in conjunction with P&T systems.

Table 5 Summary of key aspects of treatment technologies

Type of contaminant	Technology	General advantages	General disadvantages
Organic	Air stripping	• Appropriate for most VOCs and some SVOCs; • Low operator labour needs relatively low O&M costs relatively low capital costs	• Not appropriate for many SVOCs and other non-VOCs • Off-gas often needs treatment
	GAC	• Appropriate for many organic compounds, including VOCs, SVOCs, and other non-VOCs • Remove some metals and other inorganics (generally < 90% efficient) • Low operator labour needs • Relatively low O&M costs (when used for appropriate situations) • Relatively low capital costs	• Not appropriate for some organic compounds (usually low molecular weight VOCs) • More likely to need pre-treatment for solids removal than air stripping • Off gas may need dehumidifying prior to GAC to prevent condensation and wetting • May require backwashing as a maintenance measure • Production of a waste material containing high concentrations of the contaminant
	Polymeric resin	• Appropriate for some constituents that are not effectively treated by GAC • Low operator labour needs • Effective for high contaminant concentrations, especially with on-site regeneration	• Contaminant specific and not appropriate for process water with many constituents • More expensive than GAC for many common contaminants at typical concentrations found in ground water • Need for regeneration or disposal of resin.
	Biological treatment	• Often effective for constituents that are not easily removed by air stripping or GAC (e.g. ketones, ammonia) • Fixed-film units reduce nutrient usage	• Relatively operator intensive relative to air stripping or GAC • Generates solids that may need disposal

Type of contaminant	Technology	General advantages	General disadvantages
	UV oxidation	• Destroys wide range of organic compounds on-site and does not need off-gas treatment • Appropriate for some constituents that are not easily removed by other methods (e.g., 1,4-Dioxane) • Can avoid waste production.	• High capital costs relative to air stripping and/or GAC • Often has higher O&M costs than air stripping or GAC • More likely to need pre-treatment for metals and/or solids (to prevent fouling) than air stripping or GAC
Inorganic	Filtration	• Low operator labour needs • Often relatively low capital and O&M costs	• Does not remove dissolved substances. • May not be sufficient to remove colloidal solids and/or metals to discharge standards • Filter cake or bag or cartridge filters might need frequent replacement and disposal
	Settling and/or metals Precipitation	• Effective and reliable for metals removal including chromium and arsenic (with proper pH adjustments, and addition of an oxidant if necessary)	• Operator intensive • Relatively high capital and O&M costs relative to other treatment components • May generate a substantial amount of solids that need disposal
	Solid phase partitioning and ion exchange	• Low operator labour needs • Available for various metals • Can achieve very low concentrations	• Need for regeneration of resin, disposal of regenerant • Not cost-effective for high concentrations • Not for removal of multiple constituents

Figure 3 presents a matrix showing which treatment methods apply to particular chemical compounds.

Contaminants	Neutralization	Precipitation	Coprecipitation/Coagulation	UV/Ozone	Chemical Oxidation	Reduction	Distillation	Air Stripping	Steam Stripping	Activated Carbon	Evaporation	Gravity Separation	Flotation	Membrane Separation*	Ion Exchange	Filtration	Biological	Electrochemical
Metals																		
Heavy metals	X	●	●	X	X	○	X	X	X	○	●	●	X	●	●	●	X	●
Hexavalent chromium	X	●	X	X	X	●	X	X	X	○	●	X	X	○	●	X	X	●
Arsenic	X	○	●	○	○	X	X	X	X	○	X	○	X	●	●	●	X	X
Mercury	X	●	●	X	X	●	X	X	X	●	X	○	X	○	●	●	X	X
Cyanide	X	X	X	●	●	X	X	X	X	X	●	X	X	●	●	X	○	○
Corrosives	●	●	X	X	X	X	○	X	X	X	X	X	X	X	X	X	X	X
Volatile organics	X	X	X	○	●	X	●	●	●	●	X	X	X	○	○	X	○	X
Ketones	X	X	X	○	●	X	●	●	●	X	X	X	X	X	X	X	●	X
Semivolatile organics	X	○	○	●	●	X	●	X	●	●	○	○	○	●	●	X	●	X
Pesticides	X	○	○	●	●	X	●	X	○	●	○	○	○	●	●	●	○	X
PCBs	X	●	●	●	●	X	●	X	X	●	●	●	●	●	●	●	○	X
Dioxins	X	●	●	●	○	X	●	X	X	●	●	●	●	●	●	●	○	X
Oil and grease/floating products	X	●	●	X	X	X	●	X	X	X	●	●	●	●	●	○	○	X

● Applicable ○ Potentially Applicable X Not Applicable

Figure 3: Applicability of treatment technologies to contaminated groundwater

5. Design

There are several parameters that must be considered when designing a P&T system. These are described in Table 6 below.

Table 6: Parameters pertinent to the design of P&T systems

Parameter	Description
Design flow rate	Expected flow rate of P&T system calculated from estimated extraction rates necessary to achieve remediation objectives (e.g. plume capture). This value should be used to select treatment components and to calculate the design mass removal rate.
Hydraulic capacity	Maximum expected flow rate of P&T system, generally calculated by multiplying the design flow rate by a factor of safety greater than 1.0. This value should be used to size pumps, piping, and tanks but should not be used to calculate the design mass removal rate
Design influent concentration (for each constituent or class of constituents in system influent):	Expected blended influent concentration from all extraction sources based on concentrations obtained from sustained pumping conditions (e.g. after more than 24 hours of pumping in a pumping trial; not from routine monitoring data). This value should be used to calculate the design mass removal rate.
Maximum influent concentration (for each constituent or class of constituents in system influent)	Maximum expected blended influent concentration from combined extraction, typically calculated by multiplying the design influent concentration by a factor of safety between 1.0 and 2.0. The treatment system should be able to handle this concentration. This value should be used to help select a treatment process, but should not be used to calculate the design mass removal rate
Design mass loading rate (for each constituent or class of constituents in system influent):	Estimated mass loading rate (kilograms per day) to the treatment plant of contaminants in extracted ground water, calculated by multiplying the design flow rate by the design influent concentration. This value should be used for estimating materials/utilities usage when analysing costs of various treatment options.

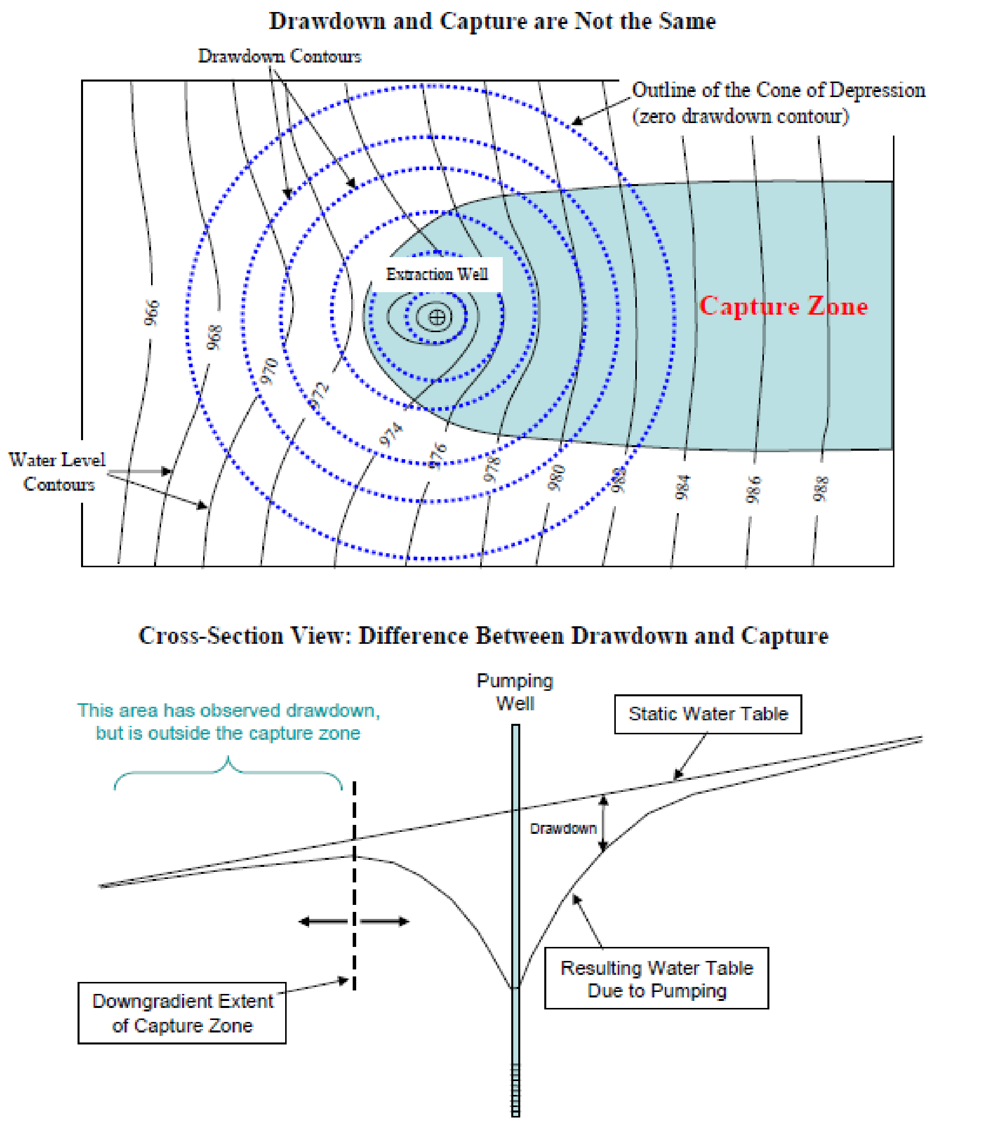
5.1 Design flow rates

P&T design flow rates are refined by performing field tests, modelling alternative injection / extraction schemes, and monitoring system performance. The first step in establishing design criteria, after characterising pre-remediation groundwater flow patterns and contaminant distributions, is to determine the desired containment and/or restoration area (two-dimensional) and volume (three-dimensional). These should be clearly specified in the remedial design and monitoring plans.

5.2 Capture zone analysis

After defining the proposed containment area, a capture zone analysis is conducted to design the P&T system and a performance monitoring plan is developed based on the predicted flow field. The capture zone of an extraction well or drain refers to that portion of the subsurface containing groundwater that will ultimately discharge to the well or drain.

It is important to realise that the capture zone of a well is not coincident with its drawdown zone of influence (or cone of depression), the extent of which depends largely on aquifer transmissivity and pumping rate under steady conditions. This is because the shape of the capture zone also depends on the natural hydraulic gradient. Relatively high natural hydraulic gradients result in narrow capture zones that do not extend far in the down gradient direction. Therefore, some side gradient and down gradient areas within the cone of depression of an extraction well will be beyond the capture zone. Figure 4 illustrates this concept.



Drawdown is the change of water level due to pumping. It is calculated by subtracting water level under pumping conditions from the water level without pumping.

Cone of Depression is the region where drawdown due to pumping is observed.

Capture Zone is the region that contributes the ground water extracted by the extraction well(s). It is a function of the drawdown due to pumping and the background (i.e., without remedy pumping) hydraulic gradient. The capture zone will only coincide with the cone of depression if there is zero background hydraulic gradient.

Figure 4: Schematic illustrating the difference between drawdown and capture

5.3 Design influent concentration

With respect to estimating design influent concentrations, this can be calculated using data from representative wells, which should be averaged (weighted based on the flow per well) to give the design influent concentrations for each constituent. The use of concentration data obtained during sustained pumping conditions, rather than during non-pumping or low flow conditions, reduces the chance of over designing the system to handle an erroneously high mass removal rate.

5.4 Efficient Pumping Operations

Removal of contaminated groundwater should be a dynamic process that uses information on the response of the groundwater system to improve the efficiency of pumping operations. Elements of efficient pumping operations are presented in Table 7.

Table 7: Elements of efficient pumping operations

Element	Description
Combined plume containment and source remediation	which can be achieved through the design of the initial pumping flow field. This can limit the area requiring remediation and maximise contaminant removal.
Phased construction of extraction wells,	which allows data on the monitored response of the aquifer to pumping operations to be used in siting subsequent wells.
Adaptive pumping	which involves designing the well field such that extraction and injection can be varied to reduce zones of stagnation. Extraction wells can be periodically shut off, others turned on, and pumping rates varied to ensure that contaminant plumes are remediated at the fastest rate possible.
Pulsed pumping,	which has the potential to increase the ratio of contaminant mass removed to groundwater volume where mass transfer limitations restrict dissolved contaminant concentrations. Figure 5 illustrates the concept of pulsed pumping. During the resting phase of pulse pumping, contaminant concentrations increase due to diffusion, desorption, and dissolution in slower moving groundwater. Once pumping is resumed, groundwater with a higher concentration of contaminants is removed.

The pulsed pumping concept is illustrated in Figure 5 below.

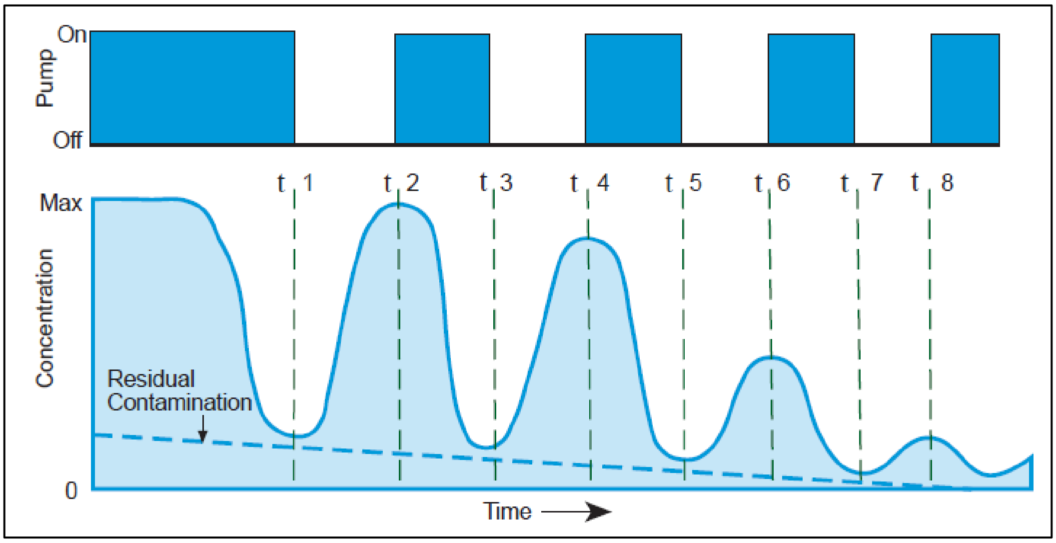


Figure 5: Schematic illustrating the pulsed pumping concept

6. Validation

The following information describes the specific validation appropriate for P&T, 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.

Recommended lines of evidence for the validation of P&T systems include:

- Documented reduction in COC concentrations;
- Field measurements; and
- Geophysical survey data.

Figure 6 outlines procedures for determining the success and/or timeliness of closure of a P&T system.

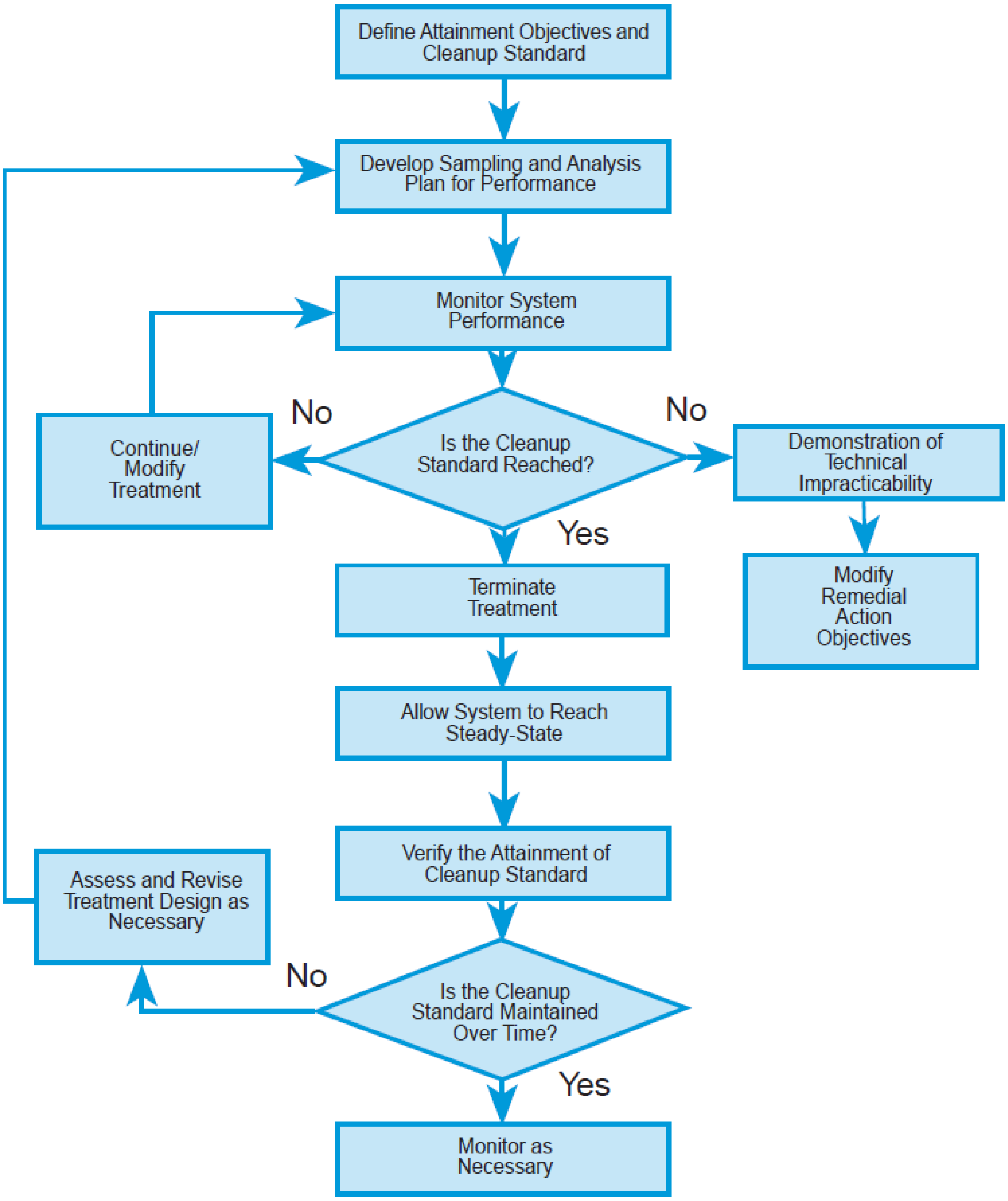


Figure 6: Flow chart to predict the success and/or timeliness of closure of a P&T system

Groundwater sampling and analysis can be used to determine when concentrations of COC have dropped to the point where remedial objectives have been met, or whether further extraction is no longer efficient. It is important to note that concentrations may rebound to exceed validation criteria, due to diffusion from secondary sources or fluctuations in the water table mobilising contaminants. Contaminated groundwater is likely to persist in areas with lower permeability and transmissivity following the extraction of contaminants from areas of higher hydraulic conductivity and may serve as a secondary source to re- contaminate these areas. Sampling of less permeable materials using core samples can be undertaken to assess the extent to which lower hydraulic conductivity media are impacted. Geophysical methods may be appropriate in monitoring the distribution of any residual contamination and the depth of migration of high concentrations of ionic contaminants such as chloride.

Groundwater monitoring wells should be located:

- Up-gradient of the plume;
- Within the plume;
- Down-gradient of the plume;
- Aligned parallel to the direction of groundwater flow; and
- Aligned cross-gradient to the direction of groundwater flow.

This arrangement allows the delineation of the lateral and vertical extent of the plume following remediation to assess the subsurface distribution of contaminants and their mobility. Data collected from outside the remediation area are essential to determine background concentrations and can be used to assess and quantify the migration of contaminants beyond the remediation area. Natural attenuation should be accounted for when assessing the efficacy of pump and treat systems.

7. Health and safety

Common health and safety hazards associated with P&T remediation systems are highlighted in Table 8, together with possible control measures. The list is intended to provide an indication of the hazards potentially associated with P&T application. They will vary significantly from site to site and the list is not intended as a substitute for a detailed hazard assessment of the operation, which should be provided in the RAP.

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 8 Common pump and treat hazards and controls

Hazard	Sources of hazard	Suggested controls
Site contaminants Chemical exposure	• Dermal or inhalation exposure to contaminants in groundwater. • Release of untreated water.	• Use of appropriate personal protective equipment (PPE), including gloves protective clothing that are suitable for the task e.g. ensure they provide chemical resistance to the hazardous chemicals. Refer AS/NZS 2161, AS/NZS 1336, and AS/NZS 4501. • If necessary, use respiratory protection that is suitable for the task and selected used and maintained in accordance with AS/NZS 1715. • Pump and treat system should have an alarm for any parameter value that is outside of the typical operating range. The alarm should link to the system controls to prevent a release of untreated water (or other problems) by shutting down the relevant system components or the entire system as appropriate. • Typical parameters for which alarms are installed include: • High tank levels (including PSH tanks). • High differential pressure across a filter. • High or low blower air stripper. • Well vault or building sump water accumulation. • Low water flow in the treatment system. • Lower explosive limit (LEL) detection. • Other system specific items.

Hazard	Sources of hazard	Suggested controls
Explosion and fire	Vapour concentrations exceed the lower explosion level, or flammable and combustible liquid or solid material is present (for example, if hydrocarbons are involved)	• Use of appropriate hazard rated equipment and storage.
Ergonomic risks	Lifting or performing any other movement with too much force and/or in an awkward position, or repeating the lift/movement too often.	• Provide conveniently located equipment for the job, like carts, adjustable work stations (operators), and correctly sized tools. • Train workers on ergonomic risks and prevention.
Slips, trips and falls	• Storing construction materials or other unnecessary items on walkways and in work areas. • Creating and/or using wet, muddy, sloping, or otherwise irregular walkways and work surfaces. • Constructing and/or using improper walkways, stairs, or landings or damaging these surfaces. • Creating and/or using uneven terrain in and around work areas. • Working from elevated work surfaces and ladders. • Working in confined spaces • Using damaged steps into vehicles.	• Keep walking and working areas free of debris, tools, electrical cords, etc. • Keep walking and working areas as clean and dry as possible. • Install handrails, and guardrails on work platforms. • Clean and inspect ladders and stairs routinely. • Perform a Job Hazard Analysis. • Ensure workers use proper PPE, including fall arrest systems. • Train workers on fall hazards and use of ladders. • Use an observer (spotter or signal person) when visibility is limited.

Appendix A – Case studies

- The Orica Botany Bay Groundwater Remediation project:
  - Large and complex P&T system;
  - Designed to prevent discharge of contaminated groundwater to Botany Bay;
  - http://www.orica.com/Locations/Asia-Pacific/Australia/Botany/Botany-Transformation-Projects/Groundwater-Cleanup

There are numerous P&T case studies cited in the USEPA literature. Figure 7 summarises the projects reviewed in US EPA (2002). Readers are also directed to US EPA (2007) for further case studies.

RSE Report Name	EPA Document Number
Remediation System Evaluation, Oconomowoc Electroplating Superfund Site	EPA 542-R-02-008b
Remediation System Evaluation, MacGillis and Gibbs Superfund Site	EPA 542-R-02-008c
Remediation System Evaluation, Elmore Waste Disposal Superfund Site	EPA 542-R-02-008d
Remediation System Evaluation, FCX Statesville Superfund Site	EPA 542-R-02-008e
Remediation System Evaluation , Bayou Bonfouca Superfund Site	EPA 542-R-02-008f
Remediation System Evaluation, Midland Products Superfund Site	EPA 542-R-02-008g
Remediation System Evaluation, Savage Municipal Water Supply Superfund Site	EPA 542-R-02-008h
Remediation System Evaluation, Mattiace Petrochemical Superfund Site	EPA 542-R-02-008i
Remediation System Evaluation, Baird and McGuire Superfund Site	EPA 542-R-02-008j
Remediation System Evaluation, Cleburn Street Well Superfund Site	EPA 542-R-02-008k
Remediation System Evaluation, Hellertown Manufacturing Superfund Site	EPA 542-R-02-008l
Remediation System Evaluation, Raymark Superfund Site	EPA 542-R-02-008m
Remediation System Evaluation, Claremont Polychemical Superfund Site	EPA 542-R-02-008n
Remediation System Evaluation, Modesto Groundwater Contamination Superfund Site	EPA 542-R-02-008o
Remediation System Evaluation, Silresim Chemical Corp. Superfund Site	EPA 542-R-02-008p
Remediation System Evaluation, Comm. Bay/South Tacoma Channel, Well 12A Superfund Site	EPA 542-R-02-008q
Remediation System Evaluation, McCormick and Baxter Superfund Site	EPA 542-R-02-008r
Remediation System Evaluation, Ott/Story/Cordova Superfund Site	EPA 542-R-02-008s
Remediation System Evaluation, Brewster Wellfield Superfund Site	EPA 542-R-02-008t
Remediation System Evaluation, Selma Pressure Treating Superfund Site	EPA 542-R-02-008u

Figure 7: Summary of P&T projects reviewed in US EPA (2002)

Appendix B – References

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