

## AUSTRALIAN GUIDELINES 24 FOR WATER RECYCLING: MANAGING HEALTH AND ENVIRONMENTAL RISKS (PHASE 2)

### MANAGED AQUIFER RECHARGE

JULY 2009



Natural Resource Management Ministerial Council  
Environment Protection and Heritage Council  
National Health and Medical Research Council

**Natural Resource Management Ministerial Council**

**Environment Protection and Heritage Council**

**National Health and Medical Research Council**

# **Australian Guidelines for Water Recycling**

## **Managed Aquifer Recharge**

**National Water Quality Management Strategy**

**Document No 24**

**July 2009**

Web copy: ISBN 1 921173 47 5

Print copy: ISBN 1 921173 46 7

A publication of the Natural Resource Management Ministerial Council, Environment Protection and Heritage Council, and the National Health and Medical Research Council.

© July 2009

This work is copyright. It may be reproduced in part subject to the inclusion of acknowledgment of the source and no commercial sale.

The contents of this document have been compiled using a range of source materials, and, while reasonable care has been taken in its compilation, the member governments of the Natural Resource Management Ministerial Council, the Environment Protection and Heritage Council, and the National Health and Medical Research Council, and the organisations and individuals involved with the compilation of this document, shall not be liable for any consequences that may result from using the contents of this document.

Edited and produced by Biotext, Canberra

# Contents

<b>1</b>	<b>Introduction .....</b>	<b>1</b>
1.1	Origin and purpose of national guidelines on managed aquifer recharge .....	1
1.2	Scope of the managed aquifer recharge guidelines.....	3
1.2.1	Relationship with other guidelines.....	3
1.2.2	Sources of water, types of aquifers and purposes .....	6
1.2.3	Water allocation, water trading and other water governance issues .....	7
1.3	Stages of project development and assessment .....	8
1.4	How to use the managed aquifer recharge guidelines .....	10
<b>2</b>	<b>Managed aquifer recharge .....</b>	<b>13</b>
2.1	Definition, purposes and types of managed aquifer recharge.....	13
2.1.1	Definition and purposes of managed aquifer recharge .....	13
2.1.2	Types of managed aquifer recharge.....	15
2.2	Selection of recharge method.....	18
2.3	Benefits of managed aquifer recharge for recycling.....	19
2.4	Situations where managed aquifer recharge is not viable.....	20
2.5	Existing recharge increase and managed aquifer recharge .....	21
<b>3</b>	<b>Framework for managing aquifer recharge .....</b>	<b>23</b>
3.1	Element 1: Commitment to responsible use and management of recycled water quality .....	24
3.2	Element 2: Assessment of the managed aquifer recharge system .....	24
3.2.1	Hazard identification.....	25
3.2.2	Dose–response and exposure assessment of the identified hazards .....	25
3.2.3	Risk characterisation.....	25
3.3	Element 3: Preventive measures for recycled water management.....	26
3.4	Element 4: Operational procedures and process control.....	29
3.5	Element 5: Verification of water quality and environmental performance .....	29
3.6	Element 6: Management of incidents and emergencies.....	30
3.7	Element 7: Operator, contractor and end-user awareness and training .....	30
3.8	Element 8: Community involvement and awareness.....	30

3.9	Element 9: Validation, research and development .....	31
3.10	Element 10: Documentation and reporting.....	31
3.11	Element 11: Evaluation and audit.....	32
3.12	Element 12: Review and continuous improvement .....	32
<b>4</b>	<b>Stages of managed aquifer recharge project development and assessment.....</b>	<b>33</b>
4.1	Overview.....	33
4.2	Simplified assessment.....	39
4.3	Entry-level assessment.....	40
4.3.1	Entry-level assessment — viability .....	41
4.3.2	Entry-level assessment — degree of difficulty .....	43
4.4	Maximal risk assessment .....	51
4.5	Precommissioning residual risk assessment .....	51
4.6	Operational residual risk assessment .....	52
<b>5</b>	<b>Hazard identification and preventive measures .....</b>	<b>53</b>
5.1	Pathogens .....	57
5.1.1	Effect of pathogens on public health and the environment.....	57
5.1.2	Source of pathogens in managed aquifer recharge .....	57
5.1.3	Fate and behaviour of pathogens in managed aquifer recharge.....	58
5.1.4	Other preventive measures.....	62
5.1.5	Management of pathogens via managed aquifer recharge.....	62
5.2	Inorganic chemicals .....	64
5.2.1	Effect of inorganic chemicals on public health and the environment .....	64
5.2.2	Sources and fate of inorganic chemicals in managed aquifer recharge.....	64
5.2.3	Management of inorganic chemicals .....	68
5.3	Salinity and sodicity.....	70
5.3.1	Effects of salinity and sodicity on public health and the environment .....	70
5.3.2	Sources of salt in managed aquifer recharge .....	70
5.3.3	Management of salinity and sodicity .....	71
5.3.4	Mitigation of salinity and sodicity hazards in relation to stages of risk assessment .....	71
5.4	Nutrients: nitrogen, phosphorus and organic carbon.....	72
5.4.1	Effect of nutrients on public health and the environment.....	73
5.4.2	Sources and fate of nutrients in managed aquifer recharge.....	73
5.4.3	Management of nutrients .....	74

5.5	Organic chemicals.....	76
5.5.1	Effect of organic chemicals on public health and the environment .....	76
5.5.2	Sources and fate of organic chemicals in managed aquifer recharge.....	77
5.5.3	Management of organic chemicals .....	78
5.6	Turbidity and particulates .....	80
5.6.1	Effect of turbidity on public health and the environment.....	80
5.6.2	Sources of turbidity in managed aquifer recharge .....	81
5.6.3	Management of turbidity.....	81
5.7	Radionuclides.....	82
5.7.1	Effect of radionuclides on public health and the environment .....	83
5.7.2	Sources of radionuclides in managed aquifer recharge .....	83
5.7.3	Management of radionuclides.....	84
5.8	Pressure, flow rates, volumes and groundwater levels .....	85
5.8.1	Confined and semiconfined aquifers .....	85
5.8.2	Unconfined aquifers.....	90
5.9	Contaminant migration in fractured rock and karstic aquifers .....	94
5.10	Aquifer dissolution and stability of well and aquitard.....	99
5.10.1	pH and redox status of injectant.....	100
5.10.2	Labile organic carbon .....	100
5.10.3	Aquifer depletion .....	101
5.10.4	Surfactants.....	101
5.10.5	Algal blooms.....	101
5.11	Aquifer and groundwater-dependent ecosystems .....	103
5.11.1	Microorganisms .....	103
5.11.2	Stygofauna .....	104
5.11.3	Phreatophytic vegetation.....	105
5.11.4	Aquatic flora and fauna.....	105
5.11.5	Risk assessment and management for ecosystem protection.....	106
5.12	Energy and greenhouse gas considerations.....	110
<b>6</b>	<b>Operational issues and their management.....</b>	<b>113</b>
6.1	Clogging.....	114
6.1.1	Types and causes of clogging .....	115
6.1.2	Management of clogging .....	116
6.1.3	Tools for predicting clogging.....	119
6.1.4	Recharge water-quality requirements for sustained managed aquifer recharge operations.....	120
6.2	Salinity of recovered water .....	121
6.2.1	Recovery efficiency .....	122

6.2.2	Factors affecting mixing and recovery efficiency .....	123
6.2.3	Recovery efficiency data for Australian aquifer storage and recovery operations .....	124
6.2.4	Management of mixing and recovery efficiency .....	125
6.2.5	Evaluation of recovery efficiency .....	126
6.2.6	Reliability and continuity of supply .....	126
6.3	Interactions with other groundwater users .....	128
6.3.1	Competition for source water — treated sewage, stormwater or groundwater .....	128
6.3.2	Competition for aquifer storage space .....	129
6.4	Protection against saline water intrusion .....	129
6.5	Operations designed to protect groundwater-dependent ecosystems .....	130
6.6	Management of purge water, basin scrapings and water treatment byproducts .....	131
<b>7</b>	<b>Monitoring managed aquifer recharge systems .....</b>	<b>133</b>
7.1	General principles .....	133
7.2	Types of monitoring .....	134
7.2.1	Baseline monitoring .....	134
7.2.2	Validation monitoring .....	134
7.2.3	Operational monitoring (including supervisory control and data acquisition and web-based reporting systems) .....	135
7.2.4	Verification monitoring .....	135
7.3	Monitoring for management of health and environmental risks in managed aquifer recharge systems .....	136
7.3.1	Baseline monitoring of the subsurface component for managing health and environmental risks .....	138
7.3.2	Validation monitoring of the subsurface component for health and environmental risks .....	138
7.3.3	Operational monitoring of the subsurface component for managing health and environmental risks .....	141
7.3.4	Verification monitoring for health and environmental risks in managed aquifer recharge systems .....	142
7.4	Monitoring of small-scale managed aquifer recharge systems .....	144
7.5	Quality assurance and quality control .....	145
7.6	Data analysis and interpretation .....	145
7.7	Reporting and information dissemination .....	145
7.8	Review and feedback .....	146

<b>Appendix 1</b>	<b>Environmental values and entry-level assessment.....</b>	<b>147</b>
<b>Appendix 2</b>	<b>Examples of information requirements for Stage 2 investigations .....</b>	<b>149</b>
<b>Appendix 3</b>	<b>Examples of methods available for investigations and validation monitoring, as part of Stage 3 commissioning and trials .....</b>	<b>153</b>
<b>Appendix 4</b>	<b>Inactivation rates for pathogens in aquifers (informative only).....</b>	<b>157</b>
<b>Appendix 5</b>	<b>Environmental fate data for organic chemicals (informative only) .....</b>	<b>161</b>
<b>Appendix 6</b>	<b>Prediction of pathogens and organic chemicals in groundwater and recovered water (informative only).....</b>	<b>177</b>
<b>Appendix 7</b>	<b>Decision trees to identify potential arsenic and iron release in managed aquifer recharge .....</b>	<b>185</b>
<b>Appendix 8</b>	<b>Aquifer characteristics and suitability for managed aquifer recharge .....</b>	<b>191</b>
<b>Appendix 9</b>	<b>Operational performance data .....</b>	<b>195</b>
<b>Appendix 10</b>	<b>Examples of Australian managed aquifer recharge sites.....</b>	<b>199</b>
<b>Appendix 11</b>	<b>Case study of assessment of risks in relation to preventive measures.....</b>	<b>201</b>
<b>Glossary</b>	<b>.....</b>	<b>203</b>
<b>Tables, figures and boxes</b>	<b>.....</b>	<b>217</b>
<b>References</b>	<b>.....</b>	<b>223</b>



# Acronyms and abbreviations

## General

AHMC	Australian Health Ministers' Conference
ANZECC	Australian and New Zealand Environment and Conservation Council (replaced in 2001 by EPHC and NRMMC)
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand (replaced in 2001 by NRMMC)
ASR	aquifer storage and recovery
ASTR	aquifer storage, transport and recovery
CSIRO	Commonwealth Scientific and Industrial Research Organisation
EPHC	Environment Protection and Heritage Council
IAH	International Association of Hydrogeologists
NHMRC	National Health and Medical Research Council
NRMMC	Natural Resource Management Ministerial Council
NTU	nephelometric turbidity unit
NWQMS	National Water Quality Management Strategy
PAH	polycyclic aromatic hydrocarbon
SAT	soil aquifer treatment
THM	trihalomethanes

## Units

Atm	atmosphere
Bq	Becquerel
cm	centimetre
G	gram
GL	gigalitre
Kg	kilogram
kL	kilolitre
kN	kilonewton
kPa	kilopascal
kWh	kilowatt hour
L	litre
M	metre
M	molarity
Mg	milligram
ML	megalitre
Mm	millimetre
Mol	mole
mSv	millisievert
Ng	nanogram
Sv	sievert
T	tonne
µg	microgram
µS	microsiemens

# Acknowledgments

The Natural Resource Management Ministerial Council, the Environment Protection and Heritage Council and the National Health and Medical Research Council acknowledge the contributions of the individuals listed below to the development of these guidelines.

## Joint Steering Committee

### Chair

Mr Chris Bell Mr John Williamson	Environment Protection Authority, Victoria
-------------------------------------	--

### Members

Ms Jo Beatty	Department of Sustainability & Environment, Victoria
Ms Jan Bowman	Department of Human Services, Victoria
Dr Paul Burrell	Department of Natural Resources and Water, Queensland
Dr Helen Cameron	Australian Government Department of Health and Ageing
Dr David Cunliffe	Department of Health, South Australia
Mr Leon English	Department of Water, Western Australia
Dr Helen Foard Ms Kerry Olssen Dr Paul Smith	National Water Commission
Dr Karin Leder Ms Cathy Clutton	National Health and Medical Research Council
Dr Robyn Maddalena Mr Ian Marshall Dr Greg Jackson	Department of Health and Ageing, Queensland
Mr Peter Marczan	Department of Environment and Climate Change, New South Wales
Dr Kaye Power	Department of Health, New South Wales
Mr Neil Power	Department of Water, Land and Biodiversity Conservation, South Australia
Ms Nina Rogers Mr Michael Barry	Australian Local Government Association
Ms Chris Schweizer	Australian Government Department of the Environment, Water Resources, Heritage and the Arts
Mr Ross Young	Water Services Association of Australia

## Managed Aquifer Recharge Guidelines Working Group

### Chair

Leon English	Department of Water, Western Australia
--------------	--

### Members

Melissa Bromly	Department of Water, Western Australia
Wes Douglass Chandrika Jayatilaka	Environment Protection Authority, Victoria
Ian Marshall	Department of Health and Ageing, Queensland (subsequently Golder Associates)
Haemish Middleton	National Environment Protection Council Service Corporation
Peter Newland	Environment Protection Authority, South Australia
Sanjeev Pandey	Natural Resources and Water, Queensland
Paul Smith	National Water Commission
Alan Thomas	Australian Government Department of the Environment, Water, Heritage and the Arts
Nick Turner	Water Corporation, Western Australia
Michael Williams	Department of Natural Resources, New South Wales

## Managed Aquifer Recharge Guidelines Writing Team

Peter Dillon, Declan Page, Paul Pavelic, Simon Toze, Joanne Vanderzalm and Kerry Levett, CSIRO Land and Water and Water for a Healthy Country Flagship.

Daryl Stevens of Arris Pty Ltd and Peter Newland of Environment Protection Authority, South Australia, also contributed.

Scientific review by Jorg Drewes and Jack Schijven.

## **Managed Aquifer Recharge Guidelines Reference Panel**

The members of this panel reviewed the early draft

Jim Lockley	Pitt and Sherry Consultants, Hobart
Wendy Timms	Water Research Laboratory, University of New South Wales
Simon Sherriff	South Australian Murray–Darling Basin Natural Resources Management Board, Murray Bridge
Stephen Parsons	SKM Consultants, Melbourne
Deborah Reed	Environment Protection Authority, Victoria
Jeff Morton	PowerWater, Northern Territory

### **Public comments**

The councils wish to thank all those who provided comment during public consultation on the draft guidelines.

### **Consultancy services**

The EPHC, NHMRC and NRMCC also acknowledge the significant financial contribution of the National Water Commission towards consultancy services employed in developing these guidelines.



# 1 Introduction

National water recycling guidelines are being produced in two phases, as shown in Box 1.1. This publication is one of the three modules that comprise the second phase of the *Australian Guidelines for Water Recycling*, which address health and environmental risks associated with water recycling.

The guidelines as a whole, including this module, are designed to provide an authoritative reference that can be used to support beneficial and sustainable recycling of waters generated from sewage, grey water and stormwater, which represent an underused resource. The guidelines describe and support a broad range of recycling options, without advocating particular choices. It is up to communities as a whole to make decisions on uses of recycled water at individual locations. The intent of these guidelines is simply to provide the scientific basis for implementing those decisions in a safe and sustainable manner.

## **Box 1.1 Summary of Australia’s existing and planned water recycling guidelines**

National water recycling guidelines are being produced in two phases.

### **Phase 1**

- Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Natural Resource Ministerial Management Council (NRMMC), Environment Protection and Heritage Council (EPHC), Australian Health Ministers’ Conference (AHMC) 2006).  
Phase 1 of the guidelines provides a generic ‘framework for management of recycled water quality and use’ that applies to all combinations of recycled water and end uses. It also provides specific guidance on the use of treated sewage and grey water for purposes other than drinking and environmental flows.

### **Phase 2**

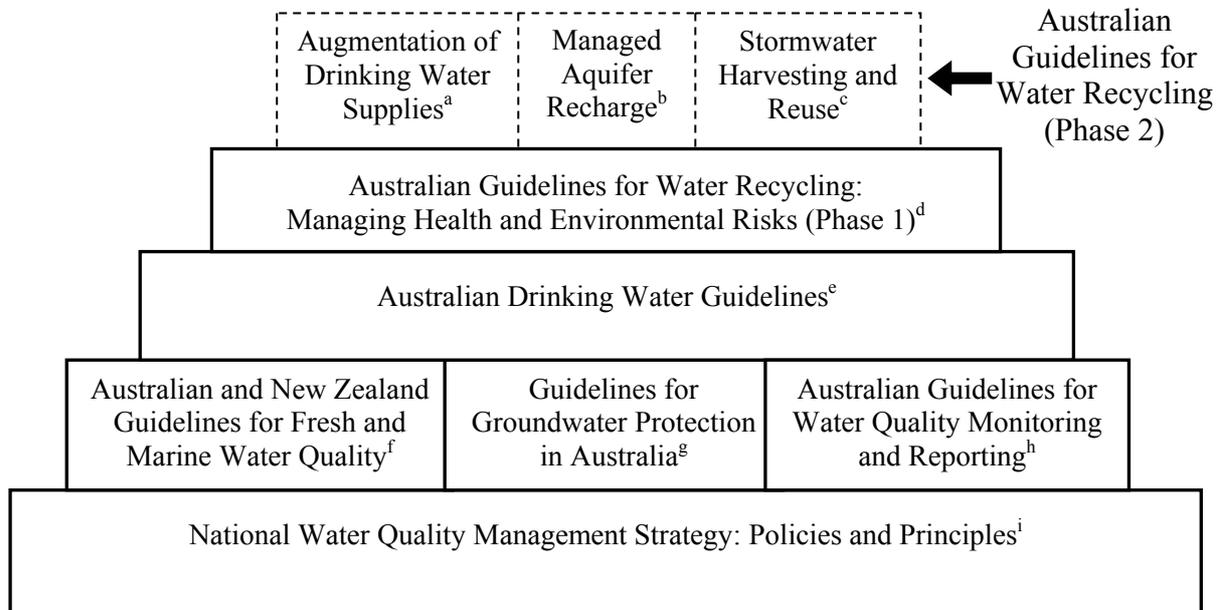
- *Australian Guidelines for Water Recycling: Augmentation of Drinking Water Supplies* (NRMMC–EPHC–National Health and Medical Research Council (NHMRC) 2008).  
The first module of Phase 2 of the guidelines extends the guidance given in Phase 1 on the planned use of recycled water (treated sewage and stormwater) to augment drinking water supplies.
- *Australian Guidelines for Water Recycling: Stormwater Harvesting and Reuse*.  
The second module of Phase 2 of the guidelines extends the guidance given in Phase 1 to cover the harvesting and reuse of stormwater.
- *Australian Guidelines for Water Recycling: Managed Aquifer Recharge* (NRMMC–EPHC–NHMRC 2009).  
The current document is the third module of Phase 2 of the guidelines and focuses primarily on the protection of aquifers and the quality of the recovered water in managed aquifer recharge projects using all water sources including recycled waters.

## **1.1 Origin and purpose of national guidelines on managed aquifer recharge**

An aquifer is an underground reservoir of water contained by rock or unconsolidated materials (gravel, sand, silt or clay), from which groundwater can be extracted. In ‘managed aquifer recharge’ a water source, such as recycled water (eg derived from urban stormwater or treated sewage) or natural water (eg from a lake or river), is used to ‘recharge’ an aquifer with water under controlled conditions. The aquifer is used to store surplus water for later use or for environmental benefit.

Managed aquifer recharge is the purposeful recharge of water to aquifers for subsequent recovery or environmental benefit. It is not a method for waste disposal.

These guidelines form an integral part of the National Water Quality Management Strategy (NWQMS). They build on the policies and principles of the strategy, and on other key NWQMS guidelines (Figure 1.1). Hence, these guidelines conform to the risk assessment framework for management of water quality detailed in the Phase 1 guidelines. The risk assessment framework has 12 elements, which are summarised in relation to managed aquifer recharge in Chapter 3 of this document.



- a** NRMCC–EPHC–NHMRC (2008)
- b** Current document
- c** NRMCC–EPHC–NHMRC (2009)
- d** NRMCC–EPHC–AHMC (2006)
- e** NHMRC–NRMCC (2004)
- f** ANZECC–ARMCANZ (2000a)
- g** ARMCANZ–ANZECC (1995)
- h** ANZECC–ARMCANZ (2000b)
- i** ARMCANZ–ANZECC (1994).

**Figure 1.1 National Water Quality Management Strategy guidelines and documents**

Managed aquifer recharge includes the subsurface component of water, which sets it apart from the other water recycling examples in the Phase 1 guidelines. Although the subsurface component provides water storage and treatment functions, it may add hazards to stored water and create other environmental problems. These guidelines provide a sound and consistent basis for protecting human health and the environment at managed aquifer recharge operations in all of Australia’s states and territories. They should:

- give more certainty to risk assessments used in project approval, and speed up these assessments
- prevent failure of managed aquifer recharge projects
- uphold the confidence of investors and the public in future innovations.

The managed aquifer recharge guidelines are intended for use by project proponents, regulators and any individuals or groups with an interest in a project or its impacts.

The guidelines aim to:

- provide a sound scientific basis to guide the development of managed aquifer recharge projects using recycled and natural water sources
- give proponents early warning of the extent of work needed for a project's success (including assessments for regulatory approvals)
- establish the basis for risk assessment, and make risk management as transparent as possible
- focus effort where it is most needed, lower residual risks to acceptable levels and guide proponents in the identification of preventive measures
- minimise the time and effort required for proponents to achieve successful projects
- help proponents discard projects that will not meet objectives at the earliest possible stage
- maximise the efficiency of the time spent by regulators and other stakeholders in making decisions
- make accessible knowledge that will reduce the cost of establishing a project
- encourage innovation by allowing appropriate commissioning trials that validate management controls (ie preventive measures)
- consider the effects of the operation of managed aquifer recharge on factors such as waste (eg greenhouse gases), water quality and aquifer protection
- provide a basis for legislative change, allowing safe managed aquifer recharge where required
- inform decision making, so that decisions are defensible and consistent
- ensure that monitoring requirements are rational and adaptable
- improve the knowledge base, while constraining risks.

Box 1.2 lists the main principles of sustainable use of recycled water, the requirements for adhering to them, and implementation. The risk management framework is expanded on in Chapter 3.

## **1.2 Scope of the managed aquifer recharge guidelines**

### **1.2.1 Relationship with other guidelines**

These guidelines focus on the protection of aquifers and the quality of recovered water in managed aquifer recharge projects. Where managed aquifer recharge is part of water recycling projects, these guidelines should be used in conjunction with the Phase 1 guidelines.

If the source water for recharge is treated sewage (for which there is inadequate data at the outset to characterise the water quality) the Phase 1 guidelines lay the foundations for managing health and environmental risks and provide default values for water-quality parameters for use in risk assessment

If the source water for recharge is stormwater, then the *Australian Guidelines for Water Recycling: Stormwater Harvesting and Reuse* (NRMMC–EPHC–NHMRC 2009) should be

used to provide default values for water-quality parameters for use in risk assessment if there is inadequate data at the outset to characterise the stormwater water quality.

If recovered water is intended for use as a drinking water supply, then the *Australian Guidelines for Water Recycling: Augmentation of Drinking Water Supplies* (NRMMC–EPHC–NHMRC 2008) should be used to provide an amplified risk assessment framework and, together with the *Australian Drinking Water Guidelines* (NHMRC–NRMMC 2004), provide targets for drinking water quality.

For all water sources, regardless of recycling, foundational guidelines apply as shown in Figures 1.1 and 1.2.

These guidelines replace previous Australian guidance on reclaimed water for aquifer recharge (Australian Water Resources Council, 1982) and for aquifer storage and recovery (Dillon and Pavelic 1996, Dillon and Molloy 2006), and extend from a state government code and report (eg Environment Protection Authority (SA) 2004, DSE–DHS Victoria 2006).

### **Box 1.2 Principles of sustainable use of recycled water**

Sustainable use of recycled water is based on three main principles, which are based on the Phase 1 guidelines for water recycling:

1. The protection of public and environmental health is of paramount importance and should never be compromised.
2. The protection of public and environmental health depends on implementing a preventive risk management approach.
3. Preventive measures and requirements for water quality should be applicable to the source of recycled water, its intended uses and identified environmental values.

#### **Adherence**

Adherence to these principles requires:

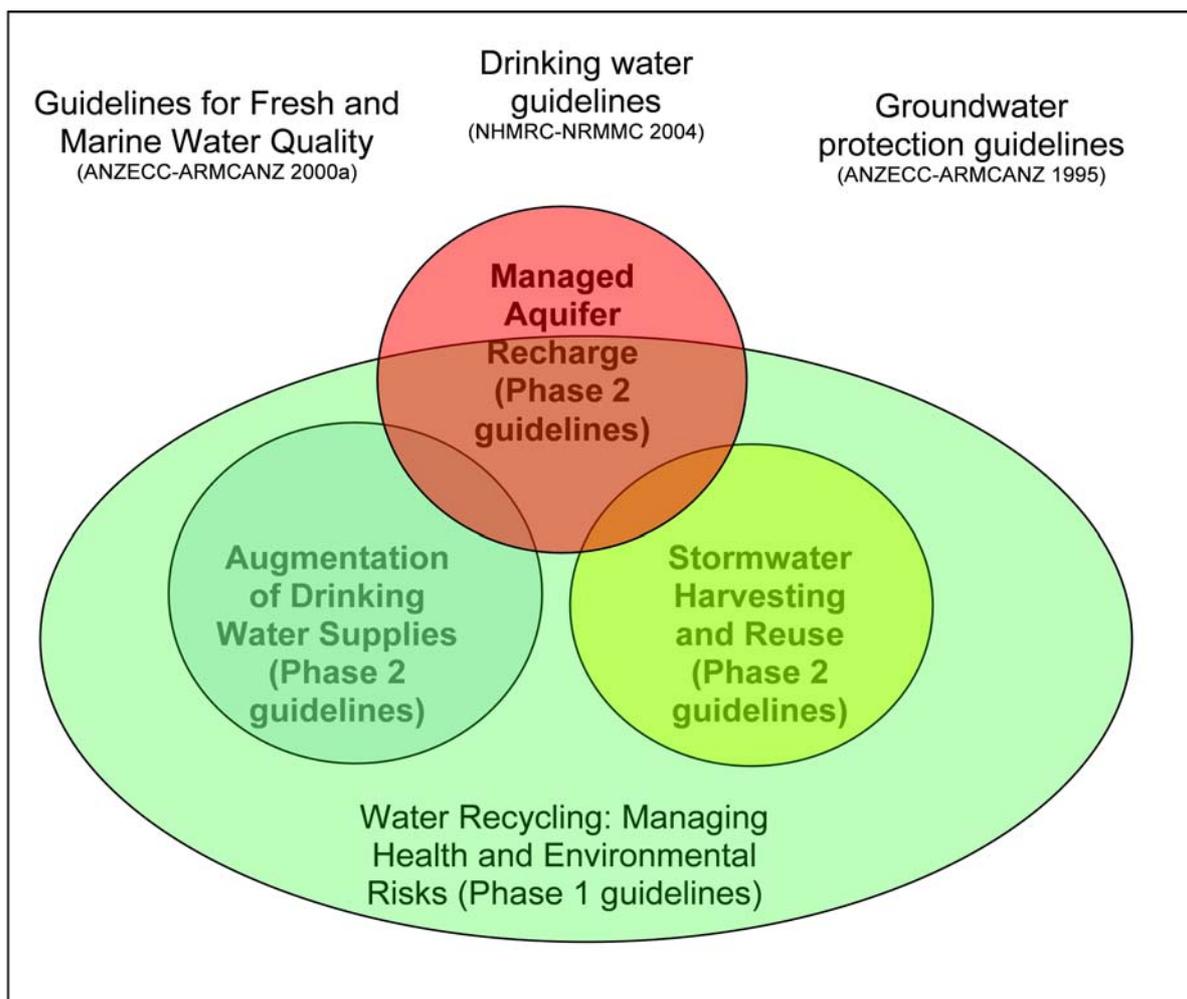
- an awareness and understanding of how recycled water-quality management can affect public health and the environment
- maintenance of recycled water schemes and reinforcement of the importance of ongoing management (by senior managers) to employees, stakeholders and end users
- an organisational philosophy that supports continuous improvement and cultivates employee responsibility and motivation
- ongoing communication (supported by audits and inspections) between regulators, owners, operators, plumbers, end users, and other stakeholders.

#### **Implementation**

These principles are implemented by a process that:

- establishes the environmental values to be protected<sup>1</sup>
- determines the criteria that assure protection
- undertakes risk assessment to determine the level of protection against hazards
- designs barriers and management strategies to assure protection
- monitors compliance, responds to change and increases knowledge.

<sup>1</sup> The environmental values to be protected for a particular aquifer, and connected ecosystems that depend on surface water and groundwater, are locally relevant values or beneficial uses (eg sustaining biodiversity plus water supplies for drinking, irrigation, industry or livestock— see Table A1.1). The relevant environmental values — determined from ambient groundwater quality and a process involving community engagement (ARMCANZ–ANZECC 1995) — are used to define limits of acceptable water quality within the aquifer.



Note: Managed aquifer recharge guidelines may also be used for recharge of water not considered to be recycled.

**Figure 1.2 Relationship between managed aquifer recharge guidelines and other water recycling guidelines**

These guidelines should be used to assess and manage risks for all new managed aquifer recharge projects; they may also be used to assess risks associated with existing unintentional or unmanaged recharge (defined in Section 2.5), and for recharge of water not considered to have been recycled.

General principles described in the Phase 1 guidelines apply to this module. Key aspects are repeated or expanded in this module as appropriate, but further information on aspects such as managing environmental risks can be obtained by referring to the Phase 1 document. Box 1.2 shows how the water recycling guidelines, including this module, relate to state and territory guidelines.

### **Box 1.3 Relationship between the national guidelines and state and territory guidelines**

A nationally consistent approach to the management of health and environmental risks from water recycling requires high-level national guidance on risk assessment and management. Such guidance is provided in the suite of documents that make up the *Australian Guidelines for Water Recycling*. This current document describes one particular process, and forms part of the guidelines.

Although the guidelines are not mandatory and have no formal legal status, their adoption provides a shared national objective; at the same time, this allows flexibility of response to different circumstances at regional and local levels. All states and territories are encouraged to adopt the approach described in the guidelines. However, application may vary across jurisdictions, depending on the arrangements for water and wastewater management. This document describes a range of uses without advocating particular choices. Decisions on uses may also vary across jurisdictions.

Water recycling is regulated by states and territories. State or local jurisdictions may use their own legislative and regulatory tools to refine the information given here into their own guidelines. Where there are relevant state and territory regulations, standards or guidelines, these should be consulted to ensure that any local requirements are met. Where state and territory guidelines differ from this document, the state and territory guidelines should be followed or the local regulatory agency consulted to clarify requirements.

### **1.2.2 Sources of water, types of aquifers and purposes**

These guidelines, used in conjunction with other NWQMS guidelines, cover all types of source water for managed aquifer recharge in urban and rural areas. Sources include:

- stormwater
- water recycled from wastewater treatment plants
- water from streams and lakes
- groundwater drawn from other aquifers or drawn remotely from the same aquifer
- water from drinking water distribution systems, including desalinated sea water.

All waters, including industrial effluents containing elevated concentrations of hazards, require a level of treatment appropriate to the risks. The aquifer storage component of managed aquifer recharge should not generally be relied on as the sole treatment before reuse. These guidelines refer to managed systems with planned recharge and recovery; unmanaged recharge is discussed in Section 2.4.

This document applies to all types of aquifers, including unconfined, fractured rock and karstic aquifers. Recharge of unconfined aquifers requires additional considerations of factors such as waterlogging, soil salinisation, geotechnical issues and groundwater-quality protection. These considerations are addressed in Chapter 5. For fractured rock and karstic aquifers, the spatial distribution of recharged water and the residence time between recharge and recovery are less well defined. In these situations, it is important to allow for higher risks when determining how hazards will be reduced within recharge water (Chapter 5). The suitability of different types of aquifers for managed aquifer recharge is discussed in Dillon and Jimenez (2008) (Appendix 8).

Recharged water may be intended for reuse by the proponent or by third parties, for uses such as:

- drinking water supplies
- irrigation
- industrial purposes
- environmental purposes, including
  - increasing baseflow in streams
  - maintaining lakes or phreatophytic (groundwater-using) vegetation
  - protecting against entry of saline or contaminated water.

In all cases, human health and the environmental values of the aquifer, its connected ecosystems, and the water-quality requirements of the end uses are to be protected. These values are summarised in ARMCANZ–ANZECC (1994). Preventive measures, monitoring and incident response plans will be required, and these must be applicable to the assessed level of environmental risk and the intended end uses of recovered water.

Related topics, such as acid injection in mining operations and injection of carbon dioxide-rich water into petroleum or gas fields for secondary recovery or carbon sequestration, are outside the scope of these guidelines, and are covered under environmental protection policies in relevant jurisdictions.

### **1.2.3 Water allocation, water trading and other water governance issues**

Effective implementation of managed aquifer recharge, in any jurisdiction, requires integrated water resources management, because recharge involves managing the quantity and quality of both surface water and groundwater. Regulators need a sound basis for policies, because managed aquifer recharge creates the potential for conflict between water conservation and water-quality protection. Sectoral responsibilities for environmental regulation, health regulation and water resource management need to be coordinated, to ensure that approval of new managed aquifer recharge projects is efficient, and perverse outcomes (ie detrimental outcomes resulting from well-intentioned actions) are avoided.

These guidelines cover only the water quality and protection of human health and environment aspects required for effective managed aquifer recharge; that is, only the right-hand side of the policy matrix shown in Table 1.1. The document does not cover allocation of water resources, available storage space in aquifers, water trading or other water governance issues.

In 2009, the National Water Commission released a detailed review of water resource entitlement and allocation issues for managed aquifer recharge (Ward and Dillon 2009). That review is intended to inform relevant policies for each of Australia's states and territories. A summary of the review is contained in the commission's introductory report on aquifer recharge (Dillon *et al* 2009a). Guidance on environmental flow requirements (a water allocation issue) is available from the relevant authority in each jurisdiction.

Information on interactions between surface water and groundwater can be found in the 'Connected Water' toolbox (Bureau of Rural Sciences 2007). This toolbox addresses integrated management of surface water and groundwater resources.

**Table 1.1 Resource management and environmental protection policies invoked by managed aquifer recharge operations**

<b>Resource</b>	<b>Management issue:</b> Water storage allocation and entitlements <b>Attribute:</b> Quantity (not addressed in this guideline)	<b>Management issue:</b> Protection of human health and environment <b>Attribute:</b> Quality (addressed in this guideline)
Source of water for recharge	<ul style="list-style-type: none"> <li>• Environmental flow requirements</li> <li>• Water allocation plans and surface water entitlements</li> <li>• Interjurisdictional agreements</li> <li>• If source is groundwater, see next row</li> </ul>	<ul style="list-style-type: none"> <li>• Catchment pollution control plan — see Appendix 3 of Phase 1 of the guidelines</li> <li>• Water-quality requirements for intended uses of recovered water — see <i>Australian Guidelines for Water Recycling: Augmentation of Drinking Water Supplies</i> (NRMMC–EPHC–NHMRC 2008) or the Phase 1 guidelines</li> <li>• Risk management plan for water-quality assurance — see the Phase 1 guidelines</li> <li>• If source water is groundwater, quality protection plan for source aquifer must be in accordance with the groundwater protection guidelines (ARMCANZ–ANZECC 1995)</li> </ul>
Groundwater	<ul style="list-style-type: none"> <li>• Groundwater allocation plan and groundwater entitlements</li> <li>• Resource assessment accounting for groundwater-dependent ecosystems</li> <li>• Demand management</li> <li>• Allocatable capacity and entitlement for additional storage in the aquifer</li> <li>• Interjurisdictional agreements</li> </ul>	<ul style="list-style-type: none"> <li>• Groundwater-quality protection plan for recharged aquifer in accordance with groundwater protection guidelines (ARMCANZ–ANZECC 1995)</li> <li>• Water-quality requirements for intended uses of groundwater — see <i>Australian and New Zealand Water Quality Guidelines for Fresh and Marine Waters</i>, (ANZECC–ARMCANZ 2000a), the Phase 1 guidelines, or <i>Australian Guidelines for Water Recycling: Augmentation of Drinking Water Supplies</i> (NRMMC–EPHC–NHMRC 2008)</li> <li>• Risk management plan for water-quality assurance beyond attenuation zone, accounting for aquifer biogeochemical processes</li> </ul>

### 1.3 Stages of project development and assessment

These guidelines adopt the risk management approach defined in the Phase 1 guidelines. The approach recognises that the level of some risks cannot be fully understood before managed aquifer recharge is implemented at full scale, due to uncertainties associated with aquifer processes. However, with adequate system characterisation and assessment, it is possible to adopt preventive measures and operational procedures (including incident and emergency management). These measures and procedures allow the system to be implemented and protective measures to be validated, without compromising acceptable uses of recovered

water or the environmental values of an aquifer beyond an attenuation zone (ie the area surrounding the zone of recharge where natural attenuation of contaminants such as chemicals and microorganisms takes place).

Validation of managed aquifer recharge can be more repetitive than for other forms of water recycling. If initial validation indicates that risks have not been adequately mitigated, further preventive measures will need to be included (and will also require validation) before the project can proceed. The structure of the risk assessment guides investigations and focuses effort. It helps to ensure that decisions on where to invest effort are based on an informed understanding of the next required level of investigation.

The approach to assessment of managed aquifer recharge is summarised briefly here, and is described in more detail in Chapter 4. For small scale projects with low inherent risks a simplified assessment is possible. For all other projects there are four assessment stages:

- Entry-level assessment — This involves gathering information that is normally readily available within the locale of the project and performing a basic desktop assessment to determine whether the project is viable and the likely degree of difficulty. This indicates the extent of field investigations required in step 2.
- Maximal risk assessment — These baseline investigations and site-specific data reveal inherent risks associated with a checklist of key hazards. This assessment will reveal whether preventive measures are required (as is normally the case).
- Residual risk assessment (precommissioning) — This assessment identifies proposed preventive measures and operational procedures that will ensure acceptably low residual risks to human health and the environment from constructing and commissioning the project. This assessment also informs on hazards or aspects that require validation monitoring during commissioning trials.
- Residual risk assessment (operational) — This is based on the results of commissioning trials and determines whether the ongoing operation of the project has acceptably low residual risks to human health and the environment. This assessment also informs the risk management plan including types and levels of verification and operational monitoring for ongoing operation of the project.

Basically, a maximal risk assessment assesses risk in the absence of preventive measures, whereas a residual risk assessment assesses risk in the presence of preventive measures. Residual risk assessment may also be applied to recharge activities that are already in operation but have not yet been assessed (Section 2.5). Because they identify existing preventive measures and operational procedures, verification monitoring data may be evaluated to determine whether they demonstrate sufficient protection of human health and the environment.

This document also provides for simplified assessment of small-scale projects with low inherent risks before Stage 1, above. For example, domestic roof catchments can be used to generate non-drinking supplies in aquifers with prescribed characteristics, by incorporating design features that compensate for assumed low levels of operator competency. This provision acknowledges that monitoring costs of small-scale projects on a site-by-site basis may be prohibitive. It requires a water resources agency, or another regulator or groundwater user group to take responsibility for monitoring cumulative effects (eg excessive watertable rise) resulting from multiple small operations, and to implement preventive measures if required. Details are given in Section 4.2.

## 1.4 How to use the managed aquifer recharge guidelines

These guidelines provide a logical, staged process for acquiring information and making decisions in accordance with the risks. Chapters and appendixes should be used to guide risk assessment, in the sequence shown in Figure 1.3.

Chapter 2 defines managed aquifer recharge, demonstrates a range of such systems currently in use and outlines the considerations made when selecting a recharge method. This chapter also defines situations in which managed aquifer recharge is not viable, and addresses the transition from unmanaged to managed aquifer recharge.

Chapter 3 briefly reiterates the 12 elements of the risk management framework from the Phase 1 guidelines, within the context of managed aquifer recharge projects. Specific elements are expanded in subsequent chapters.

Chapter 4 describes the four stages of project development and assessment.

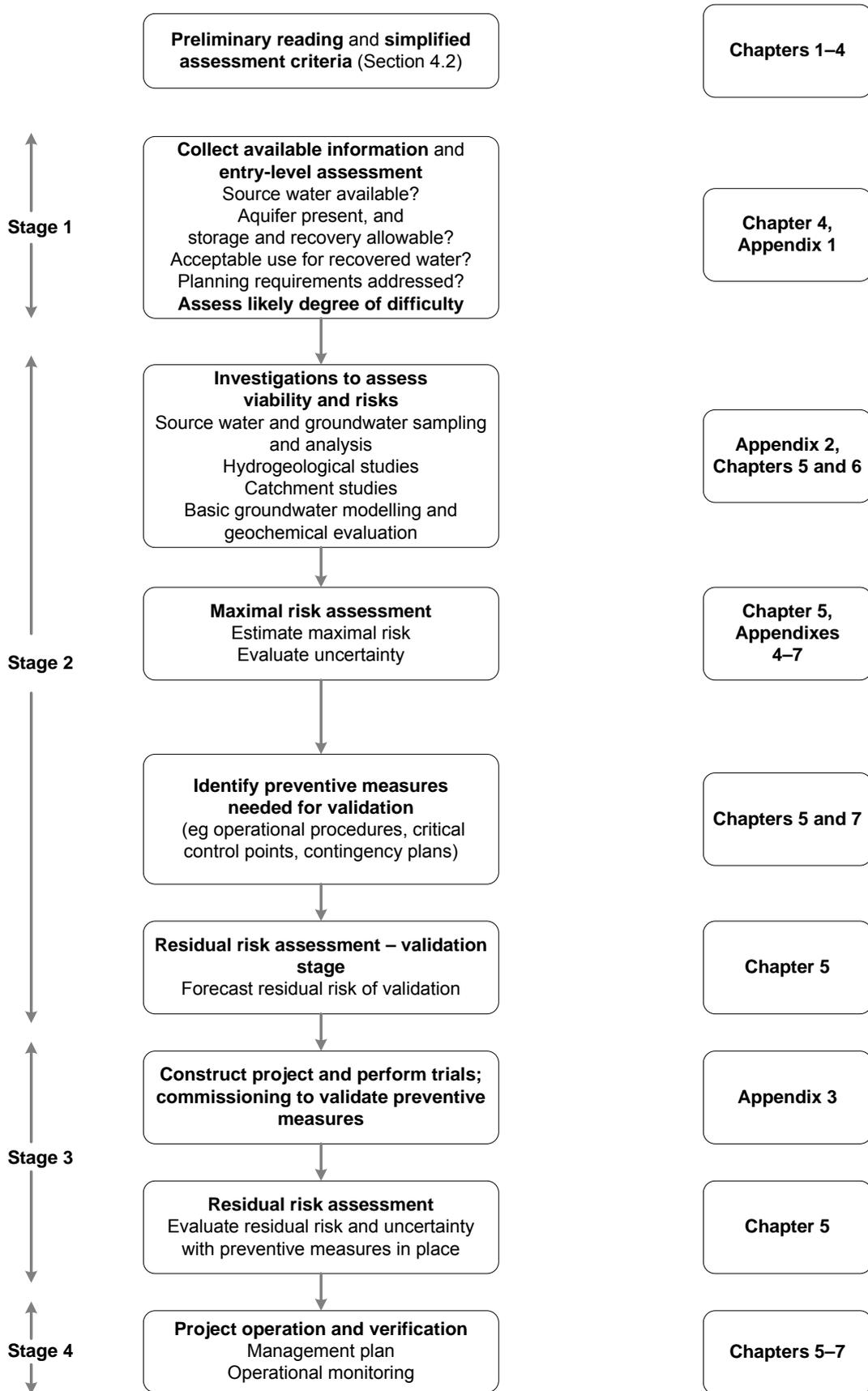
Chapter 5 identifies the key hazards to human health and the environment associated with managed aquifer recharge. These include:

- water quality
- water pressures and levels
- effects on hydrogeological properties of aquifers and aquitards (low-permeability geological layers that confine or separate aquifers)
- effects on the ecosystem and greenhouse gas considerations.

Chapter 5 focuses on system analysis and management (Elements 2–6 of the risk management framework). For each hazard, it provides acceptance criteria, suggested management controls (preventive measures and operational procedures) and monitoring requirements for consideration in the residual risk assessment.

Chapter 6 addresses important operational issues and their management. Although management of clogging and recovery efficiency may not be critical for human and environmental health, these operational issues must be taken into account for the operational viability of a managed aquifer recharge project. This chapter addresses supply reliability, interactions with other groundwater users, saline water intrusion barriers, operations designed to protect ecosystems, and the discharge of residuals from treatment and maintenance processes (Elements 4 and 7 of the risk management framework).

Chapter 7 addresses monitoring of managed aquifer recharge projects. The aim is to link monitoring efforts to validate the effectiveness of preventive measures in managing residual risks. This chapter gives greater guidance on the validation and verification monitoring requirements identified in Chapter 5 (Elements 5 and 9 of the risk management framework), and on documentation and reporting, evaluation and audit, and review and continuous improvement (Elements 10–12 of the risk management framework).



**Figure 1.3** How to use the managed aquifer recharge guidelines to assess and manage risk

Chapter 4 explains the staged approach to risk assessment, providing a template entry-level assessment for Stage 1 in two parts — viability and degree of difficulty — with supplementary information in Appendix 1 on environmental values in relation to entry-level assessment. Chapter 5 details the risk assessment and preventive measures for the most common classes of hazards or hazardous events. Appendix 2 contains a checklist of methods and baseline information requirements for Stage 2. Appendix 3 lists methods of validation monitoring for Stage 3, and sources of additional information.

Appendixes 4–6 provide data on attenuation of pathogens and organic chemicals in aquifers. They also contain simple models to estimate the size of an attenuation zone, beyond which the aquifer’s environmental values should be continuously met.

Appendix 7 provides decision trees to identify whether arsenic or iron mobilisation problems can be expected.

Appendix 8 summarises information on aquifer characteristics and their influence on the potential for managed aquifer recharge.

Appendix 9 summarises information on clogging rates and recovery efficiency for various managed aquifer recharge projects.

Appendix 10 lists examples of managed aquifer recharge sites in Australia.

Appendix 11 gives insights on using the managed aquifer recharge guidelines to assess risks associated with each hazard at a specific stormwater aquifer storage and recovery site.

## 2 Managed aquifer recharge

This chapter defines managed aquifer recharge, outlines the components of a managed aquifer recharge system, demonstrates a range of such systems currently in use and outlines the considerations made when selecting a recharge method. It also identifies benefits of aquifer recharge as part of water recycling, defines situations in which managed aquifer recharge is not viable, and addresses the transition from unmanaged to managed aquifer recharge.

### 2.1 Definition, purposes and types of managed aquifer recharge

#### 2.1.1 Definition and purposes of managed aquifer recharge

Managed aquifer recharge is the intentional recharge of water to aquifers for subsequent recovery or environmental benefit; the managed process assures adequate protection of human health and the environment. Aquifers may be recharged by diversion of water into wells or infiltration of water through the floor of basins, galleries or rivers.

The water recharged into an aquifer may be:

- stored as banked water for emergency supplies
- recovered for drinking, industrial or irrigation supplies
- used to sustain environmental flows and phreatophytic vegetation (ie deep-rooted plants) in stressed surface water or groundwater systems
- used as a barrier to prevent saline intrusion in overexploited aquifers.

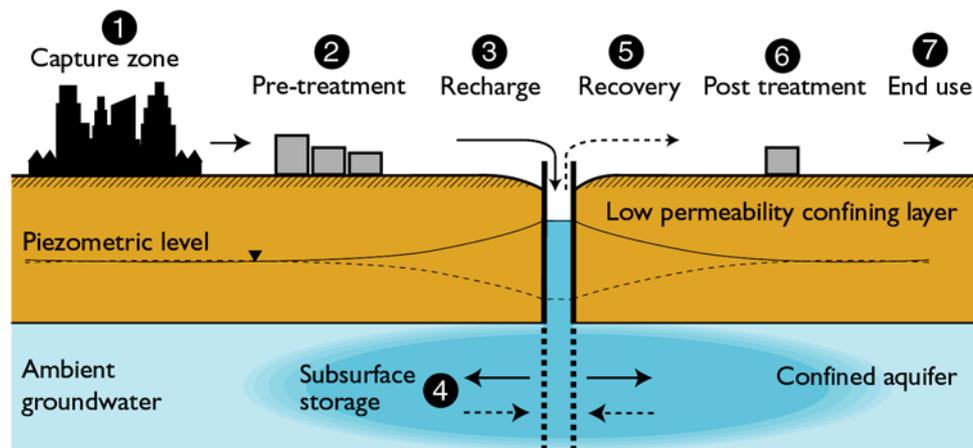
Two examples of managed aquifer recharge are shown in Figure 2.1. The figure shows the seven components of the system (also listed in Table 2.1).

Climate change and increasing urban population have increased pressures on water resources. Therefore, more diligent management is needed to secure adequate supplies of suitable water for human and environmental needs. Managed aquifer recharge offers ways to generate water supplies and protect the environment using water that may otherwise be wasted. Below-ground storage — particularly in urban areas where there are few alternatives — allows excess seasonal water to be conserved until water is in higher demand. Well-designed and operated systems can improve groundwater quality.

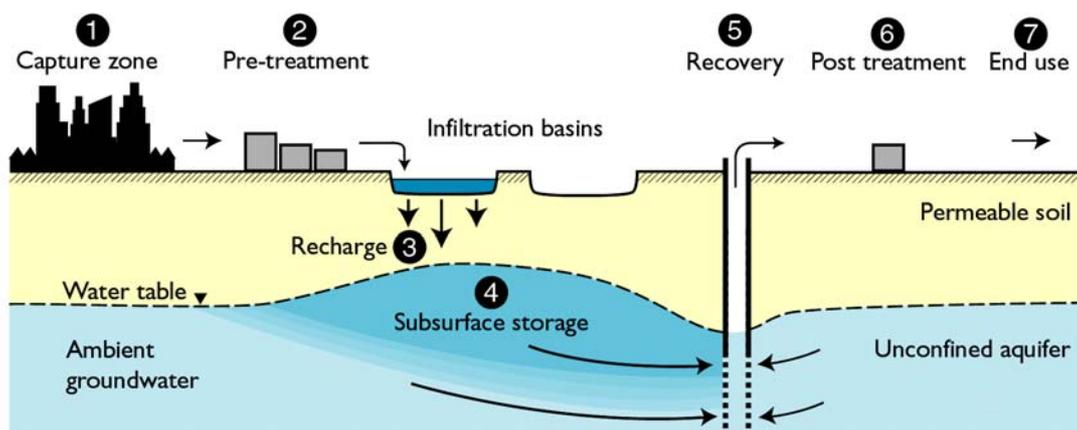
Managed aquifer recharge, particularly via wells, has many advantages, including (Pyne 2006):

- low capital costs — managed recharge is often the most economic form of new water supply
- no evaporation loss, algae or mosquitoes (unlike dams)
- no loss of prime valley floor land
- ability to use brackish aquifers that could not be directly used for supplies
- potential location close to new water sources, and where demand for water is high
- aquifers providing treatment as well as storage
- low greenhouse gas emissions compared to remote pumped storages
- able to be built to the size required for incremental growth in water demand

- provision of emergency and strategic reserves
- improved reliability of existing supplies
- improved environmental flows in water supply catchments for urban areas.



(a)



(b)

(a) Aquifer storage and recovery system storing water in a confined aquifer.

(b) Soil aquifer treatment system infiltrating water to an unconfined aquifer.

Note: The seven components that should be mapped in a diagram of a managed aquifer recharge process (Element 2 of the risk management framework) are presented in Table 2.1. These components are referred to throughout these guidelines.

### Figure 2.1 Two examples of managed aquifer recharge, showing the seven components of the system

Managed aquifer recharge involving urban stormwater also produces social and economic benefits such as increased water supply security, flood mitigation, improved urban amenities and increased land value. In some situations, recharge involving stormwater and recycled water may improve receiving-water quality and better protect downstream aquatic ecosystems. Hence, factors beyond water supply costs must be considered when determining the viability of managed aquifer recharge projects. This is called ‘economy of scope’, and is part of a triple-bottom-line evaluation — one that considers social, economic and environmental aspects.

**Table 2.1 Components of a managed aquifer recharge system**

Component	Examples
1. Capture zone	<ul style="list-style-type: none"> <li>• Harvesting using weirs and wetlands in urban stormwater catchments</li> <li>• Connection to a recycled water pipe from a treatment plant</li> </ul>
2. Pretreatment	<ul style="list-style-type: none"> <li>• Passive systems such as wetlands</li> <li>• Engineered treatments (if needed) to produce source water suitable for recharge</li> </ul>
3. Recharge	<ul style="list-style-type: none"> <li>• Injection well</li> <li>• Infiltration basin</li> <li>• Infiltration gallery</li> </ul>
4. Subsurface storage	<ul style="list-style-type: none"> <li>• The aquifer that water is stored in and where aquifer passive treatment occurs</li> </ul>
5. Recovery	<ul style="list-style-type: none"> <li>• Recovery well</li> <li>• Intentional discharge to a groundwater-dependent ecosystem</li> </ul>
6. Post-treatment	<ul style="list-style-type: none"> <li>• Passive systems such as wetlands</li> <li>• Engineered treatments (if needed) to produce water suitable for its intended use</li> </ul>
7. End use	<ul style="list-style-type: none"> <li>• Distribution to users, such as <ul style="list-style-type: none"> <li>– drinking water supplies</li> <li>– irrigators or industry</li> <li>– aquatic ecosystems (ie human health and environmental receptors)</li> </ul> </li> </ul>

Note: Catchment water quality management is important and is addressed in NRMCC-EPHC-NHMRC (2008).

Several types of managed aquifer recharge are shown in Figure 2.2 (after Dillon 2005), and each type of managed aquifer recharge is briefly described below. Specific examples are documented in Dillon (2002), UNESCO IHP (2003, 2006), Dillon and Toze (2005), Gale (2005), Fox (2007) and NRC (2008).

The components listed in Table 2.1 are common to all systems. A range of preventive measures and monitoring techniques (outlined in subsequent chapters) may be applied to each component, depending on the specific risks associated with the system's operation.

### 2.1.2 Types of managed aquifer recharge

#### *Aquifer storage and recovery (ASR)*

ASR involves injection of water into a well for storage, and recovery from the same well. The aquifer may be confined or unconfined. Examples are found at Salisbury, Grange, Tea Tree Gully, and other suburbs of Adelaide, South Australia.

#### *Aquifer storage, transport and recovery (ASTR)*

ASTR involves injection of water into a well for storage, and recovery from a different well, generally to provide additional water treatment. An example is at Salisbury, South Australia.

### ***Vadose zone wells***

Vadose zone or ‘dry’ wells are typically shallow wells in areas with deep watertables. They allow infiltration of high-quality water through the unsaturated zone to the unconfined aquifer at depth. Examples are found in Phoenix, United States.

### ***Percolation tanks and recharge weirs***

Percolation tanks and recharge weirs are dams built in ephemeral streams (ie stream channels that contain water only after rainfall or snowmelt) to detain water that infiltrates through the bed, increasing storage in unconfined aquifers. The water is extracted down-valley. Examples are found in Callide Valley, Queensland.

### ***Rainwater harvesting***

In ‘rainwater’ harvesting, roof runoff is diverted into a well, sump or caisson filled with sand or gravel, and allowed to percolate to the watertable. It is collected by pumping from a well. Examples are common in Perth, Western Australia.

### ***Bank filtration***

In bank filtration, groundwater is extracted from a well or caisson near or under a river or lake to induce infiltration from the surface water body. The quality of recovered water is thereby improved and more consistent. Examples are found in Berlin, Germany.

### ***Infiltration galleries***

Infiltration galleries are geotechnically-stabilised buried trenches (eg with polythene cells), or slotted pipes in permeable media. They allow infiltration through the unsaturated zone to an unconfined aquifer. An example is at Floreat Park, Western Australia.

### ***Dune filtration***

In dune filtration, water is infiltrated from ponds constructed in dunes, and extracted from wells or ponds at lower elevation. The filtration improves water quality and helps to balance supply and demand. Examples are found in Amsterdam, The Netherlands.

### ***Infiltration ponds***

Infiltration ponds and channels are usually constructed off-stream. Surface water is diverted into them and allowed to infiltrate (generally through an unsaturated zone) to the underlying unconfined aquifer. Examples are found on the Burdekin Delta, Queensland.

### ***Soil aquifer treatment***

In soil aquifer treatment, treated sewage effluent is intermittently infiltrated through infiltration ponds, to facilitate nutrient and pathogen removal. The effluent passes through the unsaturated zone and is recovered by wells after residence in the aquifer. An example is at Alice Springs, Northern Territory.

### ***Underground dams***

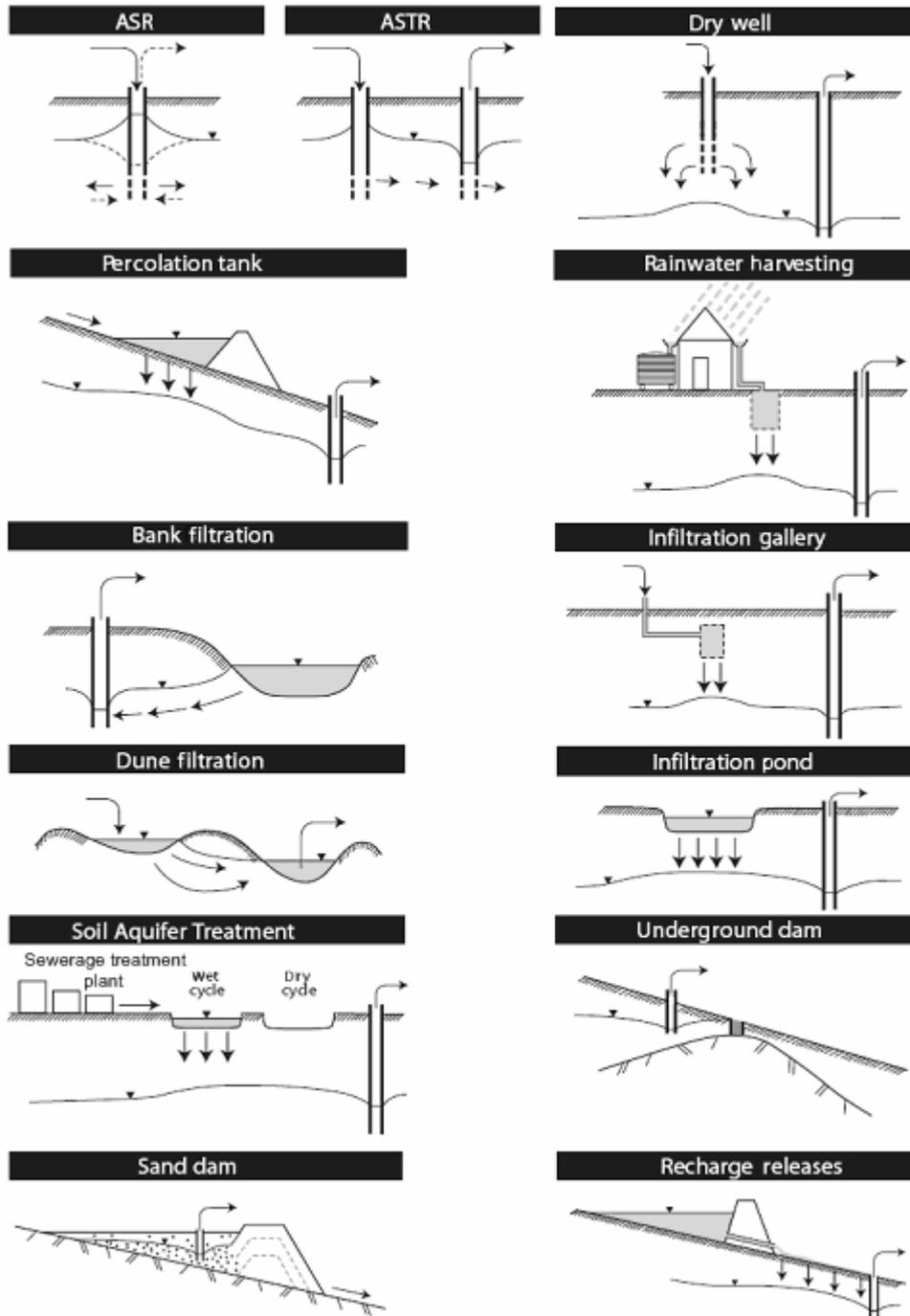
In construction of underground dams, a trench is constructed across the stream bed in ephemeral streams where flows are constricted by basement highs. The trench is keyed to the basement and backfilled with low-permeability material, helping to retain flood flows in saturated alluvium for stock and domestic use. Examples are found in northeast Brazil.

### ***Sand dams***

Sand dams are built in ephemeral stream beds in arid areas on low-permeability lithology. They trap sediment when flow occurs and, following successive floods, are raised to create an 'aquifer' that can be tapped by wells in dry seasons. An example is at Kitui, Kenya.

### ***Recharge releases***

Dams on ephemeral streams detain flood water. They may be used for slow release of water into the stream bed downstream, to match the infiltration capacity into underlying aquifers, thereby significantly improving recharge. An example is Little Para River, South Australia.



ASR = aquifer storage and recovery; ASTR = aquifer storage, transport and recovery.

**Figure 2.2** Schematic of types of managed aquifer recharge

## 2.2 Selection of recharge method

The method chosen for recharge depends on site-specific conditions. If aquifers are confined, then well-injection methods are preferred; these include ASR and ASTR. If infiltration is restricted by surficial clay, then galleries, ponds, sumps or wells may be constructed to

completely penetrate the low-permeability layer, exposing underlying formations that have higher permeability. The chosen configuration and size will depend on:

- the thickness of the low-permeability layer
- the required infiltration rate
- land availability and cost
- compatibility with other land uses
- ease of traffic access
- the need to avoid insect pests, or even to prevent the attraction of birds (eg at airports).

Some recharge methods depend on specific geomorphological characteristics; for example:

- sand dunes and swales (shallow depressions that carry water mainly during rainstorms or snowmelts)
- shallow bedrock saddles or dykes beneath alluvial streams
- restrictions in valleys of alluvial streams to allow percolation tanks or sand dams.

In urban areas land is relatively expensive, favouring methods that use land efficiently, for example, ASR or ASTR. The method used will depend on whether the aquifer is unconfined or confined, or whether there are several aquifers available for storage. In rural areas, where land prices are lower, infiltration ponds and soil aquifer treatment are the most cost-effective ways of recharging large volumes of water.

Source-water quality may also play a role in method selection. In general, if the turbidity or nutrient concentration of the source water is high or variable, well-injection methods are likely to lead to rapid clogging (Chapter 6). In this situation, infiltration basins that can be periodically scraped or ploughed are preferred. Alternatively, if higher treatment levels are required, provision must be made for back-flushing wells to purge them of sediment and biomass, or for discharge or recycling of water treatment byproducts.

All these factors must be considered before selecting a recharge method. Investigation costs may be substantially greater for projects involving unconfined aquifers than for confined systems because, in addition to characterising the aquifer, an understanding of the soil profile through to the watertable is needed. In some locations, it may be desirable to store waters destined for different end uses in separate aquifers, and possibly use different methods of recharge.

### **2.3 Benefits of managed aquifer recharge for recycling**

Radcliffe (2004) identified a wide range of approaches to water recycling in Australia. Where aquifers are available, subsurface storage is of benefit to projects that involve indirect reuse of recycled water for drinking. The storage provides an important natural buffer, which has advantages in terms of public perception (Leviston et al 2006); it also provides a longer minimum residence time than recycling via reservoirs. The subsurface storage extends treatment time and hence improves water quality, reducing risks associated with hazards such as pathogens. If sampling exposes a breach in the quality of source water, managed aquifer recharge systems allow more time for interventions to protect human health and the environment.

Managed aquifer recharge makes it possible to harvest and reuse urban stormwater in significant quantities. This also allows saline recycled water to be diluted in blended recycled supply systems (eg Mawson Lakes, South Australia) without requiring desalination — resulting in greatly reduced greenhouse gas emissions.

The benefits of managed aquifer recharge systems using stormwater often extend beyond the value of the water recovered. For example, stormwater detention systems mitigate flooding of downstream urban areas, and increase the value of land and homes surrounding ponds and parks. Although the risk assessment and management involved in managed aquifer recharge may seem onerous, the effort involved needs to be weighed against the economic, social and environmental benefits of the process.

The largest Australian managed aquifer recharge projects are in Queensland's Burdekin Delta. Infiltration ponds recharge 100 GL/year in wet years, sustaining groundwater levels for sugar cane irrigation. The potential of managed aquifer recharge has so far been assessed in three Australian cities:

- Perth — 100–250 GL/year (Scatena and Williamson 1999)
- Adelaide — 20–80 GL/year (Hodgkin 2005), with 60 GL/yr achievable using urban stormwater (Stormwater Management Authority, 2009)
- Melbourne — 100 GL/year (Dudding et al 2006).

Hence, managed aquifer recharge could be a major contributor to alleviating the projected shortfall in water supplies to Australian cities, which is expected to reach about 800 GL/year by 2030 (WSAA 2007).

## **2.4 Situations where managed aquifer recharge is not viable**

Managed aquifer recharge is only feasible if there is a suitable aquifer; that is, one that can accept a sufficient volume of water at a sufficient recharge rate for the benefits to justify the costs of establishing the project. If no suitable aquifer is detected within the affordable drilling depth, and local hydrogeological studies do not reveal a suitable aquifer near the source or sufficient demand for water to allow its economical transfer, then managed aquifer recharge is not feasible.

If well yields are low, viability can be determined by calculating a minimum economic rate of recharge or recovery. The number of injection or recovery wells, or the area of infiltration galleries or ponds required to recharge and recover water at the required rate can then be compared to the project's budget. Generally, if the yield of wells in an aquifer is marginal, then treatment for recharge water to avert clogging will generally have a high cost; alternatively, maintenance costs will be even higher per unit volume of water recovered.

Managed aquifer recharge is not recommended if the environmental risk cannot be reduced to an acceptably low level by economically viable preventive measures (taking all costs and benefits of the project into account). Marginally feasible projects — those with only small net benefits to the proponent — are not encouraged if incentives and capacity for effective management are low.

Locations with an unconfined aquifer and shallow watertable should be avoided. There is nowhere to store additional recharge without causing waterlogging, salinisation, or geotechnical problems for buildings and other infrastructure. Unless the managed aquifer

recharge project is an integral part of a proposal for increased extraction of water, such sites should be avoided. However, management of these situations is highly constrained and watertable fluctuations are likely to significantly exceed those that occur naturally.

If the available storage capacity of an aquifer is already fully committed to other managed aquifer recharge operations, then additional managed aquifer recharge is impractical and would have a negative effect on the performance of the existing operations.

Managed aquifer recharge also requires a source of recharge water for sufficient time to ensure that the recoverable volume warrants the project's establishment costs. Urban stormwater requires land for detention storage. In new subdivisions, the increase in land value due to water views exceeds the costs of land used for detention storage. In built-up areas, finding land for detention storage is much more difficult, unless managed aquifer recharge is a coherent component of an urban renewal project.

Appendix 8 summarises characteristics of aquifers that favour or hinder managed aquifer recharge.

## 2.5 Existing recharge increase and managed aquifer recharge

Human impacts on hydrologic systems can increase recharge (Table 2.2). Some of these impacts are unintentional consequences of deliberate activities that have an unrelated purpose, such as:

- land clearing
- irrigation
- water and sewerage services
- road construction.

These activities may have desirable and undesirable consequences for the quantity and quality of groundwater. Aquifer recharge can be classified as:

- *unmanaged aquifer recharge* — an intentional water-related activity known to increase aquifer recharge, but one that is usually undertaken to dispose of water rather than to recover it
- *managed aquifer recharge* — an intentional activity to recharge aquifers to recover water for economic or environmental purposes, which must assure adequate protection of human health and the environment.

**Table 2.2 Examples of unintentional, unmanaged and managed aquifer recharge**

Unintentional	Unmanaged	Managed
<ul style="list-style-type: none"> <li>• Clearing deep-rooted vegetation or soil tillage</li> <li>• Leakage from water pipes and sewers</li> <li>• Irrigation deep seepage</li> <li>• Infiltration of runoff from impervious areas</li> <li>• Spraying defoliant</li> </ul>	<ul style="list-style-type: none"> <li>• Stormwater drainage wells and sumps</li> <li>• Septic tank leach fields</li> <li>• Mining and industrial water disposal to sumps</li> <li>• Floodplain water harvesting</li> </ul>	<ul style="list-style-type: none"> <li>• Injection and recovery wells</li> <li>• Infiltration basins and recovery wells</li> <li>• See Figure 2.2</li> </ul>

Recharge may progress from unmanaged to managed by appropriately accounting for human health and environmental risks (as covered in these guidelines), and by approval of the effects of the activity in regional groundwater management and surface water allocation plans.

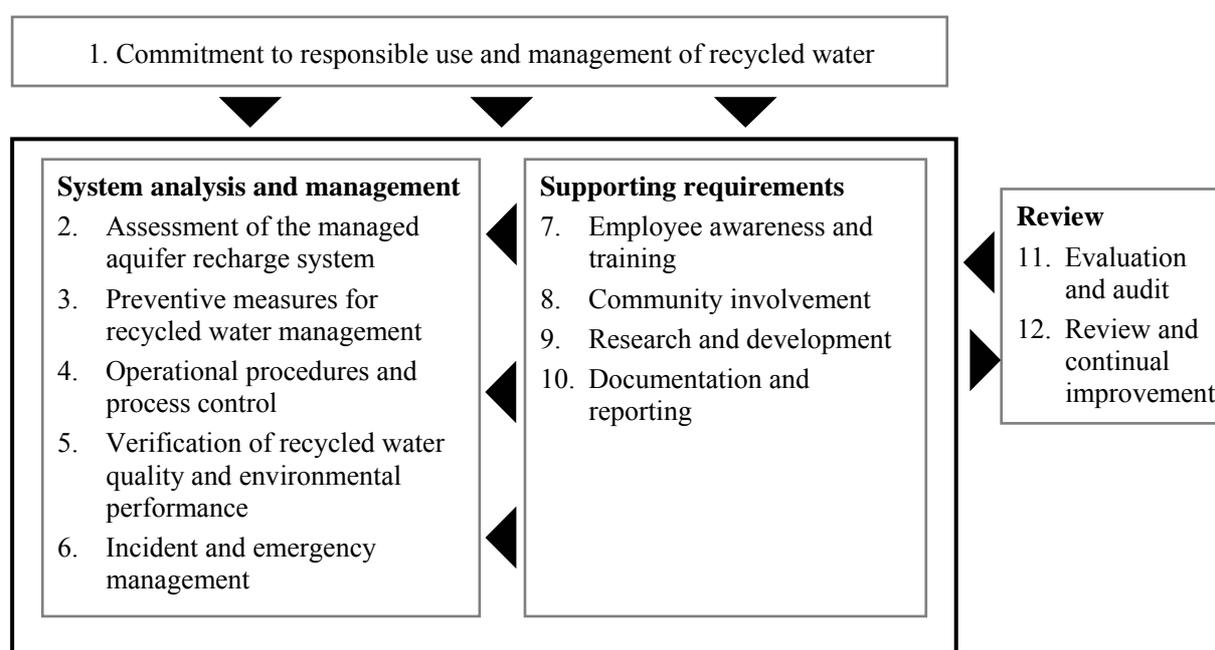
For example, stormwater disposal to aquifers in Mount Gambier (South Australia) and Perth (Western Australia) has occurred since the 19<sup>th</sup> century. This water makes a valuable contribution to the groundwater balance and to securing future supplies. In Mount Gambier, the risks to groundwater quality and drinking water supplies from stormwater drainage were recently evaluated and found to be acceptable. Minor refinements in wellhead protection to improve the levels of water supply protection were also suggested (Cook et al 2006). The transition from unmanaged to managed aquifer recharge will be complete when current plans for water-quality protection and security are adopted and implemented by the relevant authorities. The conversion from unmanaged to managed recharge may occur without the recharge proponent taking responsibility for recovery. In this case, the recharging activities would be an intentional component of regional groundwater management plans.

In Perth, domestic-scale recharge of roof runoff via infiltration pits is currently essential to sustain residential irrigation wells. Identification of appropriate land use activities in public drinking water source areas in Western Australia is the jurisdiction of the Department of Water, and is supported by the Western Australian Planning Commission and identified in the relevant statement of planning policies. The commission is responsible for ensuring compliance with these policies. Risks are managed by control of activities and land uses within drinking water catchments via drinking water source protection plans, rather than assessment of individual dwellings on a case-by-case basis. Local regulators consider that adequate risk assessment has been undertaken to assure adequate protection of human health and the environment and therefore regard domestic infiltration pits as managed aquifer recharge.

### 3 Framework for managing aquifer recharge

Risks to human health and the environment, including the receiving aquifer, can occur within each component of the managed aquifer recharge system. The development of a risk management plan for managed aquifer recharge involves the 12 fundamental elements adopted in the Phase 1 guidelines for water recycling (NRMMC–EPHC–AHMC 2006). These elements are listed in Figure 3.1.

The 12 elements of the framework presented in the Phase 1 guidelines apply as much to managed aquifer recharge as to other applications of recycled water management, and this chapter describes how the framework is applied to managed aquifer recharge. Although the elements are not necessarily sequential, they should all be followed to ensure that the risk management plan is comprehensive.



Source: NRMMC–EPHC–AHMC (2006).

**Figure 3.1 Elements of the framework for managing water quality and use**

A managed aquifer recharge risk management plan is a documented system for the management of aquifer recharge. The central philosophy of these guidelines is that it is better to prevent hazardous events from occurring than to clean up their effects afterwards. This is the philosophy that underpins the drinking water guidelines (NHMRC–NRMMC 2004) and all the documents in Phases 1 and 2 of Australia’s guidelines for water recycling.

The multiple barrier approach is a key concept in the management of risks in aquifer recharge. This approach is well established as a means of protecting drinking water quality in Australia (NHMRC–NRMMC 2004) and internationally (WHO 2006). The application of the multiple barrier approach through the managed aquifer recharge risk management plan should encompass every component of the managed aquifer recharge system, and be

submitted to the regulator of managed aquifer recharge projects in the relevant jurisdiction for scrutiny and approval.

### **3.1 Element 1: Commitment to responsible use and management of recycled water quality**

Managed aquifer recharge schemes are generally complex, and should only be operated and regulated by people with sufficient expertise. Therefore, Element 1 must be addressed during the planning and investigative stages of any managed aquifer recharge scheme. Further information on Element 1 is given in Section 2.1 of the Phase 1 guidelines. In general, the user of the recovered water will be a proponent of the managed aquifer recharge project; this situation provides a means of assuring that the user has an ongoing commitment to achieving the quality of recovered water that is required for its intended uses.

One type of managed aquifer recharge can be relatively simple; that is, roof runoff from a single household recharging specific aquifer types, with recovery for non-potable uses. The householder would be required to have only limited expertise, due to the design requirements imposed by a local authority. Also, a local authority would need to take responsibility for monitoring regional effects on the aquifer and implementing contingency plans.

### **3.2 Element 2: Assessment of the managed aquifer recharge system**

To identify and manage all health and environmental hazards and associated risks in a managed aquifer recharge system, proponents must have a thorough documented knowledge of the entire managed aquifer recharge system (Figure 2.1 and Table 2.1), from sources of recharged water to uses of recovered water and the fate of recharged water in the aquifer.

The first step of risk assessment is to construct a process diagram that clearly indicates all of the components of the managed aquifer recharge system. This should be done by people who have an appropriately detailed knowledge of the system and of the end uses. Information about the source water and native groundwater composition should be analysed for evidence of trends or hazards that may influence the final quality of the recovered water. The analysis should include the potential effect on treatment systems of hazardous events that may affect human health and the environment, such as:

- storms
- sewer overflows
- power failures
- illegal disposal of contaminants.

The method used to identify and assess hazards must be structured, consistent and comprehensive. Hazard identification and risk assessment typically involve the following steps that help to classify the managed aquifer recharge system:

- hazard identification
- dose–response and exposure assessment of the identified hazards
- risk characterisation.

Each of these steps is discussed below.

### 3.2.1 Hazard identification

Hazards to human health and the environment from source water or treatment processes are described in detail in the Phase 1 guidelines, and the hazards associated with managed aquifer recharge are discussed in detail in Chapter 5.

Hazards may include:

- constituents in source water or groundwater
- products of reactions between source water, aquifer material and groundwater
- geotechnical and hydrogeological hazards
- constituents of byproducts of water treatment and managed aquifer recharge maintenance operations.

For example, aerobic water recharging of an anaerobic aquifer may oxidise pyrite, and hazardous concentrations of arsenic may be mobilised on re-establishment of reducing conditions. Identifying the causes or sources of all hazards will inform the selection of preventive measures. One option to reduce risk in this example is to remove oxygen from the injectant, to inhibit pyrite oxidation. Another example of a preventive measure is to restrict injection pressure if the confining layer of the aquifer is thin, to prevent the layer from bursting.

If hazardous levels of chemicals come from a point source in a catchment, an obvious preventive measure would be to control the source, reducing or eliminating discharge (ie an exclusion barrier; see Figure 4.5 in the Phase 1 guidelines).

### 3.2.2 Dose–response and exposure assessment of the identified hazards

Hazardous events, such as spills in an urban stormwater catchment or failure of a wastewater treatment plant, may lead to predictable changes in hazard concentrations and exposure. Because many hazards do not have established dose–response relationships, alternative methods may be applied; for example, the determination of organic chemical guideline levels described in NRMCC–EPHC–NHMRC (2008). Aquifer characterisation will be necessary to estimate the fate of recharged water, and its potential to affect other groundwater users or groundwater-affected ecosystems.

### 3.2.3 Risk characterisation

Several potential qualitative risk ranking methods can be used to characterise risks. Tables 2.5–2.7 in the Phase 1 guidelines use qualitative measures of likelihood and impact to estimate and prioritise the risks associated with each hazard. Quantitative risk assessments are accepted as a standard method for determining risks posed by the microbial hazards for which dose–response relationships are available (see Chapter 3 in the Phase 1 guidelines).

Box 3.1 gives an example of managed aquifer recharge system assessment for a stormwater ASTR (aquifer storage, transport and recovery) system.

### **Box 3.1 Example of managed aquifer recharge system assessment for a stormwater ASTR system**

The Parafield ASTR system is located on the Northern Adelaide Plains. The system captures and treats urban stormwater via a series of stormwater detention ponds and a reedbed, before injection into a brackish limestone aquifer for subsequent recovery from separate wells. The project is a sequel to an existing ASR (aquifer storage and recovery) system that uses the same harvesting and pretreatment facility.

A screening-level risk assessment at concept stage, which used preliminary information on source water and groundwater quality, suggested that recovered water could potentially meet drinking water quality with the pretreatment system already in place. The system was mapped as a process diagram, and more detailed information was collected on source-water quality, pretreatment effectiveness and aquifer characteristics. Hydrological, groundwater and geochemical modelling were performed.

The consequent maximal risk assessment showed that aquifer heterogeneity would result in excessive salinity in recovered water. Further aquifer testing and modelling suggested an aquifer interval, well spacing and operating strategy likely to meet the requirements for recovered water quality. On this basis, wells were drilled, pipes and pumps were installed, and approval was obtained for recharge (and validation monitoring) to commence.

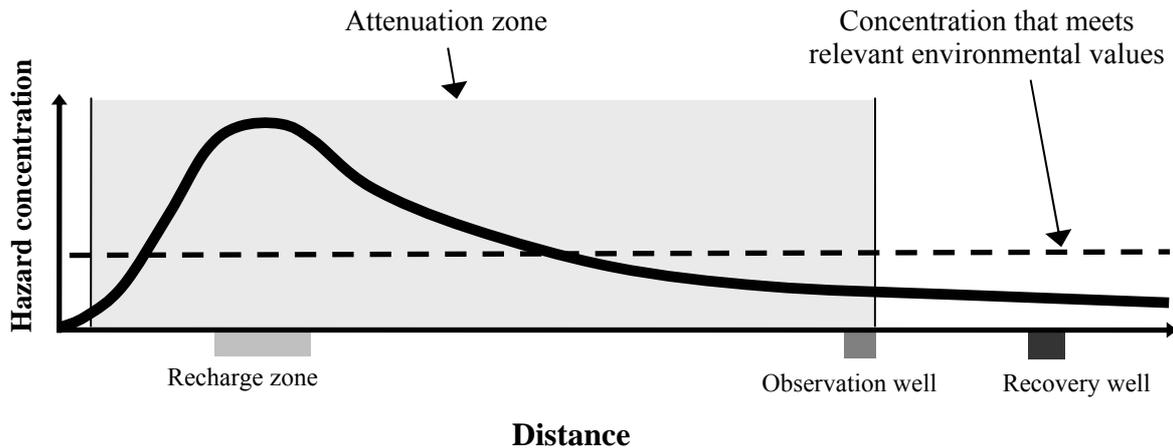
Baseline monitoring is important during risk characterisation, to establish the existing conditions of a managed aquifer recharge scheme (see Chapter 7). Ongoing environmental monitoring would verify the effectiveness of preventive measures in protecting human health and the environment. The selection of environmental receptors for monitoring should be informed by the maximal risk assessment and by taking account of preventive measures.

### **3.3 Element 3: Preventive measures for recycled water management**

Preventive measures for recycled water management include all actions, activities and processes used to:

- exclude hazards (exclusion barriers)
- reduce hazard concentrations (eg by treatment above or below ground)
- manage water usage (end-use restriction barrier).

Managed aquifer recharge differs from the other water recycling examples given in the Phase 1 guidelines, in that it includes a subsurface component that provides storage and water treatment functions. The concept of an attenuation zone is useful for defining the subsurface treatment barrier. Figure 3.2 illustrates an attenuation zone in an aquifer, and Box 3.2 describes how the zone functions.



This plot of hazard concentration on a transect through the aquifer from recharge zone to recovery well, shows that an observation well on the perimeter of the predetermined attenuation zone would verify that the required attenuation is achieved within the zone.

**Figure 3.2 Attenuation zone in an aquifer**

**Box 3.2 Attenuation zone in an aquifer**

Attenuation is the reduction in hazard concentration by natural processes (especially biodegradation) that are sustainable if the subsurface treatment system is not overloaded. Biodegradation occurs when the metabolic activity of microorganisms (or their enzymes) resident in an aquifer break down a contaminant into innocuous products.

Chemical and pathogen hazard behaviour in groundwater varies depending on the aquifer’s temperature and geochemical conditions. These may vary in time and space within the aquifer, particularly along the flow path from the point of recharge to the point of recovery. Attenuation rates for selected pathogens are given in Section 5.1 and Appendix 4; rates for organic chemicals are given in Section 5.5 and Appendix 5. Some chemicals may not attenuate, and these should be reduced to acceptable concentrations before recharge. The information provided on attenuation rates is specific to the site, and should be regarded as only indicative in designing schemes. The attenuation rates for pathogens and chemicals must be validated specifically for each scheme. Validation is the body of scientific evidence that demonstrates the capability of the attenuation zone in the aquifer. It must also demonstrate that the process control and operational monitoring provide ongoing assurances that the attenuation zone is operating effectively and is producing water of an appropriate quality.

The attenuation zone, which surrounds the zone of recharge, is the area where natural attenuation takes place. All pre-existing environmental values of the aquifer will be continually met beyond the attenuation zone, because there will have been adequate residence time of recharged water for all constituents to be attenuated to those values. The attenuation zone may be as small as a 5–50 m radius in some stormwater aquifer ASR projects. After a project ceases, the attenuation zone will shrink and disappear, as the groundwater is restored to pre-existing environmental values. (This is in strong contrast to contaminated sites, where noxious materials discharged to aquifers in unknown masses and concentrations can violate ambient environmental values for many generations and effectively annex the aquifer indefinitely from other productive uses.) Methods for calculating the size of the attenuation zone in simple cases are given in Appendix 6. Methods for measuring attenuation rates and groundwater hydraulic characteristics from which attenuation zones can be determined for more complicated cases are given in Appendix 3. The specific cases of fractured and karstic aquifers are covered in Sections 5.9 and 7.3. The methods provided to calculate the size of the attenuation zone are informative only and must be validated for each specific scheme.

Strategic placement of one or more observation wells at the perimeter of the attenuation zone can verify that the aquifer's attenuation barrier is effective. If treatment processes and rates of attenuation in the aquifer need to be validated, piezometers located closer to the recharge zone may be used.

Unless there is provision for an attenuation zone, water recycling using managed aquifer recharge would not benefit from the demonstrated sustainable treatment barriers within aquifers.

Element 3 includes *critical* and *non-critical control points* (also referred to as *quality control points*), plus supporting programs such as catchment management or instrument calibration. Examples of preventive measures for managed aquifer recharge are summarised in Table 5.1. For recycled water systems, see Box 2.6 in the Phase 1 guidelines).

Selection of critical control points is detailed in the Phase 1 guidelines. The flow chart shown in Figure 2.2 of that document may be used to determine whether a process step is a critical control point. During the hazard identification phase of the risk assessment, all hazards in the managed aquifer recharge system are identified and each of the process steps is documented (what these steps are will depend on the configuration of the managed aquifer recharge scheme).

The *critical limit* is the maximum (or minimum) value to which a hazard must be controlled at a critical control point to reduce its risk to an acceptably low (or high) level. Critical control points are based on operational monitoring requirements or on appropriate water quality parameters (eg indicators such as turbidity for drinking water). Examples of preventive measures and critical control points for a stormwater ASR system are given in Box 3.3.

If a critical limit is not met, then the hazard is not controlled and corrective action must be taken. Critical limits must be established for each control measure applied at a critical control point. Examples of critical control points and associated limits are given in Section 2.3 of the Phase 1 guidelines. Target criteria that are outside critical limits should also be established, to serve as operational monitoring triggers for investigation. For details, see Figure 4.5 in the Phase 1 guidelines.

### **Box 3.3 Examples of preventive measures and critical control points for a stormwater ASR system**

The physical configuration of the ASR project described in Box 3.1 enabled a number of potential critical control points and associated critical limits to be identified. These control points and limits permitted real-time control via a supervisory control and data acquisition system. They included the initial stormwater intake into the system and the recovery point, which were to function as critical control points through monitoring of turbidity and electrical conductivity. Initial discussions with stakeholders led to the adoption of a critical limit of <100 NTU for turbidity at the source-water intake and <500  $\mu\text{S}/\text{cm}$  for electrical conductivity of the recovered water. Other potential critical control points based on salinity and turbidity were also identified, but further validation monitoring would be required to set critical limits.

The adopted critical control points, critical limits and target criteria for risk management form the basis of the operational procedures and process controls that are adopted (Element 4). These should be documented as discussed in Element 10.

### **3.4 Element 4: Operational procedures and process control**

The parameters selected for process control are determined by the assessment of the managed aquifer recharge system (Element 2) and from a detailed knowledge of each component (Table 2.1). Parameters critical to the safety of the system will need to be monitored at critical control points; those that are not critical will provide additional information on the operation of the system.

During the operation of a managed aquifer recharge system, operational procedures and process control monitoring is performed to check the performance of preventive measures (Element 3). The procedures should be designed to identify nonconformance with target criteria and to indicate a decline in system performance.

To ensure that critical limits are complied with, they must have associated operational procedures and suitable process control activities. For the purpose of operational monitoring, continuous or online monitoring is preferable to discrete or 'grab' sampling. Chapter 7 gives additional guidance on monitoring.

Other methods to monitor operational processes include the use of devices such as passive samplers, which remain in situ at water-quality monitoring points and concentrate hazards such as organic chemicals over time. Passive samplers are unlikely to provide information that can be used to monitor a critical control point, but could be useful in assessing whether the level of organic chemicals could present long-term risks to human health or the environment.

Operational monitoring does not solely encompass treatment indicators; it should also include aspects of the system that require regular checking to ensure that preventive measures are applied. Examples include operating pressures, groundwater levels and subsurface residence times. Further details of operational monitoring requirements for recycled water are given in Section 1.4 of the Phase 1 guidelines.

An example of operational procedures and process control for a stormwater ASTR system is given in Box 3.4.

#### **Box 3.4 Examples of operational procedures and process control for a stormwater ASTR system**

A research trial of an ASTR system in Parafield, South Australia, found that the occurrence and fate of organic chemicals was a key uncertainty in the initial system and risk assessment. The system shares source water with the Parafield ASR scheme, but aims to recover potable quality water.

Passive samplers were deployed in the source water and after the cleansing reedbed, to assess the presence and indicative concentrations of organic chemicals, such as pesticides, known to be used in the stormwater catchment. The samplers detected many pesticides that the conventional monitoring program using grab or integrated samples failed to detect. The conventional monitoring program was subsequently updated to reflect the improved knowledge of the system.

### **3.5 Element 5: Verification of water quality and environmental performance**

Element 5 verifies that the managed aquifer recharge system poses very low (acceptable) risks to human health and the environment. Verification of the recovered water quality

assesses the overall performance of the managed aquifer recharge system in relation to specific uses of the water. Water-quality monitoring was undertaken on the cleansing reedbed of the project described in Boxes 3.1, 3.3 and 3.4, to verify wetland treatment performance under a variety of flow regimes.

More details on verification water-quality monitoring are given in Section 2.5 of the Phase 1 guidelines. This information is used to audit the performance of the managed aquifer recharge system (see Element 11). Information concerning the monitoring program required for management of a managed aquifer recharge scheme is given in Chapter 7. The risk management plan includes provision for decommissioning of the managed aquifer recharge operation, including the verification monitoring that needs to be undertaken until the aquifer has been restored to its ambient environmental values.

### **3.6 Element 6: Management of incidents and emergencies**

Responses to incidents or emergencies can compromise the operation of a managed aquifer recharge system. The development of preventive measures appropriate to the risks should be documented as part of Elements 2 and 3 in the system's risk management plan.

Management of incidents and emergencies for managed aquifer recharge systems should include response to:

- spills or dumping of hazards into the catchment or source-water catchment zone
- disruption to pretreatment or post-treatment processes that result in the production of nonconforming water
- disruption to power supplies that affects treatment or injection and recovery systems
- protocols for communication between suppliers, users and other stakeholders
- any other incident that could affect the safe operation of a managed aquifer recharge system.

Specific guidance on contingencies for managed aquifer recharge is given in Table 6.1. Additional considerations for the management of incidents and emergencies, which may include more frequent monitoring of hazards, are given in Section 2.6 of the Phase 1 guidelines.

### **3.7 Element 7: Operator, contractor and end-user awareness and training**

All operators, contractors and end users who work with managed aquifer recharge systems must be given appropriate training. Training and awareness programs for such systems should include induction programs for new employees, site visitors and contractors, and employee training in the principles of risk management. All employees should be aware that any observable problems must be reported in a timely manner, instead of waiting until the equipment or process fails. Further information on Element 7 is given in Section 2.7 of the Phase 1 guidelines.

### **3.8 Element 8: Community involvement and awareness**

As noted in Section 2.8 of the Phase 1 guidelines, appropriate levels of community consultation are essential in planning water recycling; this applies equally to managed aquifer

recharge schemes. Community engagement should begin during the development of the risk management plan for the scheme (Element 2). However, engagement will vary with the scheme's nature, location and scale, and the risks involved. Establishing appropriate processes for engaging and communicating with stakeholders is an important step in the planning of the managed aquifer recharge scheme; Chapter 6 of the Phase 1 guidelines covers this in detail. If environmental values for the aquifer to be recharged are undefined, a degree of community consultation may be needed before consultation on the specific project.

### **3.9 Element 9: Validation, research and development**

Validation involves investigating the effectiveness of preventive measures in reducing risks posed by hazards or hazardous events (Element 3). It can be achieved by obtaining evidence about the performance of preventive measures, and by making sure that information supporting the managed aquifer recharge risk management plan is correct.

The ASTR system described in Box 3.1 was subjected to extensive validation monitoring to determine:

- the water residence time
- attenuation of pathogens and organic chemicals in the subsurface
- whether any metals would be mobilised during passage between injection and recovery wells.

Validation plays an important role during establishment of a managed aquifer recharge system. For example, during the commissioning phase for a new system, the operator needs to demonstrate the system's capability to consistently produce recovered water of the quality required for the planned uses.

Formal investigation or research may be needed if there is insufficient knowledge of the effectiveness or reliability of the barriers within the system to maintain recovered water quality within critical limits, or if the environmental impact of hazards is unknown. For example, if there is concern about the possible attenuation of hazards (eg organic chemicals in the subsurface), then sampling and analysis of source water and at observation wells, or the use of passive samplers, may be necessary.

Validation is also required whenever new processes or equipment are introduced, or when significant changes to the managed aquifer recharge system take place.

### **3.10 Element 10: Documentation and reporting**

The management plan for the managed aquifer recharge system will contain most of the recorded documentation relating to the system's operation, including monitoring information, as proof of plan compliance. The management plan is likely to contain the following features (proponents should check with the local regulatory authority for the complete list):

- register of relevant regulatory requirements
- names and contact details of stakeholders
- a process diagram of the entire managed aquifer recharge system (capture, pretreatment, injection, storage, recovery, post-treatment and end use)
- operational procedures and process controls
- critical control points, quality control points and associated critical limits

- incidence response procedures
- training programs and records for employees and contractors
- monitoring information (baseline, operational, validation and verification data)
- communication with authorities concerning system performance and monitoring results.

Routine reporting of operational monitoring data should be kept to the minimum required to identify adverse trends or declining operational performance. Evaluation of results and internal and external audits (Element 11) should be reported to everyone responsible for operational procedures and process controls. Routine external reporting requirements for regulators are generally specified in approvals for managed aquifer recharge systems; in general, annual reporting is anticipated.

### **3.11 Element 11: Evaluation and audit**

Where third party certification does not exist, the managed aquifer recharge management plan (Element 10) should be audited regularly. This should preferably be done by an external party with appropriate certifications (if available) or by the regulator; internal auditing is also recommended. Auditing is essential to ensure the maintenance of standards and encourage continuous improvement (Element 12). Annual review is initially recommended. Based on the results, the evaluation period may be extended; however, to account for changes in the source-water catchment and changes in pressures on the aquifer system, the period should not exceed five years.

### **3.12 Element 12: Review and continuous improvement**

Managed aquifer recharge risk management plans should be internally reviewed periodically, to ensure that they accurately reflect the current understanding of the system's risks and controls (Elements 2 and 3). Reviews should be overseen by the operator responsible and should include all components of the system, including end uses. All monitoring data, particularly environmental parameters subject to long-term degradation (eg groundwater quality) should be included.

The outcome of each review should be documented, and improvements in operational procedures and process controls should be implemented within an appropriate timeframe before the next review.

## 4 Stages of managed aquifer recharge project development and assessment

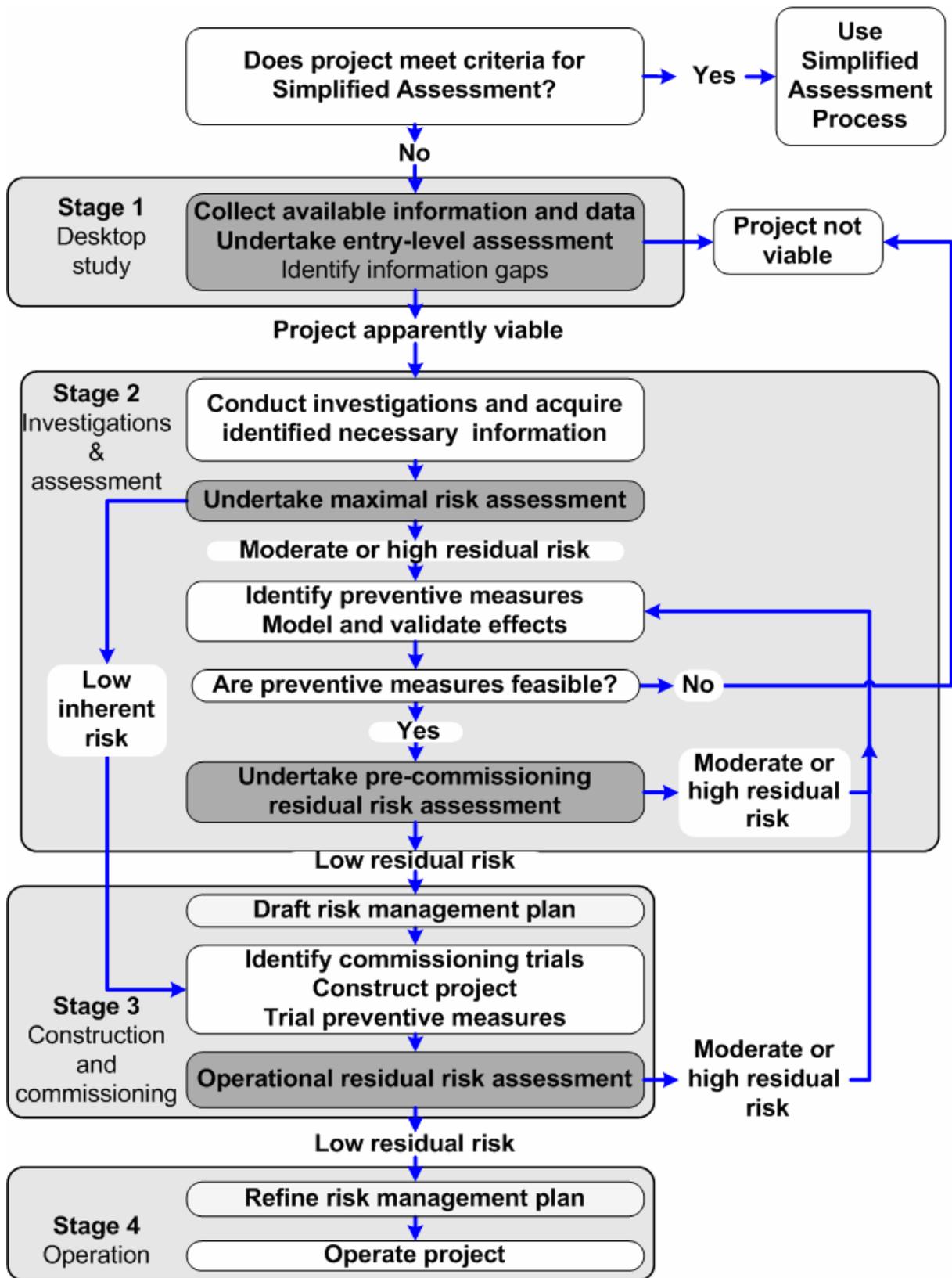
### 4.1 Overview

Two types of risk assessment are described in this chapter. The first is a broadly applicable general assessment. The second is a simplified assessment applying to domestic-scale projects under a limited range of conditions with low inherent risks. Criteria and procedures for such projects are given in Section 4.2. The following description applies to projects that require a general assessment.

The development of managed aquifer recharge projects generally follows the sequence of:

- concept design
- investigations to prove the concept and enable detailed design
- approvals
- construction
- commissioning trials
- implementation of an ongoing operation.

Assessments are interspersed between these steps to address catchment and groundwater plans and local government requirements. Figure 4.1 shows a series of risk assessments that are designed to ensure protection of human health and the environment, as in the Phase 1 guidelines (NRMMC–EPHC–AHMC 2006). These assessments allow decision points for investment, based on an informed understanding of the next required level of investigation. The objectives of the general assessment steps are shown in Table 4.1. The stages described in Figure 4.1 and Table 4.1 are shown sequentially in Figure 4.2.



**Figure 4.1 Risk assessment stages in managed aquifer recharge project development**

**Table 4.1 Assessment stages and objectives**

<b>Assessment step</b>	<b>Information available</b>	<b>Objectives</b>
Entry-level assessment	Existing information and regulations (Stage 1)	<ul style="list-style-type: none"> <li>To assess likely presence of a suitable aquifer</li> <li>To assess conformity with catchment and aquifer management plans and local government requirements</li> <li>To identify, using only rudimentary information, the likely degree of difficulty of the managed aquifer recharge project; this will inform the extent of investigations and level of operational expertise likely to be required at Stage 2</li> </ul>
Maximal risk assessment	Investigations (Stage 2) plus Stage 1	<ul style="list-style-type: none"> <li>To assess whether the project has low maximal (inherent) human health and environmental risks based on investigation data</li> <li>In low maximal risk cases, planning for construction and commissioning is simplified. This avoids the requirement for additional preventive measures and precommissioning residual risk assessment</li> <li>In moderate or high maximal risk cases, preventive measures must be identified</li> </ul>
Residual risk assessment: precommissioning	Investigations (Stage 2) plus Stage 1	<ul style="list-style-type: none"> <li>To assess whether proposed preventive measures and operational procedures ensure acceptably low residual risks to human health and the environment from constructing and commissioning the project</li> <li>To inform on hazards or aspects that may require validation monitoring during commissioning trials</li> </ul>
Residual risk assessment: operational	Validation data from commissioning (Stage 3) plus Stages 1 and 2	<ul style="list-style-type: none"> <li>To assess whether ongoing operation of the project has acceptably low human health and environmental risks</li> <li>To inform the management plan, including operational and verification monitoring for ongoing operation (Stage 4)</li> </ul>

Entry-level assessments largely address allocation issues (outlined in Section 1.2.2 and Table 1.1) that are usually adequately determined without detailed site-specific information. Governance of these issues will generally be in the hands of a state or regional water resources management agency. A preliminary assessment of the effort likely to be required to demonstrate low risks to human health and the environment is also carried out at this stage. This does not accord with the screening-level assessment found in the Phase 1 guidelines, because Stage 1 information concerning source water and the aquifer is unlikely to eliminate any hazards from further consideration. Rather, the entry-level assessment is intended to inform on the likely degree of difficulty of the managed aquifer recharge project, and hence inform proponents of the extent of field investigations needed in Stage 2.

Stage 1 is the most cost-effective stage at which to abandon projects for which the potential rewards do not justify the high degree of difficulty. If the potential value of recycled water or new resource generated is large, an investment in Stage 2 investigations can focus on the key issues affecting viability. Causes of the high degree of difficulty may be resolved with feasible preventive measures; if not, such projects will not be viable.

As described in Section 1.3, risk should be assessed at two levels — maximal risk and residual risk.

Maximal risk (also referred to as unmitigated or inherent risk) is risk in the absence of preventive measures. A maximal risk assessment:

- identifies high-priority risks
- determines where attention should be focused
- prepares for emergencies and appropriate preventive measures
- determines the targets that preventive measures need to achieve.

Residual risk is risk after consideration of preventive measures. A residual risk assessment provides an indication of the safety and sustainability of the recycled water scheme. Residual risk needs to be less than the upper limits of tolerable risk.

Following investigations in Stage 2, maximal risk is determined for each hazard. If the responsible authority in the jurisdiction assesses the maximal risk to be low for all hazards, the project may proceed directly to construction. However, the more usual case is that the assessment will determine that some preventive measures are needed to reduce risk related to some hazards. This will be followed by reassessment of residual risk at the precommissioning stage, based on known or predicted effects of preventive measures on hazards. This step estimates the residual risk of commissioning the project. Preventive measures, operational procedures and incident and emergency management plans are intended to give confidence that the project will be safe during commissioning trials (Stage 3). If residual risks fail to reach acceptance criteria, preventive measures are added and residual risks reassessed until residual risks are determined to be low, or the project proponent determines that the expense of these measures makes the project unviable.

The risks for each project will depend on the quality of the source water, the intended uses of recovered water and the environmental values of the aquifer, as discussed in Section 4.3. While all projects follow the same risk assessment pathway, the level of effort required in risk assessment and management can vary markedly between projects, based on the specific risk profile of the project. For example, projects producing drinking water supplies will generally require substantially more effort than those producing irrigation supplies from initially brackish aquifers. For many managed aquifer recharge projects, the level of some risks can only be estimated before full-scale implementation and validation monitoring occurs.

Following construction of the project, or at least a pilot or demonstration project, commissioning trials are run to enable validation of processes that could not be measured until recharge occurs, and to allow verification of the efficacy of the preventive measures. At this stage (Stage 3; Figure 4.1), it is possible to make an accurate calculation of residual risk; that is, an operational residual risk assessment. A low residual risk assessed at Stage 3 provides a basis for ongoing operation of the site and development of risk management plans (including verification and operational monitoring and reporting) (Stage 4). The risk management plans may be periodically reviewed, subject to monitoring results. In the event that the low risks anticipated are not achieved, the proponent needs to identify and adopt additional preventive measures, and perform further commissioning trials if the project is to continue.

A template for entry-level assessment is given in Section 4.3. Appendix 2 contains the information to be generated at Stage 2 to enable a maximal risk assessment and a precommissioning residual risk assessment. The acceptance criteria for the maximal and

residual risk assessment levels, and relevant preventive measures for each hazard are given in Chapter 5. A range of methods that could provide validation information to inform a residual risk assessment is given in Appendix 3. Table 4.2 shows that the extent of investigations required is determined by the perceived level of risk, and in turn reduces uncertainty in risk estimates. A typical ‘Gantt’ chart for project development is shown in Figure 4.2.

**Table 4.2 Issues addressed at each stage of investigations**

Investigation stage	Issues addressed
1. Desktop	<ul style="list-style-type: none"> <li>• Type and scale of scheme</li> <li>• Source-water availability</li> <li>• Compatibility with catchment and groundwater management plans</li> <li>• Intended uses of recovered water</li> <li>• Existence of a suitable aquifer</li> <li>• Source water, native groundwater and end-use environmental values</li> <li>• Similarity to successful projects</li> <li>• Management capability</li> <li>• Planning and development requirements</li> <li>• Preliminary evaluation of project viability and degree of difficulty</li> </ul>
2. Investigations, drilling, basic modelling	<ul style="list-style-type: none"> <li>• Source-water quality</li> <li>• Source-water catchment land use assessment</li> <li>• Groundwater quality</li> <li>• Soil, aquifer and aquitard characteristics, and fate of recharged water</li> <li>• Aquifer storage competence</li> <li>• Groundwater pressures and gradients</li> <li>• Reactions between recharge water, groundwater and aquifer minerals</li> <li>• Water treatment options and effectiveness</li> <li>• Management of clogging</li> <li>• Biodegradation and inactivation of contaminants</li> </ul>
3. Trials, detailed modelling	<ul style="list-style-type: none"> <li>• Effectiveness of preventive measures and operational controls</li> <li>• Suitability of recovered water for intended uses</li> <li>• Size of attenuation and impact zones</li> <li>• Recovery efficiency</li> <li>• Targeted studies covering identified hazards</li> </ul>

Implementing additional preventive measures may reduce residual risk to an acceptable level. In order of priority, preventive measures generally cover:

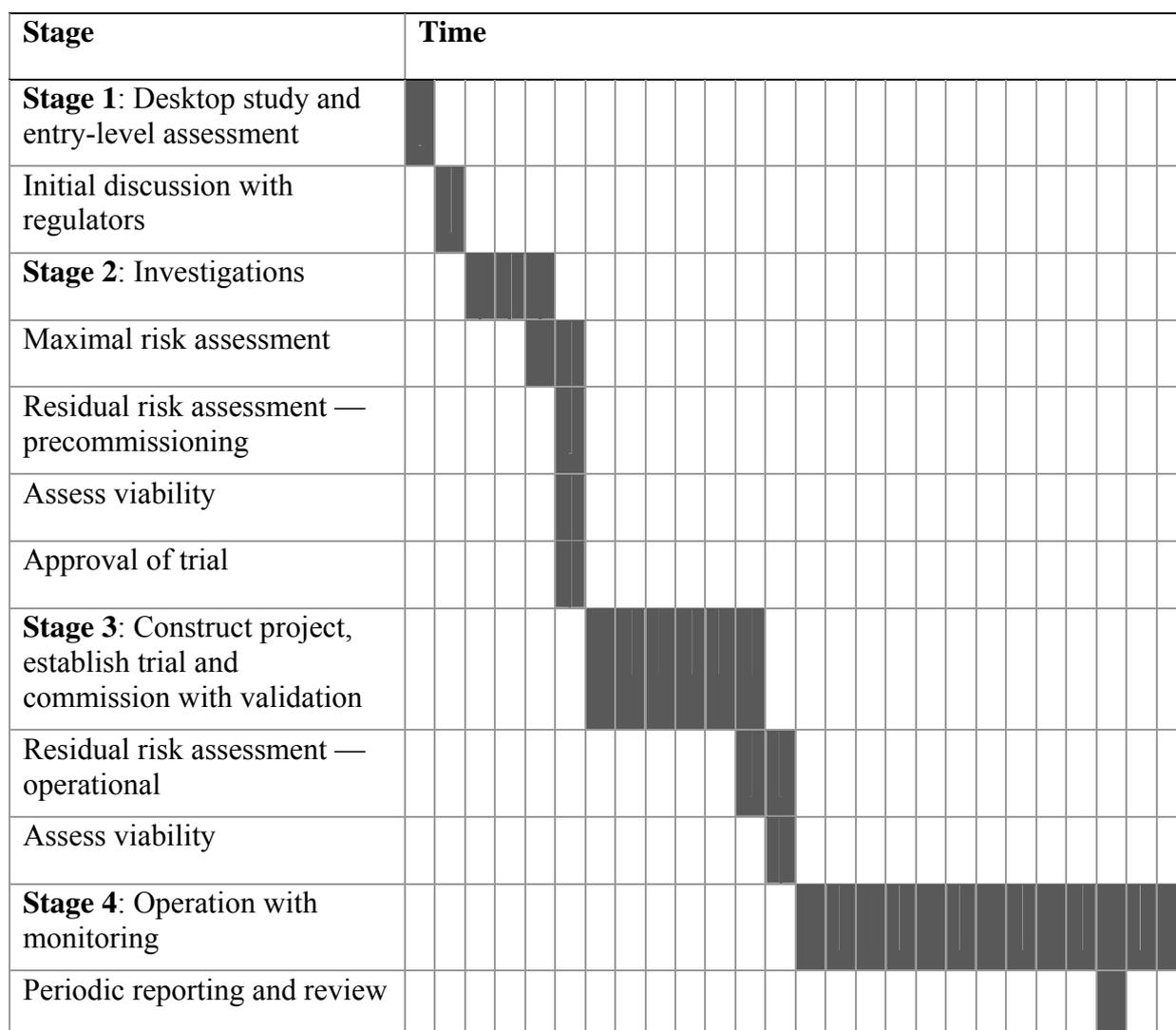
- avoidance (eg excluding poor quality water by catchment selection, aquifer selection, or use of isolating valves that respond to water quality)
- treatment (eg engineered processes and time in aquifer storage)
- management at the end use (eg withholding periods or irrigation method selection) to minimise exposure (see ARMCANZ–ANZECC (1994)).

Figure 4.1, and Tables 4.1 and 4.2, apply to all managed aquifer recharge projects, except for small-scale projects with prescribed characteristics that have low inherent risks. Provision has been made for these in the form of simplified assessments, which recognise that site-by-site

monitoring costs of small-scale projects may be prohibitive (Section 4.2). However, if water resources agencies, other regulators or groundwater user groups take responsibility for monitoring and controlling cumulative effects of multiple small operations, then significant cost-effective benefits can be achieved.

Hazards may be controlled by incorporating design features that compensate for assumed low levels of operator competency (see Section 4.2 for details). For example, the agency may stipulate:

- source-water selection (eg only roof catchments)
- specified treatment of recharge water (eg screen or sand filter to be included)
- overflow provisions (to avoid overcharging the aquifer or causing nuisance to neighbours)
- a requirement to recover some water (to ensure vested interest in the quality of water recharged).



**Figure 4.2 Indicative Gantt chart for development of a typical managed aquifer recharge project requiring risk assessment**

In some situations, the economics of providing the required protection level will exceed the value of the project to the proponent. Such projects would be abandoned. These guidelines

will help proponents assess the likelihood of this as early as possible, thus saving time and resources.

## 4.2 Simplified assessment

All commercial-scale projects will follow the risk assessment process shown in Figure 4.1. However, domestic-scale projects with inherently low risks may be permitted to progress, provided they conform to local conditions and criteria, via a simplified assessment process. At the discretion of the local authority, these criteria would generally be defined in association with a regional groundwater monitoring plan rather than site-by site monitoring.

Simplified assessments are needed because monitoring can be a substantial cost component of small projects, and because effective design may manage risks in particular cases, without a need to rely on skilled operators to protect human health and the environment. In these cases, the commitment to responsible use and management of recycled water quality is held by the local regulator, rather than by the project proponent alone. Preventive measures need to be incorporated into the project's site and design to assure sustained protection; for example, by allowing for changes in ownership of the property.

To be eligible for a simplified assessment, a managed aquifer recharge project would need to meet the following criteria:

- source water is roof runoff from a single dwelling
- recovered water is for irrigation or other non-drinking uses specified by the local authority
- an aquifer capable of storing additional water exists
- the aquifer
  - has not been identified as being affected by industrial or agricultural contamination to an extent that precludes use
  - is not used for drinking water supplies in the area, and is not capable of use as a drinking water supply based on ambient groundwater quality
  - is confined and not artesian, or is unconfined and has a watertable deeper than 4 m in rural areas or 8 m in urban areas, or as otherwise specified by the local authority.

If all the qualifying criteria are met, proponents should contact the local authority for further information about permit requirements and conditions. At the discretion of the authority, conditions may include requirements for:

- the design of the recharge system
- preventive measures prior to recharge
- safe discharge of system overflow
- maintenance of the recharge system
- compliance with noise, odour and insect nuisance requirements
- protection of public safety
- contribution to regional monitoring costs
- recording cumulative volumes of recharge and recovery
- water sampling

- stopping or limiting recharge or recovery (if advised to do so by the authority).

In the absence of specific advice from the authority, proponents should consider the above factors when requesting approval from their authority. The authority's role will normally include monitoring groundwater levels and quality at a regional scale, to indicate the effect of aggregated impacts on aquifers or connected ecosystems.

An example of a simplified assessment is given in Box 4.1.

#### **Box 4.1 Example of a simplified assessment**

A project likely to use a simplified assessment is domestic-scale roof runoff, recharged via sumps at the base of household downpipes in highly permeable soils with deep watertables, into an unconfined aquifer. The water would be recovered for localised irrigation use, but not for drinking. This situation has low likelihood of incidence of all hazards (identified in Chapter 5); and is thus qualitatively judged to have a low inherent (maximal) risk to human and environmental health.

In such circumstances, and within defined areas, the relevant jurisdiction may elect to approve specified recharge practices that comply with standard designs and adhere to conditions applicable to all installations. Monitoring data at a few existing installations may provide evidence of the range of conditions and control measures that protect human and environmental health. The jurisdiction would assess the cumulative effect of many similar sites on groundwater levels and quality using a regional monitoring network of piezometers.

### **4.3 Entry-level assessment**

Entry-level assessment evaluates the apparent viability of managed aquifer recharge, using relevant existing data and information.

Entry-level assessment is undertaken in two parts:

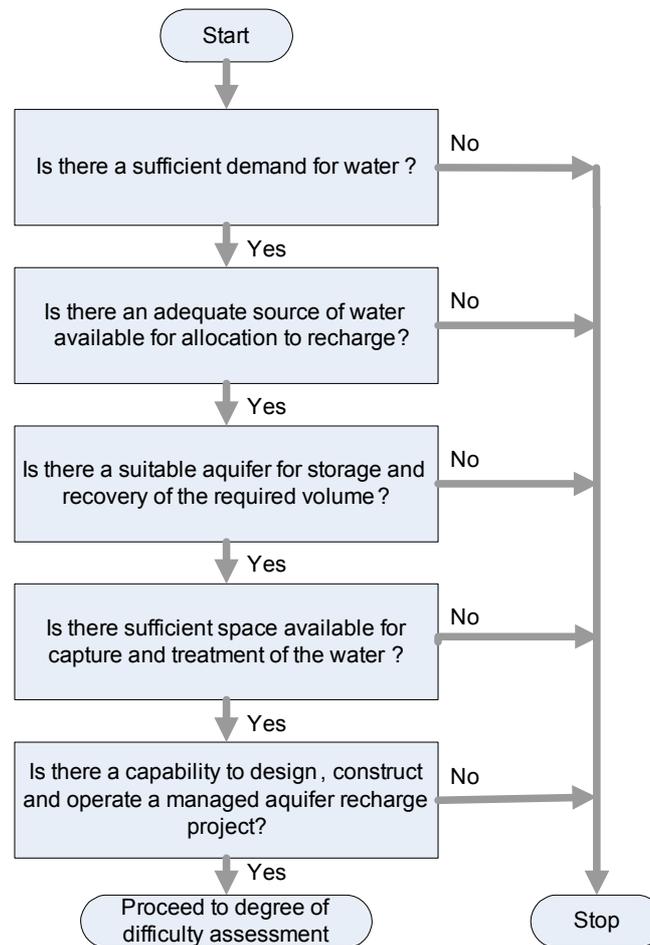
- *a viability assessment*, which is intended to inform proponents of any fatal flaws in their intended project, based on existing, readily available information
- *assessment of the likely degree of difficulty of the project*, which is intended to provide information about the amount of effort likely to be needed to achieve public health and environmental approvals from the relevant jurisdiction.

These assessments are described in more detail below.

Tables 4.3 and 4.4 provide specific guidance for project proponents on the entry-level assessment. These tables are templates that are intended to be easy to complete, and show the types of fundamental information required to establish managed aquifer recharge projects.

### 4.3.1 Entry-level assessment — viability

Figure 4.3 is a diagrammatic representation of the entry-level viability assessment.



**Figure 4.3** A schematic for entry-level viability assessment for managed aquifer recharge projects

The key factors, shown in Figure 4.3, that determine viability of managed aquifer recharge from readily available information are as follows:

- *Demand* — The ongoing volumetric demand for recovered water should be sufficient to warrant investment in the proposed project; if this is not the case, there needs to be a clearly defined environmental benefit. Either one of these criteria is essential for managed aquifer recharge. Projects involving recharge of partially treated water where recovery is incidental do not qualify as managed aquifer recharge.
- *Source* — Entitlement to water to be used for recharge needs to be secured. Mean annual volume of recharge should exceed mean annual demand, with sufficient excess to build up a buffer storage to meet reliability and quality requirements. In an already overallocated catchment, an entitlement to surface water is unlikely to be available.
- *Aquifer* — Presence of a suitable aquifer is critical for managed aquifer recharge. Such an aquifer needs to have an adequate rate of recharge and sufficient storage capacity; it also needs to be capable of retaining the water where it can be recovered. Low salinity and marginally brackish aquifers are preferred, to maximise the volume of recovered water that is fit for use after fresh recharge water mixes with ambient groundwater. Regional maps

showing the potential of aquifers as storages for managed aquifer recharge have been developed for some urban and rural areas, and are available from water resources managers in the local jurisdiction. In overallocated aquifers, water managers may have additional constraints on the proportion of recharge that may be recovered.

- *Detention storage* — For stormwater recharge systems (either open space or dams), wetlands, ponds or basins are needed to detain sufficient water to achieve the target volume of recharge. Similarly, space needs to be available for whatever treatment process, if any, is subsequently determined to be required. For recycled water from a sewage treatment plant, generally no additional detention storage will be required at the recharge facility.
- *Management capability* — Knowledge of hydrogeology and water-quality management is vital for the successful design, construction and operation of managed aquifer recharge projects. Also necessary for some projects are geotechnical know-how, and expertise in water storage and treatment design, water sensitive urban design, hydrology, monitoring and reporting. Proponents who do not have these skills are encouraged to gain access to them before proceeding with Stage 2 investigations. The number of consultants experienced in investigations and design of managed aquifer recharge projects is growing.

The template for the viability assessment (Table 4.3) addresses these key factors. The template includes items related to quantity of water and water allocation, which were discussed in Chapter 1 (see Section 1.2.3 and Table 1.1). If the answer to **all** of the questions given in Table 4.3 is ‘Yes’, proponents then proceed to determine the degree of difficulty, shown in Table 4.4, below.

**Table 4.3 Entry-level assessment**  
**Part 1 — viability assessment**

<b>Attribute</b>	<b>Yes</b>	<b>No</b>
<i>1. Intended water use</i>		
Is there is an ongoing local demand or clearly defined environmental benefit for recovered water that is compatible with local water management plans?	Continue viability assessment	Managed aquifer recharge is not recommended
<i>2. Source-water availability and right of access</i>		
Is adequate source water available, and is harvesting this volume compatible with catchment water management plans?	Continue viability assessment	Managed aquifer recharge is not recommended
<i>3. Hydrogeological assessment</i>		
Is there at least one aquifer at the proposed managed aquifer recharge site capable of storing additional water?	Continue viability assessment	Managed aquifer recharge will not work
Is the project compatible with groundwater management plans?	Continue viability assessment	Managed aquifer recharge is not recommended
<i>4. Space for water capture and treatment</i>		
Is there sufficient land available for capture and treatment of the water?	Continue viability assessment	Managed aquifer recharge is not recommended until this has been addressed
<i>5. Capability to design, construct and operate</i>		
Is there a capability to design, construct and operate a managed aquifer recharge project?	Go to Part 2: degree of difficulty assessment	

#### **4.3.2 Entry-level assessment — degree of difficulty**

As explained above, the second part of the entry-level assessment is intended to inform stakeholders of the degree of difficulty of the proposed project. It also serves as a preliminary indicator of human health and environmental risks. This assessment is not as rigorous or conclusive as a screening risk assessment (see the Phase 1 guidelines). The entry-level assessment is simply intended to help proponents to make better informed decisions about whether to proceed with the Stage 2 investigations that would allow a more rigorous risk assessment. The costs of embarking on Stage 2 of a managed aquifer recharge project are not trivial; they involve activities such as drilling investigation wells, conducting pumping tests on aquifers, and sampling and analysis of source water and groundwater quality. For more difficult projects or sites, investigations will be more extensive and more expensive.

The template for the second part of the entry-level assessment provides 14 questions (Table 4.4), related to information needs, and the answers determine the scope of Stage 2 investigations. The specific information required for each assessment is contained alongside each question in Table 4.4. Answering Question 4 and referring to Table A1.2 in Appendix 1

provides a fundamental indicator of degree of difficulty. The number of questions for which additional information is required in Stage 2 is a further qualitative indicator of the degree of difficulty of a project. It is also an indicator of the order of magnitude of resources likely to be required for investigations and for the preventive measures that would be needed to result in a low level of risk at a subsequent precommissioning risk assessment, which in turn would enable construction and trials. If answers to all 14 questions reveal uncertainties or the need for more information, this does not mean a project is impossible; but it is likely to be expensive. Similarly, if few answers reveal the need for more information, it is likely that the project implementation will be relatively simple; but this does not guarantee there will be no fatal flaws.

Entry-level acceptance criteria are also listed in the tables of Chapter 5, as advance notice of each hazard that needs to be addressed in the subsequent stages of risk assessment. The intention of these criteria is to provide supplementary guidance to proponents of projects at an early stage, given the limited information likely to be available at the first stage of a project.

Stage 2 information is required for a maximal risk assessment (as shown in Figure 4.1); it is generally also needed for a consequent precommissioning residual risk assessment. Imprecise information at Stage 2 leads to more stringent preventive measures. Proponents can weigh up the benefits of acquiring more information or providing additional preventive measures, to deliver equivalent acceptable low residual risk.

In Table 4.4, several of the questions relate to environmental values. The range of environmental values and the water-quality requirements for each are referenced in Table A1.1. If defined environmental values for groundwater are lacking in a jurisdiction, for entry-level assessment purposes it should be assumed that all environmental values that are met by the native groundwater quality need to be protected.

**Table 4.4 Entry-level assessment  
Part 2 — degree of difficulty assessment**

Information required for assessment	Questions and indicators of degree of difficulty
<i>1 Source-water quality with respect to groundwater environmental values</i>	
<ul style="list-style-type: none"> <li>• Where multiple samples are available, the highest concentration of each analyte should be used in the evaluation, unless there is justification that events resulting in those values will be prevented when the MAR project is established.</li> <li>• In the absence of water-quality data from actual source water, data may be used from existing, similar MAR projects that use the same type of source water and recharge the same aquifer.</li> <li>• In the absence of either of the above data sources, generic data from Australian water recycling guidelines may be used, as follows:               <ul style="list-style-type: none"> <li>– for stormwater; Appendix 2 of NRMCC–EPHC–NHMRC, (2009) gives generic data on concentrations of selected hazards in stormwater from roof catchments and urban catchments; in the absence of other information, use 95 percentile data</li> <li>– for treated sewage; maximum concentrations detected in secondary treated sewage may be used as a starting point and the Phase 1 guidelines give generic data (Table 4.10); these data range from sewage that has been treated in water reclamation plants (minimum value) to raw secondary treated effluent (maximum value).</li> </ul> </li> <li>• Assessment of quality variability and factors affecting quality are deferred to the maximal risk assessment.</li> </ul>	<p>Q1. Does source water meet the water-quality requirements for the environmental value of ambient groundwater? (Note: environmental values of water are listed in Table A1.1 along with a reference to water-quality criteria for each.)</p> <p>If the answer is ‘Yes’, a low risk of pollution is expected. This is a necessary, but not sufficient, condition for low risk.</p> <p>If the answer is ‘No’, a high maximal risk is likely. Stage 2 investigations are likely to be necessary to assess preventive measures to reduce the risk of groundwater contamination beyond the attenuation zone (and the size of the attenuation zone).</p>
<i>2 Source-water quality with respect to recovered water end-use environmental values</i>	
<ul style="list-style-type: none"> <li>• If the source water does not meet the water-quality requirements for the environmental values of intended end uses of recovered water, then there is a reliance on attenuation of hazards within the subsurface.</li> </ul>	<p>Q2. Does source water meet the water-quality requirements for the environmental values of the intended end uses of the water on recovery?</p> <p>If the answer is ‘Yes’, a low risk of pollution of recovered water is expected. However, due to aquifer reactions, this is not a sufficient condition for low risk.</p> <p>If the answer is ‘No’, a high maximal risk is likely. Stage 2 investigations will be necessary to assess this risk.</p>

**Table 4.4 (continued)**

Information required for assessment	Questions and indicators of degree of difficulty
<i>3 Source-water quality with respect to clogging</i>	
<ul style="list-style-type: none"> <li>• Where source-water quality is poor and soil or aquifer are fine-grained, clogging of the infiltration basin and gallery or recharge well is likely to occur, unless the water is pretreated before recharge.</li> <li>• Clogging is most prevalent when water contains moderate or high levels of suspended solids or nutrients, such as nitrogen or labile organic carbon.</li> <li>• Clogging can also occur when oxygenated water is introduced into an aquifer that contains iron. If the soil or aquifer are coarse grained or contain macropores, clogging with such waters is less likely, but the risk of pollution of groundwater is high (as covered in Questions 1 and 2).</li> <li>• Lack of evidence of clogging is insufficient to indicate that risk of pollution is low, even in fine-grained media.</li> </ul>	<p>Q3. Does source water have low quality; for example:</p> <ul style="list-style-type: none"> <li>• total suspended solids &gt;10 mg/L</li> <li>• total organic carbon &gt;10 mg/L</li> <li>• total nitrogen &gt;10 mg/L?</li> </ul> <p>Also, is the soil or aquifer free of macropores?</p> <p>If the answer is ‘Yes’, there is a high risk of clogging of infiltration facilities or recharge wells. Pretreatment will need to be considered, regardless of the answers to Questions 1 and 2.</p> <p>If the answer is ‘No’, a lower risk of clogging is expected. However, this is not a sufficient condition for low risk, because clogging depends on aquifer characteristics that would be revealed by Stage 2 investigations.</p>
<i>4 Groundwater quality with respect to recovered water end-use environmental values</i>	
<ul style="list-style-type: none"> <li>• Where samples are available, the highest parameters detected in each sample should be used in the analysis, unless there is the justification that events resulting in those values will be prevented when the MAR project is established.</li> <li>• In the absence of data on groundwater quality from the proposed site, data from nearby wells in the same aquifer may be used.</li> </ul>	<p>Q4. Does ambient groundwater meet the water-quality requirements for the environmental values of intended end uses of water on recovery?</p> <p>If the answer is ‘Yes’, a low risk of inadequate recovery efficiency is expected.</p> <p>If the answer is ‘No’, some risk of inadequate recovery efficiency is expected. In this case, see Table A1.2 for degree of difficulty expected.</p>

**Table 4.4** (continued)

Information required for assessment	Questions and indicators of degree of difficulty
<i>5 Groundwater and drinking water quality</i>	
<ul style="list-style-type: none"> <li>• The environmental values of the aquifer need to be defined by the relevant authority. These will depend on the ambient groundwater quality and any groundwater-affected ecosystems, as identified in the NWQMS groundwater protection guidelines (ARMCANZ–ANZECC 1995).</li> <li>• Setting these values involves a stakeholder consultation process and, in practice, will possibly be related to groundwater allocation planning processes.</li> <li>• If defined environmental values (for entry-level assessment purposes) are lacking, all environmental values that are met by the native groundwater quality need to be protected. Such environmental values may include <ul style="list-style-type: none"> <li>– raw water for drinking supplies</li> <li>– irrigation</li> <li>– aquaculture, recreation or livestock water</li> <li>– support of aquatic ecosystems with various conservation values.</li> </ul> </li> <li>• The water-quality requirements for these environmental values are referenced in Table A1.1.</li> </ul>	<p>Q5. Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?</p> <p>If the answer is ‘Yes’, there is a high risk of groundwater pollution if the aquifer is recharged by water, if the answer to Question 1 is ‘No’.</p> <p>If the answer is ‘No’, a low risk of groundwater pollution is expected. However, this is not a sufficient condition for low risk.</p> <p>For a broader view on this topic for the spectrum of environmental values, see Table A1.2.</p>
<i>6 Groundwater salinity and recovery efficiency</i>	
<ul style="list-style-type: none"> <li>• If native groundwater has high salinity, the proportion of native groundwater that can be present as a mixture with source water in recovered water is limited.</li> <li>• At such sites, density-affected flow may also occur. Fresh recharge water can form a lens above the native saline groundwater, making recovery difficult and reducing recovery efficiency (ie the volume of recovered water meeting the environmental values for its intended uses as a proportion of the volume of recharged water).</li> </ul>	<p>Q6. Does the salinity of native groundwater exceed either of the following:</p> <p>(a) 10 000 mg/L</p> <p>(b) the salinity criterion for uses of recovered water?</p> <p>If the answer to both parts of the question is ‘Yes’, there is a high risk of achieving only low recovery efficiency. Aquifer hydraulic characteristics, especially layering within the aquifer, will need careful examination in Stage 2.</p> <p>If the answer is ‘Yes’ only to Part (b), then a moderate risk of low recovery efficiency is expected. However, this is not a sufficient condition for low risk (eg in brackish aquifers with high rates of ambient lateral flow).</p> <p>If the answer is ‘No’ to both parts of the question, there is a low risk of low recovery efficiency.</p>

**Table 4.4** (continued)

Information required for assessment	Questions and indicators of degree of difficulty
<i>7 Reactions between source water and aquifer</i>	
<ul style="list-style-type: none"> <li>• Reactions between source water and aquifer minerals may result in deterioration of water quality for recovered water, and possibly for water in the aquifer beyond the attenuation zone; alternatively, they may cause excessive clogging or dissolution of the aquifer.</li> <li>• A full evaluation may be undertaken in Stage 2, but a simple indicator of the likelihood of potential problems at entry-level stage is to note the extent of contrasts between quality of source water and native groundwater.</li> </ul>	<p>Q7. Is redox status, pH, temperature, nutrient status and ionic strength of groundwater similar to that of source water?</p> <p>If the answer is ‘Yes’, a low risk of adverse reactions between source water and aquifer is expected. However, this is not a sufficient condition for low risk.</p> <p>If the answer is ‘No’, a high risk of adverse reactions between source water and the aquifer is possible, and will warrant geochemical modelling in Stage 2 (see Sections 5.2, 5.4 and 6.1).</p>
<i>8 Proximity of nearest existing groundwater users, connected ecosystems and property boundaries</i>	
<ul style="list-style-type: none"> <li>• Proximity of nearest existing groundwater users and groundwater-connected ecosystems is likely to influence the extent of investigations required in Stage 2.</li> <li>• Typically, attenuation zones will have aquifer residence times of up to a year.</li> <li>• If property boundaries are close to the MAR site, then the attenuation zone may extend beneath a neighbouring property.</li> <li>• Groundwater pressure effects in confined aquifers due to MAR may propagate over considerably longer distances than water quality effects.</li> </ul>	<p>Q8. Are there other groundwater users, groundwater-connected ecosystems or a property boundary within 100–1000 m of the MAR site?</p> <p>If the answer is ‘Yes’, a high risk of impacts on users or ecosystems is possible, and this will warrant attention in Stage 2.</p> <p>If the answer is ‘No’, a low risk of impacts on users or ecosystems is likely. However, this is not a sufficient condition for low risk.</p>
<i>9 Aquifer capacity and groundwater levels</i>	
<ul style="list-style-type: none"> <li>• Groundwater mound height induced by MAR depends on aquifer hydraulic properties, size of recharge area and recharge rate.</li> <li>• Mounding is normally calculated in Stage 2 when aquifer properties are measured. However, excessive mounding can cause <ul style="list-style-type: none"> <li>– waterlogging</li> <li>– soil heave</li> <li>– flooding of below-ground infrastructure</li> <li>– salt damp</li> <li>– soil salinisation.</li> </ul> </li> <li>• Unconfined aquifers with shallow watertable sites are thus generally unsuitable as storage targets for large-scale recharge projects,</li> <li>• For confined artesian aquifers, care needs to be taken against overpressurisation, and to seal existing wells that might otherwise start to flow.</li> </ul>	<p>Q9. Is the aquifer:</p> <p>(a) confined and not artesian?</p> <p>(b) unconfined, with a watertable deeper than 4 m in rural areas or 8 m in urban areas?</p> <p>If the answer to either part of the question is ‘Yes’, a low risk of waterlogging or excessive groundwater mound height is expected. However, this is neither a necessary nor a sufficient condition for low risk.</p> <p>If the answer to both parts of the question is ‘No’, a high risk of waterlogging or excessive groundwater mound height is expected. However, Stage 2 investigations may reveal that the risk is acceptable.</p>

**Table 4.4** (continued)

Information required for assessment	Questions and indicators of degree of difficulty
<i>10 Protection of water quality in unconfined aquifers</i>	
<ul style="list-style-type: none"> <li>If the aquifer is unconfined and the intended recovery is for drinking water supplies, then overlying land and waste disposal (including intensive horticulture and septic tanks) should be managed carefully or precluded from the groundwater capture zone.</li> </ul>	<p>Q10. Is the aquifer unconfined, with an intended use of recovered water that includes drinking water supplies?</p> <p>If the answer is ‘Yes’, there is a high risk of groundwater contamination from land and waste management.</p> <p>If the answer is ‘No’, there is a lower risk of groundwater contamination from land and waste management.</p>
<i>11 Fractured rock, karstic or reactive aquifers</i>	
<ul style="list-style-type: none"> <li>If the aquifer is fractured rock or karstic, the ability to recover stored water will require evaluation, especially if the ambient groundwater is saline or the hydraulic gradient is steep.</li> <li>Provision will also need to be made for a larger attenuation zone, due to more rapid migration of recharge water from the recharge area.</li> </ul>	<p>Q11. Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?</p> <p>If the answer is ‘Yes’, a high risk of migration of recharge water is expected. An enlarged attenuation zone is needed, beyond which pre-existing environmental values of the aquifer are to be met. Dissolution of aquifer matrix and potential for mobilisation of metals warrant investigation in Stage 2.</p> <p>If the answer is ‘No’, a low risk of the above events is expected. However, this is not a sufficient condition for low risk.</p>
<i>12 Similarity to successful projects</i>	
<ul style="list-style-type: none"> <li>A founding principle of managed aquifer recharge is that all validation and verification monitoring data should be in the public domain, and that these data should be accompanied by sufficient operational data to enable accurate interpretation.</li> <li>This information is of value for future managed aquifer recharge projects, for improving design and operation, and reducing costs, and for further refining these guidelines.</li> <li>A national or state repository for these data should be accessible for proponents.</li> </ul>	<p>Q12. Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?</p> <p>If the answer is ‘Yes’, validation and verification data from the existing projects needs to be taken into account when designing the current project, in the Stage 2 investigations, and in subsequent risk assessments.</p> <p>If the answer is ‘No’, all uncertainties are likely to need to be addressed in the Stage 2 investigations.</p>

**Table 4.4 (continued)**

Information required for assessment	Questions and indicators of degree of difficulty
<i>13 Management capability</i>	
<ul style="list-style-type: none"> <li>• A proponent new to managed aquifer recharge operation needs to gain appropriate expertise in parallel with Stage 2 investigations, to demonstrate a low level of residual risk for the precommissioning risk assessment.</li> </ul>	<p>Q13. Does the proponent have experience with operating managed aquifer recharge sites with the same or higher degree of difficulty (see Table A1.2), or with water treatment or water supply operations involving a structured approach to water-quality risk management?</p> <p>If the answer is ‘Yes’, there is a low risk of water-quality failure due to operator inexperience.</p> <p>If the answer is ‘No’, there is a high risk of water-quality failure due to operator inexperience. The proponent should gain instruction in operating such systems (eg a MAR operator’s course or ASR course), or engage a suitable manager committed to effective risk management in parallel with Stage 2, to reduce precommissioning residual risks to low.</p>
<i>14 Planning and related requirements</i>	
<ul style="list-style-type: none"> <li>• Planning and related requirements include               <ul style="list-style-type: none"> <li>– proximity of nearest neighbour</li> <li>– provision for safe public access or exclusion</li> <li>– dimensions and slopes of water-holding structures</li> <li>– location, dimensions and design of any buildings or engineering structures</li> <li>– method by which power will be brought to site and water connections</li> <li>– nuisance insect abundance before and after construction, and proposed control measures</li> <li>– noise emissions of any mechanical plant, and noise abatement measures</li> <li>– earthmoving and construction plans and measures for dust and noise control</li> <li>– provision of information to neighbours concerning the development</li> <li>– information to address other provisions of planning and development regulations within the relevant jurisdiction.</li> </ul> </li> </ul>	<p>Q14: Does the proposed project require development approval? Is it in a built up area; built on public, flood-prone or steep land; or close to a property boundary? Does it contain open water storages or engineering structures; or is it likely to cause public health or safety issues (eg falling or drowning), nuisance from noise, dust, odour or insects (during construction or operation), or adverse environmental impacts (eg from waste products of treatment processes)?</p> <p>If the answer is ‘Yes’ to any of these, a development-approval process will require that each potential issue is assessed and managed. This may require additional information and steps in design.</p> <p>If the answer is ‘No’, the process for development approval, if required, is likely to be considerably simpler.</p>

ASR = aquifer storage and recovery; MAR = managed aquifer recharge; NWQMS = National Water Quality Management Strategy.

Answers to questions in Table 4.4 are indicative only. They suggest the level of effort required for Stage 2 investigations, the results of which will then be used in the subsequent maximal and residual risk assessments undertaken before commissioning. Inability to answer a question shows the information that will be required in Stage 2 investigations to address the question more quantitatively.

Some criteria used in Table 4.4 are more onerous than for subsequent assessments (eg depth to watertable for infiltration systems), because considerably more information on subsurface conditions is needed than is presumed to be available at the entry-level stage in order to be able to assess actual risk. By answering these entry-level questions, proponents will discover the types of information that will subsequently be required. Projects that have a high degree of difficulty for a large number of questions will require substantial Stage 2 investigations and/or preventive measures. In such cases, reconsideration of the project concept or location may potentially be more cost effective.

Examples of entry-level assessments for two managed aquifer recharge projects are given in Box 4.2.

#### **Box 4.2 Examples of entry-level assessment for two managed aquifer recharge projects**

##### **Low degree of difficulty**

A managed aquifer recharge project likely to have a low degree of difficulty from an entry-level assessment would be a commercial-scale stormwater ASR project in a brackish confined aquifer that is too saline for irrigation or drinking water supplies, with water recovered for local irrigation use. This assessment would be reinforced if verification monitoring at similar, existing projects recharging water of a similar quality and quantity into the same aquifer showed that human and environmental health was protected. This example demonstrates the value of keeping the managed aquifer recharge information repository, in any jurisdiction, in the public domain.

##### **High degree of difficulty**

A managed aquifer recharge project likely to have a high degree of difficulty from an entry-level assessment would be a soil aquifer treatment project in which effluent from a sewage treatment plant recharges a shallow unconfined aquifer close to a wetland with high conservation value. The potential for a rise in the watertable and effects on the wetland's water quality suggest that relocating the project may be more economical than the alternative, which is to undertake investigations and monitoring to demonstrate that the potential impacts will either not occur or be benign. The true situation would probably not be known reliably until commissioning with validation monitoring (Stage 3).

#### **4.4 Maximal risk assessment**

The maximal risk assessment may be completed for each identified hazard to human health or the environment. The key hazards and acceptance criteria are given in Chapter 5. In some cases, there will be inadequate data on source-water quality to support a risk assessment. In such situations, default hazard concentrations for source water may be derived from other Australian water recycling guidelines. If the source water is stormwater, the guidelines on stormwater harvesting and reuse (NRMMC–EPHC–NHMRC 2009) provide default concentrations and pathogen numbers. For treated sewage this equivalent information may be found in the Phase 1 guidelines on managing health and environmental risks. These data also serve for precommissioning residual risk assessment.

#### **4.5 Precommissioning residual risk assessment**

The residual risk assessment may be completed for each identified hazard to human health or the environment, if the maximal risk assessment shows that preventive measures are required.

Assessment criteria, preventive measures and validation monitoring requirements (Stage 3) are given in Chapter 5.

Validation monitoring is required for all projects, but must be tailored to the level of risk or uncertainty. It is only required for processes and parameters relating to the hazards identified in the precommissioning residual risk assessment for which there is uncertainty about the level of residual risk (based on the acceptance criteria specified in Chapter 5).

Projects in which validation monitoring will be intensive for one or more hazards (to demonstrate low residual risk) are likely to include those identified as having a high degree of difficulty in the entry-level assessment. Such projects may, for example:

- be intended to produce public drinking water supplies
- involve aquifers in which ambient environmental values include drinking water supplies
- recharge more than 1 GL/year or occupy an aquifer storage zone beyond the property boundary of the proponent
- be for systems with heavy dependence on aquifer treatment to achieve the required water quality
- be within or adjacent to connected, sensitive ecosystems protected under conventions and natural heritage agreements
- involve soil aquifer treatment
- have unknown criteria for system design or operation that need defining.

#### **4.6 Operational residual risk assessment**

A residual risk assessment for the operational stage of managed aquifer recharge is made possible by validation monitoring during project trials and commissioning. The assessment provides the most reliable data on which to base decisions about the project's long-term operation.

Validation monitoring also provides information on adjustments to treatments and recharge and recovery systems, to improve performance. In large-scale projects, residual risk assessment of one site before replicating the operation will generally be more efficient, in case unforeseen risks or operational problems emerge during trials.

The residual risk assessment also allows the verification monitoring program required for the operational project (Stage 4) to be defined. At Stage 4, validation monitoring is replaced by verification monitoring (details of the distinctions are given in Chapter 7). Trial report documents should be made public to widen learning from experience and management of problems. This will increase the national knowledge base. A national information repository is warranted, to make exchange of information more efficient and continually reduce costs and delays of future projects.

Specific information on the most significant hazards encountered in managed aquifer recharge projects is given in Chapter 5.

## 5 Hazard identification and preventive measures

Applying the system analysis and management components (Elements 2–6) of the framework for water-quality management to managed aquifer recharge reveals hazards and hazardous events that will be common to many projects. These hazards extend beyond water quality to geotechnical and hydrogeological hazards.

This chapter covers each of these hazards and hazardous events. It provides technical guidance about their occurrence, consequences, control measures and monitoring relevant to each stage of risk assessment. Criteria to assess maximal and residual risk are provided for each hazard. For hazards with uncertain levels of residual risk, the chapter provides guidance on the validation and additional investigations required during commissioning to determine whether the level is low enough for an operational project.

Hazards to human health or the environment encountered in managed aquifer recharge projects may originate from:

- source water for recharge
- native groundwater
- aquifer minerals reacting with recharge water
- byproducts of treatment processes or maintenance practices.

Table 5.1 summarises key human and environmental health hazards that are known to occur or may be potentially found at managed aquifer recharge operations, from each of these sources. In a risk assessment for a proposed managed aquifer recharge project, each of these hazards needs to be considered. For most projects, some of these hazards will be found to have a low risk in a maximal risk assessment, in which case, risk management plans will not need to address preventive measures for these hazards. This list was considered exhaustive at the time of preparation, but local knowledge may identify additional hazards requiring evaluation.

The key hazards impact on:

- the aquifer beyond the attenuation zone (and hence other groundwater users and groundwater-dependent ecosystems)
- the uses of recovered water
- situations where the byproducts of managed aquifer recharge water treatments and operations are reused or discharged (see Table 5.2).

**Table 5.1 Summary of key hazards in source water, groundwater and aquifer materials for managed aquifer recharge projects, with examples of specific hazards and preventive methods**

<b>Hazard</b>	<b>Origin<sup>a</sup></b>	<b>Examples</b>	<b>Preventive measures</b>	<b>Relevant section of document<sup>d</sup></b>
Pathogens	S, (G)	Viruses	Adequate aquifer residence time	5.1
Inorganic chemicals	G, A, S	Arsenic	Control Eh during recharge (avoid mobilisation) <sup>b</sup>	5.2
Salinity and sodicity	G, (S)	Salinity	Increase volume of freshwater recharged	5.3
Nutrients	S, (G)	Nitrogen	Pretreat water (eg activated sludge)	5.4
Organic chemicals	S, (G)	Pesticides	Exclude prone subcatchments	5.5
Turbidity and particulates	S, (G)	Suspended solids	Pretreat water (eg wetland)	5.6
Radionuclides	G, A, (S)	Alpha radiation	Aquifer selection (avoidance)	5.7
Pressure, flow rates, volumes and levels	S	Waterlogging	Reduce injection pressure	5.8
Contaminant migration in fractured rock and karstic aquifers	S, (G)	PAHs <sup>c</sup>	Pretreat or extend attenuation zone (exclusion)	5.9
Aquifer dissolution and aquitard and well stability	S, A	Excess sand recovery	Control pH of source water (avoid dissolution)	5.10
Impacts on groundwater-dependent ecosystems	S, A	Levels outside historical range	Avoid proximity to groundwater-dependent ecosystems	5.11
Greenhouse gases	S	Excessive energy use	Substitute passive treatments for active	5.12

**a** A = aquifer minerals; G = groundwater ; S = source water for recharge; Brackets show possible secondary source.

**b** Eh = a measure of redox potential — the propensity for oxidation and reduction reactions.

**c** PAHs = polycyclic aromatic hydrocarbons.

**d** See also the Phase 1 guidelines, the augmentation guidelines (NRMCC–EPHC–NHMRC 2008) and the fresh and marine water quality guidelines (ANZECC–ARMCANZ 2000a).

**Table 5.2 Examples of hazardous byproducts of managed aquifer recharge operations**

<b>General hazard</b>	<b>Example of specific hazards</b>
Greenhouse gases	Greenhouse gases produced during pretreatment or post-treatment and pumping of water should be considered, and processes should be examined to determine opportunities to minimise emissions.
Water treatment byproducts	Any process with reject water (eg reverse osmosis) or byproduct (eg coagulation, filtration, backwash water) may produce water with elevated concentrations of suspended solids, pathogens, inorganic chemicals, nutrients, salinity and organic chemicals.
Purge water	Suspended solids, pathogens, metals, nutrients and organics in recharge water may be concentrated in water purged from an aquifer storage and recovery well during maintenance.
Basin scrapings	Pathogens, metals, nutrients and organics in recharge water may be concentrated in scrapings produced by infiltration basin maintenance. If they meet quality criteria, scrapings may be reused in agriculture as a component in soil conditioner.

Note: The waste management hierarchy should be invoked in the priority order of: avoid, reduce, reuse, recycle, treat and dispose. For further guidance on managing these byproducts see ANZECC–ARMCANZ (2000a) — fresh and marine water quality; NRMCC (2004) — biosolids; and City of Melbourne (2007) — greenhouse gases.

Proponents developing a managed aquifer recharge project should engage specialist consultants to identify and quantify health, environmental (eg hydrogeological and geotechnical) and management risks.

This chapter provides acceptance criteria, preventive measures to mitigate risks, and validation, verification and operational monitoring methods appropriate to the assessment stage for each hazard.

Hazard preventive measures may include one or more of the following barriers:

- source water selection
- recharge control system (eg recharge shut down if the monitored indicator variable is outside critical control limits)
- aquifer selection
- project location (away from sensitive groundwater-dependent ecosystems or end uses)
- treatment of recharge water to remove hazards or precursor/s to their formation or occurrence
- adequate detention time for passive treatment within the aquifer
- treatment of recovered water before distribution to end uses
- appropriate pump selection and well completions
- flow rate and pressure control
- operational energy efficiency
- incident response plans, including feedback from real-time monitoring.

In many managed aquifer recharge operations multiple barriers may be needed and are recommended so that, if any one barrier fails, human health and the environment will still be protected. The maximal risk assessment will help inform the type and number of preventive measures required. Table 5.3 summarises preventive measures, many of which apply to more

than one hazard. The lists given in the table are not definitive. Depending on the particular project, other critical control points and preventive measures may be more appropriate. Education and training are important components of implementing and maintaining prevention measures.

**Table 5.3 Summary of preventive measures and critical control points for managed aquifer recharge**

<b>Preventive measures</b>	<b>Description</b>	<b>Critical control point</b>
<i>Exclusion barriers — preventing entry</i>		
Hazard source control	Selection or management of water sources before recharge (eg catchment, recycled water, roof runoff, stormwater)	No
Intake levels	Exclusion of floating hazards by maintaining intake levels below the water surface	No
Exclusion of water that does not meet critical limits	Continuous monitoring of indicator variable, to provide feedback to divert water flow or stop recharge when critical limit is exceeded	Possibly: depends on the hazard, associated risk prevented and monitoring system
<i>Exclusion barriers — removing hazards</i>		
Residence time in the soil or aquifer	Attenuation of all human pathogens and selected organic chemicals	Yes: the system needs to provide required residence time; recovery rate is restricted to ensure adequate time between recharge and recovery
Travel distance in aquifer	Travel distance (between recharge and recovery) chosen to provide a minimum residence time under the range of operating conditions	No: component of system design
Treatment processes	Concentration of specific hazards decreased before recharge or on recovery	Possibly: at the point of recharge and/or recovery; depends on the hazard and effect on the specific environmental endpoint

**Table 5.3** (continued)

<b>Preventive measures</b>	<b>Description</b>	<b>Critical control point</b>
<i>Preventive measures to manage risks in commissioning and validation monitoring (Stage 3)</i>		
Operate early warning feedback system	Monitor wells near recharge for early warning of treatment effectiveness and to allow corrective actions to be implemented	Yes: detection exceeding critical limit triggers corrective action
Recover recharged water and re-treat	Recover contaminated water to prevent exposure	No: however, volume to be recovered would be reduced by use of an early warning system
Prevent distribution of recovered water to unacceptable end uses	If recovered water does not meet water-quality requirements for intended uses, stop recovery (to allow longer residence time), divert to acceptable uses or re-treat	Possibly: surrogate parameter correlated with water-quality concern may be used
Post-treatment of recovered water	Treat recovered water to remove identified hazards	Yes: direct or surrogate parameters exceeding critical limit trigger corrective action
Reduce rate of recharge or recovery	Modify flow rates to increase residence times, reduce pressure gradients across thin aquitards, or reduce managed aquifer recharge-induced flow and level variations at groundwater-dependent ecosystems	No: subject to validation monitoring

## 5.1 Pathogens

### 5.1.1 Effect of pathogens on public health and the environment

Public health risks associated with human pathogens in managed aquifer recharge systems are identical to the risks described in Table 3.1 of the Phase 1 guidelines. Consequently this section focuses on the impact of pathogens that affect humans only. Little information is available on the microbial impact of managed aquifer recharge on the environment. Until more is known, hazard identification and responses should be as indicated in Chapter 4 of the Phase 1 guidelines.

### 5.1.2 Source of pathogens in managed aquifer recharge

In confined aquifers, sources of enteric (ie intestinal) pathogens are primarily limited to those present in the recharge source water. However, in unconfined aquifers, other sources of such pathogens may also be significant (eg sewage contamination of infiltrating water or pathogens from manure spread over pastures).

Potential water sources for managed aquifer recharge (eg wastewater, grey water, stormwater) can contain a wide range of enteric pathogens that pose a risk to human health. The types of pathogenic hazards present in source waters are described in Chapter 3 of the Phase 1 guidelines.

### 5.1.3 Fate and behaviour of pathogens in managed aquifer recharge

There are considerable challenges in validating and continually demonstrating the attenuation of pathogens in aquifers. The scientific literature demonstrating the removal of pathogens in managed aquifer recharge is limited. As indicated in Table 5.4 and Appendix 4, only a few pathogens have been studied, and in many cases these are not the worst-case target pathogen. Further, this data is aquifer-specific and not transferable.

The most conservative target pathogens should be selected for the purpose of validation.

In undertaking validation it is essential to identify appropriate operational monitoring to demonstrate ongoing performance of detention in achieving attenuation. This will include identification of critical limits. Proponents of schemes must scientifically justify the selection of operational monitoring parameters and critical limits. Critical limits identify when the required attenuation is being achieved and therefore they should be rigorously established.

Pathogen survival in groundwater is affected by physical, chemical and biological processes (Schijven and Hassanizadeh 2000, Toze and Hanna 2002, Gordon and Toze 2003, Toze 2004, John and Rose 2005, Foppen and Schijven 2006, Pedley et al 2006, Tufenkji et al 2006). The potential for the inactivation of pathogens in aquifers highlights the potential use of aquifers as robust treatment barriers in the multibarrier approach to pathogens, described in Section 2.3.1 of the Phase 1 guidelines. Pathogen presence and survival in aquifers is highly variable and is influenced by a variety of factors, including:

- pathogen type
- recharge water source
- temperature
- redox state and oxygen concentrations
- activity of indigenous groundwater microorganisms
- aquifer geochemistry.

Dillon and Toze (2005) and NRC (2008) provide reviews of pathogen survival and factors affecting survival in aquifers, including quantitative data. Although all of the factors given above may (either independently or collectively) influence pathogen survival, pathogens can also vary in their environmental stability (eg between different locations), depending on local groundwater conditions. In Australian aquifers, enteric viruses and protozoa have been found to be the most resistant of the pathogens. Some differences have been noted in other countries with different conditions, eg pathogenic bacteria have been shown to persist for longer in colder groundwater (Foppen and Schijven 2006). The resistance of pathogens is very type-specific, and testing of selected pathogens from each of the groups of microbial pathogens (eg viruses, protozoa and bacteria) is strongly recommended.

Little is known about the fate of helminths during managed aquifer recharge. In Australia (except for the tropical northern regions), helminths pose minimal risk. They can be controlled by suitable pretreatment, and are effectively removed from water by simple treatment systems such as coagulation, flocculation and sedimentation in stabilisation ponds (Jimenez 2003). Even if helminth eggs were able to pass through these treatment systems, their relatively large size (40–90 µm) means that simple filtration processes in more consolidated and sand aquifers would be likely to remove them.

Managed aquifer recharge projects that rely on aquifer treatment as a barrier against microbial pathogens before recovery for drinking water supplies will always require validation that tests the removal of a range of specific target microbial pathogens in the aquifer. Such validation should include several enteric viruses and *Escherichia coli* (*E. coli*) as a minimum. In cases where a quantitative health risk assessment is needed, or the receiving aquifer is karstic or has preferential flow, it will be important to test for *Campylobacter* and oocysts of *Cryptosporidium* as well. Where managed aquifer recharge is used for purposes for which water can be of lower quality than that for drinking water supplies (eg irrigation of green open spaces), the validation requirements may be less rigorous (depending on local regulatory requirements and frameworks). In these cases, the time required for the removal of specific pathogen types or indicators should be determined based on an understanding of the following:

- the source of the water and the potential for the presence of different pathogen types
- the potential for human contact with the recovered water.

The selection of enteric pathogen, surrogate or indicator microorganisms, for use in in situ decay studies to validate pathogen attenuation in an aquifer and for verification monitoring, is important. The examples given in Appendix 4 and in other reviews (eg Toze 2004, Pedley et al 2006) on pathogen decay in groundwater have often shown that enteric viruses can have significantly greater survival times than bacteria, although there is much variation. It is strongly recommended that enteric viruses be included in any survival study used to validate the treatment capacity of an aquifer. Adenovirus is currently thought to be a suitable indicator of aquifer treatment capacity because it:

- is a recognised human pathogen
- can be detected through culture or molecular methods
- is considerably smaller than bacteria and protozoan cysts, and hence more mobile in fluid flow in porous media
- has been shown in both in situ and laboratory studies to be more persistent in aquifers than many other enteric microorganisms.

Testing for enteric viruses is important because of their greater persistence in groundwater (Toze 2004); however, such testing is expensive and time consuming. Testing for male-specific coliphage can also be useful for ongoing monitoring, because detection is quicker and cheaper than for enteric viruses. The presence or absence of coliphage has previously been used as part of the determination of the ongoing removal of enteric viruses during managed aquifer recharge (Toze et al 2004). It needs to be understood that bacteriophage (both male-specific and somatic) are only surrogates for enteric viruses. They are pathogens for *E. coli*, not for humans, and thus some of their source and survival characteristics may differ from many enteric viruses. Therefore, if a specific enteric virus is considered a potential risk, then testing should be done for that specific virus. This does not, however, necessarily preclude the need to test for other microbial pathogen types where specific pathogens are considered an elevated risk. For example, *Cryptosporidium* oocysts may need to be included in survival studies if stormwater runoff from cattle paddocks is considered at risk from *Cryptosporidium*.

At a minimum, for managed aquifer recharge schemes that are considered to be low risk and have minimal potential human contact, it is recommended that proponents undertake

verification monitoring using the indicator and surrogate microorganisms *E. coli*, enterococci and coliphage in the target aquifer.

The efficiency of pathogen removal depends on site-specific conditions, and uncertainties can be resolved by monitoring to validate attenuation rates. The mere monitoring of microorganisms numbers in the source water used in a managed aquifer recharge scheme and of numbers in the recovered water is rarely adequate for an appropriate risk assessment. Pathogens are discrete particles and may be present in low numbers in very large volumes of water. This means that they may pose a health risk even when they are below the detection limits of current analytical methods. Direct testing of pathogen decay in the aquifer is therefore strongly recommended, and a direct log reduction can be obtained.

In terms of log removals, aquifers are conceptually much like other natural and engineered water treatment processes for the pathogens given in Table 3.4 in the Phase 1 guidelines. Log removals in aquifers are primarily related to the residence time of the recharge water, the activity of the indigenous groundwater microorganisms, the redox state of the aquifer, and the temperature. The log removals achieved are typically expressed in terms of the number of days required for a 1-log reduction in pathogen numbers. There are other mechanisms within the aquifer that can remove or retard the movement of microbial pathogens through the aquifer and thus reduce their potential presence in the recovered water. Such mechanisms include adsorption to the aquifer matrix, dilution and straining. However, these mechanisms are not considered as ‘treatments’ because the pathogens are simply retarded and may not necessarily be removed from the recharged water; they could still appear later in the recovered water as viable infectious pathogens. Also, the wide range of pathogens in the different pathogen groups all have different behaviour under varying conditions; thus, predicting straining or adsorption kinetics for all pathogens under the set of conditions in an aquifer is extremely difficult. Further, should conditions suddenly change (eg freshening of the recharge water due to high rainfall), pathogens may be remobilised and become present in the recovered water. Thus, unless there is sound site-specific evidence to the contrary, inactivation is the only factor that should be used to measure effectiveness of aquifer treatment, and it should be assumed that pathogens move freely through the aquifer with the recharged water. Any actual retardation that occurs during managed aquifer recharge is thus an additional benefit, and only increases the effectiveness of the barrier by increasing the residence time of the pathogens in the aquifer.

Table 5.4 shows pathogen inactivation rates in aquifers; the rates shown are taken from studies of only a few sites, where in situ decay studies were used. Appendix 4 gives examples of more specific pathogen survival data obtained from a wider source of pathogen decay studies, including laboratory-based studies using groundwater and recharge water from active managed aquifer recharge pilot projects, and laboratory studies by a number of Australian and international researchers where conditions were manipulated to study decay under various aquifer conditions.

As a rule of thumb, the most reliable assessment of pathogen attenuation at a given site is the measurement of pathogen survival in situ using diffusion chambers, as given in Table 5.4. Results from in situ diffusion chamber studies are similar but not identical to laboratory-based pathogen decay studies. The log reduction times given in Table 5.4 are for a small number of studies in aerobic and anoxic aquifers only. Laboratory-based pathogen decay studies where the redox potential is reduced to sulfate-reducing conditions have indicated that log reduction times become significantly longer as the redox drops, particularly for viruses (Vanderzalm et al, 2009). Similarly, Pedley et al (2006) and Schijven et al (2006) found that

the attachment and inactivation of viruses could be significantly reduced under anoxic conditions. Thus, without site-specific information, any aquifer with redox potential that is more reducing than anoxic conditions should not be relied on to remove microbial pathogens, and other treatment methods should be used before recharge of the water.

**Table 5.4 Maximum inactivation times, in days, observed for microorganisms in situ in Australian aerobic and anoxic aquifers, using diffusion chambers<sup>a</sup>**

1-log reduction times		
<i>Escherichia coli</i>	<i>Salmonella typhimurium</i>	<i>Bacteriophage MS2</i>
3	6	6

<sup>a</sup> The results given here as examples are the slowest rates obtained from in situ diffusion chamber studies in managed aquifer recharge schemes where the groundwater temperature is greater than 20°C. This table should not be used for aquifers with temperatures less than 20°C. Where reliance is placed on pathogen inactivation in the aquifer, a pathogen survival assessment will be needed. These rates are derived from log-linear decay curves, the most commonly used decay function, but other forms may be used where data justify. Hence, for example, 3-log removal of MS2 for the conditions described is estimated to occur within 18 days, and a 6-log removal within 36 days. There were insufficient data in 2009 to tabulate reliable maximum inactivation times for *Campylobacter*, *Cryptosporidium*, rotavirus or other viruses. Source: compiled from Toze et al (2004), Wall et al (2004) and Dillon et al (2005a).

Due to temporal variations in pathogen numbers in source water, detecting no pathogens in groundwater samples sheds little light on the aquifer’s actual pathogen inactivation rate. Relevant laboratory-derived attenuation data must be obtained at a temperature and redox status relevant to the aquifer, using chambers inoculated with microorganisms from the aquifer. However, ongoing monitoring of microbial indicators, surrogates and selected pathogens can be useful in the ongoing validation of the attenuation of microorganisms during managed aquifer recharge. Monitoring at managed aquifer recharge schemes involving basin infiltration of treated effluent into aerobic carbonate aquifers indicated at least 5-log removal of thermotolerant coliforms, and removal of all coliphage and selected enteric viruses within 10 m of the infiltration site (Toze et al 2004, Bekele et al 2008). Another example can be seen in Figure A4.1, which shows how the monitoring of *E. coli* cells in anoxic aquifers during ASR (aquifer storage and recovery) was used as a measure of microbial removal in aquifers.

Generalised data, such as those given in Table 5.4, are also suitable for precommissioning residual risk assessments. As validation data from managed aquifer recharge sites accumulates, greater precision in estimating pathogen attenuation rates in aquifers is expected.

Precommissioning residual risk assessments can estimate pathogen attenuation using the methods described in Appendix 6 and the pathogen decay rates in Table 5.4 and Appendix 4. Performance claims need validating wherever they relate to a human health or environmental hazard assessed to be a significant risk. Validation methods are listed in Appendix 3.

Laboratory studies suggest that secondary treated effluent does not affect the numbers of indigenous microorganisms that can act as opportunistic pathogens in an aquifer (S Toze, CSIRO Land and Water, pers comm, 2007).

Recent studies (Reed 2007, Reed et al 2007) have documented the changes in native microbial populations near the treated sewage ASR trial at Bolivar (South Australia) and the treated sewage infiltration galleries at Floreat Park (Western Australia). These studies

confirmed trends in aquifer microbial populations related to the proximity to nutrient-rich recharge water and changes in redox status. Microbial populations were observed to react and change as the front of the recharge water moved through the aquifer. Once the recharged water occupied a specific region of the aquifer, the microbial community population structure, biodiversity and activity became more stable and relatively unchanged. Although the evidence is not conclusive, it suggests that managed aquifer recharge is unlikely to stimulate recovery of higher numbers of indigenous opportunistic pathogens (eg *Pseudomonas*, *Aeromonas*) than would be recovered by pumping native groundwater.

#### **5.1.4 Other preventive measures**

Other preventive measures to reduce the risk of pathogenic hazards and achieve performance targets include:

- source control (eg catchment management for stormwater sources)
- removing pathogens using treatment processes (eg engineered or natural treatment processes to achieve the required log removal rate of the reference pathogens)
- reducing exposure through preventive measures on-site (eg controlling public access during irrigation with recovered water).

These three measures are described in Sections 3.4.1–3.4.3 and Appendix 3 of the Phase 1 guidelines.

#### **5.1.5 Management of pathogens via managed aquifer recharge**

The concept of tolerable risk is central to the management of enteric pathogens via managed aquifer recharge. These guidelines adopt a tolerable risk of  $10^{-6}$  disability adjusted life years (DALYs) per person per year (as described in Box 3.1 of the Phase 1 guidelines).

Given the potentially large number of pathogenic hazards in source waters, three reference pathogens — rotavirus, *Cryptosporidium* and *Campylobacter* — have been identified to represent viral, protozoan and bacterial hazards respectively. For a detailed description of DALYs, and the calculation of microbial health-based performance targets for the reference pathogens, refer to Appendix 2 of the Phase 1 guidelines.

Table 5.5 provides the general criteria for assessing the appropriate level of management for pathogenic hazards. The unique feature of managed aquifer recharge is the consideration of the aquifer's effects on pathogens.

**Table 5.5 Criteria, controls and monitoring to mitigate pathogen hazards in relation to the stages of risk assessment**

	<b>Entry-level assessment and simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Acceptance criteria</b>	<ul style="list-style-type: none"> <li>• Source water for recharge has low risk of pathogen contamination</li> <li>• Exposure to recovered water is no greater than to the source water used for recharge</li> <li>• End use for recycled water and environmental values of aquifer exclude drinking water</li> </ul>	<ul style="list-style-type: none"> <li>• Source water has a residual risk <math>&lt;10^{-6}</math> DALYs per person per year without reliance on aquifer for treatment or dilution (eg use of 95<sup>th</sup> percentile pathogen numbers); or in the absence of data, use values from other guidelines<sup>a</sup> to determine DALYs</li> </ul>	<ul style="list-style-type: none"> <li>• Confirm residual risk <math>&lt;10^{-6}</math> DALYs per person per year for water recovered (by project and by any third party), based on additional data collection if dependent on treatment in the aquifer</li> </ul>
<b>Preventive measures</b>	na	<ul style="list-style-type: none"> <li>• Source water protection</li> <li>• Removal using treatment processes</li> <li>• Residence time in the soil and/or aquifer</li> <li>• Reducing exposure</li> </ul>	<ul style="list-style-type: none"> <li>• As per precommissioning residual risk assessment</li> </ul>
<b>Validation monitoring</b>	na	na	<ul style="list-style-type: none"> <li>• Validate that the process control and operational monitoring correlate with pathogen inactivation; provide ongoing assurances that the attenuation zone is operating effectively, and that water of an appropriate quality is being produced. This includes setting critical limits to differentiate between acceptable and unacceptable performance.</li> </ul>
<b>Verification monitoring</b>	na	na	<ul style="list-style-type: none"> <li>• Monitor pathogens or indicator organisms in recovered water and in observation wells at edge of attenuation zone</li> <li>• Achieve the specified log removal to achieve acceptance criteria<sup>b</sup></li> </ul>

**Table 5.5 (continued)**

	<b>Entry-level assessment and simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Operational monitoring</b>	<ul style="list-style-type: none"> <li>Determine volumetric estimates of recharge and recovery</li> </ul>	na	<ul style="list-style-type: none"> <li>As appropriate for treatment process used (eg turbidity post-coagulation–filtration)</li> <li>Determine volumetric recharge and recovery</li> <li>Monitor limits for turbidity of recharge, if correlated with pathogen risk</li> </ul>

DALYs = disability adjusted life years; na = not applicable.

**a** Pathogen levels for treated sewage effluent are to be drawn from the Phase 1 Guidelines and for urban stormwater from the stormwater harvesting and reuse guidelines (NRMMC–EPHC–NHMRC 2009).

**b** as per Table 3.4 of the Phase 1 guidelines.

## 5.2 Inorganic chemicals

This section is applicable to the major ions (calcium, magnesium, sodium, potassium, chloride, sulfate, bicarbonate, bromide and fluoride), metals (aluminium, cadmium, chromium, copper, iron, manganese, nickel, lead, strontium and zinc), metalloids (arsenic, boron and silicon) and gases (hydrogen sulfide and methane). Nitrogen and phosphorus are discussed separately in Section 5.4.

### 5.2.1 Effect of inorganic chemicals on public health and the environment

Unlike pathogens, there is insufficient information on chemical parameters to support DALYs. Tolerable risk is therefore defined in terms of guideline concentrations. This reflects human health protection in the *Australian Drinking Water Guidelines* (NHMRC–NRMMC 2004) and in the the Phase 2 augmentation of drinking water supplies guidelines (NRMMC–EPHC–NHMRC 2008), and protection of specified environmental values in ANZECC–ARMCANZ (2000a). The bases for these guideline concentrations are explained in Chapter 3 of this document and in ANZECC–ARMCANZ (2000a).

The key inorganic hazards resulting from aquifer storage are:

- increased arsenic, iron, manganese, trace species or hydrogen sulfide, producing recovered concentrations in excess of the beneficial use guideline values
- increased iron in recovered water, which impacts on water supply infrastructure (eg irrigation)
- changes to major ion chemistry that alter the sodicity or nutrient balance of the recovered water, affecting its suitability for potential uses (eg irrigation).

When elevated metal concentrations exceeding the beneficial use guideline value occur in backwash water from injection wells, or in the initial water recovered from an ASR well, care should be taken in the treatment, use and disposal of this waste stream.

### 5.2.2 Sources and fate of inorganic chemicals in managed aquifer recharge

The chemistry of water stored in an aquifer during managed aquifer recharge is affected by chemical reactions, driven by the aquifer’s conditions (eg pH, redox state, minerals, organic

matter, microbial activity) and the quality of recharged water. Reactions can occur between the source water and the native groundwater, and between the source water and the aquifer material (Vanderzalm et al, 2009). This can change water quality and aquifer permeability.

The key risks related to subsurface reactions are described below.

#### ***Arsenic increase***

Mobilisation of arsenic from the aquifer sediments can occur when pyrite in the storage zone is oxidised, or iron (III) oxides are dissolved (see decision tree in Appendix 7). This is a key issue for confined target zones in which reduced minerals are present, despite starting with source water at acceptable arsenic concentrations (Arthur et al 2003), and may lead to concentrations of arsenic greater than the drinking water guideline value. An example of arsenic release is given in Box 5.1.

#### ***Iron increase***

Release of iron from the sediments in the storage zone occurs mainly when organic matter in the source water reacts with iron (III) oxyhydroxides and oxides (ie goethite, hematite). It can also occur from pyrite oxidation or by changing the pH of the storage zone (see decision tree in Appendix 7). Iron release is generally an aesthetic water-quality concern, potentially causing an elevated colour; but, it can also contribute to aquifer clogging (Section 6.1). Iron increases can be associated with the release of other hazards such as arsenic and radium (Section 5.7).

#### ***Manganese increase***

Dissolution of manganese from manganese oxides and oxyhydroxides in the sediments occurs by reaction with organic matter in the source water, or by changing the pH of the storage zone (Ibison et al 1994). Like iron, manganese may contribute to the colour of the recovered water.

#### ***Trace ion increase***

The ion species affected include: aluminium, antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, fluoride, iron, lead, manganese, molybdenum, nickel, vanadium, uranium and zinc. All of these can cause health or environmental concerns (see Table A7.1). Increases in trace constituents frequently coincide with an increase in iron, manganese or arsenic.

Mechanisms for trace ion release include:

- oxidation of sulfide minerals, such as pyrite, due to presence as trace elements within the mineral (similar to arsenic, although arsenic is generally more mobile than cations)
- iron (III) oxide dissolution under changing pH or Eh, as these surfaces often contain adsorbed trace species
- exchange or displacement from the solid surface by another species (eg cation exchange)
- mineral equilibrium, when water in the storage zone is not in equilibrium with the dominant mineral phases
- dissolution of mineral phases or accumulated particulates under changing pH or Eh.

### ***Hydrogen sulfide increase***

Hydrogen sulfide gas is produced when organic matter, introduced to an anoxic storage zone, reacts with dissolved sulfate. In the sequence of microbial-mediated redox reactions, iron mobilisation is likely to precede the production of hydrogen sulfide under sulfate-reducing conditions. Hydrogen sulfide contributes an aesthetic hazard by imparting taste and odour to the recovered water.

### ***Changes to major ion composition***

Mixing of the source water with saline groundwater, or ion exchange between the source water and the solid phase exchange sites, can significantly affect the contribution of sodium, calcium and magnesium. This is an important consideration if the recovered water is to be used for irrigation, because it can alter the risk of soil sodicity (Section 5.3).

### ***Excessive dissolution of carbonate minerals***

Excessive dissolution of carbonate minerals can:

- lead to injection well and aquitard stability concerns (Section 5.10)
- increase production of sand in recovered water
- extend preferential flow paths, which may reduce the residence time available for hazard attenuation (Section 5.9).

Carbonate mineral dissolution may also expose reactive surfaces such as sulfide minerals, and increase the potential for release of metal and metalloid species.

#### **Box 5.1 Arsenic release**

Arsenic release was reported during ASR testing in Florida, United States, in which oxygen-rich source water was injected into a confined limestone aquifer (Arthur et al 2003). Despite arsenic concentrations of <10 µg/L in the native groundwater and the source water, recovered water concentrations reached 112 µg/L.

Arsenic release was attributed to oxidation of an arsenic-bearing pyrite, a trace component (~0.1%) of the aquifer matrix. The decision tree in Appendix 7 can be used to identify the potential for arsenic release during managed aquifer recharge, while management options are outlined in Table 5.6.

The source water used in a managed aquifer recharge scheme is unlikely to be in equilibrium with the minerals present in the storage zone. As a result, some dissolution of minerals will occur when the source water comes into contact with minerals in the aquifer. The degree of dissolution depends on the solubility of the mineral in the given conditions (eg pH, temperature, pressure, ionic strength, contact time). Mineral equilibrium can also be altered during subsurface storage by other reaction processes; for example, barium can be released by the dissolution of barite (BaSO<sub>4</sub>) in aquifer sediments, after dissolved sulfate concentrations have been reduced by bacterial sulfate reduction (Zhou and Li 1992).

Carbonate minerals can be a major influence on the quality of water recovered, because carbonate dissolution is a rapid reaction. In contrast, silicate dissolution is a very slow buffering reaction between pH 6 and 8 (Appelo and Postma 1999), and has minimal impact on water quality over the timescale of a managed aquifer recharge scheme. Dissolution of carbonate minerals will increase aquifer permeability, and the impact on the stability of injection wells and the aquitard must be considered (Section 5.10).

Mineral dissolution can increase the salinity and hardness of the water available for recovery, and also increase minor constituents such as barium or fluoride (fluorite dissolution). Solubility controls may limit the dissolved concentration of some hazards, such as barium (barite solubility), phosphate (apatite solubility) or iron (iron oxyhydroxides or oxides), but mineral precipitation can lead to clogging concerns (Section 6.1). The tendency for mineral dissolution or precipitation can be examined through the saturation index of a solution.

The redox state within the storage zone alters the inorganic chemistry of the recovered water. Redox reactions in managed aquifer recharge will often be induced by addition of source water that contains oxygen to an anoxic aquifer, or by addition of organic matter to an aquifer.

Redox zones, and the resulting water quality, can vary spatially and temporally during a managed aquifer recharge operation. A highly reactive zone often develops near the point of injection or infiltration, resulting in water quality that differs from the bulk of the stored water. For example, if source water high in organic matter is used, the reactive zone can become anaerobic. This can lead to dissolution of iron (either present in the aquifer sediments or accumulated around the injection well from filtration of particulate matter in the source water) or in situ generation of hydrogen sulfide.

Changes in redox conditions and water quality can also occur:

- over time under different flow rates (eg injection or infiltration versus storage)
- where degree of saturation changes (eg wetting and drying cycles in soil aquifer treatment)
- in flow reversal during recovery in an ASR operation.

Sorption to clay minerals, organic matter or iron oxide surfaces can act as an attenuation mechanism for trace metals and metalloids (see sorption coefficients in Appendix 5). However, sorption is not permanent. It can be reversed by preferential sorption of another species, or by pH–Eh-dependent changes in the surface properties that alter the number of available sorption sites. In addition, the sorption capacity of an aquifer may be limited, delaying breakthrough of the hazard to a downstream monitoring or recovery location.

Mixing is an important influence on the quality of recovered water, if the native groundwater is brackish or contains hazards that exceed target values for the specific beneficial use. Mixing of two waters can produce a solution that is more aggressive toward the aquifer minerals (Runnels 1969); or can dilute the concentration of a hazard in the source water. However, any potential for dilution of the concentrations of an inorganic constituent in groundwater must be considered together with processes that may release that species from the aquifer sediments (eg mineral dissolution). The effect of mixing should be considered in relation to salinity targets or operational constraints (see Section 6.2).

Metals in source water are largely in particulate form and will accumulate in the subsurface, close to the point of entry (ie well face or basin floor). Accumulated metals may be removed permanently from the system by operational maintenance, such as well redevelopment or basin scraping (see Section 6.1.2). Some in situ dissolution may occur, producing a localised increase in soluble metal concentration. This is most likely to affect the first water recovered from an ASR well.

### 5.2.3 Management of inorganic chemicals

General criteria for assessing the appropriate level of management for the major inorganic hazards are provided in Table 5.6.

Source control may include limiting the contribution from hazardous activities (eg catchment management, trade waste discharge agreements), and diversion of flow outside water-quality criteria (eg pH, conductivity).

Pretreatment measures include:

- source-water treatments (eg filtration, coagulation, flocculation)
- pH adjustment (eg prevention of manganese release from sediments) (Ibison et al 1994)
- redox (Eh) control to limit reaction within the aquifer (eg limiting organic carbon in source water, deoxygenating to prevent arsenic release).

Residual risk assessment management of inorganic chemicals within the aquifer requires validation of the conceptual understanding of geochemical processes and of the preventive measures necessary to manage risks to human health and the environmental. Validation monitoring (Stage 3) is necessary because the presence of trace amounts of some minerals can cause problems. Drill core and groundwater samples collected in Stage 2 cannot be relied on to detect all minerals present in the aquifer that recharged water will come into contact with.

Upon recovery and (where necessary) for high-value use, the major ions contributing to salinity can be removed. This can be achieved by post-recovery treatments such as aeration and filtration, or other techniques (individually or in combination) including oxidation, precipitation, coagulation, sorption, ion exchange, lime softening and filtration (NHMRC–NRMMC 2004).

**Table 5.6 Criteria, controls and monitoring to mitigate inorganic chemical hazards in relation to the stages of risk assessment**

	<b>Entry-level assessment and simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Acceptance criteria</b>	<ul style="list-style-type: none"> <li>Major ion chemistry concentration meets the environmental target for the aquifer</li> <li>Low risk of mobilisation from the aquifer</li> </ul>	<ul style="list-style-type: none"> <li>Inorganic chemical concentrations in source water meet target for beneficial use</li> <li>Decision tree in Appendix 7 suggests metal mobilisation is unlikely to be a problem</li> <li>Geochemical modelling shows release from aquifer is unlikely to produce inorganic chemical concentrations above target values</li> </ul>	<ul style="list-style-type: none"> <li>As per precommissioning residual risk assessment</li> </ul>
<b>Preventive measures</b>	na	<ul style="list-style-type: none"> <li>Refer to Sections 6.1 and 6.2 for operational management</li> <li>pH and redox (Eh) adjustment in source water</li> </ul>	<ul style="list-style-type: none"> <li>As per precommissioning residual risk assessment, plus               <ul style="list-style-type: none"> <li>– source control</li> <li>– treatment of source water to minimise release from aquifer</li> <li>– post-treatment of recovered water</li> </ul> </li> </ul>
<b>Validation monitoring</b>	na	na	<ul style="list-style-type: none"> <li>Determine inorganic chemical concentrations in               <ul style="list-style-type: none"> <li>– source water</li> <li>– groundwater in storage zone (observation well/s)</li> <li>– recovered water</li> </ul> </li> <li>Evaluate aquifer physiochemical and redox conditions</li> </ul>
<b>Verification monitoring</b>	<ul style="list-style-type: none"> <li>Not applicable at project scale (undertaken at regional scale)</li> </ul>	na	<ul style="list-style-type: none"> <li>Determine inorganic chemical concentrations in recovered water and at margin of attenuation zone</li> </ul>

**Table 5.6 (continued)**

	<b>Entry-level assessment and simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Operational monitoring</b>	<ul style="list-style-type: none"> <li>Estimate or measure annual injection and recovery volumes</li> </ul>	na	<ul style="list-style-type: none"> <li>See verification and validation monitoring above, plus online conductivity, pH, and Eh in source and recovered water</li> </ul>

Eh = a measure of redox potential, which is the propensity for oxidation and reduction reactions; na = not applicable; pH = a measure of the acidity or alkalinity of a solution.

## 5.3 Salinity and sodicity

### 5.3.1 Effects of salinity and sodicity on public health and the environment

The public health and environmental risks associated with salinity and sodicity (the abundance of sodium relative to calcium and magnesium) in relation to managed aquifer recharge include:

- salinity values exceeding the beneficial use value for total dissolved salts or sodium content
- osmotic effects on plant health and yields, due to irrigation with saline water
- rising watertables, due to leaching requirements to remove excessive salinity
- sodicity-related decline in structure of agricultural soils
- salinity effects on infrastructure and other assets (eg excessive corrosion or scaling in pipes, fittings and appliances; salt damp in stone and masonry structures).

The mixing of recharge water and ambient groundwater in managed aquifer recharge will cause the salinity of recovered water to differ from that of the recharge water. In general, the salinity of ambient groundwater within aquifers targeted for managed aquifer recharge should be similar to or higher than the source water (in keeping with the principles outlined in the groundwater protection guidelines (ARMCANZ–ANZECC 1995). Therefore, native groundwater will represent an additional source of salinity (and sodicity) in recovered water. Details on physical interactions between the recharge water and receiving groundwater are given in Section 6.2.

The environmental risks of salinity and sodicity and their effects on soil structure and agricultural production are discussed in the Phase 1 guidelines.

### 5.3.2 Sources of salt in managed aquifer recharge

All source waters for managed aquifer recharge contain natural salinity levels, derived from inorganic salts, minor amounts of dissolved organic matter and small colloidal material. The inorganic constituents of source waters may be characterised by measures such as conductivity, total dissolved salts and sodicity.

Typically, the salinity of roof runoff is lower than stormwater runoff, as shown in the stormwater harvesting and reuse guidelines (NRMMC–EPHC–NHMRC 2009). Stormwater runoff, in turn, has lower salinity than water recycled from sewage effluent (see Table 4.10 in

the Phase 1 guidelines). This is because the enrichment or addition of salts from natural or anthropogenic processes in water transported through a rural or urban catchment increases its salinity levels.

Salinity levels in groundwater range from fresh to highly saline. Infiltration of shallow saline groundwater into leaky sewers can substantially increase the salinity and sodicity of sewage effluent, rendering it unfit for recycling via managed aquifer recharge unless it is treated or blended.

### 5.3.3 Management of salinity and sodicity

Management controls include preventive measures such as:

- catchment water-quality management and source control (to minimise salt export and remove or mitigate point sources of salinity, where viable)
- source water selection
- site selection to target aquifers that minimise risk
- pretreatment or post-treatment (desalination)
- shandying of recovered water with alternative, lower salinity sources (shandying is the addition of one water source to another).

### 5.3.4 Mitigation of salinity and sodicity hazards in relation to stages of risk assessment

General criteria for assessing the appropriate level of management for salinity and sodicity hazards are provided in Table 5.7.

**Table 5.7 Criteria, controls and monitoring to mitigate salinity and sodicity hazards in relation to the stages of risk assessment**

	<b>Entry-level assessment and simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Acceptance criteria</b>	<ul style="list-style-type: none"> <li>• Source water for recharge &lt;500 mg/L TDS</li> <li>• Source water of better quality than ambient groundwater</li> </ul>	<ul style="list-style-type: none"> <li>• Low anticipated mixing leading to acceptable recovery efficiencies</li> <li>• Low risk of mobilising salt stored in the soil profile or in aquifer mineral deposits</li> <li>• Low probability of undesirable off-site impacts</li> </ul>	<ul style="list-style-type: none"> <li>• As per precommissioning residual risk assessment criteria, based on validation monitoring during commissioning and further modelling</li> </ul>
<b>Preventive measures</b>	na	<ul style="list-style-type: none"> <li>• Refer to Section 6.2</li> </ul>	<ul style="list-style-type: none"> <li>• Refer to Section 6.2</li> </ul>

**Table 5.7** (continued)

	<b>Entry-level assessment and simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Validation monitoring</b>	na	na	<ul style="list-style-type: none"> <li>• Determine salinity and sodicity of recharge and recovered water, supported by volumetric inputs and outputs to allow a salt mass balance</li> <li>• Quantify impacts on receiving ecosystems, plus monitoring and investigations to define the level of residual risk</li> <li>• Validate solute transport model for predicting recovery efficiency and residence time</li> <li>• Model density effects on recovery efficiency, if needed</li> </ul>
<b>Verification monitoring</b>	<ul style="list-style-type: none"> <li>• Not applicable at project scale (undertaken at regional scale)</li> </ul>	na	<ul style="list-style-type: none"> <li>• Refer to Section 6.2</li> <li>• Monitor salinity of recovered water</li> </ul>
<b>Operational monitoring</b>	<ul style="list-style-type: none"> <li>• Estimate or measure annual injection and recovery volumes</li> </ul>	na	<ul style="list-style-type: none"> <li>• Determine salinity of recharge and recovered water, supported by volumetric inputs and outputs to allow a salt mass balance</li> <li>• Refer to Section 6.2</li> </ul>

na = not applicable; TDS = total dissolved salts.

## 5.4 Nutrients: nitrogen, phosphorus and organic carbon

This section discusses nitrogen and phosphorus — recognised as environmental hazards for water recycling (NRMMC–EPHC–AHMC 2006) — and organic carbon, an important nutrient in relation to microbial processes in the subsurface.

### **5.4.1 Effect of nutrients on public health and the environment**

Nitrogen and phosphorus are identified as key environmental hazards in the Phase 1 guidelines. This is due to their potential to cause nutrient imbalance in irrigation water, soil eutrophication, and toxic effects on terrestrial biota. While subsurface storage is likely to reduce nutrient concentrations, the overall nutrient balance of the recovered water still needs to be considered in relation to its beneficial use.

Nutrients (predominantly organic matter) in the source water will stimulate microbial activity in the subsurface. In turn, this alters the concentration of inorganic (Section 5.2) and organic chemicals in the water (Section 5.5), and affects aquifer permeability (Section 6.1).

### **5.4.2 Sources and fate of nutrients in managed aquifer recharge**

The level and variability of nutrient loads in source waters is largely affected by pretreatment measures. Recycled water potentially contains high nutrient loads that may vary with seasonal effects on microbial treatment processes. Nutrient concentrations in stormwater are generally likely to be lower than in recycled water, but will vary with catchment type (eg industrial areas).

Removing organic carbon and nitrogen is a passive water-quality treatment provided by managed aquifer recharge operations (Dillon and Toze 2005). Organic matter can be removed by biodegradation, microbial assimilation, filtration, sorption or precipitation.

Biodegradation occurs through redox processes that influence the mobility of inorganic chemicals (Section 5.2) and the fate of organic chemicals (Section 5.5). Colloidal organic matter can also facilitate the transport of other chemical hazards. The amount of organic matter removed by biodegradation depends on its character; the easily biodegradable portion can be removed within days of introduction to the subsurface, while less reactive material may degrade over a longer time (Fox et al 2001). Reactive organic matter present in the sediments may also be degraded.

Microbial assimilation occurs when the nutrient-rich source water is introduced to the subsurface, leading to the development of a biofilm near the point of entry (ie well face or basin floor). The biofilm forms a reactive zone that can have distinct redox chemistry from the rest of the storage zone, and is largely responsible for subsurface water-quality treatment (Vanderzalm 2004). Filtration of particulate organic carbon provides an additional energy source to sustain microbial activity, and can produce soluble degradation byproducts.

Nitrogen can exist in various forms in source waters, including organic nitrogen (predominantly proteins), ammonium, nitrate, nitrite and gaseous nitrogen. The dominant nitrogen species in recycled water are organic nitrogen, ammonium and nitrate.

The fate of nitrogen depends on its form and the redox conditions encountered. Under aerobic conditions, nitrification will convert ammonium to nitrate; under anaerobic conditions, ammonium can be adsorbed to mineral surfaces by ion exchange until the exchange capacity is exceeded. Nitrate can be removed by reduction to nitrogen gas (denitrification) or ammonium. In the unsaturated zone, some partitioning of ammonium to gaseous ammonia and loss through volatilisation at the air–water interface may occur. An example of optimising nitrogen removal is given in Box 5.2 and Table 5.8.

### Box 5.2 Optimising nitrogen removal through soil aquifer treatment

Soil aquifer treatment combines dry and wet cycles to provide alternative aerobic and anaerobic conditions for nitrogen removal. A comparison of several soil aquifer treatment operations in the United States reports nitrogen removal efficiencies of 12–93% (Crites 1985; see Table 5.8 below). This shows that the subsurface cannot be relied upon to provide complete nitrogen removal. Removal efficacy is influenced by system operation; the highest removal occurs under low hydraulic loading rates, long drying (aerobic) intervals and high organic matter loadings in the source water.

**Table 5.8 Nitrogen removal efficiencies in different soil aquifer treatment operations**

Location	Hydraulic loading rate (m/year)	Flooding:drying time	BOD:N (mg/L)	Nitrogen removal (%)
Hollister, California	15	1:14	5.5	93
Brookings, South Dakota	12	1:2	2.0	80
Calumet, Michigan	17	1:2	3.6	75
Phoenix, Arizona	60	3:4	1.0	65
Ft Devons, Massachusetts	30	1:6	2.4	60
Lake George, New York	58	1:4	2.0	50
Disney World, Florida	55	75:7	0.3	12

BOD = biochemical oxygen demand; N = nitrogen.

Although phosphorus is also an essential nutrient for microbial growth, removal is predominantly through precipitation as highly insoluble calcium phosphate, or by adsorption to iron and aluminium oxides (Section 5.2).

### 5.4.3 Management of nutrients

Table 5.9 provides criteria for assessing the risks and appropriate level of management for nutrient hazards (based on nitrogen, which can be a key hazard for various end uses). The assessment can also be made using phosphorus and organic carbon, to determine whether either is a more significant nutrient in source water, in relation to aquifer protection beyond the attenuation zone and for end uses of recovered water. Biological clogging of recharge wells and infiltration basins and galleries should also be considered. This is discussed in Section 6.1.

Source control may include limiting the contribution from hazardous activities, and diverting flow when water-quality indicators (eg colour and turbidity) exceed pretreatment or discharge criteria. Pretreatment measures include:

- in-line filtration on source-water delivery infrastructure (for particulate organic carbon)
- biofiltration
- passive treatment through wetlands.

The effectiveness of natural treatment systems such as wetlands for nutrient removal depends on their maintenance. Monitoring is necessary to assist with managing wetland treatment systems.

Removal of subsurface organic carbon and nitrogen relies on treatment through redox processes. Validation would need to be supported by evidence of declining concentrations and physiochemical conditions. Phosphorus removal would also need evidence of declining concentrations, supported by mineralogy (iron, aluminium oxides) or mineral saturation calculations. Organic carbon can be recovered from recovered water by granular activated carbon and membrane filtration, if necessary, for high-value use (NHMRC–NRMMC 2004).

**Table 5.9 Criteria, controls and monitoring to mitigate nutrient hazards in relation to the stages of risk assessment**

	<b>Entry-level assessment and simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Acceptance criteria</b>	<ul style="list-style-type: none"> <li>Source-water nitrogen species meet environmental value for the aquifer and recovered water use</li> </ul>	<ul style="list-style-type: none"> <li>Nutrient concentrations meet environmental values for aquifer beyond attenuation zone and beneficial use of recovered water</li> </ul>	<ul style="list-style-type: none"> <li>As per precommissioning residual risk assessment</li> </ul>
<b>Preventive measures</b>	na	<ul style="list-style-type: none"> <li>Source control</li> <li>Pretreatment, subsurface treatment and post-treatment</li> <li>Refer to Section 6.1 for operational management (avoidance of clogging)</li> </ul>	<ul style="list-style-type: none"> <li>As per precommissioning residual risk assessment, plus attenuation within the subsurface</li> </ul>
<b>Validation monitoring</b>	na	na	<ul style="list-style-type: none"> <li>Determine nitrogen species concentration in               <ul style="list-style-type: none"> <li>– source water</li> <li>– attenuation zone observation well/s</li> <li>– recovered water</li> </ul> </li> <li>Evaluate physicochemical and redox conditions</li> </ul>
<b>Verification monitoring</b>	na	na	<ul style="list-style-type: none"> <li>Ensure nutrients meet target values in recovered water and in the aquifer beyond the attenuation zone</li> </ul>
<b>Operational monitoring</b>	<ul style="list-style-type: none"> <li>Estimate or measure annual injection and recovery volumes</li> </ul>	na	<ul style="list-style-type: none"> <li>See verification monitoring above</li> <li>Refer to Section 6.1 for operational management (avoidance of clogging)</li> </ul>

na = not applicable.

## 5.5 Organic chemicals

This section discusses trace organic compounds (often referred to as micropollutants) including:

- pesticides
- hydrocarbons
- polycyclic aromatic hydrocarbons (PAHs)
- algal toxins
- disinfection byproducts (eg trihalomethanes (THMs))
- emerging chemicals of concern
  - endocrine disrupting chemicals
  - personal care products
  - pharmaceuticals
  - flame retardants.

Trace organic compounds are predominantly anthropogenic in origin (eg PAHs are a combustion product of carbon fuels); however, some may be naturally occurring (eg algal toxins). Organic chemicals are identified in more detail in the Phase 1 guidelines. The Phase 2 *Australian Guidelines for Water Recycling: Augmentation of Drinking Water Supplies* (NRMMC–EPHC–NHMRC 2008) also include information on protection of human health in water recycling.

### 5.5.1 Effect of organic chemicals on public health and the environment

Organic chemicals can pose health risks (NHMRC–NRMMC 2004) and environmental risks (NRMMC–EPHC–AHMC 2006). Specific information about environmental risks associated with organic chemicals can be found in the National Chemical Reference Guide<sup>1</sup>.

There are numerous emerging chemicals — for example, endocrine disrupting chemicals, pharmaceuticals and personal care products, and some disinfection byproducts (eg N-nitrosodimethylamine) — for which there may be insufficient information on human toxicology to establish guideline values, as discussed in Section 3.5.4 of the Phase 1 guidelines. However, the Phase 2 guidelines on augmentation provide methods for determining guideline values for any chemical with respect to drinking water uses; it also provides guidance on dealing with mixtures of chemicals (NRMMC–EPHC–NHMRC 2008).

Environmental toxicity testing may be required to provide additional information on the impact of managed aquifer recharge projects on sensitive environments. Guidance on environmental toxicity testing is provided in Chapter 3 of the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* (ANZECC–ARMCANZ 2000a).

---

<sup>1</sup> [http://hermes.erin.gov.au/pls/crg\\_public!/CRG\\_OWNER.CRGPPUBLIC.pStart](http://hermes.erin.gov.au/pls/crg_public!/CRG_OWNER.CRGPPUBLIC.pStart)

### 5.5.2 Sources and fate of organic chemicals in managed aquifer recharge

Determining the presence of organic chemicals in source waters, and carrying out the associated risk assessment can be difficult, due to intermittent loadings and analytical detection capabilities for these substances. However, the origin of the source water should allow the likelihood and nature of organic chemical presence to be estimated (see NRMCC–EPHC–NHMRC (2008)). The effort taken to characterise organic constituents of source water must be proportionate to the risk posed to public health and the environment. Metabolic pathways of chemical compounds (eg trichloroethene to vinyl chloride) and degradation byproducts also need to be considered (see Table A5.2).

In general, subsurface storage provides a treatment step for organic chemicals (see environmental fate data in Appendix 5, Dillon and Toze 2005, Drewes et al 2008b). However, formation and attenuation of THMs has been reported during storage (Pavelic et al 2005, 2006c). The potential for formation of disinfection byproducts can be lowered by reducing the amount of organic matter in the source water, or by altering the disinfection regime to reduce residual chlorine (Jimenez 2003).

Subsurface removal of organic chemicals can occur through volatilisation (in the unsaturated zone) and biodegradation (in the unsaturated and saturated zones). Degradation rates vary with pH, temperature, redox state (eg see Box 5.3), microbial adaptation, and the presence of a suitable cosubstrate, such as biodegradable dissolved organic carbon. Biodegradation of chemicals occurring at trace levels (ng/L) requires the presence of a certain biocommunity (enzymes) that develops over time (lag phase) in the presence of these chemicals. If the exposure to these chemicals is sporadic (eg discontinuous recharge events of water containing trace organic chemicals), adaptation might not occur. In addition, the concentration level of many organic chemicals of concern usually is insufficient to support a metabolic transformation and requires a cosubstrate to support microbial growth while trace organic chemicals are transformed cometabolically (Drewes et al 2008a). A lack of biodegradable organic carbon in the source water may prevent the establishment and maintenance of a biocommunity capable of removing the organic chemicals of interest.

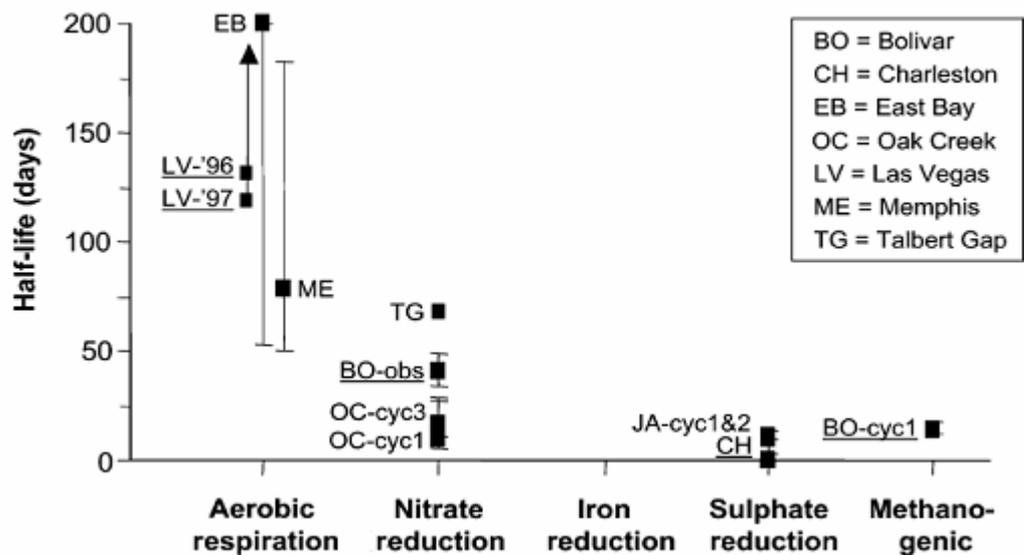
Sorption will also retard organic chemical movement, but the sorption removal capacity may be limited. However, sorption does provide additional residence time for degradation to occur. No allowance should be made for attenuation in the aquifer due to sorption alone for chemicals that do not degrade under the redox conditions and temperature relevant to the aquifer's storage zone.

The availability of environmental fate data for organic chemicals varies considerably. The fate of hazards such as benzene, for example, is reasonably well documented (Howard 1991); but there may be little information on emerging chemicals of concern. It is critical to ensure that existing environmental fate data was determined in a similar physiochemical environment to that expected in the managed aquifer recharge scheme under consideration. In the absence of relevant field data, laboratory studies can predict the fate of the hazard under the expected conditions (Oliver et al 1996, Ying et al 2003). An example of environmental fate data is given in Box 5.3.

If the storage zone is an unconfined aquifer, organic chemicals may be present from point sources (eg industrial activities) and diffuse sources (eg pesticide use). Mixing between the source and native groundwater may therefore affect the recovered water quality.

### Box 5.3 Fate of THMs during ASR

The fate of THMs was assessed at eight ASR field sites in Australia and the United States, under different subsurface environments and operating conditions (Pavelic et al 2006c). Total THM half-lives varied from <1 to >120 days and were influenced by the redox condition of the aquifer. The greatest potential for attenuation was under anaerobic conditions; aerobic aquifers provided little opportunity for THM removal. Chlorinated THMs were also shown to be more persistent than brominated species (half-lives are given in Appendix 5).



Relationship between half-life of total THMs and redox state (95% probability limits given for half-life; sites with highest confidence in the interpreted redox state are underlined)

### 5.5.3 Management of organic chemicals

A precautionary approach needs to be taken in considering attenuation. The risk of introducing persistent contamination should be minimised. It should not be considered if there are doubts about attenuation being successful or if short-term remedial responses are not available. General criteria for assessing the risks and appropriate level of management for organic chemical hazards are provided in Table 5.10.

**Table 5.10 Criteria, controls and monitoring to mitigate organic chemical hazards in relation to the stages of risk assessment**

	<b>Entry-level assessment and simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Acceptance criteria</b>	<ul style="list-style-type: none"> <li>Organic chemicals unlikely in source water at concentrations that would exceed acceptable concentrations for environmental values of aquifer or intended end uses</li> <li>Unlikely to be formed in the subsurface (ie no disinfection)</li> </ul>	<ul style="list-style-type: none"> <li>Any organic chemicals present in source water (eg using mean of measured concentrations to account for dispersion<sup>a</sup> in aquifer) or formed in the subsurface (eg disinfection byproducts) are at, or attenuate to, concentrations that meet environmental values for aquifer beyond attenuation zone and in water recovered for use</li> </ul>	<ul style="list-style-type: none"> <li>As per precommissioning residual risk assessment</li> </ul>
<b>Preventive measures</b>	na	<ul style="list-style-type: none"> <li>Source control</li> <li>Pretreatment, residence time in soil or aquifer, or post-treatment</li> <li>Reduce disinfection byproduct precursors or change the disinfection process</li> </ul>	<ul style="list-style-type: none"> <li>As per precommissioning residual risk assessment</li> </ul>
<b>Validation monitoring</b>	na	na	<ul style="list-style-type: none"> <li>Determine organic chemical (hazard) and biodegradable organic carbon (cosubstrate) concentrations in               <ul style="list-style-type: none"> <li>– source water</li> <li>– attenuation zone observation well/s</li> <li>– recovered water</li> </ul> </li> <li>Analyse minimum period of aquifer storage using ‘natural’ or introduced tracers</li> <li>Evaluate physicochemical and redox conditions</li> </ul>

**Table 5.10** (continued)

	<b>Entry-level assessment and simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Verification monitoring</b>	na	na	<ul style="list-style-type: none"> <li>Determine if organic chemical concentrations meet target values in recovered water and at edge of attenuation zone in aquifer</li> </ul>
<b>Operational monitoring</b>	<ul style="list-style-type: none"> <li>Estimate or measure annual injection and recovery volumes</li> </ul>	na	<ul style="list-style-type: none"> <li>See verification monitoring in table above</li> </ul>

na = not applicable.

**a** Dispersion is the homogenising of variable source-water concentrations. This is as a result of physical movement of water through diverse pathways composed of a myriad of interconnected aquifer pore spaces.

Source control may include limiting the contribution from hazardous activities to trade waste or stormwater discharge, and improving hazard management for high risk activities in order to reduce source concentrations or prevent against shock loadings from spills.

Pretreatment and post-treatment measures include biofiltration, passive treatment through wetlands and advanced tertiary treatment, such as membrane filtration.

Reliance on attenuation of organic chemicals in the aquifer requires validation of the reduced concentration with time and distance; this validation is needed for both the organic chemical hazard and the cosubstrate, if applicable. The validation is supported by details of the residence time in the aquifer and by the aquifer's physicochemical and redox conditions. Validation monitoring should be undertaken over a time period that is sufficient to allow adequate microbial adaption to occur.

In selecting indicators for monitoring (as described in Chapter 4 of the guidelines on augmentation of drinking water supplies (NRMMC–EPHC–NHMRC 2008)) it is useful to focus on species that will provide the most sensitive indication of effective system performance. The indicators chosen may include organic chemicals representing different treatment removal categories (good, intermediate or poor removal) (Drewes et al 2008b).

## **5.6 Turbidity and particulates**

### **5.6.1 Effect of turbidity on public health and the environment**

The public health and environmental risks associated with turbidity in relation to managed aquifer recharge include:

- recovered water having turbidity
  - in excess of drinking water guidelines (where drinking is an intended end use)
  - which, if not removed, can impact on pumps and irrigation infrastructure

- reduced disinfection performance, leading to increased risk from microbial pathogens
- increased risk of transporting a range of contaminants that can sorb to particles
  - metals and metalloids
  - phosphorus
  - various organics
  - microbial pathogens
- discharge of backwash water during redevelopment (backwashing) of injection wells (refer to Section 6.1), impacting on the stormwater catchment downstream.

### **5.6.2 Sources of turbidity in managed aquifer recharge**

All source waters for managed aquifer recharge contain natural levels of particulates — measured as turbidity or suspended solids — derived from inorganic silt, clay-sized particulates and organic matter.

Stormwater runoff usually contains highly variable turbidity levels, as a result of factors related to climate, catchment geomorphology, and land use and management. Secondary or tertiary treated sewage effluent typically contains lower concentrations of particulates, and a higher organic content, than stormwater. Roof runoff is typically low in particulate matter, but can be high due to deposition of vegetation debris or poor management. Groundwater turbidity levels are generally low, but can be high in wells that are inappropriately designed or inadequately developed.

Managed aquifer recharge practices can generate particulate hazards as a result of mineral dissolution and particle remobilisation within the soil or aquifer, and through the standard practice of backwashing injection wells to maintain recharge rates (discussed in Section 6.1).

### **5.6.3 Management of turbidity**

Turbidity management controls include preventive measures such as:

- source selection
- catchment water-quality management and source control to
  - minimise particulate export
  - remove or mitigate point sources of turbidity (where viable)
- pretreatment or post-treatment before recharge through
  - settling tanks
  - wetlands
  - coagulation
  - filtration.

General criteria for assessing the risks and appropriate level of management for turbidity hazards are provided in Table 5.11.

**Table 5.11 Criteria, controls and monitoring to mitigate turbidity hazards in relation to the stages of risk assessment**

	<b>Entry-level assessment and simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Acceptance criteria</b>	<ul style="list-style-type: none"> <li>• Source water for recharge &lt;1 NTU</li> </ul>	<ul style="list-style-type: none"> <li>• Low risk of purge water waste stream impacting on receiving environment</li> <li>• Low risk of mobilising clays or other colloids from aquifer into groundwater</li> <li>• Low risk of recovered water and aquifer turbidity beyond the attenuation zone not meeting required environmental values</li> </ul>	<ul style="list-style-type: none"> <li>• Confirmation of precommissioning residual risk assessment criteria based on validation monitoring</li> </ul>
<b>Preventive measures</b>	na	<ul style="list-style-type: none"> <li>• Refer to Section 6.1</li> </ul>	<ul style="list-style-type: none"> <li>• Refer to Section 6.1</li> </ul>
<b>Validation monitoring</b>	na	na	<ul style="list-style-type: none"> <li>• Monitor turbidity and flow of recharge and recovery to obtain a suspended solids mass balance for commissioning period. Monitor turbidity at edge of attenuation zone.</li> <li>• If solids are accumulating in aquifer, monitoring and investigations to define the level of residual risk</li> </ul>
<b>Verification monitoring</b>	na	<ul style="list-style-type: none"> <li>• Determine turbidity of recharge and recovered water, supported by volumetric inputs and outputs</li> </ul>	<ul style="list-style-type: none"> <li>• Determine turbidity of recharge and recovered water, and at observation well at edge of attenuation zone</li> </ul>
<b>Operational monitoring</b>	<ul style="list-style-type: none"> <li>• Estimate or measure annual injection and recovery volumes</li> </ul>	na	<ul style="list-style-type: none"> <li>• As per verification monitoring above</li> <li>• Maintain records of management of clogging and their effectiveness</li> </ul>

na = not applicable; NTU = nephelometric turbidity unit.

## 5.7 Radionuclides

Radioactive materials (eg uranium, thorium, potassium-40) occur naturally in the environment, and risk of human exposure to radiation is predominantly from natural sources.

Additional exposure can occur through anthropogenic activities such as medical (radiopharmaceuticals) and industrial use of radioactive materials.

### **5.7.1 Effect of radionuclides on public health and the environment**

The main radionuclide concern is recovery of water posing a risk to human health by ingestion of drinking water or foods via crop irrigation, stock watering, or food chain accumulation (radium and radon), or inhalation of gas released from the water supply (radon).

Radioactivity is measured in becquerel (Bq), where 1 Bq = 1 disintegration per second. Health considerations are based on the effective dose of radiation, measured in sievert (Sv), which takes into account the equivalent dose received by all tissues or organs, weighted to account for their different sensitivities to radiation. The acceptable radiation dose via the ingestion of water is less than 1 mSv/year (NHMRC–NRMMC 2004, Section 7.5). Dose estimates based on the dosage per unit intake of individual radionuclides can be calculated using Table 7.1 and Section 7.6 in NHMRC–NRMMC (2004).

### **5.7.2 Sources of radionuclides in managed aquifer recharge**

Recycled water or stormwater may contain radionuclides if they receive water from medical and industrial uses. Groundwater may contain naturally occurring radium and radon isotopes (radium-226, radium-228 and radon-222). Mining activities may also concentrate naturally occurring radionuclides (eg processing mineral sands, producing phosphate fertiliser).

The major source of radionuclides in managed aquifer recharge will usually be from the interaction of stored water with the aquifer matrix during aquifer storage. Native groundwater radioactivity is a useful indicator of the minimum level of radiation in the recovered water. Natural concentrations of radionuclides vary considerably, and depend on the properties of the aquifer, which are (Dillon and Toze 2005):

- geology
- porosity
- grain size
- redox state
- major ion chemistry.

In general, high radionuclide concentrations are found in granitic, fractured rock (crystalline) aquifers and near rich organic coal deposits (Herczeg and Dighton 1998). Leaching of uranium from carbonate aquifers has also been reported (Williams et al 2002).

Radon concentrations in recovered water and the native groundwater before managed aquifer recharge will be similar, because equilibrium between radon in the aquifer material and the source water is reached in less than three weeks (Dillon and Toze 2005).

Box 5.4 gives an example of radionuclide increase during ASR testing.

### Box 5.4 Radon increase during ASR testing

ASR testing of low radon source water in a Californian alluvial gravel and sand aquifer revealed 17–26 Bq/L radon in the recovered water. This is comparable to the concentration in the native groundwater (30 Bq/L). Because equilibrium of the source water with uranium-bearing minerals in the storage phase was expected to be an ongoing process, post-treatment aeration was implemented. This successfully reduced radon concentrations in the recovered water to an acceptable level (Dillon and Toze 2005).

Substantial amounts of radium can be adsorbed by iron or manganese oxyhydroxides. Thus, radium concentrations can increase through a managed aquifer recharge scheme if oxidation of organic matter leads to dissolution of these oxide surfaces (see Section 5.2). Radium concentrations can also increase through the dissolution of radium-bearing minerals such as phosphates (Dillon and Toze 2005).

### 5.7.3 Management of radionuclides

General criteria for assessing the risks and appropriate level of management for radionuclides are provided in Table 5.12. The radioactivity of native groundwater in the storage zone can be screened by measuring gross alpha and beta activity (excluding potassium-40), followed by analysis of individual radionuclides if the gross alpha or beta exceeds the target value (NHMRC–NRMMC 2004).

If the target aquifer is a potential source of radium, geochemical modelling is warranted to evaluate the potential for additional release through mineral dissolution or oxidation of organic rich deposits. Modelling would also define acceptable values for pH, oxygen, nitrate and organic carbon within the source water, to minimise the potential for geochemical reactions that could release radium during aquifer storage.

Potential pretreatment and post-treatment includes aeration for radon-222 and, for radium-226 and radium-228, lime softening, ion exchange or reverse osmosis (NHMRC–NRMMC 2004).

**Table 5.12 Criteria, controls and monitoring to mitigate radionuclide hazards in relation to the stages of risk assessment**

	<b>Entry-level assessment and simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Acceptance criteria</b>	<ul style="list-style-type: none"><li>• Low-risk lithology in storage zone (ie no granite or coal deposits)</li><li>• No radioactive isotopes in the source water</li></ul>	<ul style="list-style-type: none"><li>• Radioactivity of native groundwater meets targets for beneficial use of recovered water</li><li>• Low risk of release through geochemical reactions</li><li>• Low risk of radionuclides within the source water</li></ul>	<ul style="list-style-type: none"><li>• As per precommissioning residual risk assessment</li></ul>

**Table 5.12** (continued)

	<b>Entry-level assessment and simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Preventive measures</b>	na	<ul style="list-style-type: none"> <li>• Exclude high risk lithologies</li> <li>• Source control</li> <li>• Redox control of recharge water</li> </ul>	<ul style="list-style-type: none"> <li>• As per precommissioning residual risk assessment, plus treatment of recovered water</li> </ul>
<b>Validation monitoring</b>	na	na	<ul style="list-style-type: none"> <li>• Determine radionuclide concentrations in: <ul style="list-style-type: none"> <li>– source water</li> <li>– groundwater from storage zone (observation wells)</li> <li>– recovered water</li> </ul> </li> <li>• Evaluate physicochemical and redox conditions</li> </ul>
<b>Verification monitoring</b>	na	na	<ul style="list-style-type: none"> <li>• If indicated by validation results, measure radioactivity of recovered water and groundwater at edge of attenuation zone</li> </ul>
<b>Operational monitoring</b>	<ul style="list-style-type: none"> <li>• Estimate or measure annual injection and recovery volumes</li> </ul>	na	<ul style="list-style-type: none"> <li>• See verification monitoring (above), plus online pH and Eh</li> </ul>

na = not applicable

## 5.8 Pressure, flow rates, volumes and groundwater levels

### 5.8.1 Confined and semiconfined aquifers

Overpressurisation of injection wells can rupture an aquitard. This can connect previously unconnected aquifers, leading to adverse changes in piezometric levels and water quality; the consequences of this can outweigh all the benefits of an ASR operation.

Excessive pressure can also cause failure of poorly completed injection or other wells, allowing water to escape to other aquifers or the ground surface. Pressurising a confined aquifer can also cause existing completed wells in the same aquifer to become artesian. The discharge of water from these may create a nuisance or hazard that needs to be addressed.

On recovery of stored water from the aquifer, piezometric pressures are reduced. This increases energy requirements for pumping of bores that are hydraulically influenced, reducing their yields. In some circumstances, despite the additional storage in the aquifer, existing well owners may be disadvantaged by the ASR operation.

Excessive lowering of pressures may lead to consolidation of compressible aquitards and other overlying strata, or desaturation of confined aquifers. Either of these situations may cause land to subside. Excessive lowering of pressures can also ultimately trigger failure of an injection well or aquitard, if the aquifer beneath the confining layer is subject to chemical or physical erosion (discussed in more detail in Section 5.9).

Management controls for pressure, flow or volume-related hazards in confined and semiconfined aquifers include the following preventive measures, each of which is discussed below:

- selection of injection pressure
- estimation of the region likely to be made artesian
- determination of the transfer of fluid pressure and constituents between aquifers
- restriction of volume, recharge and recovery rates to appropriate periods
- constrain plastic deformation
- calculate maximum injection pressure.

### ***Injection pressure***

The injection pressure should be selected to ensure that it never exceeds the dry overburden pressure on the base of the aquitard. This pressure ( $p$ ) can be conservatively estimated from  $p < 15 d$  (kPa), where  $d$  is the depth in metres from the land surface to the base of the aquitard overlying the aquifer, and assuming that the dry weight density exceeds  $15 \text{ kN/m}^3$ .

This maximum pressure should not be constrained by valves because, inevitably, valve adjustments will be made. An oversized pump could then cause irreparable damage. Normally, the injection pressure will be more tightly constrained by energy efficiency and the need to avoid compaction of the clogging layer around the well perimeter.

In exceptional cases, where more accurate calculations of maximum injection pressure are needed, it may be necessary to:

- measure the bulk density of the aquitard and the material above it (overburden)
- measure the elevation of the piezometric surface in the overburden
- undertake geotechnical testing to assess the strength of the aquitard
- calculate bursting pressure by geotechnical evaluation, to account for the elastoplastic properties of the aquitard.

### ***Artesian region***

The region likely to be made artesian should be estimated using estimated injection rates and aquifer hydraulic properties derived from pumping tests. All wells in the region that penetrate the target aquifer should be identified, permission should be gained from owners, and any well forecast to overflow should be equipped with wellhead seals. If this is not viable, it will be necessary to restrict the rate of recharge so that nearest unsealed wells are not artesian.

### ***Transfer of fluid pressure and constituents***

A check of construction records of influenced wells may identify whether any are completed in more than one aquifer. If this is the case, transfer of fluid pressure and constituents

between aquifers may occur as a result of managed aquifer recharge and should be evaluated to determine if this is acceptable. Otherwise well backfilling may be necessary.

***Volume, recharge and recovery rates***

It is important to restrict volume and rate of net recharge and recovery to periods (eg annual, monthly, daily) that are appropriate to the local conditions and aquifer capacity. Normally, reducing the head in a confined aquifer (so that the aquifer becomes unconfined) is unacceptable, as this may result in consolidation and adverse geochemical changes such as oxidation of reduced iron minerals. Also, the pump should be set above the level of the top of the aquifer.

***Plastic deformation***

If the aquitard is underconsolidated, a quantitative estimate of the amount of plastic deformation likely to occur following the proposed reduction in head during withdrawal should be calculated. Pumping rates should be restricted, to constrain deformation to an acceptable level.

General criteria for assessing the risks and appropriate level of management for pressure, flow or volume-related hazards in confined and semiconfined aquifers are provided in Table 5.13.

**Table 5.13 Criteria, controls and monitoring to mitigate pressure, flow or volume-related hazards in confined and semiconfined aquifers in relation to the stages of risk assessment**

	<b>Entry-level assessment and simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Acceptance criteria</b>	<ul style="list-style-type: none"> <li>Analytical models predict no other wells to be artesian</li> <li>Wells constructed and completed according to well completion permit</li> </ul>	<ul style="list-style-type: none"> <li>Calibrated model of injection and recovery well rates of flow, cumulative recharge and discharge volumes, and pressures for proposed commissioning trial (Stage 3)</li> <li>Groundwater models predict defined maximum and minimum heads in injection well, to be achieved by pump selection and placement</li> <li>Acceptable predicted maximum and minimum heads in other wells as a result of operation, with respect to               <ul style="list-style-type: none"> <li>aquitard protection</li> <li>subsidence</li> <li>leakage losses</li> <li>head and water-quality changes in other aquifers (from calibrated model)</li> </ul> </li> <li>No wells in zone with large head changes intersect the target aquifer, have multiple completions or are known to be poorly completed</li> <li>Recharged water is confined to target storage zone and predicted upward and downward leakage is negligible</li> <li>Predicted land subsidence is negligible</li> </ul>	<ul style="list-style-type: none"> <li>As per precommissioning residual risk assessment, with confirmation, based on field and laboratory measurements, informing hydrogeological and geotechnical evaluations of uncertainties identified in precommissioning residual risk assessment</li> <li>To include quantified criteria (eg bursting pressure, subsidence, and head changes in observation and other wells)</li> <li>Modelling and trials reveal no adverse effects on other aquifers or connected ecosystems</li> </ul>

**Table 5.13 (continued)**

	<b>Entry-level assessment and simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Preventive measures</b>	<ul style="list-style-type: none"> <li>• Pump selection and placement</li> </ul>	<ul style="list-style-type: none"> <li>• Install wellhead seals on wells that are expected to become artesian</li> <li>• Backfill wells that intersect the target aquifer and are poorly completed or have multiple completions, where the rate of vertical flow is likely to adversely impact water quality in the target storage zone or water quality and levels in other aquifers</li> <li>• Restrict injection and recovery rates</li> <li>• Construct piezometers to give early detection of leakage</li> </ul>	<ul style="list-style-type: none"> <li>• As per precommissioning residual risk assessment, with refined identification of               <ul style="list-style-type: none"> <li>– artesian wells</li> <li>– poorly completed wells</li> <li>– bursting pressure</li> <li>– aquitard collapse or consolidation</li> </ul> </li> <li>• Where real-time adaptive management is required, use feedback control systems (to change pumping rates or shut down pumps) and telemetered messaging systems</li> </ul>
<b>Monitoring</b>	<ul style="list-style-type: none"> <li>• Estimate or measure seasonal or annual injection and recovery volumes</li> </ul>	<ul style="list-style-type: none"> <li>• Perform pumping test and down-hole flow metering to evaluate transmissivity and storage coefficient for the target aquifer at the injection well, and to predict fate of recharged water in the aquifer</li> <li>• Monitor observation well in the overlying aquifer adjacent to the injection well, and in the target aquifer, at a small radius. This will provide early warning of artesian conditions in other wells, potential for subsidence or aquitard failure</li> <li>• Also monitor heads in well at margin of attenuation zone (if a different well) to verify projected head changes in aquifer</li> <li>• Implement groundwater-level monitoring as early as possible before commissioning, to generate background data</li> </ul>	<ul style="list-style-type: none"> <li>• As per maximal risk assessment, plus monitoring at critical control points</li> <li>• Monitor subsidence if warranted by geotechnical evaluation and head fluctuations</li> <li>• Monitor control system to detect potential hydraulic failure, for example               <ul style="list-style-type: none"> <li>– burst aquitard</li> <li>– excessive leakage</li> <li>– subsidence</li> <li>– excessive preferential flow</li> <li>– lack of flushing</li> </ul> </li> </ul>

### 5.8.2 Unconfined aquifers

Recharge of unconfined aquifers increases storage and may protect groundwater-dependent ecosystems in stressed aquifers. However, if the watertable is raised too high, recharge of unconfined aquifers may also have adverse impacts. Examples include:

- waterlogging
- flooding of basements, below-ground cable ducts and depressions
- reduced traffic access, potholes and increased road maintenance costs
- effects of anoxia on vegetation
- increased groundwater ingress to sewers
- increased differential heave effects on footings, causing consequent structural damage to buildings
- mobilisation of pollutants from a nearby contaminated site

On recovery of stored water, lowering of the watertable may increase pumping costs for other groundwater users and reduce yields of shallow wells. It may also mobilise metals (see Section 5.2) and reduce groundwater discharge to dependent ecosystems at times when this is most needed.

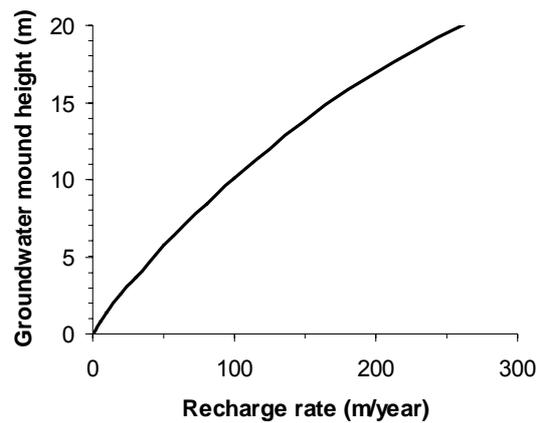
Management controls for pressure, flow or volume-related hazards in unconfined aquifers include the following preventive measures:

- install overflow diversion to prevent excessive recharge head
- prevent use of pumps for injection
- avoid selecting infiltration sites that are
  - on sloping land
  - underlain by shallow watertables or impervious layers
  - adjacent to surface depressions or groundwater-dependent ecosystems (see Section 5.11)
- restrict volume and rate of recharge to periods appropriate to the local conditions (eg annual, monthly, daily)
- increase drying time in recharge basins or infiltration galleries between infiltration events, to allow groundwater mound to subside (see Box 5.5 for an example)
- restrict the rate of initial release for recharge releases from dams into rivers, so as not to cause a drowning hazard or excessive scour of the stream bed.

### Box 5.5 Height of groundwater mound beneath infiltration basins

The height of a groundwater mound beneath a rectangular infiltration basin can be calculated from an equation for any location and time since recharge began (Hantush 1967; Bouwer 1978, 2002). The result depends on infiltration rate, aquifer transmissivity and porosity, and the size of the basin.

The plot below shows the mound height beneath the centre of a 100 m × 100 m infiltration basin overlying an unconfined aquifer with an initial saturated aquifer thickness of 10 m, hydraulic conductivity of 10 m/day and effective porosity of 0.1. Soil type and source-water quality, which affect recharge rates through clogging, therefore also affect mound height. For this example, if the mound height was constrained to 4 m or 8 m, recharge rates would need to be <30 m/year or <80 m/year respectively to comply.



**Groundwater mound height at centre of infiltration basin after 1 year of recharge, for a range of recharge rates**

General criteria for assessing the risks and appropriate level of management for pressure, flow or volume-related hazards in unconfined aquifers are provided in Table 5.14.

**Table 5.14 Criteria, controls and monitoring to mitigate pressure, flow or volume-related hazards in unconfined aquifers in relation to the stages of risk assessment**

	<b>Entry-level or simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Acceptance criteria</b>	<ul style="list-style-type: none"> <li>• Infiltration site is not on sloping land, adjacent to surface depressions or groundwater-dependent ecosystems, or underlain by known shallow impervious layers</li> <li>• At infiltration site, depth to watertable exceeds 8 m in an urban area or 4 m in a rural area with no nearby structures</li> <li>• Infiltration site is not in or adjacent to a landfill or known contaminated site</li> <li>• Reservoir release rate is restricted to avoid causing a drowning hazard or excessive scouring</li> </ul>	<ul style="list-style-type: none"> <li>• Groundwater model is calibrated based on adequate data</li> <li>• Field data on soil profile down to the aquifer, aquifer properties and calibrated groundwater modelling show that the predicted shallowest depth of watertable, outside the basin or gallery, is sufficient to not cause               <ul style="list-style-type: none"> <li>– waterlogging</li> <li>– soil salinisation</li> <li>– salt-damp</li> <li>– foundation movement</li> <li>– structural damage</li> <li>– flooding of cellars or other infrastructure</li> </ul> </li> <li>• Aquifer’s capacity can store volume intended, meeting criteria above</li> <li>• Existing land uses and waste management in the area have low risk of contaminating groundwater and inhibiting intended uses of recovered water</li> </ul>	<ul style="list-style-type: none"> <li>• Confirmation of achievement of precommissioning residual risk assessment criteria, based on additional field and laboratory measurements and validated groundwater model</li> <li>• Trials and modelling reveal no adverse effects on other aquifers, connected water bodies or ecosystems</li> </ul>

**Table 5.14 (continued)**

	<b>Entry-level or simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Preventive measures</b>	<ul style="list-style-type: none"> <li>• Install overflow diversion to prevent excessive recharge heads or volumes</li> <li>• Prevent use of pumps for injection</li> <li>• See Section 6.1 concerning clogging management</li> </ul>	<ul style="list-style-type: none"> <li>• Restrict volume and rate of recharge to periods appropriate to the local conditions (eg annual, monthly, daily)</li> <li>• Drill, slot or rip subsurface semipermeable layers to allow infiltration without surface waterlogging</li> <li>• Relocate infiltration site and redesign separation distances between recharge facilities and recovery locations, and between potentially polluting land uses and waste management practices in the area and the managed aquifer recharge operation</li> <li>• Construct piezometers and observation wells to allow early warning and assist in model calibration</li> </ul>	<ul style="list-style-type: none"> <li>• Increase drying time in basins or galleries between infiltration events, to allow groundwater mound to subside</li> <li>• Where real-time adaptive management is required, use feedback control systems (to change pumping rates or shut down flow) and telemetered messaging systems</li> </ul>
<b>Validation monitoring</b>	na	na	<ul style="list-style-type: none"> <li>• Monitor water levels in basins or galleries</li> <li>• Monitor soil moisture, suction and piezometric levels in unsaturated zone beneath basin and gallery, to discriminate between causes of any detected reduction in infiltration rate</li> <li>• Monitor function of connected ecosystem if warranted by the level of impact</li> </ul>

**Table 5.14** (continued)

	<b>Entry-level or simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Verification monitoring</b>	na	na	<ul style="list-style-type: none"> <li>• Monitor recharge and recovery rates of               <ul style="list-style-type: none"> <li>– flow</li> <li>– cumulative recharge and discharge volumes</li> <li>– watertable elevation</li> </ul> </li> <li>• Monitor observation well in target aquifer at critical control points (beneath and adjacent to the recharge basin or gallery), and at a well further away, to provide early warning of excessive mounding and discriminate between causes</li> <li>• Monitor control system to detect potential failure</li> </ul>
<b>Operational monitoring</b>	<ul style="list-style-type: none"> <li>• Estimate or measure seasonal or annual injection and recovery volumes</li> </ul>	<ul style="list-style-type: none"> <li>• Implement groundwater level monitoring as early as possible before commissioning, to generate background data</li> </ul>	<ul style="list-style-type: none"> <li>• See verification monitoring and validation monitoring above. Continue monitoring until unsaturated zone and aquifer behaviour is well understood. Ensure that flow and water-quality monitoring are coordinated</li> </ul>

na = not applicable.

## 5.9 Contaminant migration in fractured rock and karstic aquifers

In fractured rock aquifers, most water flows through cracks in the rocks, and thus may only interact with a very small percentage of the rock mass. The effective porosity of fractured rock aquifers is much less than for aquifers in which flow is predominantly through interconnected pores throughout the porous medium.

Water is conveyed through connecting fractures, and may zigzag through aquifers in three dimensions. Hence, the water injected into a fractured aquifer will travel further from the ASR well than the same volume would travel in a porous aquifer. The distribution of recharged water is therefore much more difficult to predict, which has implications for

establishing the size of the attenuation zone (see Section 7.3). If the aquifer is initially brackish, the recovery efficiency will also be diminished (see Section 6.2). Aquifer pumping tests will normally reveal low effective porosity; but, if results are difficult to interpret, the lowest realistic estimate of effective porosity should be used when estimating the required size of the attenuation zone.

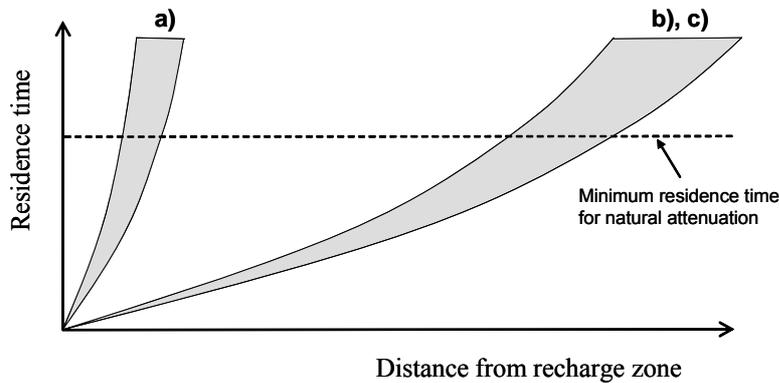
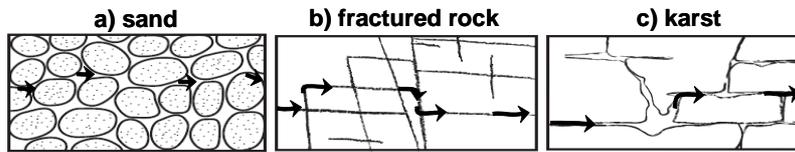
In karstic aquifers, water is conveyed largely through dissolution features such as fractures that have been enlarged, fissures, flow tubes and caves. The dimensions of the pathways of least resistance to flow, or preferential flow paths, can be many metres across. Karstic aquifers also commonly allow intergranular flow; the whole aquifer may transmit water, but most of the flow occurs in the dissolution features. In dual porosity systems such as this, it may take longer to displace the native groundwater from the porous media.

The surface area of the aquifer matrix to which the fastest flowing water is exposed in these preferential flow paths is therefore much smaller than for water flowing through the aquifer matrix. Consequently, opportunities are reduced for the aquifer biofilm to react with constituents of the fastest flowing recharged water. Bulk biodegradation rates may therefore be limited by surface area, and hence slower, than in water flowing through the matrix. Constituents can potentially travel further before biodegrading to levels complying with water-quality requirements for ambient groundwater environmental values. The attenuation zone for karstic aquifers may therefore be larger than would be predicted for an aquifer without karstic features (see Box 5.6).

This situation does not mean that karstic aquifers should be avoided for managed aquifer recharge. However, it does suggest that it will require more effort for proponents to demonstrate that managed aquifer recharge operations will not adversely affect other water supplies or connected water bodies. Hydraulic characterisation of the aquifer alone will rarely be sufficient to assess the size of the attenuation zone, but guidance from historical information gained from nearby managed aquifer recharge operations will be of great value in assessing the likely risk to human and environmental health.

When attenuation zones are relied on for pathogen inactivation or nutrient and contaminant biodegradation, their extent should be no greater than is acceptable to stakeholders and regulators. Fractured and karstic aquifers may require more than one observation well to be confident that concentrations beyond the attenuation zone meet the aquifer's environmental values.

**Box 5.6 Homogeneous porous media (a), fractured rock (b) and karst (c) aquifer characteristics, showing the opportunity for rapid migration of constituents in recharged water**



Recharged water can migrate much further in fractured rock and karstic aquifers, within the residence time required for attenuation of pathogens, for example. Hence, the attenuation zone required for fractured and karstic aquifers is much larger and may be difficult to define.

General criteria for assessing the risks and appropriate level of management for pressure, flow or volume-related hazards in fractured rock and karstic aquifers are provided in Table 5.15. If the fractured rock or karstic aquifer is unconfined, the potential for leakage to or from the surface is increased, and the considerations in this table have heightened importance.

**Table 5.15 Criteria, controls and monitoring to mitigate contaminant migration in fractured rock and karstic aquifers in relation to the stages of risk assessment**

	<b>Entry-level or simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Acceptance criteria</b>	na	<ul style="list-style-type: none"> <li>Revised assessment of attenuation zone to conservatively account for aquifer hydraulics (and possibly reduced rates of biodegradation) does not encompass other groundwater supplies or groundwater-dependent ecosystems</li> <li>Low potential for contamination of recharged water from other sources in the area</li> <li>Tangible evidence from nearby managed aquifer recharge operations in the same aquifer that human and environmental health are protected</li> </ul>	<ul style="list-style-type: none"> <li>Confirmation of achievement of maximal risk assessment criteria, based on additional field and laboratory measurements and modelling</li> <li>Modelling and trials reveal no adverse effects on other aquifers, connected water bodies or ecosystems, and attenuation zone is acceptable</li> </ul>
<b>Preventive measures</b>	na	<ul style="list-style-type: none"> <li>Restrict volume and rate of recharge to periods appropriate to the local conditions (eg annual, monthly, daily)</li> <li>Where attenuation zone is unacceptably large, improve source control or pretreatment to avoid reliance on a groundwater attenuation zone, or to reduce the size of the zone to an acceptable level</li> </ul>	<ul style="list-style-type: none"> <li>As per maximal risk assessment, plus where real-time adaptive management is required, use feedback control systems (to change pumping rates or shut down flow) and telemetered messaging systems, based on               <ul style="list-style-type: none"> <li>recharge water quality</li> <li>flow rate</li> <li>heads in observation wells or continuously monitored parameters in observation wells</li> </ul> </li> </ul>

**Table 5.15** (continued)

	<b>Entry-level or simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Validation monitoring</b>	na	na	<ul style="list-style-type: none"> <li>• Use tracer studies to assess fate of recharge water and constituents in aquifer and travel times to observation wells</li> <li>• Take in situ or laboratory attenuation measurements for critical contaminants and pathogens, with and without aquifer media</li> <li>• Report data from nearby managed aquifer recharge sites to define impacts on target aquifer and connected ecosystems</li> <li>• Report data from other hydrogeological studies, or site contamination studies, that reveal the hydraulic and solute transport characteristics of the aquifer</li> <li>• Monitor the function of connected ecosystems to validate low level of impact</li> <li>• Add more observation wells, if needed, to increase the likelihood of intersecting flow paths; caliper log and borehole video can help identify borehole intersections with karstic features and fractures</li> </ul>

**Table 5.15 (continued)**

	<b>Entry-level or simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Verification monitoring</b>	na	na	<ul style="list-style-type: none"> <li>• Monitor recharge and recovery rates of               <ul style="list-style-type: none"> <li>– flow</li> <li>– cumulative recharge and discharge volumes</li> <li>– piezometric levels</li> </ul> </li> <li>• Monitor observation wells in target aquifer at edge of calculated attenuation zone</li> <li>• Monitor water quality to verify efficacy of any pretreatment installed to reduce the size of the attenuation zone</li> <li>• Verify that storage zone of unconfined systems is not contaminated by other sources of pollutants</li> <li>• Monitor control system to detect potential failure</li> </ul>
<b>Operational monitoring</b>	na	na	<ul style="list-style-type: none"> <li>• Monitor observation well/s adjacent to the recharge location, to provide early warning of contaminant migration</li> <li>• See verification monitoring in table above</li> </ul>

na = not applicable.

## 5.10 Aquifer dissolution and stability of well and aquitard

Recharge water may react with the aquifer matrix material, resulting in dissolution of minerals or reduction in the aquifer's bulk volume or strength.

Causes of aquifer dissolution may include:

- acidic recharge water dissolving carbonate minerals (eg calcite and dolomite)
- organic carbon in recharge water oxidising to produce acidic conditions within the aquifer; this will also dissolve carbonate minerals
- aerobic recharge water oxidising sulfide minerals
- recharge water that is not in equilibrium with mineral phases, leading to mineral dissolution (or precipitation, see Section 6.1)
- fresh recharge water reacting to dispersed clay minerals in brackish or saline media and changing the physical structure and strength of the porous media

- cation exchange reactions (especially where recharge water is sodic) dispersing clay minerals and changing physical structure of the porous media.

Aquifer dissolution may increase the effective diameter of a well, consequently increasing yield, and inhibit chronic clogging problems. However, aquifer dissolution has many negative effects, including:

- collapse of uncased wells, due to reduced strength of the surrounding aquifer material
- production of turbid water or water containing a lot of sand, which can abrade pump impellers, block irrigation drippers and sprays, and cause nuisance within the distribution system
- eventual undermining of the aquitard in the vicinity of an ASR well, causing aquitard collapse during recovery, and connecting previously separate aquifers of potentially different water qualities; this has potential for significant, enduring environmental damage
- contribution to metal mobilisation problems (see Section 5.2)
- adverse effects of taste, odour and safety of recovered water for drinking, particularly following oxidation and reduction of sulfide minerals
- mobilised clay particles may become trapped further within the aquifer matrix, leading to a chronic decline in specific capacity of injection wells (see Section 6.1).

An example of the effect of calcite dissolution on well stability is given in Box 5.7.

#### **Box 5.7 Effect of calcite dissolution on well stability**

During injection of 250 ML treated sewage into a carbonate aquifer at Bolivar, South Australia, up to 7 t of calcite was estimated to have dissolved over one year from the area surrounding the ASR well (Vanderzalm, 2004).

The impact of aquifer dissolution on the stability of the overlying 7 m thick clay aquitard was considered by assuming that dissolution of a 2 m radius around the injection well would result in stability concerns. It would take over 100 years of injection at 250 ML/year to dissolve the 800 t calcite present in this 2 m radius (bulk density 1.5 g/cm<sup>3</sup> and average calcite content 74%). This indicates that aquitard stability would not be compromised over the normal operating life of a well. Periodic verification monitoring by caliper log is required (on pump replacement or maintenance) to address this long-term issue.

General criteria for assessing the risks and appropriate level of management for aquifer dissolution and well and aquitard stability hazards are provided in Table 5.16. Management methods for adverse geochemical reactions are described below.

#### **5.10.1 pH and redox status of injectant**

Adjustment of pH and redox status of injectant can have a predictable effect on geochemical reactions between recharge water and the aquifer matrix. Equilibrium geochemical models may be used to determine the acceptable Eh–pH range of recharge water.

#### **5.10.2 Labile organic carbon**

Reducing the concentration of labile organic carbon in water recharging carbonate aquifers can also reduce aquifer dissolution. However, it may have an adverse effect on clogging of wells.

### 5.10.3 Aquifer depletion

For some sites, a successful strategy may be to deplete the aquifer of offending minerals within the active storage zone, and treat the recovered water (or use it for lower valued uses) until recovered water meets the standards for its ultimate use.

### 5.10.4 Surfactants

Use of surfactants to coat aquifer minerals inhibiting their reaction with recharged water is still at an early stage of research. Until validated in trials, they should not be relied on as a control measure.

### 5.10.5 Algal blooms

Algal blooms in infiltration basins can be prevented by frequent draining and drying of basins, reducing nutrient concentrations in source water and providing shade. This may also reduce fluctuations in pH of recharging water and help to prolong the hydraulic loading capacity of infiltration basins.

**Table 5.16 Criteria, controls and monitoring to mitigate aquifer dissolution and well and aquitard stability hazards in relation to the stages of risk assessment**

	<b>Entry-level or simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Acceptance criteria</b>	<ul style="list-style-type: none"> <li>• Aquifer is nonreactive</li> <li>• Aquifer is reactive and recharge water is nonaggressive (6.5&lt;pH&lt;8.5) and has the same redox status as the aquifer</li> </ul>	<ul style="list-style-type: none"> <li>• Geochemical modelling shows that dissolution will not occur, or is so slow, or that aquitard or well instability will not occur within the working life of the well (50 years minimum)</li> <li>• Clay cation exchange calculations show that dispersion and slumping of clays in the aquifer and aquitard will not occur within the working life of the well (50 years minimum)</li> </ul>	<ul style="list-style-type: none"> <li>• Confirmation of achievement of precommissioning residual risk assessment criteria, based on additional field and laboratory measurements and modelling</li> <li>• Modelling and trials reveal no adverse effects on aquitards, other aquifers, connected water bodies or ecosystems</li> </ul>

**Table 5.16 (continued)**

	<b>Entry-level or simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Preventive measures</b>	<ul style="list-style-type: none"> <li>• Source-water selection</li> <li>• Target aquifer selection</li> </ul>	<ul style="list-style-type: none"> <li>• Adjust pH or Eh of recharge water, including use of algal control measures in recharge basins</li> <li>• Adjust sodium adsorption ratio and LSI of water to avoid clay dispersion in the aquifer and aquitard</li> <li>• Reduce TOC in water recharging carbonate aquifers (also taking account of Section 6.1)</li> </ul>	<ul style="list-style-type: none"> <li>• Preventive measures as for precommissioning residual risk assessment</li> <li>• Use controlled leaching in monitored trials to remove reactive minerals from the storage zone</li> <li>• Possibly apply surfactants in monitored trials aimed at insulating water in the storage zone from reactive minerals</li> <li>• Predict dissolution from geochemical modelling and compare caliper logs at pump maintenance periods (verification monitoring)</li> </ul>
<b>Validation monitoring</b>	na	na	<ul style="list-style-type: none"> <li>• Determine aquifer minerals present by geochemical evaluation</li> <li>• Record major ions in recharged and recovered water to allow mass balance calculations of mineral dissolution</li> <li>• Monitor piezometer in target aquifer adjacent to the recharge basin or gallery, and at a radius, to provide warning of excessive dissolution</li> <li>• Evaluate dissolution for range of source-water qualities using laboratory column studies</li> </ul>

**Table 5.16 (continued)**

	<b>Entry-level or simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Verification Monitoring</b>	na	na	<ul style="list-style-type: none"> <li>• Monitor control system to detect potential failure (eg pH trigger)</li> <li>• At pump maintenance periods (not greater than 10 years), validate that erosion does not exceed forecast rate</li> <li>• Down-hole caliper logging and geophysical logging of aquitard and aquifer</li> </ul>
<b>Operational monitoring</b>	<ul style="list-style-type: none"> <li>• Estimate or measure annual injection and recovery volumes</li> </ul>	na	<ul style="list-style-type: none"> <li>• See validation and verification monitoring above</li> </ul>

Eh = a measure of redox potential — the propensity for oxidation and reduction reactions; LSI = Langelier Saturation Index; na = not applicable; pH = a measure of the acidity or alkalinity of a solution; TOC = total organic carbon.

## 5.11 Aquifer and groundwater-dependent ecosystems

Ecosystem receptors that require protection are indigenous microorganisms and stygofauna in aquifers; the fauna and flora of wetlands, streams, lakes, springs, estuaries and coastal waters that receive or depend on groundwater; and riparian and terrestrial phreatophytic vegetation. Managed aquifer recharge may affect these receptors through excessive changes in groundwater levels, excessive rates of change in groundwater levels or excessive changes in water quality (in particular, of the water-quality hazards identified in Sections 5.1–5.7). Such changes may reduce or eliminate habitat, or impact directly on the receptor species. Also, declines in groundwater levels near groundwater-dependent water bodies in depositional environments can result in formation of acid-sulfate soils, with consequences to water quality, and aquatic and soil organisms and plants. A review of current relevant knowledge and Australian experience of impacts of managed aquifer recharge on groundwater-dependent ecosystems has been recently compiled (Dillon et al 2009b).

### 5.11.1 Microorganisms

All aquifers contain microorganisms, some of which can biodegrade unwanted constituents and should be sustained in recharge water. Such microorganisms may be native to the soil and aquifer, or introduced in recharge water.

Acclimation of microbial populations may be required for efficient biodegradation of some contaminants. Some nutrients can act as co-metabolites of organic contaminants, and attempts to reduce these nutrients in recharge waters may increase the persistence of the organic contaminants. However, overloading with nutrients or contaminants can result in environmental conditions that no longer support biodegrading organisms. In some cases, the

bounds are unknown; however, reducing concentrations of contaminants — notably nutrients — before recharge is thought to be desirable for protecting and sustaining the microbial function and environmental health of the aquifer, and for uses of the recovered water (Dillon et al 2008). Advances in microbial ecology methods, in conjunction with multivariate statistics allow changes in microbial function to be detected (eg Reed 2009). However, a simpler indicator of sustainability of microbial function is to detect no persistent (non-cyclic) shift in redox state to anaerobic conditions in the aquifer beyond the recharge facility. If an anaerobic zone is found to migrate away from the recharge facility, this would suggest that the microbial ecosystem function is impaired and nutrient loadings are excessive. Cyclic fluctuations in redox state surrounding an ASR well, which became anaerobic between injection and recovery cycles, were found to restore ambient microbial function in recovery cycles (Reed 2009).

### **5.11.2 Stygofauna**

The term ‘stygofauna’ encompasses all animals that occur in subsurface waters. Australian stygofauna include a highly diverse range of microscopic (<1 mm) to large (20–100 mm) aquatic groundwater invertebrates, and several species of blind fish (Humphreys 2006). These fish have adapted to live in total darkness, limited space, and low-energy environments that have limited food webs and are lacking in predators (Gilbert and Deharveng 2002).

Stygofauna have been found in fresh and saline aquifers that have macroporosity (eg caves and fissures), and in pores of alluvial aquifers. Although stygofauna are found in all continents except Antarctica, a large proportion of stygofauna species are highly endemic and localised. Their habitats range from aerobic, energetically rich, upper layers of an alluvial aquifer in contact with aquatic or terrestrial ecosystems, to deeper, fine-grained anaerobic substrates (Danielopol 1976, Eber 1983).

Distinct communities of stygofauna are adapted to each niche in the range. In general, a direct relationship exists between increasing depth and increasing morphological and physiological specialisations, as the groundwater becomes increasingly oligotrophic (ie offering little to sustain life) and lower in oxygen. This continues until only highly specialised organisms can persist in the anoxic conditions (Boulton et al 2003). Biodiversity also decreases with depth. Groundwater animals migrate actively within the interstitial space to find their preferred habitat (Danielopol 1989).

Knowledge of stygofauna ecology is limited but growing. A recent review found that stygofauna populations and biodiversity increased when exposed to water containing small amounts of nutrients, but that stygofauna were absent from polluted groundwater containing excessive nutrients (Leijds 2009). Restoration of stygofaunal communities after the passive remediation of sewage contamination was also evident. The review also found that larger stygofauna (>3 mm) could be stranded if groundwater levels dropped rapidly, and did not survive more than 2 days if stranded above the watertable. Thus, if a watertable drops below the maximum depth of karst features, loss of habitat is likely to adversely impact stygofaunal communities. The responses of hyporheic organisms (ie those that live in the interface between groundwater and surface water bodies) to managed aquifer recharge are unknown; however, their location suggests an inherent capacity to deal with variations in flow and quality.

The weighted plankton net is considered the most reliable method for detecting stygofaunal biodiversity and abundance. However, because stygofauna abundance is low and very

variable between bores and within bores over time, differentiating the impacts of managed aquifer recharge is likely to require at least 15–20 bores for monitoring (Leijs 2009). To overcome this problem, geochemical change could be used as a surrogate indicator (as for microbial populations), with validation monitoring and ecotoxicological studies undertaken at selected sites where monitoring requirements can be met.

### **5.11.3 Phreatophytic vegetation**

The health of phreatophytic vegetation (wetland, riparian and terrestrial) is affected by falling groundwater levels because the plants require more energy to extract the groundwater, and each species has a limit to the extent of its rooting depth. If the rate of decline of a watertable exceeds the rate at which a plant can extend its roots, then the plant suffers water stress and, without other sources of water, could die. Thus, one review found that both magnitude and rate of the decline in the watertable influence phreatophytic vegetation for a range of species with different rooting depths (Parsons 2009). Rising watertables can result in anoxia within the root zone and stress riparian plants, although wetland inhabitants are evidently more tolerant of this, because water level changes due to surface inflows can be rapid.

In situations where sustenance of groundwater-dependent ecosystems is an environmental value of the aquifer, effects of changes in water quality beyond the temporary attenuation zone due to managed aquifer recharge should not adversely affect phreatophytic vegetation. The Phase 1 guidelines provide indicators of the risk to plant health from irrigation with water of various nutrient and salt concentrations; these indicators may be used to ascribe water-quality objectives at the margin of the attenuation zone. If such objectives are more stringent than water-quality objectives for other environmental values of native groundwater and uses of recovered water, they may dictate the size of the attenuation zone or the level of pretreatment before recharge.

Measurement methods for vegetation health include leaf water potential, stomatal conductance, transpiration measurement, leaf area index, growth rate, cover and abundance (Eamus et al 2006). Groundwater level and quality measurements between the managed aquifer recharge site and the groundwater-dependent vegetation provide indicators of the need for vegetation-based monitoring to assess impacts. Increasing the distance between the location of the managed aquifer recharge site and the groundwater-dependent ecosystem is the simplest approach to mitigating potential impacts of managed aquifer recharge operations.

### **5.11.4 Aquatic flora and fauna**

Fauna and algae inhabiting groundwater-dependent water bodies, such as springs, streams, wetlands and lakes, are highly diverse. As with groundwater-dependent vegetation, they require a minimum groundwater level to be maintained for their health and survival. Without water, their habitat is lost.

Aquatic fauna and plants are a highly diverse group of ecosystem receptors, and their responses to water-quality changes can vary from highly sensitive to resilient. Ecotoxicological tools are used to identify indicator species and evaluate the effects of potential hazards that may emanate from managed aquifer recharge projects. A review (Kumar 2009) of the range of ecotoxicity assessment techniques that have been developed and applied as environmental indicators of impacts of recycled waters on aquatic organisms found that these methods include:

- acute toxicity tests

- lifecycle tests
- sublethal tests
- microbial tests
- genotoxicity and mutagenicity
- endocrine disruption
- bioaccumulation
- toxicity identification evaluation
- in situ toxicity studies.

These methods are applied to selected reference species (some of which may exhibit biomarkers) to assist in measuring levels of stress.

As with other ecosystem receptors, surrogate parameters are commonly used. The guidelines for fresh and marine waters (ANZECC-ARMCANZ 2000a) specify three sets of water-quality criteria to satisfy aquatic ecosystem protection, covering systems with high conservation value, those that have been slightly to moderately disturbed, and those that have been highly disturbed. The ecotoxicology tools listed above and described by Kumar (2009) are a useful supplement where information is lacking on the effects of particular water quality hazards introduced, or aquatic species potentially affected, by the managed aquifer recharge project.

Marine ecosystems may be influenced by changes in the quantity and quality of groundwater discharge through the sea bed as a result of coastal managed aquifer recharge projects. It can be difficult to predict the impacts of coastal managed aquifer projects on marine environments for several reasons. Firstly, the quantity, locations and mechanisms of groundwater discharge are normally difficult to define, especially in karstic aquifers and offshore wells are very expensive. Secondly, the dispersion of any enriched groundwater nutrients such as nitrogen may result in direct impacts on reefs and their resident organisms and on sea grass beds, as well indirectly by stimulating algae in the water column. Box 5.8 briefly describes two projects where marine discharge of nitrogen was a consideration.

#### **Box 5.8 Discharge to marine ecosystems**

Two recent studies have evaluated potential impacts of managed aquifer recharge with treated sewage on groundwater discharge of nutrients to coastal reefs, fish nurseries and a tidal estuary (Blair and Turner 2004, Environmental Protection Authority of Western Australia 2005, Ingleton 2009, Dillon et al 2009b). On Mosmon Peninsula in Perth, the aquifer is karstic and the proposed recharge zone was 1 km from both the Swan River and the Indian Ocean. There was minimal control over groundwater flow or the capture by irrigation wells, and modelling suggested discharge to the river and the ocean of nutrient-rich water after about 7 years. Costs of further treatment were prohibitive so the project did not proceed. At another site, 3 km from the coast near Aldinga, South Australia, modelling indicated recharged water would take 30 years to reach the coast, and controls on groundwater flow and capture could be implemented. This provided sufficient evidence at the precommissioning risk assessment stage to indicate that trials could be managed adequately with monitoring implemented to allow more rigorous assessment.

#### **5.11.5 Risk assessment and management for ecosystem protection**

Managed aquifer recharge may, in some cases, have the sole purpose of sustaining flow or levels in springs (eg Berry and Armstrong 1997) or other groundwater-dependent water bodies. Section 6.5 provides further examples. Conservation of biodiversity, including

migratory birds, is a major consideration for wetlands of high conservation value, including those listed under the Ramsar Convention (an international treaty for the conservation and sustainable use of wetlands). Hence, biodiversity conservation would need to be evaluated when assessing nearby managed aquifer recharge projects.

Table 5.17 provides general criteria for assessing the risks and appropriate level of management for groundwater-dependent ecosystem protection. The text below describes management methods to mitigate undesirable effects of managed aquifer recharge on ecosystems.

#### ***Pesticides and antibiotics***

It is necessary to prevent long-lasting pesticides and antibiotic substances being recharged at concentrations that would impair the function of ecosystems within, or dependent on, the aquifer (see Section 5.5).

#### ***Volumes and rates of recharge and recovery***

To protect targeted communities at indicative monitoring points (eg wells or springs), volumes and rates of recharge and recovery should be constrained, so that effects of managed aquifer recharge remain within the limits determined. Multiple low-rate extraction wells or horizontal collectors on extraction wells can be used to reduce drawdown of groundwater levels. In situations where thresholds are unknown, selected indicator species and related influencing variables (eg meteorological) should be monitored over sufficient time to determine the relative influence of managed aquifer recharge on the ecosystem.

#### ***Siting of managed aquifer recharge projects***

Recharge and recovery should be avoided in unconfined aquifers in areas with shallow watertables. In such locations, ecosystems are likely to be significantly affected by managed aquifer recharge operations. Increasing the distance between areas of recharge or recovery and groundwater-dependent ecosystems will reduce the amplitude and rate of water level variations affecting the ecosystems. No connected surface water body should lie within the aquifer attenuation zone.

**Table 5.17 Criteria, controls and monitoring for groundwater-dependent ecosystem protection in relation to the stages of risk assessment**

	<b>Entry-level or simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Acceptance criteria</b>	<ul style="list-style-type: none"> <li>• Avoids recharge in close proximity to sensitive groundwater-dependent ecosystems</li> <li>• Avoids unconfined aquifer with shallow watertable for recharge and recovery of water</li> </ul>	<ul style="list-style-type: none"> <li>• Modelling shows that hydraulic head variations in groundwater-dependent ecosystems are within historical range or closer to historical range than they would be without the project, or that heads do not fall below minimum levels for ecosystem maintenance, and rates of decline are within those determined acceptable for the vegetation present</li> <li>• Modelling shows that mass and concentrations of nutrients and contaminants discharged to ecosystems are within the acceptable range for indicator species present, and receiving waters remain within the water-quality criteria for the relevant ecosystem (ANZECC-ARMCANZ 2000a)</li> <li>• Aquifer unlikely to contain stygofauna (ie aquifer is anaerobic or has no macropores)</li> </ul>	<ul style="list-style-type: none"> <li>• Confirmation of achievement of precommissioning residual risk assessment criteria, based on additional field and laboratory measurements and modelling</li> <li>• Modelling and data from trials, including groundwater geochemical monitoring, or ecotoxicological studies reveal no adverse effects on aquifer ecosystems, connected water bodies or groundwater-dependent ecosystems</li> </ul>

**Table 5.17 (continued)**

	<b>Entry-level or simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Preventive measures</b>	<ul style="list-style-type: none"> <li>• Site selection as above</li> </ul>	<ul style="list-style-type: none"> <li>• Reduce concentrations of long-lasting pesticides and antibiotic substances to benign levels for the species present in the ecosystem, and in any biological treatment systems in use</li> <li>• Reduce nutrients, metals and turbidity to acceptable levels, where they impact on groundwater-dependent ecosystems or surface water systems receiving purge water</li> <li>• Operate the system to avoid inducing increased hazard concentrations via increased discharge of groundwater into the ecosystem</li> <li>• Move site to increase separation from groundwater-dependent ecosystems; ensure attenuation zone excludes groundwater-dependent ecosystems</li> <li>• Adjust recharge and recovery rates (and number or type of wells) so that hydraulic head variations in groundwater-dependent ecosystems meet acceptance criteria above</li> </ul>	<ul style="list-style-type: none"> <li>• As for precommissioning residual risk assessment</li> <li>• Further reduce concentrations of water-quality hazards</li> <li>• For ecosystems with high ecological value, establish criteria (eg groundwater level range, maximum rate of change of groundwater level, concentration range of pertinent constituents) for one or more relevant observation wells, and evaluate monitoring results obtained during the trial</li> </ul>
<b>Validation monitoring</b>	na	na	<ul style="list-style-type: none"> <li>• Perform ecotoxicological studies or validation monitoring of abundance and biodiversity of species at locations and frequencies relevant to the ecosystems, and of the potential impacts of managed aquifer recharge (including those on stygofauna, if relevant)</li> </ul>

**Table 5.17** (continued)

	<b>Entry-level or simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
<b>Verification monitoring</b>	na	na	<ul style="list-style-type: none"> <li>• Perform baseline monitoring of groundwater-dependent ecosystem composition</li> <li>• Perform verification monitoring of groundwater levels in selected observation wells in or adjacent to groundwater-dependent ecosystem</li> <li>• Perform verification monitoring of pesticide, antibiotic and nutrient concentrations at point of discharge to groundwater-dependent ecosystem</li> </ul>
<b>Operational monitoring</b>	<ul style="list-style-type: none"> <li>• Estimate or measure annual injection and recovery volumes</li> </ul>	na	<ul style="list-style-type: none"> <li>• See validation and verification monitoring above</li> </ul>

na = not applicable.

## 5.12 Energy and greenhouse gas considerations

Decisions to establish a managed aquifer recharge project need to take into account energy requirements in relation to alternative supply systems. This involves accounting for all energy use in the managed aquifer recharge system and in the alternative supply.

Wherever practical, energy efficiency should be a goal of managed aquifer recharge operators. This involves the use of:

- construction techniques, materials and equipment with low embedded energy
- gravity flows rather than pumps
- energy-efficient pumps
- passive treatment systems rather than energy-consuming treatments, wherever interchangeable
- fail-safe data acquisition and control systems to minimise unnecessary use of vehicles
- renewable energy sources such as solar-powered transducers and data loggers
- optimal recharge pressures to maximise energy efficiency

- optimal unclogging processes for wells and basins, to minimise the volume of materials to manage.

Lifecycle assessment tools (eg WSAA 2007) are available to assess the long-term consequences of alternatives, especially when comparing tradeoffs between capital and operational costs, and energy consumption. For example, most modern seawater desalination plants using reverse osmosis require 3–4 kWh/m<sup>3</sup> water produced, in comparison with passive treatment of stormwater ASTR in confined (or even artesian) aquifers that require less than 1 kWh/m<sup>3</sup> water produced (Dillon et al 2009a).

General criteria for assessing the risks and appropriate level of management to address energy and greenhouse gas considerations are provided in Table 5.18.

**Table 5.18 Criteria, controls and monitoring to address energy and greenhouse gas considerations in relation to the stages of risk assessment**

	<b>Entry-level or simplified assessment</b>	<b>Maximal and precommissioning residual risk assessment</b>	<b>Residual risk assessment (operational)</b>
Acceptance criteria	<ul style="list-style-type: none"> <li>• Avoids energy wastage</li> <li>• Uses renewable energy where practical</li> </ul>	<ul style="list-style-type: none"> <li>• Avoids energy wastage</li> <li>• Uses renewable energy where practical</li> </ul>	<ul style="list-style-type: none"> <li>• As for precommissioning residual risk assessment</li> <li>• Energy efficiency analysis has been performed and energy use per kL water recovered (in lifecycle assessment) is low compared to options that also meet all other criteria</li> </ul>
Preventive measures	<ul style="list-style-type: none"> <li>• Select appropriate pumps, pipes and treatment methods</li> </ul>	<ul style="list-style-type: none"> <li>• Select appropriate pumps, pipes and treatment methods</li> <li>• Use SCADA systems to control operations to minimise unnecessary use of vehicles</li> <li>• Optimise selection of train-of-treatment processes for water quality, energy requirements and costs</li> <li>• Optimise recharge pressures and unclogging processes (Section 6.1) to reduce energy costs</li> </ul>	<ul style="list-style-type: none"> <li>• As for precommissioning residual risk assessment</li> </ul>
Monitoring	<ul style="list-style-type: none"> <li>• Estimate or measure energy use</li> </ul>	na	<ul style="list-style-type: none"> <li>• Perform verification monitoring of energy use, including the proportion of renewable energy used</li> <li>• Evaluate energy use included in trials when testing operating strategies; this may require additional energy meters or monitoring surrogates during validation</li> </ul>

na = not applicable; SCADA = supervisory control and data acquisition.

## 6 Operational issues and their management

The location, design, operation and monitoring of a managed aquifer recharge project must take account of potential operational issues, including:

- clogging of injection wells or basins
- poor recoverability of recharge water (allowing for the reliability and continuity of source-water supply)
- interactions with other groundwater users
- managing purge water, basin scrapings and water treatment byproducts.

This chapter discusses each of these issues, providing information on their causes, consequences, assessment methods and preventive measures. These issues are of primary importance to project proponents and operators, but are of less concern to regulators responsible for human health and environmental protection. The greatest emphasis is given to clogging and recovery efficiency, because these are vital to the technical and economic viability of managed aquifer recharge projects, and hence to the perceived affordability of investigations and trials.

The chapter also addresses the operation of managed aquifer recharge projects for environmental protection, notably as barriers against saline water intrusion or to protect groundwater-dependent ecosystems (see Further information on design, operation and maintenance of surface infiltration and injection well systems, based on experience at managed aquifer recharge projects, predominantly from the United States is given by NRC (1994), EWRI/ASCE (2001) and summarised by Bouwer et al (2008). The European Commission (2001) also summarised knowledge generated at a number of European projects.

Table 6.1). In these cases, managed aquifer recharge will generally be part of a broader strategy that includes management of groundwater overdraft.

Further information on design, operation and maintenance of surface infiltration and injection well systems, based on experience at managed aquifer recharge projects, predominantly from the United States is given by NRC (1994), EWRI/ASCE (2001) and summarised by Bouwer et al (2008). The European Commission (2001) also summarised knowledge generated at a number of European projects.

**Table 6.1 Operational issues specific to managed aquifer recharge and examples of their impact**

<b>Issue</b>	<b>Description</b>	<b>Examples of impact</b>	<b>Relevant section of document</b>
Clogging	Decrease in soil or aquifer permeability at the injection well or infiltration facility, which reduces the recharge rate.	Reduction in the volume of water that can be recharged. If irreversible or expensive to remediate, this is likely to lead to site closure.	6.1
Recovery efficiency	Unacceptable proportion of recharge volume recovered of a quality suitable for its intended use; usually a result of excessive mixing between recharge water and ambient brackish groundwater.	Reduced quantity of water available of a quality suitable for its intended use.	6.2
Interactions with other groundwater users	Impacts on groundwater levels, groundwater quality or energy costs.	Hydraulic interference in groundwater levels causing a reduction in the volume of water stored or recoverable.	6.3
Protection against saline water intrusion	The use of managed aquifer recharge as a hydraulic barrier against the migration of saline water into fresh groundwater caused by overpumping of coastal or other aquifers.	Prevents an increase in salinity of groundwater that would otherwise threaten beneficial uses (eg drinking water, irrigation).	6.4
Operations designed to protect groundwater-dependent ecosystems	The use of managed aquifer recharge for environmental purposes to protect or improve groundwater-dependent ecosystems, by maintaining groundwater levels within their historical range.	Maintains baseflow in streams, stops wetlands drying, and maintains aquatic and riparian biodiversity that would otherwise be lost due to groundwater overexploitation.	6.5
Management of purge water, basin scrapings and water treatment byproducts	Production of hazards as a byproduct of the managed aquifer recharge treatment and maintenance processes.	Production of purge water, basin scrapings or water treatment byproducts that may generate specific hazards such as turbidity and particulates (see Chapter 5).	6.6

## 6.1 Clogging

Clogging is a reduction in the permeability of a porous medium. It is one of the most serious operational issues for managed aquifer recharge and affects most operations to some degree. Clogging is a more significant issue for well-injection systems, because the rate at which water enters the aquifer is orders of magnitude higher than occurs beneath recharge basins. In turn, the rate of recharge beneath infiltration basins is orders of magnitude higher than for natural recharge conditions.

Clogging develops during periods of recharge, as a result of interactions between the source water, its constituents and the porous media. It occurs mainly around the entry zone for

recharge water, affecting the surface of infiltration systems or concentrating around the well screen, gravel pack or adjacent aquifer in well-injection systems.

Clogging leads to a reduction in flow rates, thereby restricting the volume of water stored. This poses a constraint to the scale and economic viability of managed aquifer recharge operations, and in severe cases, can lead to the operational failure of managed aquifer recharge systems. Wells in inappropriately designed and operated managed aquifer recharge systems may clog within a matter of days or weeks; basins may clog within weeks or months.

### **6.1.1 Types and causes of clogging**

Clogging occurs as a result of one or more physical, chemical or biological processes, such as:

- filtration of suspended solids
- microbial growth
- geochemical reactions
- air entrainment and gaseous binding.

Each of these causes is discussed below.

#### ***Filtration of suspended solids***

Clogging of soil or aquifer pore spaces, by filtration of suspended solids present in the recharge water, results in the formation of a low-permeability clogging layer. Clogging is generally most severe where suspended solid concentrations are highest, but there are other determining factors. Significant factors are the flow rate, and hence the cumulative mass of sediment deposited within the porous media; and the hydrologic properties of the porous media that control the extent and penetration of deposition of particles within the system.

#### ***Microbial growth***

Microbial clogging of aquifers occurs through the multiplication of bacterial cells, and the production of extracellular polysaccharides (biofilms). Bacteria produce biofilms when nutrients (eg organic carbon, nitrogen, phosphorus) are present in the recharge water stimulate microbial activity.

Clogging due to growth of algae on basin floors can be an issue in surface infiltration systems. This may be compounded by precipitation of carbonate minerals, such as calcite, induced by photosynthetic consumption of carbon dioxide. Daily or seasonal variations in water temperature can affect the infiltration rate, through effects on algal growth and influence on the viscosity of the recharge water. All other factors being equal, infiltration and injection rates are typically higher in summer than winter.

#### ***Geochemical reactions***

Recharge of waters not in equilibrium with the groundwater or aquifer materials can cause chemical reactions. These lead to the production of insoluble precipitates that alter the permeability of the porous media. Such reactions may include:

- dissolution
- precipitation

- ion exchange
- ion adsorption
- oxidation–reduction.

If the aquifer contains iron-rich or manganese-rich minerals, then the presence of oxygen or nitrate in the recharge water can stimulate bacteria (eg *Gallionella*) to precipitate iron or manganese oxides and hydroxides that lead to clogging.

Exchange of cations between the recharge water and the clays within the aquifer can lead to either swelling or dispersion. This tends to be most prevalent where reactive clays (eg montmorillonite) are present, and where there is a large decrease in the salinity of the recharge waters compared to the ambient groundwater. Other geochemical reactions, such as dissolution, may have an unclogging effect by increasing permeability (eg in places where calcite cement dissolves). In pronounced cases, this may lead to well instability (see Section 5.9).

Precipitation of iron oxides and hydroxides and calcium carbonate are the predominant forms of geochemical clogging, but are not widely identified as the major clogging mechanism. This is because they coincide with other forms of clogging, or may take long periods of time to develop. Many geochemical reactions, especially redox reactions, are catalysed by bacteria; thus it is difficult to separate chemical and biological processes in many situations.

#### ***Air entrainment and gaseous binding***

Clogging by air entrainment can occur if water is allowed to cascade into the well, and bubbles are produced that block pore spaces and restrict flow. Dissolved gases may also be released from solution due to temperature changes, where cool source waters meet warm groundwater, or as a result of biogeochemical reactions, such as denitrification, which produces nitrogenous gases.

Further information on clogging in managed aquifer recharge systems can be found in Olsthoorn (1982), Pyne (1995), Pérez-Paricio and Carrera (1999), Bouwer (2002) and Pavelic et al (2007a,b).

### **6.1.2 Management of clogging**

The generic measures of clogging are declining recharge rates and increased pressures. A summary of the methods used to diagnose and address the four main forms of clogging described above are presented in Table 6.2. This table indicates the means by which clogging may be minimised or prevented, which are:

- adequate source-water pretreatment
- appropriate site selection
- construction of suitably designed installations
- implementation of appropriate operational controls, renovation practices and monitoring.

A variety of measures can prevent or minimise clogging, where this offers a more effective strategy than managing a higher degree of clogging. For example, pretreatment of source water to remove suspended solids, organic matter and nutrients reduces clogging, and hence the degree of renovation required. Some pretreatment measures may be effective in dealing

with clogging, but have less desirable side effects. For example, disinfecting the source water will reduce microbial activity and minimise bioclogging, but can lead to the production of disinfection byproducts in the aquifer (see Section 5.5). Preventing air entrainment during well injection is relatively straightforward to achieve, by placing the intake pipe below the static water levels and fitting a flow control valve to ensure a positive pressure is maintained.

The aim of renovation is to return the performance of the injection well or recharge basin to its previous state, by restoring the hydraulic properties of the clogged zone (also known as unclogging). Unclogging is relatively straightforward for recharge basins, since it simply relies upon regular drying out and occasional scraping away of clogging agents.

In soil aquifer treatment systems, for example, periods of infiltration lasting from several days to several weeks are followed by periods where the basins are allowed to drain and dry out over similar timescales, although these may need to be seasonally adjusted.

A variety of mechanical methods have been used to redevelop injection wells. These include backwash pumping (typically at a rate higher than recharge), surging (variable speed pumping) or jetting with compressed air (also known as air lifting). Redevelopment is undertaken periodically, often daily, depending on how quickly recharge rates decline. Typically, only a few per cent of the recharge volume is foregone.

Chemical methods used include the addition of oxidising agents (eg chlorine), flocculants (eg calcium chloride), or, in cases of severe clogging, acids. Renovation measures are effective as a routine operational method for unclogging wells and basins, demonstrated by the fact that some sites have operated continually for decades. An example of the identification and management of chemical clogging is given in Box 6.1.

In fine-grained soils or aquifers, the high quality of water required to manage clogging may demand a higher degree of treatment of source water than would be required to meet water-quality criteria for protection of human health and the environment. Therefore, subject to validation and verification in these situations, monitoring requirements for effective operation are likely to meet water-quality requirements of regulators. In coarse-grained soils or aquifers, the converse is likely to be true.

**Table 6.2 Clogging types, causes, diagnosis and methods for management**

<b>Clogging mechanism</b>	<b>Cause</b>	<b>Minimisation and prevention</b>	<b>Renovation technique</b>	<b>Measurements and techniques</b>
Air entrainment, gas binding	<ul style="list-style-type: none"> <li>Free falling water</li> <li>Presence of gas in source water</li> <li>Biogeochemical reactions</li> </ul>	<ul style="list-style-type: none"> <li>Avoid cascading</li> <li>Gas trap</li> <li>Degas source water</li> <li>Prevent reactions (eg N<sub>2</sub> production)</li> </ul>	<ul style="list-style-type: none"> <li>Pumping</li> <li>Waiting for gas to redissolve</li> <li>Improving well design</li> </ul>	<ul style="list-style-type: none"> <li>Analyse water temperature and specific gases</li> </ul>
Filtration of suspended solids	<ul style="list-style-type: none"> <li>Particulates in source water or deposited in pipes</li> <li>Treatment byproducts (eg alum)</li> <li>Algal growth in basins</li> </ul>	<ul style="list-style-type: none"> <li>Improve pretreatment of source water, especially removal of suspended solids</li> <li>Prevent light (algal growth)</li> <li>Backwash wells or dry out basins more frequently</li> </ul>	<ul style="list-style-type: none"> <li>Pumping</li> <li>Surging</li> <li>Jetting</li> <li>Basin drying or scraping</li> </ul>	<ul style="list-style-type: none"> <li>TSS, turbidity, MFI, particle size distribution of source water and soil/aquifer</li> <li>Bypass filter testing</li> <li>Changes in specific capacity (wells)</li> </ul>
Chemical precipitation, ion exchange	<ul style="list-style-type: none"> <li>Redox reactions</li> <li>Incompatibility between source water, groundwater and aquifer materials</li> <li>Presence of reactive clays (swelling/dispersion)</li> </ul>	<ul style="list-style-type: none"> <li>Improve pretreatment</li> <li>Adjust source-water pH or cation concentration</li> <li>Avoid or remove dissolved oxygen in source water</li> <li>Backwash more frequently</li> </ul>	<ul style="list-style-type: none"> <li>Pumping</li> <li>Wire brushing</li> <li>Acid treatment</li> <li>Basin scraping</li> </ul>	<ul style="list-style-type: none"> <li>Water-quality analyses (especially redox conditions and mineral saturation indices)</li> <li>SEM analysis of backwash water or soil and aquifer samples (scrapes of well face for deep systems)</li> <li>Photography (basins) and down-hole TV camera survey</li> </ul>

**Table 6.2 (continued)**

<b>Clogging mechanism</b>	<b>Cause</b>	<b>Minimisation and prevention</b>	<b>Renovation technique</b>	<b>Measurements and techniques</b>
Microbial growth	<ul style="list-style-type: none"> <li>Abundant substrate in source water (especially N, P and AOC)</li> </ul>	<ul style="list-style-type: none"> <li>Improve source-water pretreatment, especially nutrient removal or chlorine dosing</li> <li>Backwash more frequently</li> <li>Adapt duration of wetting and drying cycles in basins</li> </ul>	<ul style="list-style-type: none"> <li>Pumping</li> <li>Chlorine shock dosing</li> <li>Acid treatment</li> <li>Heat</li> <li>Wire brushing</li> <li>Multienzyme solutions</li> <li>Basin drying or scraping</li> </ul>	<ul style="list-style-type: none"> <li>Water-quality analyses</li> <li>Photography (basins) and down-hole TV camera survey</li> <li>Chemical and microbial analyses on soil and aquifer samples</li> </ul>

AOC = assimilable organic carbon; MFI = membrane filtration index; N = nitrogen; P = phosphorous; SEM = scanning electron microscope; TSS = total suspended solids; TV = television.  
 Source: adapted from Pyne (1995), Pérez-Paricio and Carrera (1999).

### **Box 6.1 Identification and management of chemical clogging**

Fresh, oxygenated, low-pH groundwater from a surficial aquifer on South Goulburn Island, Northern Territory, was injected into an underlying brackish sandstone aquifer known to contain pyrite. This resulted in clogging of the injection well by iron oxyhydroxides. This was largely anticipated during the feasibility phase of the project, on the basis of geochemical modelling drawn from source and receiving water-quality data and core sample mineralogical analyses. Clogging was subsequently controlled by installation of a dedicated pump, to enable weekly backwashing of the aquifer storage and recovery well (Pavelic et al 2002a).

### **6.1.3 Tools for predicting clogging**

Numerous techniques have been developed to predict clogging. These range in complexity from the measurement of simple water-quality indices through to sophisticated process-based modelling. A summary of the main techniques is given below.

#### *Measures of recharge water-quality parameters*

Measures of recharge water-quality parameters that are useful indicators of the clogging potential of managed aquifer recharge systems include:

- physical clogging
  - turbidity
  - total suspended solids
  - membrane filtration index
- microbial clogging
  - total organic carbon
  - dissolved organic carbon
  - assimilable organic carbon.

Application of a single parameter can be problematic when multiple forms of clogging occur at the same time. Characterisation of clogging potential of the prospective source water in a target aquifer should include assessment of the physical, chemical and microbiological composition of the source water. The assessment needs to take temporal variability into account. The physiochemical and mineralogical properties of the soil and aquifer and the quality of the ambient groundwater also need to be defined.

#### ***Laboratory column studies***

Laboratory column studies using soil and aquifer core materials and source waters can identify the extent of clogging and define source-water pretreatment needs (eg Rinck-Pfeiffer et al 2000, Wood et al 2005). However, due to spatial variability in subsurface properties, these small-scale tests only offer a guide, and can not always be relied upon to accurately predict field-scale performance.

#### ***Graphical techniques***

Simple graphical techniques to predict clogging have been developed. Hutchinson and Randall (1995) developed type curves for broad-based prediction of the physical clogging rate of injection wells, using aquifer transmissivity and membrane filtration index data. Taylor and Jaffé (1990) determined the relative reduction in permeability from biomass levels within the porous medium, using experimental data from a laboratory column study.

#### ***Numerical or mass balance modelling***

Sophisticated numerical modelling codes that couple flow and transport to biogeochemical reactions for site-specific prediction of porosity and permeability changes have been developed and applied (Pérez-Paricio and Carrera 1998). However, these codes are highly complex, data-intensive and only suitable for research purposes at present. Alternatively, simpler mass balance modelling can be performed, to gauge the likely impact of physical, chemical or microbial processes on permeability (Pavelic et al 2007b).

### **6.1.4 Recharge water-quality requirements for sustained managed aquifer recharge operations**

Decades of operational experience have shown that clogging prevention is a better option than renovation, particularly for well-injection systems. While various renovation measures that can yield excellent results exist (Table 6.2), ensuring that recharge water meets the appropriate water-quality target through adequate pretreatment is a key factor in ensuring successful and sustainable long-term managed aquifer recharge operations. Although all forms of clogging can be avoided through pretreatment, in practice there is a trade-off between the costs associated with pretreatment, and the degree of clogging that is acceptable in terms of the type and frequency of renovation that would be required.

Definitive guideline values on the quality of water needed for sustainable Australian managed aquifer recharge operations are a highly desirable target. This target is yet to be achieved, and is an area of active research.

Managed aquifer recharge practitioners in the Netherlands have determined, through trial and error, that the suitability of source water for injection into sandy aquifers is defined by a membrane filtration index of <3–5 seconds/L<sup>2</sup> and assimilable organic carbon of <10 µg/L, to manage physical and biological clogging respectively (Olsthoorn 1982, Hijnen and van der Kooij 1992). Such single guideline values are inappropriate for Australia, which has a greater

diversity of source-water types and hydrogeological conditions than the Netherlands. Pérez-Paricio and Carrera (1999) developed guidelines on source-water quality in relation to likely degree of clogging of injection wells and surface basins. These guidelines offer a useful starting point, but do not consider the soil or aquifer conditions, which are known to be important (Appendix 8).

Clogging rates at 14 ASR (aquifer storage and recovery) sites were classified by quality of the source water and type of aquifer. The results (derived from Appendix 9, and summarised in Table 6.3) show that both factors may affect clogging rates.

For ASR projects in alluvial aquifers, source waters with total suspended solids and total organic carbon of less than 10 mg/L have lower rates of clogging than more turbid or nutrient-rich waters. For poor-quality water, limestone aquifers clogged slowest, followed by alluvial aquifers; fractured rock aquifers clogged fastest. These results are not surprising, because unclogging in limestone aquifers is facilitated by matrix dissolution, and alluvial (sand and gravel) aquifers offer more flow paths than fractured rock aquifers.

At a site-specific level, the treated sewage injection into a limestone aquifer at Bolivar, South Australia (Pavelic et al 2007a) more clearly demonstrates the link between well clogging and turbidity, total nitrogen and pH levels in the source water. To meet operational requirements, site-specific evaluation to assess clogging potential and identify water-quality targets suited to the aquifer is needed at all sites.

**Table 6.3 Rates of clogging at 14 ASR sites according to aquifer type and quality of source water**

	Source-water quality		
	Low (TSS >10 mg/L, TOC >10 mg/L)	Moderate (TSS 1–10 mg/L, TOC 1–10 mg/L)	High (TSS <1 mg/L, TOC <1 mg/L)
Aquifer type	Rate of clogging		
Limestone	Low–moderate	Low–moderate	No data available
Sand and gravel	Moderate–severe	Low–moderate	Low–moderate
Fractured rock	Severe	No data available	No data available

TSS = total suspended solids; TOC = total organic carbon.

## 6.2 Salinity of recovered water

The development of managed aquifer recharge operations depends on the capacity to store useful quantities of water (see Section 6.1) and to recover useful quantities of good-quality water.

When water infiltrates (or is injected into) an aquifer, it mixes with the ambient groundwater, as a result of localised variations in pore–water velocities (dispersion) and solute concentration gradients (diffusion). Mixing may also occur in saline aquifers, due to convection arising from density contrasts. The degree of mixing between the two waters therefore depends on the local hydraulic characteristics of the aquifer, and on the quality of the ambient groundwater.

Restricting mixing is important for the storage of fresh water in brackish or saline aquifers. Where the ambient groundwater is too saline (or contains other constituents at excessive concentrations) for the intended use of recovered water, mixing must be restricted to maximise the volume of recovered water meeting water-quality requirements. Mixing is of little significance when the source and ambient waters are both of good quality, unless geochemical processes within the subsurface produce reaction byproducts (eg iron, arsenic) exceeding guidelines.

In cases where the salinity of the recharge water may be marginal, a variety of management control measures can improve water quality (see Section 5.3.3).

The primary questions answered within this section are:

- How much of the recharge water can the managed aquifer recharge operator recover?
- What is the extent of mixing between the recharge water and the more saline ambient groundwater?
- What proportion of recovered water will be fit for use?
- What is the distribution of the recharge water within the aquifer, and how far will it migrate?
- Can the recharge water be contained, or will it be drawn by other groundwater users?

### **6.2.1 Recovery efficiency**

Recovery efficiency can be defined as the proportion of recovered water that is of suitable quality for its intended use, expressed as a fraction of the injected or infiltrated volume (Pyne 1995). Thus, a recovery efficiency of one (1) indicates an equivalent volume of recovery to recharge, and a value of zero indicates that none of the recharge water could be pumped at a quality suitable for use.

In practice, recovery is limited by the maximum permissible concentration of the dissolved solids in the recovered water, according to the requirements for its intended use. For example, potable use would imply an upper limit of 500 mg/L total dissolved salts, to meet Australian drinking water guidelines. Irrigation supplies would be highly dependent on the salt tolerance of any particular land use application, as given, for example, within the Phase 1 guidelines (NRMMC–EPHC–AHMC 2006). In cases where recovered water is blended with fresher water, a higher permissible concentration may be tolerated, resulting in an increase in recovery efficiency.

There are numerous physical, chemical and microbial species that may be used to ‘trace’ the recharge water within the subsurface. Many are naturally present in the source water; others can be deliberately added. Some of the more commonly used tracers of recharge water include:

- total dissolved salts
- electrical conductivity
- chloride
- bromide
- fluoride
- temperature

- deuterium
- oxygen-18.

Reactive chemicals, and those that contribute to buffering of the system, do not behave conservatively and should not be used.

### **6.2.2 Factors affecting mixing and recovery efficiency**

Numerous factors affect the movement and mixing of recharge water in aquifers, ultimately controlling recovery efficiencies. These variables can be divided into two categories: hydrogeological and management.

Hydrogeological variables are intrinsic to a site, and include:

- aquifer thickness, transmissivity, porosity and heterogeneity (dispersivity and diffusivity)
- regional and local pre-existing hydraulic gradients
- ambient groundwater quality and density
  - solute concentration of the recharge water and ambient groundwater
  - density difference between the recharge water and ambient groundwater

Management variables include:

- well design
  - recovery well
  - injection well, where applicable
- total stored volume
- open interval of the injection and recovery well
- infiltration and injection rates and volumes
- recovery rate and volume
- location of recovery well/s
- residence time within the aquifer
- consecutive years or cycles of operation.

Hydrogeological variables cannot be controlled at any given site, but should be considered during site selection. Management variables, however, can be controlled to varying degrees. For example, residence time may be adjusted according the groundwater velocity by adjusting the storage time (well-injection scenario) or the separation distance between recharge basin and pumping well (basin scenario). The role of the unsaturated zone in basin systems may need to be considered, for example, with respect to the potential for mobilisation of salts stored within the soil profile.

### 6.2.3 Recovery efficiency data for Australian aquifer storage and recovery operations

Recovery efficiency data has emerged from several Australian experimental and operational ASR sites over the past decade. Data for six Australian sites (recalculated from the concentration and volumetric data for a common threshold concentration of 1500 mg/L) are presented in Appendix 9. The data show that:

- recovery efficiency varies significantly (from  $<0.02$  to  $>1.0$ ) between sites, due to factors discussed in Sections 6.2.1 and 6.2.2
- moderate to high recovery efficiency can be achieved in limestone aquifers, in which major secondary porosity features are absent (Section 5.9)
- improvements in recovery efficiency can occur in successive cycles of ASR operation, due to salinity buffering by unrecovered recharge water (Figure 6.1, Box 6.2)
- low recovery efficiency is characteristic of highly saline aquifers, due to a combination of
  - the low degree of mixing that can be tolerated
  - density effects that can cause buoyancy stratification of the recharge water.

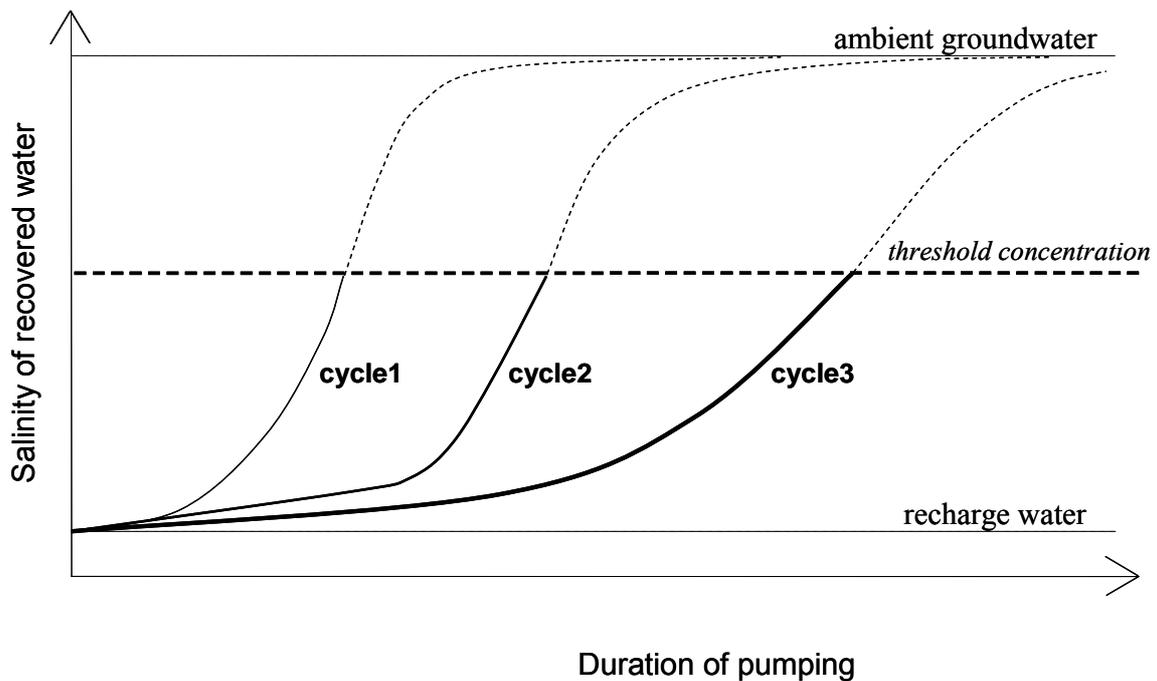
Similar data for other forms of managed aquifer recharge (eg for surface recharge methods in coastal sand aquifers) are not yet available.

#### **Box 6.2 Reduction in salinity of recovered water with successive cycles**

A fractured rock ASR scheme storing stormwater for irrigation of school grounds has operated at Scotch College in Adelaide, South Australia, since the late 1980s.

Over the first six seasons, the average salinity (total dissolved salts) of the recovered water was reduced from an ambient concentration of 2100 mg/L to 1400 mg/L. The unrecovered proportion of the injected water serves to improve the quality of water in subsequent seasons.

Figure 6.1 shows three cycles in which pumping stops when the maximum permissible concentration is reached. The unrecovered recharge water forms a salinity buffer, and recovery efficiency improves with subsequent cycles. The dashed curves project the salinity response if pumping was allowed to proceed beyond the threshold concentration.



**Figure 6.1 Change in salinity of pumped water during recovery stage**

#### **6.2.4 Management of mixing and recovery efficiency**

Guiding principles in site selection and operational management to maximise recovery efficiency are drawn from national and international experience, and include the following data (see Appendix 9):

- avoid highly saline groundwaters
- reduce salinity of source water
- select aquifers with low ambient groundwater velocities
- avoid highly heterogeneous aquifers
- avoid highly permeable aquifers, particularly when ambient groundwater is highly saline
- ensure target aquifer (and unsaturated zone where applicable)
  - is appropriately characterised
  - has appropriately defined storage intervals
  - has appropriately designed injection/recovery well/s
- ensure adequate volumes of water are stored (performance depends on size)
- position recovery wells to maximise capture of recharge water
- minimise storage time to constrain regional drift of recharge water.

Some of these principles will conflict with other objectives of managed aquifer recharge, requiring some trade-off. For example, to avoid poor recoverability of recharge water, do not use aquifers or subaquifers that are highly permeable; this contrasts with the principles of minimising well clogging outlined in Section 6.1.

Design scenarios for managed aquifer recharge systems that offer some degree of flexibility to meet water-quality objectives. For example, recovery wells for recovering water after surface infiltration can be located so that they largely pump recharge water, minimising the spread of recharge water beyond the storage zone. This is useful when mixing with ambient groundwater is not desirable. Alternatively, wells can be located where they consistently pump a mixture of recharge water and ambient groundwater.

Recovery efficiency may also be improved by blending recovered water with alternative lower salinity sources, or providing post-treatment by reverse osmosis.

### **6.2.5 Evaluation of recovery efficiency**

Recovery efficiency is controlled by many interacting variables that have large uncertainties. It is therefore difficult to predict recovery efficiency in advance of managed aquifer recharge development. Two main methods are available to evaluate recovery efficiency — pilot field trials, and groundwater modelling (using analytical or numerical techniques).

Pilot field trials are essential for establishing operating procedures. However, when they are conducted at a small scale, they often can not reliably predict operational-scale recovery efficiency. This is due to the scale dependence of hydrogeological variables such as aquifer dispersivity.

Groundwater modelling predictions can be indicative of recovery efficiency when aquifer hydraulic and transport properties are reasonably well known. In most cases, these predictions would not be expected to preclude the need for field trials.

Further information on recovery efficiency pertaining to well-injection methods is given by Pyne (1995) and Pavelic et al (2002b), and concerning density effects, by Ward et al (2009).

### **6.2.6 Reliability and continuity of supply**

Managed aquifer recharge is often used to create supplies for commercial use that are aligned with the existing demand requirements; it can also build strategic reserves for drought and emergency supplies. Managed aquifer recharge can therefore make a substantial contribution to the reliability of urban water supplies. However, the degree to which managed aquifer recharge can be used to stabilise supplies depends on many factors, including:

- variability and availability of source water used for recharge
- size of the net accumulated storage available for recovery
- rate at which it can be abstracted.

Source-water reliability can therefore be an issue for operational management, depending on the type of source water to be recharged. Reliability is considered to be high for treated sewage, moderate for urban stormwater, and quite variable for rural runoff.

Factors affecting reliability of supply include:

- natural variability in climate
- climate change
- capture efficiency
- catchment changes affecting runoff

- sewer catchment changes
- source-water availability
- planning and management to increase reliability of supply.

Each of these is discussed below.

### *Natural variability in climate*

The natural variability in Australia's climate implies that for rainfall-fed managed aquifer recharge systems, the volumes of water that are stored annually may vary by an order of magnitude or more.

### *Climate change*

In the future, lower and more variable rainfall, higher evaporation, and longer and more severe droughts are likely to reduce the availability of water and increase demand.

### *Capture efficiency*

Capture efficiency is the proportion of the flow that can be detained for long enough to be recharged. Due to climate change, and an increasing proportion of rain falling in large events, capture efficiency is likely to decline in future. This should be taken into account in the design of detention storages.

### *Catchment changes affecting runoff*

Urbanisation and urban consolidation increase the proportion of impervious area, and significantly increase runoff when it occurs. Rainwater tanks and competition for stormwater harvesting (see NRMCC–EPHC–NHMRC 2009) can reduce the supply of stormwater for recharge. Catchment water management plans are necessary to allocate the common-good resource to uses that maximise the benefits, taking account of social, environmental and economic drivers.

### *Sewer catchment changes*

Sewage flows translate to an increasing proportion of mainswater supply volume, as urban areas consolidate and outdoor residential usage of water declines. However, effluent availability declines with increased grey water reuse and sewer mining. Ageing sewerage infrastructure can lead to losses as well as gains through groundwater ingress, including from saline groundwater.

### *Source-water availability*

In addition to the subsurface factors contributing to salinity of recovered water and hence recovery efficiency (discussed in Section 6.2), variability in source-water availability is also a factor.

Climate change is expected to lead to longer average residence times in storage, and hence lower recovery efficiencies, particularly where the salinity contrast between recharge water and native groundwater is large.

Climate change may also result in increased groundwater use, and the clustering of new managed aquifer recharge operations. This may affect the recovery efficiency of all managed aquifer recharge operations in brackish groundwater, due to 'sloshing'; that is, each recharge

or recovery event will change the hydraulic head distribution in the aquifer, and the centroid of the recharged fluid at any site is then likely to be displaced from the recovery well. This effect will be more pronounced in confined aquifers, in which hydraulic effects of managed aquifer recharge operations can propagate over large distances within the aquifer.

### ***Planning and management to increase reliability of supply***

Several steps are available to improve the accuracy of predictions of the availability of source water of a suitable quality:

- take account of climate and catchment change to simulate time series availability of water for recharge
- where viable, recharge bigger volumes to create buffer storage mixing zones around the volume intended for recovery and reuse
- de-rate expected recovered volume for current managed aquifer recharge projects based on climate-dependent sources
- understand the overall management plans for the water source catchment and for the groundwater system so that managed aquifer recharge projects can be sited, designed and operated to take into account the changes that are likely to occur during the life of the project.

The increasing role of water sensitive urban design has the potential to improve the quality of runoff available for recharge, but has been shown to reduce flows. Hence, adoption of streetscape water sensitive urban design may become a factor in reliability of future stormwater supplies for managed aquifer recharge.

Issues associated with variability in source-water quality are addressed in Chapter 5.

## **6.3 Interactions with other groundwater users**

Operators of managed aquifer recharge projects need to take account of the project's effect on local groundwater users, and of users' effects on the operation of the project. Other managed aquifer recharge operators also create particular issues, which must be addressed in catchment and groundwater management plans to avoid future conflicts.

To avoid litigation and allow optimum combined management of interacting projects, and to maximise recovered water and minimise energy use, a single entity should be given responsibility for managing all proximal managed aquifer recharge projects within a given aquifer. This recognises that storage capacity is a valuable resource. Each state and territory has a regulatory framework for water allocation, and proponents of managed aquifer recharge projects should consult this framework.

Two of the issues that may arise when managed aquifer recharge operations are located close together are outlined below.

### **6.3.1 Competition for source water — treated sewage, stormwater or groundwater**

Catchment-water allocation plans require designation or licensing of volume for each recharge project. Where flow or resource is variable, and there are multiple users, this may be expressed as an entitlement; being a percentage of the recharge season or annual flow for each user, after accounting for environmental flow requirements. This should be addressed at entry-level assessment-viability (Section 4.3.1).

Rights of access to groundwater near a managed aquifer recharge project require definition by the regulator of the jurisdiction within a water allocation plan.

### **6.3.2 Competition for aquifer storage space**

Nearby recharge operators are likely to be recharging concurrently when there is excess surface water, and recovering concurrently when there is a deficit of surface water. Hence, there will be superimposing effects on piezometric heads in the aquifer. In the case of ASR, for example, each operation will decrease the head gradient of the other during injection, and increase the head against which recovered water needs to be pumped by the other. Each operation therefore increases the costs and energy requirements of the neighbouring operation (Section 5.11).

The energy cost per unit volume of water stored within a confined aquifer increase with cumulative injection volume. There is a limit to watertable levels within an unconfined aquifer; so there is a finite practical storage volume within any aquifer shared among recharge projects over a recharge season.

In brackish or saline aquifers, adjacent recharge operators will also reduce the recovery efficiency of a neighbouring operation. This is because the hydraulic gradient they impose on the aquifer ensures that the centre of mass of injected fresh fluid of the neighbour is displaced from their injection well.

## **6.4 Protection against saline water intrusion**

Managed aquifer recharge can act as a barrier to saline water intrusion. Overextraction of groundwater in coastal aquifers, or in inland freshwater aquifers bounded by saline groundwater, can induce lateral or vertical migration of sea and saline water from adjoining areas. This deteriorates the quality of the groundwater resource, which may be compounded by climate change-related reduced recharge, increased groundwater abstraction and sea level increases.

Managed aquifer recharge offers a method of protecting against saline water intrusion by increasing the groundwater levels to create a hydraulic mound on the freshwater side of the fresh water–salt water interface. This will prevent migration of saline water into the well fields.

Considerations in the development of a saline water intrusion barrier include:

- selection of the appropriate form of managed aquifer recharge (eg injection wells or recharge ponds), which depends on local hydrogeological conditions, land availability and cost
- determination of the location of recharge facilities and the recharge rates and volumes necessary to create an effective salinity barrier; this usually requires groundwater and solute transport modelling with a density-dependent groundwater model.

If water of impaired quality is used as the recharge source to protect a drinking water supply, then an evaluation of the recharge water's residence time within the groundwater system is needed, to ensure environmental and public health protection. Nutrient discharge into coastal waters also warrants evaluation, regardless of the quality of groundwater being protected.

An example of a saline water intrusion barrier is given in Box 6.3.

### **Box 6.3 Burdekin Delta saline water intrusion barrier**

Northern Queensland's Burdekin Delta groundwater recharge project, which commenced in the 1960s, is the oldest and largest managed aquifer recharge scheme in Australia. It currently recharges around 45 GL of river water annually, via infiltration basins, channels, and sand dams on permeable soils.

The Burdekin Delta represents a significant groundwater resource at shallow depth. It is used for the production of sugar cane and other crops. Managed aquifer recharge is central to maintaining high watertables across the area, to push back the saltwater wedge that would otherwise migrate inland due to groundwater pumping (Charlesworth et al 2002).

## **6.5 Operations designed to protect groundwater-dependent ecosystems**

Managed aquifer recharge can be designed for environmental as well as economic purposes. However, without a reuse component by the proponent, care must be taken that managed aquifer recharge is not a disguise for disposal.

Before initiating a managed aquifer recharge project, a market for recovered water needs to be established. Normally, environmental allocations would be made directly from surface waters and groundwaters without requiring managed aquifer recharge. However, in some overallocated systems, managed aquifer recharge could be a useful way to achieve environmental and economic benefits. For jurisdictions to consider such operations under their regulations for managed aquifer recharge, protection of the aquifer and environmental benefits for the groundwater-dependent ecosystem would need to be demonstrated. Such evaluations may be complex, and would require validation monitoring (see Section 5.11).

An example is recharge to maintain groundwater levels in aquifers that have been drawn down for irrigation or industrial supplies. In such cases, managed aquifer recharge may help restore summer baseflows in perennial streams, or maintain levels in groundwater-fed lakes and wetlands. This may involve:

- recharging water at locations that have an average of six months' travel time before discharge in the incised stream or wetland
- recovering water for discharge directly to the stream or wetland
- reinjecting recovered water between the point of abstraction and the ecosystem to be protected (eg to maintain baseflows in mound springs, see Box 6.4)
- providing a hydraulic barrier to sea water or contamination (see Section 6.4).

Objectives need to be clearly defined for ecosystem protection (see Section 3.11), with appropriate monitoring to verify the achievement. An example of managed aquifer recharge for environmental protection is given in Box 6.4.

### **Box 6.4 Example of managed aquifer recharge for environmental protection**

A well field on the edge of the Great Artesian Basin supplies mining operations at Roxby Downs, South Australia. ReInjection of water was used to sustain artesian heads at a mound spring in order to protect groundwater-dependent ecosystems from the effects of the well field (Berry and Armstrong 1997, Appendix 8 in Dillon et al 2009b). In this case, head maintenance was the sole criterion for environmental protection.

## 6.6 Management of purge water, basin scrapings and water treatment byproducts

Purge water produced by flushing of ASR wells, as part of clogging management (Section 6.1), will normally be treated and returned to the source-water supply. However, if off-site discharge is required, it would be expected to comply with requirements following the Phase 1 guidelines. Examples of discharge include:

- to the stormwater system
- to sewers
- through a trade waste agreement
- a proposed beneficial use such as irrigation.

The same requirements would apply to liquid wastes generated from other treatment processes. Proponents should check with local jurisdictions concerning requirements for discharge of waste streams. Impacts of such discharges into urban stormwater systems would need to be taken into account through the system and in water harvesting projects downstream, regardless of whether such projects were associated with other managed aquifer recharge activities.

An example of purge water management is given in Box 6.5.

For solid wastes, such as scrapings from infiltration basins or soil aquifer treatment, the material should be tested to determine its potential end uses with and without treatment. If the quality of solid waste fails to comply with requirements, it should be identified as a solid waste and dispatched to a secure landfill licensed to accept its class of waste material. Where possible, it is preferable to recycle than to send solid waste to landfill.

### **Box 6.5 Backwashing performance in relation to purge water management**

Treated sewage injection at the ASR site in Bolivar, South Australia, results in short-term clogging that is reversible by routine backwashing. Several methods of backwashing the injection well were tested. Intermittent pumping at high rates (purging) was more effective in restoring well performance than continuous pumping from the well. Significantly less water loss occurred, resulting in reduced volumes of purge water to manage (Pavelic et al 2007b).



## 7 Monitoring managed aquifer recharge systems

Monitoring is an integral part of the risk assessment of managed aquifer recharge. It forms a central component of the risk management framework described in Chapter 3, and given in more detail in the Phase 1 guidelines (NRMMC–EPHC–AHMC 2006). In particular, the following elements of the framework require monitoring:

- Element 4: Operational procedures and process control
- Element 5: Verification of recycled water quality and environmental performance
- Element 9: Validation, research and development.

### 7.1 General principles

The general principles of water quality and monitoring programs in relation to water recycling are outlined in Chapter 5 of the Phase 1 guidelines.

While specific requirements of differing systems may vary, managed aquifer recharge monitoring programs should always:

- be commensurate with the complexity and risk of the proposed managed aquifer recharge scheme
- be integrated with the risk assessment and management processes being adopted
- have clear objectives, in terms of the types of monitoring being undertaken and the information content that is obtained
- aim to maximise information content and the value of measurements in relation to the objectives.

In general, when source-water quality is highly variable, grab sample analyses have low information value compared to integrated measurements such as from passive samplers, or from measurements of groundwater after mixing has occurred; in such cases, mean concentrations are more meaningful for determining water-quality changes in the aquifer.

An example of the use of passive samplers is given in Box 7.1.

### **Box 7.1 Use of integrated passive samplers to assess pesticides in recharge water**

Hazards such as organic chemicals may occur at trace levels that are difficult to detect and quantify, and can occur in spikes related to intense rainfall events. Traditional grab sampling provides limited information about concentrations at single moments in time; therefore, time-integrated passive sampling techniques have been developed. In these passive sampling techniques, trace organic chemicals in the water are sorbed during an extended deployment period (up to one month). Sorbed solutes are later eluted and measured, and their mean concentration in source water is estimated.

Passive samplers have been used at the ASTR (aquifer storage, transport and recovery) site in Parafield, South Australia, to quantify levels of the pesticide simazine in urban stormwater before injection into the subsurface (Page et al 2008).

Despite an extensive event-based sampling regime using standard analytical techniques with a detection limit of 500 ng/L, no simazine was detected. Hence, passive samplers were deployed that have lower detection limits, and simazine concentrations of ~65 ng/L in inflow and ~15 ng/L in wetland outflow were determined. This allowed assessment of the treatment performance of the constructed wetland before recharge.

## **7.2 Types of monitoring**

The four principal types of monitoring, detailed in Section 5.2 of the Phase 1 guidelines, are:

- baseline monitoring
- validation monitoring
- operational monitoring
- verification monitoring.

These monitoring types generate useful data and information for initial risk assessment of a managed aquifer recharge project, and subsequent risk management. The following sections give guidance on the four types of monitoring specific to managed aquifer recharge.

### **7.2.1 Baseline monitoring**

Baseline monitoring provides information for the maximal risk assessment. It is used to define the state of the system before commissioning a managed aquifer recharge scheme. Baseline monitoring is not typically required for entry-level assessments, but is fundamental to subsequent risk assessments.

### **7.2.2 Validation monitoring**

Validation monitoring is essential when there is a reliance on the treatment capacity of the aquifer. It quantifies the treatment efficacy of any new or uncharacterised treatment steps, such as subsurface treatment at a new locality. It may also include pretreatment and post-treatment technologies, and exploration of water-quality deterioration (eg arsenic release, formation of disinfection byproducts).

Validation monitoring includes monitoring surrogate parameters and the use of observation wells (in particular, piezometers). An example of validation monitoring is given in Box 7.2.

### **Box 7.2 Examples of validation monitoring for a treated sewage aquifer storage and recovery scheme**

In South Australia's Bolivar ASR (aquifer storage and recovery) project, validation of the aquifer's pathogen attenuation rate required monitoring of diffusion chambers, spiked with several pathogen types and suspended in wells for repeated sampling and analysis (Toze and Hanna 2002). Inactivation rates determined from diffusion chambers were combined with known residence time of water between recharge and recovery to estimate the number of log removals within the aquifer for each tested pathogen.

Pathogen inactivation was verified by sampling the recharge water and a nearby fully penetrating observation well. However, variable source-water quality with frequent non-detection of pathogens and a broad spectrum of flow paths and travel times to the observation well, prevented meaningful quantification of the attenuation rate through verification monitoring. This reinforced the importance of validation monitoring.

### **7.2.3 Operational monitoring (including supervisory control and data acquisition and web-based reporting systems)**

Operational monitoring is fundamental to the risk management of all operational managed aquifer recharge projects. The bulk of the monitoring effort for most managed aquifer recharge applications occurs in the day-to-day operation of the system, and is used by operators to manage risks.

Operational monitoring provides timely information for use as critical control points in the risk management plan. It often includes supervisory control and data acquisition (SCADA) and web-based reporting systems that provide near real-time data. Operational monitoring is fundamental to setting appropriate critical limits and management responses such as:

- shutting down recharge due to poor quality source water
- shutting down recovery due to salinity limits being reached in recovered water
- backflushing ASR wells at the onset of clogging
- changing dose concentrations in pretreatment processes.

### **7.2.4 Verification monitoring**

Verification monitoring is required for all operational projects, except for those with low inherent risks and eligible for simplified assessment.

Although verification monitoring is not timely enough for operational management, it provides an important check to confirm that the managed aquifer recharge system and its components are performing as anticipated. Verification monitoring can be performed on a compliance basis, and is necessary for regulatory agencies assessing the whole of the managed aquifer recharge system.

Where there is reliance on an attenuation zone to meet the aquifer's pre-existing environmental values, then verification would require one or more observation wells at the perimeter of that zone (see Figure 7.1).

On decommissioning of a managed aquifer recharge operation, the verification monitoring specified in the site management plan needs to be undertaken until the aquifer has been restored to its ambient environmental values.

### 7.3 Monitoring for management of health and environmental risks in managed aquifer recharge systems

This section highlights components of the monitoring program specific to managed aquifer recharge and not discussed in Section 5.3 of the Phase 1 guidelines. Monitoring concepts presented in those guidelines, and supplemented by hydrogeological considerations specific to managed aquifer recharge, form part of this section's background information.

Indicators and surrogates are increasingly being used to monitor hazards to human health and the environment. This is due to the continually expanding number of analytes and the cost of the analyses, particularly for trace organic chemicals and pathogens.

Indicators are individual parameters that can be used to measure the effectiveness of treatment processes in removing or inactivating broader groups of hazards that have similar properties. They should correlate closely with targeted hazards. Indicators need to have characteristics that can be linked to a process (eg filtration), because different treatment processes target different properties.

Surrogate analytes are typically easy to measure, have low detection levels, and are representative of classes of hazards exposed to the respective treatment. Biological, chemical and physical treatment processes may warrant different surrogate parameters to be representative of the same class of hazards. Examples of indicators and surrogates are given in Box 7.3.

#### **Box 7.3 Examples of indicators and surrogates**

##### **Indicators**

Meprobamate is regarded as a good indicator of soil aquifer treatment operation using wastewater. Meprobamate should not be detectable in well-functioning systems.

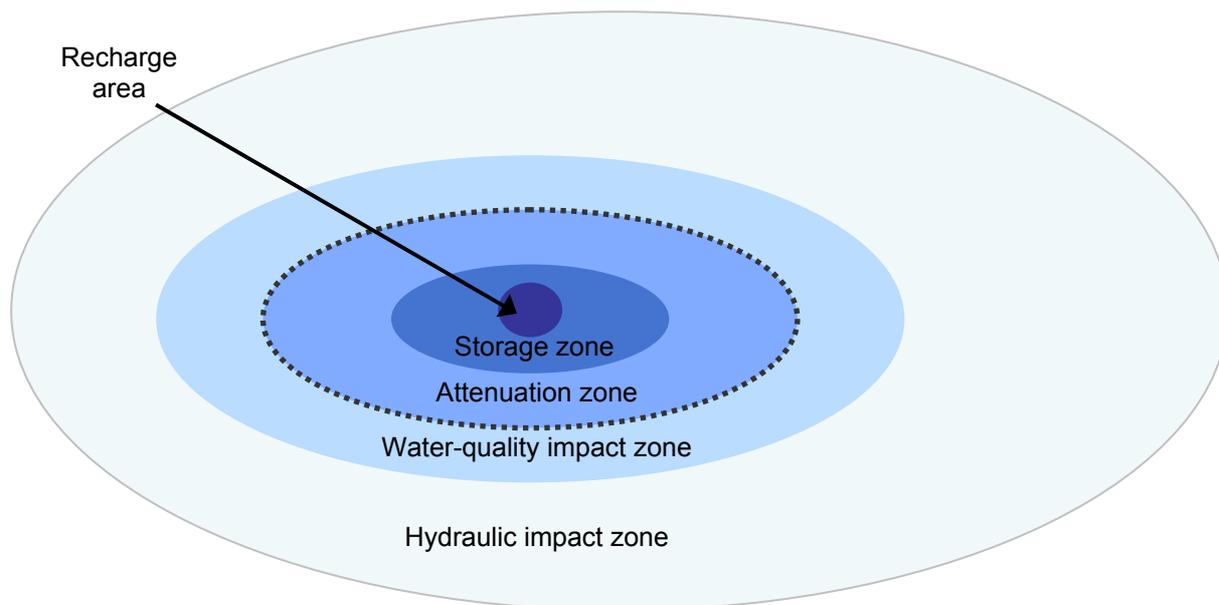
##### **Surrogates**

Total organic carbon is used as a surrogate for overall soil aquifer treatment operations; this is similar to the use of turbidity for determining filter efficacy.

Figure 7.1 shows a conceptual plan of the subsurface zones of influence in a managed aquifer recharge system. In actual systems, the shape of these zones depends on the:

- spatial variability of aquifer hydraulic properties within the aquifer
- ambient hydraulic gradient in the aquifer
- influence of pumping from other wells.

For example, plumes will be elongated where groundwater gradients are steep. In aquifers with layers of high and low permeability, the size of the zone within a layer will be proportional to the hydraulic conductivity. A single two-dimensional (plan) representation oversimplifies the three-dimensional pattern.



The storage zone contains water that is fit for its intended use when recovered. Beyond the attenuation zone, the environmental values of the ambient groundwater are always preserved. Beyond the water-quality impact zone, there is no measurable change in groundwater quality. Beyond the hydraulic impact zone, there is no attributable change in hydraulic head (this zone is typically many times larger than the water-quality impact zone, especially for confined aquifers). The dotted line represents the maximum separation distance between the managed aquifer recharge structure and the observation well/s for verification monitoring, to ensure that the ambient groundwater is protected.

**Figure 7.1 Schematic showing zones of influence of a managed aquifer recharge operation**

In The storage zone contains water that is fit for its intended use when recovered. Beyond the attenuation zone, the environmental values of the ambient groundwater are always preserved. Beyond the water-quality impact zone, there is no measurable change in groundwater quality. Beyond the hydraulic impact zone, there is no attributable change in hydraulic head (this zone is typically many times larger than the water-quality impact zone, especially for confined aquifers). The dotted line represents the maximum separation distance between the managed aquifer recharge structure and the observation well/s for verification monitoring, to ensure that the ambient groundwater is protected.

Figure 7.1, the attenuation zone is defined as the aquifer domain enveloping the managed aquifer recharge system, beyond which the water quality always meets the environmental values of the native groundwater. The boundary of the attenuation zone is defined by a common travel time from the recharge source. Following the elapse of that travel time once recharge has ceased, the ambient environmental values of the aquifer will also be met throughout the attenuation zone.

Hydraulic head impacts may extend considerably further than water-quality impacts. This is most pronounced in confined aquifers, where hydraulic effects can propagate around 200 times further than the water-quality effects.

At least one observation well is required to verify attenuation at managed aquifer recharge sites, in which reliance is placed upon water treatment within the aquifer to meet water-quality objectives. In fractured or karstic aquifers (Section 5.9), in complex lithologies, or

where there are time-varying directions of groundwater flow, more wells may be needed. This is due to the added complexity of flow systems.

One or more observation wells should be placed at the margins of the attenuation zone (Figure 7.1) to verify that the ambient environmental values of the aquifer are being met. Provision may be made for analysis of samples taken from the recharge zone once a managed aquifer recharge operation has ceased, to verify natural restoration of the initial environmental values.

If an observation well is used to define attenuation rates as part of validation monitoring, the open interval of the well should be short (ie it is a piezometer). Observation wells that have long, open intervals (relative to the aquifer thickness) typically sample water from multiple flow paths that encompass a large range of travel times. This makes determining attenuation problematic. In theory, observation wells used for verification monitoring should be fully penetrating, to ensure that hazards are detected over the entire aquifer thickness. However, in cases where the aquifer stratigraphy is well-defined, wells that are screened within the highest permeability layer could meet both validation and verification requirements.

### **7.3.1 Baseline monitoring of the subsurface component for managing health and environmental risks**

Baseline monitoring is important in establishing a managed aquifer recharge system because the system will be managed relative to the baseline conditions (environmental values of the native groundwater). Hence, baseline monitoring underpins the risk assessment process.

A representative sampling scheme is likely to establish the groundwater quality and inform the use of critical control points and limits in subsequent management. Baseline monitoring should address any spatial and temporal variability (eg due to climatic and human influences) of the native groundwater quality.

Typically, baseline monitoring is not required for entry-level assessments. However, subsequent risk assessments should always define a suitable baseline reference. In situations where the quality of source water for managed aquifer recharge is highly variable (eg stormwater), sampling over an extended time and differing hydrological regimes is also required.

### **7.3.2 Validation monitoring of the subsurface component for health and environmental risks**

Validation monitoring of managed aquifer recharge is primarily focused on the subsurface treatment and other barriers of the system. Examples are provided in

Table 7.1, and further detail on specific hazard assessment techniques is given in Appendix 3. Details of validation monitoring specific to hazards are given in Chapter 5. This requires monitoring attenuation rates in observation wells closer to the recharge well or area, when the aquifer forms a barrier in the treatment train. Any additional water treatment before recharge or after recovery should be validated as described in the Phase 1 guidelines. An example of groundwater sampling as an integrator of variable source-water quality is given in Box 7.4.

### Box 7.4 Groundwater sampling as an integrator of variable source-water quality

Due to mixing in aquifers, the emphasis of validation monitoring in managed aquifer recharge is on determining the mean concentrations in the recharge water, rather than peak concentrations.

If concentrations of hazards in source waters are drawn from skewed distributions (ie with relatively rare high spikes in concentrations, or frequent samples (eg pathogens and chemicals) below the detection level), sampling theory suggests that:

- samples that integrate over larger source-water volumes have lower variance
- integrated samples have a high probability of a mean value exceeding that of sparse random grab samples of source water. (This was illustrated in a study by Clinton (2007) who found 46% of trace organics detected (at greater than 5 times the detection limit) in samples from water recovered from ASR wells at four sites in United States and Australia were more than 30% higher than concentrations in sparse samples of the relevant source water.)

For a finite number of samples, groundwater samples close to the recharge facility convey more information about the mean than the same number of grab samples of source water; they therefore give increased certainty about treatment requirements and environmental impacts.

**Table 7.1 Examples of subsurface validation monitoring for managing health and environmental risks in managed aquifer recharge systems**

Process step to be validated	Validation monitoring	Associated operational monitoring
Travel time and distance to wells	<ul style="list-style-type: none"> <li>• Tracer studies to demonstrate adequate residence times for natural attenuation to occur</li> </ul>	<ul style="list-style-type: none"> <li>• Recharge and recovery rates</li> <li>• Concentrations of               <ul style="list-style-type: none"> <li>– pathogens</li> <li>– microbial indicators</li> <li>– reactive organic chemicals</li> </ul> </li> </ul>
Water flow direction	<ul style="list-style-type: none"> <li>• Sufficient piezometers to reveal hydraulic gradients</li> </ul>	<ul style="list-style-type: none"> <li>• Recharge and recovery rates</li> </ul>
Attenuation rates of pathogens	<ul style="list-style-type: none"> <li>• Microbial indicator concentrations in injectant and recovered water</li> <li>• Monitoring should include <i>Escherichia coli</i>, would ideally include coliphage and clostridia spores, and may include some pathogens</li> </ul>	<ul style="list-style-type: none"> <li>• Flow rate and residence time in the system</li> <li>• Microbial indicator and pathogen concentrations in               <ul style="list-style-type: none"> <li>– source water</li> <li>– recovered water</li> <li>– observation bores</li> </ul> </li> </ul>
Degradation of organic chemicals	<ul style="list-style-type: none"> <li>• Organic chemical concentrations in injectant and recovered water</li> <li>• Monitoring may include some degradation byproducts</li> <li>• Biodegradation performance surrogates (Drewes et al 2008b)</li> </ul>	<ul style="list-style-type: none"> <li>• Flow rate and residence time in the system</li> <li>• Physicochemical parameters (pH, Eh, dissolved oxygen, temperature)</li> <li>• Organic chemical concentrations in:               <ul style="list-style-type: none"> <li>– source water</li> <li>– recovered water</li> <li>– observation bores</li> </ul> </li> </ul>

**Table 7.2** (continued)

<b>Process step to be validated</b>	<b>Validation monitoring</b>	<b>Associated operational monitoring</b>
Dissolution of arsenic	<ul style="list-style-type: none"> <li>Total and dissolved arsenic concentrations in injectant and recovered water</li> </ul>	<ul style="list-style-type: none"> <li>Physicochemical parameters (pH, Eh, dissolved oxygen, temperature)</li> <li>Redox indicators or pairs</li> <li>Flow rate and residence time in the system</li> </ul>
Aquitard stability	<ul style="list-style-type: none"> <li>Studies and modelling to determine strength, integrity and bursting pressure</li> <li>Piezometer above aquitard to determine pressure and fluid transmission</li> </ul>	<ul style="list-style-type: none"> <li>Injection pressure</li> </ul>

Eh = a measure of redox potential — the propensity for oxidation and reduction reactions; MAR = managed aquifer recharge.

Environmental tracers that distinguish the recharge source from native groundwater, within the aquifer and in recovered water, should be identified (unless this is illogical, due to dispersed recharge nearby from the same water source).

Ideally, tracers will include generally conservative species such as chloride and bromide, but may also include generally non-conservative species such as:

- organic chemicals (see Section 5.5 and Appendix 5)
- nutrients
- boron
- other ions and trace elements.

Electrical conductivity and temperature are commonly used as surrogate tracers, and may be adequate for Stage 2 investigations, but would require validation by correlations with tracers in Stage 3 trials.

Conservative tracers are required to determine mixing fractions (the proportion of recharged source water in a given sample of groundwater or recovered water; see Appendix 9). This is essential for accurate calculation of biodegradation rates of non-sorbed hazards, or rates of removal of other hazards in validation monitoring. Tracers are also useful in calibration of groundwater flow and solute transport models, when these are needed as diagnostic and operational design tools.

Monitoring of conservative tracers is essential to provide a measure of the changes in concentration of constituents that occur naturally within the aquifer due to mixing, and to enable these changes to be partitioned from the effects of natural attenuation.

If an attenuation zone is to be used, the concentration of any hazard in the recharge water may lie outside the allowable range of environmental values relevant to the ambient groundwater. Attenuation zone size is determined by considering, for each constituent, the residence time needed for the concentration in recharge water to be reduced by the sustainable attenuation rate in the aquifer, to the allowable concentration in the native

groundwater. The longest required residence time of any constituent present in the recharge water defines the minimum residence time on the locus that defines the attenuation zone boundary.

The attenuation zone boundary (Figure 7.1) is mapped out using measurements of recharge rates and ambient groundwater flow rates, which may also be influenced by nearby wells. Appendixes 4 and 5 define attenuation rates for selected pathogens and organic chemicals, under various environmental conditions in aquifers. Appendix 6 allows calculation of the distance to the edge of the attenuation zone, in the downgradient direction, for simple approximations for uniform flow in the aquifer. This may be used for the precommissioning residual risk assessment.

Stage 3 validation studies may consider more complex flow cases by groundwater modelling and validation monitoring, or a wider range of hazards by laboratory attenuation studies relevant to aquifer conditions. Similarly, if hazard concentrations are forecast to increase in the aquifer (eg by using flow charts for metal mobilisation in Appendix 7), or disinfection byproduct concentrations are expected to increase in chlorinated recharge water, then evaluation using geochemical or biogeochemical models may be required in Stage 2 investigations. Subsequent validation monitoring will also be required.

If the edge of the attenuation zone is forecast to lie outside the boundaries of the proponent's property, the proponent may elect to improve the pretreatment of water to be recharged, so that the attenuation zone (and the observation well used for verification monitoring) is located within the proponent's property. Alternatively, the appropriate regulator may develop an agreement with affected neighbours and undertake more intensive validation monitoring; in this case, any validation piezometers would have to be located close to the recharge area. The risk management plan would prescribe response actions for contingencies based on such monitoring. For example, if water quality is inadequate at the validation piezometer, then a sufficient volume of groundwater would be recovered within sufficient time to continually honour the environmental values beyond the attenuation zone.

In the event of a fractured rock or karstic aquifer (see Section 5.9) it may be difficult to establish the extent of the attenuation zone. At the discretion of the relevant jurisdiction and based on local evidence, the extent of the permitted attenuation zone at which verification monitoring may be undertaken could be limited. For example, it could be limited to the property boundary, or to a zone in which a caveat on groundwater extraction is applied; this zone would preclude connected surface water bodies and wells of other groundwater users.

### **7.3.3 Operational monitoring of the subsurface component for managing health and environmental risks**

Operational monitoring is important for managing human and environmental health risks. Suitable parameters correlated to the hazard of interest should be chosen. Table 7.3 presents some examples of operational monitoring for the subsurface component of a managed aquifer recharge system.

Any additional operational monitoring for other components of the managed aquifer recharge system (eg pretreatment, post-treatment) should be performed as described in the Phase 1 guidelines.

**Table 7.3 Examples of subsurface operational monitoring and supporting programs for managing health and environmental risks and clogging**

<b>Process step to be monitored</b>	<b>Operational monitoring</b>	<b>Supporting programs</b>
Subsurface storage and water travel time	<ul style="list-style-type: none"> <li>• Online conductivity</li> <li>• Other parameter for evidence of short circuit</li> </ul>	<ul style="list-style-type: none"> <li>• Instrument calibration</li> </ul>
Groundwater mixing	<ul style="list-style-type: none"> <li>• Online conductivity</li> <li>• Other parameter for evidence of short circuit</li> </ul>	<ul style="list-style-type: none"> <li>• Instrument calibration</li> </ul>
Arsenic dissolution	<ul style="list-style-type: none"> <li>• Redox potential</li> <li>• Dissolved oxygen</li> </ul>	<ul style="list-style-type: none"> <li>• Instrument calibration</li> </ul>
Clogging	<ul style="list-style-type: none"> <li>• Recharge rate</li> <li>• Head loss               <ul style="list-style-type: none"> <li>– between injection well and nearby well</li> <li>– between infiltration basin or gallery and tensiometers beneath the bed</li> </ul> </li> <li>• Turbidity and nutrient levels in the recharge water</li> </ul>	<ul style="list-style-type: none"> <li>• Online instrument calibration</li> <li>• Periodic pump testing</li> <li>• Infiltration rate testing</li> </ul>

### **7.3.4 Verification monitoring for health and environmental risks in managed aquifer recharge systems**

Verification monitoring is the final check of system integrity. It can be used by regulatory agencies to assess risk management plan compliance. Details of verification monitoring are given for each hazard in Chapter 5, and examples of verification monitoring are given in Table 7.4.

Verification monitoring of groundwater quality is typically undertaken at the boundary of the attenuation zone (Figure 7.1). It is normally performed to assess the quality of the recovered water, and to verify that environmental values of the aquifer are protected. The latter may be performed by sampling in one or more observation wells on the downgradient margin of an attenuation zone (defined as the area around a recharge source, beyond which water quality should at least meet its original environmental values). Verification monitoring is also performed to assess the quality of the recovered water.

In ASR systems, monitoring of the recovery well will, in general, provide a tighter constraint for groundwater quality than monitoring of an observation well at the margin of the attenuation zone. Verification monitoring for the recovered water and for aquifer protection may therefore be achieved from the same set of samples. Observation wells may also be required to verify achievement of hydraulic head constraints.

**Table 7.4 Examples of verification monitoring and supporting programs for managing health and environmental risks**

Process step	Example of verification monitoring
Throughout managed aquifer recharge system	<ul style="list-style-type: none"> <li>• Check that               <ul style="list-style-type: none"> <li>– calibration schedules comply with requirements for monitoring equipment used for operational monitoring</li> <li>– preventive maintenance schedules are adhered to for equipment that controls recycled water quality</li> <li>– non-conformance detected during operational monitoring is responded to quickly, and details of corrections and corrective actions taken in response to any deviations detected are recorded and reported</li> <li>– during site decommissioning, verification monitoring continues until initial environmental values of the aquifer are restored.</li> </ul> </li> </ul>
At the recovery point	<ul style="list-style-type: none"> <li>• Monitor pathogen indicators, including sampling for small, low-exposure schemes over a time period are commensurate with the               <ul style="list-style-type: none"> <li>– variability in source-water concentration</li> <li>– time constant associated with mixing in the aquifer.</li> </ul> </li> <li>• For higher exposure schemes (eg when used for a drinking water supply), pathogen indicator testing could be undertaken more frequently. Monitoring would ideally include               <ul style="list-style-type: none"> <li>– weekly testing for coliphage and <i>Clostridium</i> spores</li> <li>– in some cases, monthly or quarterly pathogen testing (eg <i>Cryptosporidium</i>, viruses).</li> </ul> </li> </ul>

Table 7.5 provides a summary of indicative sampling frequencies for the hazards described in Chapter 5. The fresh and marine water quality guidelines (ANZECC–ARMCANZ 2000a) provide values for the protection of aquatic ecosystems through water-quality monitoring and management. Similarly, NHMRC–NRMCC (2004) provides guidelines for drinking water.

The actual sampling frequency and hazards shown in Table 7.4 will depend on the:

- hazard
- scheme-specific considerations
- historical data
- maximal risk assessment.

For example, variability in concentrations may affect the ratio of mean or maximum concentration to critical limits.

Verification monitoring samples should be taken after the final step in the managed aquifer recharge system, where water is delivered to the end user or the environment; or, at the perimeter of the attenuation zone in the aquifer. The frequency of sampling, and the analytes or variables measured, may be subject to periodic review to increase the value and cost-effectiveness of monitoring. The program must also account for increased frequency of monitoring during hazardous events (eg failure of a water diversion or treatment system, extreme rainfalls, other events likely to lead to errant water quality).

Stage 3 validation monitoring may be targeted on the specific hazards that require further investigation.

**Table 7.5 Example of sampling program for operational, validation and verification monitoring of health and environment protection in stages of system development**

Monitoring program (managed aquifer recharge project development stage)								
Hazard or hazardous event	Operational (Stage 1) <sup>a</sup>	Baseline (Stage 2)	Validation (Stage 3)	Operational (Stage 3)	Verification (Stage 3)	Operational (Stage 4)	Verification (Stage 4)	Relevant section
Pathogens	na	*	**	**	*	*	*	5.1
Metals and inorganics	na	*	**	**	*	*	*	5.2
Salinity and sodicity	na	*	***	**	**	*	**	5.3
Nutrients	na	*	**	**	*	*	*	5.4
Organic chemicals	na	*	**	*	*	*	*	5.5
Turbidity and particulates	na	*	***	**	**	*	**	5.6
Radionuclide and radiation	na	*	*	*	*	*	*	5.7
Pressure, flow rates, volumes and groundwater levels	*	*	***	**	**	*	**	5.8
Contaminants in fractured rock and karstic aquifers	na	*	**	**	*	*	*	5.9
Aquifer dissolution and stability of well and aquitard	na	*	**	*	*	*	*	5.10
Impacts on aquifer and GDEs	na	*	**	*	*	*	*	5.11
Energy consumption and greenhouse gas emissions	na	*	*	*	*	*	*	5.12

GDE = groundwater-dependent ecosystem; na = not applicable;

\* = low sampling frequency; \*\* = medium sampling frequency; \*\*\* = high sampling frequency.

<sup>a</sup> For project with low inherent risk, under simplified assessment (estimates only).

## 7.4 Monitoring of small-scale managed aquifer recharge systems

Operators of small managed aquifer recharge systems should monitor fewer parameters more frequently, rather than a lengthy list of parameters annually. This is similar to the situation for monitoring small drinking water supplies as described in Section 10.5 of the *Australian Drinking Water Guidelines* (NHMRC–NRMCC 2004).

Projects with low inherent risk qualifying for simplified assessment warrant a blanket control and monitoring program by the groundwater resource manager, other regulator or groundwater user groups. This will allow the cumulative effects of numerous managed aquifer recharge projects to be observed at intervals related to risk, using an observation or monitoring well network, with an action plan devised to maintain levels and quality within their intended range.

## **7.5 Quality assurance and quality control**

Quality assurance and quality control should be an essential part of a managed aquifer recharge system's adopted risk management plan. Table 5.12 in the Phase 1 guidelines gives a list of common quality assurance and quality control procedures. These include:

- training personnel
- using standardised methodologies
- using appropriately certified companies and supporting programs such as instrument calibration.

## **7.6 Data analysis and interpretation**

Common statistical methods for the analysis of water-quality data are described in Chapter 6 of the *Australian Guidelines for Water Quality Monitoring and Reporting* (ANZECC–ARMCANZ 2000b).

The results of these analyses should be integrated into the risk management plan, to reduce risk or uncertainty with each sampling program undertaken. These methods should provide feedback on the adequacy of the monitoring program, and allow for revision to increase the value and cost-effectiveness of data for risk assessment. The methods should also account for temporal and spatial variability of analytes and other variables at their respective monitoring locations, whenever they are revealed by monitoring results.

For example (but only in agreement with the jurisdiction), hazards that are not detected over one or more annual cycles, and are unlikely to be present in future source water, may be removed from the monitoring schedule. A bias towards integrated samples or measurements, where these may replace data from sampling locations with more random values, is also warranted. This will provide greater precision in assessing risks, and also reduce costs.

## **7.7 Reporting and information dissemination**

Reporting requirements should be outlined in the risk management plan and should include all interested stakeholders. Advice on communication and reporting is provided in Chapter 6 of the Phase 1 guidelines. As outlined earlier, such data and information has public value, and should be made available to proponents of new projects and for research purposes. Web-based automated reporting is expected to reduce the cost and effort of reporting, and assist in timely provision of information.

Maintenance of a central repository (nationally or in state jurisdictions) for validation data and relevant verification and operational data and information is warranted. This would enable future proponents to determine hazard attenuation rates applicable for their sites before proceeding with the project, and hence increase the knowledge basis for decision making.

The loss of privacy of information is a small cost in comparison with the national benefit for future managed aquifer recharge operations. Jurisdictions are encouraged to ensure that such information, as well as the supporting operational data (recharge and recovery history) and baseline data, are available for use by others and research purposes. New regulations being established under the Australian Government's *Water Act 2007* will require certain data to be provided to the Bureau of Meteorology, and data from managed aquifer recharge operations may be candidates for centralised collection and dissemination.

## **7.8 Review and feedback**

Reviews and feedback are the final check on managed aquifer recharge system performance. Whether self-assessment, external or independent reviews are required will depend on the risk of the managed aquifer recharge system. Section 2.12 of the Phase 1 guidelines gives a list of common actions for review by senior managers. Sections 5.8 and 5.9 of those guidelines describe the feedback and review processes.

# Appendix 1 Environmental values and entry-level assessment

**Table A1.1** References for water-quality requirements for environmental values of water

Environmental values of water	Source of information on water-quality requirements
Aquatic ecosystems (with high conservation or ecological values, slight to moderate disturbance or high level of disturbance) Aquaculture Recreation Livestock	<i>Australian and New Zealand Guidelines for Fresh and Marine Water Quality</i> (ANZECC–ARMCANZ 2000a)
Drinking	<i>Australian Drinking Water Guidelines</i> (NHMRC–NRMMC 2004) <i>Australian Guidelines for Water Recycling: Augmentation of Drinking Water Supplies</i> (NRMMC–EPHC–NHMRC 2008)
Irrigation	<i>Australian and New Zealand Guidelines for Fresh and Marine Water Quality</i> (ANZECC–ARMCANZ 2000a) <i>Australian Guidelines for Water Recycling: Managing Health and Environmental Risks</i> (NRMMC–EPHC–AHMC 2006)

Table A1.2 contains information about entry-level assessment, indicating the relative degree of difficulty in relation to specific environmental values of the aquifer and intended uses of recovered water. This table is used by selecting the relevant environmental values for the target aquifer (beyond the attenuation zone) and intended uses of recovered water. The harshest of the values at the intersections of these selected columns and rows is the one that best relates to the project.

This table is a subjective compilation, where it is crudely assumed that achieving:

- drinking water, or high conservation value aquatic ecosystem protection, has a high degree of difficulty
- aquaculture or recreation, or slightly to moderately disturbed aquatic ecosystem protection, has a moderate degree of difficulty
- irrigation, livestock supplies or highly disturbed aquatic ecosystem protection, has a low degree of difficulty.

The table may assist in exploring options where several alternative aquifers or sites are available for a project. Projects with a high degree of difficulty will need an appropriate level of operational expertise for effective management.

**Table A1.2 Entry-level assessment, indicating relative degree of difficulty in relation to specific environmental values of the aquifer and intended uses of recovered water**

Recovered water environmental values	Aquifer environmental values							
	Aquatic ecosystems 1 <sup>a</sup>	Aquatic ecosystems 2 <sup>b</sup>	Aquatic ecosystems 3 <sup>c</sup>	Drinking	Aquaculture	Recreation	Irrigation	Livestock
Aquatic ecosystems 1 <sup>a</sup>	H	H	H	H	H	H	H	H
Aquatic ecosystems 2 <sup>b</sup>	H	M	M	H	M	M	M	M
Aquatic ecosystems 3 <sup>c</sup>	H	M	L	H	M	M	L	L
Drinking	H	H	H	H	H	H	H	H
Aquaculture	H	M	M	H	M	M	M	M
Recreation	H	M	M	H	M	M	M	M
Irrigation	H	M	L	H	M	M	L	L
Livestock	H	M	L	H	M	M	L	L

H = higher difficulty, generally corresponding with high risk;

M = moderate difficulty, generally corresponding with moderate risk;

L = lower difficulty, generally corresponding with low risk.

**a** Aquatic ecosystems 1 = high conservation or ecological values.

**b** Aquatic ecosystems 2 = slightly to moderately disturbed systems.

**c** Aquatic ecosystems 3 = highly disturbed systems.

## **Appendix 2 Examples of information requirements for Stage 2 investigations**

A Stage 2 investigation is a quantitative assessment of the hazards, and the means by which they are managed, to achieve a low level of residual risk (Figure 4.1).

All elements of the framework for management of water quality and use (Figure 3.1) need to be addressed. To demonstrate that all hazards described in Chapter 5 have been addressed, a description of the project's infrastructure, and proposed operations and characterisation of the hydrogeology is required, accompanied by sufficient supporting information and a management plan.

An example of a checklist of baseline information requirements that provides the necessary input for maximal risk assessment for regulators at Stage 2 is given below. Some of this information will require specialist skills to undertake investigations and to collect, interpret and report data. The proponent will also need to consider developing the competencies required to manage the proposed managed aquifer recharge operation (see Section 3.7).

Where further information is required to achieve acceptance criteria, which may require establishment of a pilot project, Stage 2 investigations should result in a management plan that gives evidence of effective management of human and environmental health risks when advancing to a Stage 3 trial. This would address contingencies and response plans to ensure that the residual risk of all hazards is acceptably low.

### **Scheme concept**

To develop the scheme concept (extending Stage 1 information):

- confirm
  - objectives of scheme
  - viable water demand and uses exist
  - uses of recovered water
  - source water is available
  - presence of aquifer and its environmental values
  - type of managed aquifer recharge
- detail volume and quality of recovered water required, and confirm volumes and storage requirements
- detail source-water volume, variability and quality with respect to requirements for relevant environmental values
- determine
  - commercial viability of project

- management capability.

## **Source water and catchment information**

To detail source-water and catchment information:

- prepare detailed map/s or model of scheme detailing
  - physical extent of scheme
  - stormwater, industrial water or sewer catchment (water source)
  - topography and drainage pattern (hydrology)
  - path of captured water
  - scheme supply point
  - any existing treatment systems and locations
  - extent of groundwater basin
- document land uses within catchment, including
  - residential developments
  - industrial developments
  - roadways and hard surfaces
  - agricultural activities (eg crops, livestock, horticulture)
  - livestock yards, feedlots and abattoirs
- identify
  - known and potential hazard sources from land uses
  - any hazards on or in project site
  - how waste streams will be dealt with
- verify available volume of water
  - identify seasonal rainfall patterns (storms and floods)
- sample (multiple samples) and analyse source water
  - identify concentrations of hazards
  - document identified actual and potential hazards
- develop conceptual understanding of geochemical processes
- define water-quality targets and identify water treatment methods.

## **Aquifer information**

To compile aquifer information:

- identify
  - one or more aquifers for potential storage
  - type of aquifer and suitability for type of managed aquifer recharge
  - degree of confinement

- nearest wells and uses of water
- nearest point of natural discharge and environmental sensitivity to managed aquifer recharge
- phreatophytic vegetation dependent on the target aquifer
- prepare a hydrogeological cross-section including target and surrounding aquifers
- prepare a hydrogeological model (conceptual or computer generated) of target aquifer, detailing
  - hydraulic conductivity and transmissivity
  - fracture zones (for fractured rock aquifers)
  - hydraulic interaction between target aquifer and overlying and underlying aquifers
  - proposed volumes of discharge and recovery
  - capacity of aquifer to accommodate recharge
  - local and regional groundwater flow and quality
  - piezometric heads (hydraulic gradient)
- model the aquifer to provide
  - hydraulic head changes
  - migration of recharged water
  - extent of attenuation zone
  - aquifer response to injection and extraction
  - water-quality changes due to geochemical processes
- for infiltration systems, identify
  - the soil and subsoil characteristics for the site
  - presence of low permeability layers
  - geochemical characteristics that may influence water quality and permeability when water is applied.



## Appendix 3 Examples of methods available for investigations and validation monitoring, as part of Stage 3 commissioning and trials

Table A3.1 provides examples of the tools available for conducting a Stage 3 assessment, including validation monitoring. Examples are given on a hazard-specific basis. A basic description and reference to sources of information or case studies is provided for each method.

**Table A3.1** Examples of the tools available for a Stage 3 assessment

Hazard	Methods of analysis	Information provided	References
Pathogens	<ul style="list-style-type: none"> <li>Literature</li> <li>In situ or laboratory chamber decay studies</li> <li>Sampling and analysis of source water and native groundwater<sup>a</sup></li> <li>Tracer testing, aquifer pump testing, electromagnetic flow metering</li> <li>Transport models that include removal processes</li> </ul>	<ul style="list-style-type: none"> <li>Indicative source concentrations and decay rates for specific pathogens or indicator species</li> <li>Site-specific decay rates</li> <li>Source concentration, physicochemical characteristics of ambient groundwater</li> <li>Groundwater flow velocity, travel times</li> </ul>	<p>Appendixes 4 and 6, NRMMC–EPHC–AHMC (2006)</p> <p>Toze and Hanna (2002)</p> <p>Toze et al (2002)</p> <p>Pavelic et al (2006b)</p>
Inorganics	<ul style="list-style-type: none"> <li>Literature</li> <li>Decision trees</li> <li>Sampling and analysis of source water and native groundwater<sup>a</sup></li> <li>Sampling and analysis of soil and aquifer</li> <li>Laboratory-scale column and batch tests</li> <li>Geochemical modelling (PHREEQC<sup>b</sup>, PHT3D<sup>c</sup>)</li> </ul>	<ul style="list-style-type: none"> <li>Indicative source concentrations</li> <li>Qualitative view of processes</li> <li>Source concentration, physicochemical characteristics of ambient groundwater</li> <li>Presence and quantity of reactive phases</li> <li>Kinetics of processes</li> <li>Quantitative understanding of processes</li> </ul>	<p>Appelo and Postma (2005)</p> <p>Appendix 7</p> <p>Herczeg et al (2004)</p> <p>Stuyfzand et al (2002), Bekele et al (2007)</p> <p>Bekele et al (2007)</p> <p>Greskowiak et al (2005)</p>

**Table A3.1 (continued)**

<b>Hazard</b>	<b>Methods of analysis</b>	<b>Information provided</b>	<b>References</b>
Salinity and sodicity	<ul style="list-style-type: none"> <li>• Literature</li> <li>• Sampling and analysis of source water and native groundwatera</li> <li>• Sampling and analysis of soil and aquifer</li> <li>• Laboratory-scale column and batch tests</li> <li>• Geochemical modelling</li> <li>• Solute transport modelling</li> </ul>	<ul style="list-style-type: none"> <li>• Indicative source concentrations</li> <li>• Source concentration, physicochemical characteristics of ambient groundwater</li> <li>• Presence and quantity of reactive clays and salt loads</li> <li>• Assistance with operational design</li> <li>• Degree of mixing in subsurface</li> </ul>	NRMMC–EPHC–AHMC (2006) Herczeg et al (2004) Bekele et al (2007) Bekele et al (2007), Cavé (2000) Pavelic et al (2006b,c)
Nutrients	<ul style="list-style-type: none"> <li>• Literature</li> <li>• Sampling and analysis of source water and native groundwatera</li> <li>• Sampling and analysis of soil and aquifer</li> <li>• Laboratory-scale column and batch tests</li> </ul>	<ul style="list-style-type: none"> <li>• Indicative source concentrations</li> <li>• Source concentration, physicochemical characteristics of ambient groundwater</li> <li>• Presence and quantity of reactive phases</li> <li>• Fate and transport, assistance with operational design</li> </ul>	NRMMC–EPHC–AHMC (2006) Vanderzalm et al (2006) Vanderzalm et al (2006) Fox (2002)
Organic chemicals	<ul style="list-style-type: none"> <li>• Literature</li> <li>• Sampling and analysis of source water and native groundwater</li> <li>• Sampling and analysis of soil and aquifer</li> <li>• Passive samplers</li> <li>• Laboratory-scale column and batch tests</li> <li>• Geochemical modelling (PHREEQCb, PHT3Dc)</li> <li>• Tracer testing, aquifer pump testing, electromagnetic down-hole flow metering</li> </ul>	<ul style="list-style-type: none"> <li>• Indicative source concentrations and environmental fate data</li> <li>• Source concentration, physicochemical characteristics of ambient groundwater</li> <li>• Presence and quantity of reactive phases</li> <li>• Integrated source concentrations at low levels of detection</li> <li>• Fate and transport, assistance with operational design</li> <li>• Quantitative understanding of processes</li> <li>• Groundwater flow velocity, travel times</li> </ul>	Appendixes 5 and 6, NRMMC–EPHC–AHMC (2006), NRMMC–EPHC–NHMRC (2009) Pavelic et al (2005) Pavelic et al (2005) Komarova et al (2006) Ying et al (2003) Greskowiak et al (2006) Freeze and Cherry (1979), Clark et al (2005), Pavelic (2006b)

**Table A3.1 (continued)**

<b>Hazard</b>	<b>Methods of analysis</b>	<b>Information provided</b>	<b>References</b>
Turbidity and particulates	<ul style="list-style-type: none"> <li>• Literature</li> <li>• Sampling and analysis of source water and native groundwatera</li> <li>• Sampling and analysis of soil and aquifer</li> <li>• Laboratory-scale column and batch tests</li> </ul>	<ul style="list-style-type: none"> <li>• Indicative source concentrations</li> <li>• Source concentration, physicochemical characteristics of ambient groundwater</li> <li>• Presence and quantity of reactive phases</li> <li>• Fate and transport, assistance with operational design</li> </ul>	<p>NRMMC–EPHC–AHMC (2006)</p> <p>Pavelic et al (2006c, 2007a)</p> <p>Rinck-Pfeiffer et al (2000)</p> <p>Rinck-Pfeiffer et al (2000)</p>
Radionuclides	<ul style="list-style-type: none"> <li>• Literature</li> <li>• Sampling and analysis of source water and native groundwatera</li> <li>• Sampling and analysis of soil and aquifer</li> </ul>	<ul style="list-style-type: none"> <li>• Indicative concentrations</li> <li>• Source concentration, physicochemical characteristics of ambient groundwater</li> <li>• Reactivity of sediments</li> </ul>	<p>Cook and Herczeg (2000)</p> <p>Popit et al (2004)</p> <p>Gundersen and Wanty (1993); Herczeg and Dighton (1998)</p>
Hydraulics: pressure, groundwater levels, dissolution, aquitard stability	<ul style="list-style-type: none"> <li>• Literature</li> <li>• Monitoring of groundwater levels</li> <li>• Aquifer pump testinga</li> <li>• Geophysical well logging</li> <li>• Groundwater modelling</li> <li>• Geotechnical evaluation</li> <li>• Geochemical evaluation and modelling</li> </ul>	<ul style="list-style-type: none"> <li>• Initial parameter estimates</li> <li>• Hydrostatic conditions</li> <li>• Local aquifer hydraulic properties</li> <li>• Aquifer confinement, well integrity</li> <li>• Scenario modelling of piezometric fluctuations</li> <li>• Geotechnical properties of aquitard</li> <li>• Effect of mineral dissolution on well stability</li> </ul>	<p>Freeze and Cherry (1979)</p> <p>Freeze and Cherry (1979)</p> <p>Freeze and Cherry (1979)</p> <p>Pavelic et al (2001)</p> <p>Dillon et al (1999)</p> <p>Jones et al (2005)</p> <p>Le Gal La Salle et al (2005)</p>

**Table A3.1** (continued)

<b>Hazard</b>	<b>Methods of analysis</b>	<b>Information provided</b>	<b>References</b>
Groundwater-dependent ecosystems	<ul style="list-style-type: none"> <li>• Literature</li> <li>• Monitoring of groundwater levels</li> <li>• Sampling and analysis of source water, native groundwater and receiving surface water<sup>a</sup></li> <li>• Hydraulic and solute transport modelling</li> <li>• Ecotoxicity testing</li> </ul>	<ul style="list-style-type: none"> <li>• Initial parameter estimates</li> <li>• Hydrostatic conditions</li> <li>• Source concentration, physicochemical characteristics of ambient groundwater</li> <li>• Scenario modelling of piezometric fluctuations and impacts on surface water</li> <li>• Environmental impacts</li> </ul>	<p>Freeze and Cherry (1979)</p> <p>Freeze and Cherry (1979)</p> <p>Fies et al (2002)</p> <p>Fies et al (2002), Escalante et al (2005)</p> <p>ANZECC–ARMCANZ (2000a)</p> <p>Kumar (2009)</p>

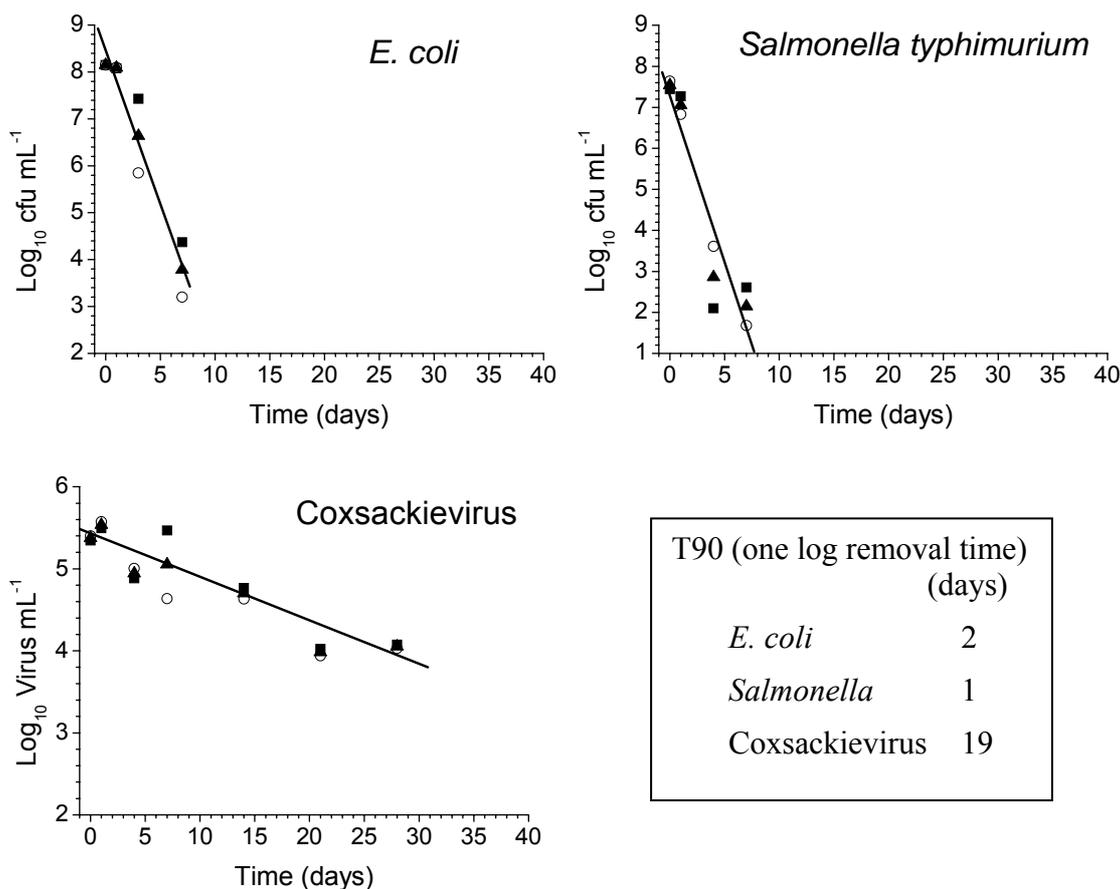
**a** Drilling of new wells may be required.

**b** A computer program designed to perform a wide variety of low-temperature aqueous geochemical calculations.

**c** A reactive multicomponent transport model for saturated porous media.

## Appendix 4 Inactivation rates for pathogens in aquifers (informative only)

Figure A4.1 shows examples of results of in situ diffusion chamber studies of attenuation of various enteric microorganisms in an unconfined aerobic aquifer at 23°C where reclaimed water from Subiaco sewage treatment plant is recharged via infiltration galleries at Floreat Park, Western Australia.



Source: Toze and Bekele (in press).

**Figure A4.1** Decay of enteric bacteria and virus in an aquifer at Floreat Park where infiltration galleries recharge secondary treated sewage effluent

Other available information from laboratory and field studies of degradation rates is listed in Table A4.1. Table A4.2 gives a brief description of the different enteric microorganisms used in the studies reported in Table A4.1. The results given in Figure A4.1 and Table A4.1 should be used only as an indication of the relative persistence of different enteric microorganisms in groundwater, and not as a general guide. Pathogen decay should be assessed at each specific site where reliance is placed on the aquifer for pathogen inactivation. Attenuation rates are best estimated using in situ chambers suspended in wells. An in situ assessment of pathogen survival is described in Pavelic et al (1998). If the residual risk of pathogens remains unacceptable, then additional forms of disinfection should be considered (along with their consequences, eg trihalomethane risks).

**Table A4.1 1 log<sub>10</sub> reduction times (T90) of enteric microorganisms**

Microorganism	Aerobic			Anaerobic	
	Temp (°C)	T90 (days)	Reference	T90 (days)	Reference
Coxsackievirus <sup>a</sup>	15	10	Gordon and Toze (2003) <sup>b</sup>	–	–
Coxsackievirus <sup>c</sup>	19–21	20	Jansons et al (1989) <sup>d</sup>	–	–
Coxsackievirus <sup>a</sup>	27	8	Toze and Hanna (2002) <sup>d</sup>	–	–
Coxsackievirus <sup>a</sup>	28	10	Gordon and Toze (2003) <sup>b</sup>	–	–
Coxsackievirus <sup>a</sup>	28	7–9	Toze et al (2002) <sup>d</sup>	144	Gordon and Toze (2003) <sup>b</sup>
MS2 <sup>a</sup>	12	77	Collins et al (2006) <sup>be</sup>	–	–
MS2 <sup>a</sup>	12	6–33	Yates et al (1985) <sup>bf</sup>	–	–
MS2 <sup>a</sup>	13	9–13	Yates et al (1985) <sup>bf</sup>	–	–
MS2 <sup>a</sup>	15	1	Gordon and Toze (2003) <sup>b</sup>	–	–
MS2 <sup>a</sup>	17	13	Yates et al (1985) <sup>bf</sup>	–	–
MS2 <sup>a</sup>	18	12	Yates et al (1985) <sup>bf</sup>	–	–
MS2 <sup>c</sup>	22	6	Toze et al (2002) <sup>d</sup>	–	–
MS2 <sup>a</sup>	23	<1	Blanc and Nasser (1996) <sup>be</sup>	–	–
MS2 <sup>a</sup>	23	2–6	Yahya et al (1993) <sup>bf</sup>	–	–
MS2 <sup>a</sup>	23	2–5	Yahya et al (1993) <sup>bf</sup>	–	–
MS2 <sup>a</sup>	27	5	Toze and Hanna (2002) <sup>d</sup>	–	–
MS2 <sup>a</sup>	27	<1	Alvarez et al (2000) <sup>bf</sup>	–	–
MS2 <sup>a</sup>	28	3	Gordon and Toze (2003) <sup>b</sup>	8	Gordon and Toze (2003) <sup>b</sup>
MS2 <sup>a</sup>	28	8–9	Toze et al (2002) <sup>d</sup>	–	–
Poliovirus <sup>a</sup>	15	5	Gordon and Toze (2003) <sup>b</sup>	–	–
Poliovirus <sup>a</sup>	28	1	Gordon and Toze (2003) <sup>b</sup>	77	Gordon and Toze (2003) <sup>b</sup>
<i>Escherichia coli</i> <sup>a</sup>	15	1	Gordon and Toze (2003) <sup>b</sup>	–	–
<i>E. coli</i> <sup>c</sup>	22	3	Toze et al (2002) <sup>d</sup>	–	–
<i>E. coli</i> <sup>a</sup>	27	1	Toze and Hanna (2002) <sup>d</sup>	–	–
<i>E. coli</i> <sup>a</sup>	28	1	Gordon and Toze (2003) <sup>b</sup>	6	Gordon and Toze (2003) <sup>b</sup>
<i>Salmonella Typhimurium</i> <sup>c</sup>	22	7	Toze et al (2002) <sup>d</sup>	–	–
<i>Salmonella Typhimurium</i> <sup>a</sup>	27	1	Toze and Hanna (2002) <sup>d</sup>	–	–

– = not determined.

**a** Survival rates determined using laboratory studies.

**b** Studies on pathogen decay in groundwater not necessarily relating to specific managed aquifer recharge schemes.

**c** Survival rates determined using in situ studies.

**d** Studies undertaken as part of specific managed aquifer recharge schemes.

**e** Redox conditions were not specified in the journal paper and not enough information was provided on the methodology to subsequently determine redox conditions.

**f** Redox conditions were not specified in the journal paper but are suspected to be aerobic due to the experimental methods used.

**Table A4.2 Brief descriptions of enteric microorganisms used in Table A4.1**

<b>Enteric microorganism</b>	<b>Details</b>
Coxsackievirus	<ul style="list-style-type: none"><li>• An enteric virus closely related to poliovirus and a common pathogen in most human communities, particularly in the young</li><li>• Causes a range of diseases including hand, foot and mouth disease</li><li>• Has been noted to be more resistant than poliovirus under most conditions</li><li>• An obligate intercellular pathogen</li></ul>
<i>Escherichia coli</i>	<ul style="list-style-type: none"><li>• An enteric bacterium commonly used as an indicator of fecal contamination and for treatment effectiveness</li><li>• The toxigenic form can be a pathogen in its own right</li><li>• Metabolically active in water</li></ul>
MS2	<ul style="list-style-type: none"><li>• A virus that only infects certain types of <i>E. coli</i> cells.</li><li>• Non-pathogenic to humans or animals</li><li>• Often used as a surrogate for enteric viruses, due to its similar morphology and great ease of detection and study</li></ul>
Poliovirus	<ul style="list-style-type: none"><li>• An enteric virus well documented for causing poliomyelitis (polio)</li><li>• Not a serious health hazard in Australia, due to broad vaccination of the community; but the vaccine strain is commonly detected in sewage effluent</li><li>• One of the enteric viruses least resistant to environmental conditions</li><li>• An obligate intercellular pathogen</li></ul>
<i>Salmonella Typhimurium</i>	<ul style="list-style-type: none"><li>• A bacterial pathogen causing gastroenteritis</li><li>• Metabolically active in water</li></ul>



## Appendix 5 Environmental fate data for organic chemicals (informative only)

Table A5.1 contains environmental fate parameters relevant to attenuation of selected organic chemicals in managed aquifer recharge. Where there are no specific fate data for an organic chemical hazard, research may be required to obtain site-specific data.

For chemicals subject to degradation, first-order exponential decay is assumed. However, the kinetic order of biotransformation for many organic chemicals occurring at the ng/L range is not known. If transformation of organic chemicals is characterised by co-metabolism, a zero-order kinetic has been shown to apply (Drewes et al 2008a); therefore, assuming first-order rate constants can result in overprediction of removal for the same residence time.

Degradation rates are known to vary with redox state (eg see Box 5.4), which can be defined by the concentrations of dissolved constituents (eg organic carbon, oxygen, nitrogen, manganese, iron, sulfate and methane). However, the half-life data in Table A5.1 are mainly defined by the presence (aerobic) or absence (anaerobic) of oxygen, rather than the range of redox states. In addition, laboratory attenuation studies are unlikely to simulate the microbial community that develops in an aquifer. Thus, the half-life data provided in Table A5.1 is intended for use in precommissioning risk assessments, in the absence of more specific data for comparable managed aquifer recharge case studies. The general information provided can be used to determine the most persistent organic chemical hazard or hazards affecting the recharge operation. For emerging chemicals without established guideline values, a process for setting guideline values for any chemical with respect to drinking water use is given in NRMCC–EPHC–NHMRC (2008).

Explanation of how to apply the fate parameters is given below; further information is given in Appendix 6.

### *Physical properties*

The aqueous concentration of an organic chemical will be limited by its solubility in water.

The movement of any undissolved (immiscible) organic chemicals through the subsurface is affected by the chemical's density. Light, non-aqueous phase liquids will accumulate at the top of the aquifer; dense, non-aqueous phase liquids will accumulate at the base.

### *Sorption*

When applying attenuation parameters such as linear distribution coefficients (defined below), it is assumed that:

- these processes are independent of residence time
- sorption at low concentrations can be extrapolated to higher concentrations.

Other non-linear sorption models may apply, but in practice are often linearised for simplicity of use. This especially applies to low-aqueous concentrations of chemicals.

For chemicals retarded by sorption, the partitioning between the solid and aqueous phases for linear isotherms (and often approximated for non-linear isotherms) is given by the distribution coefficient, commonly  $K_{OC}$  or  $K_d$  as defined in equation A5.1:

$$K_{OC} = \frac{100K_d}{f_{OC}} \text{ and } K_d = \frac{C_s}{C_{aq}} \quad (\text{equation A5.1})$$

where:

- $K_{OC}$  ( $\text{m}^3/\text{kg OC}$ ) is the adsorption coefficient related to the organic carbon (OC) content of the sediments  $f_{OC}$  (%)
- $K_d$  is the distribution coefficient for a linear isotherm (L/kg)
- $C_s$  is the concentration adsorbed to the solid phase (mol/kg)
- $C_{aq}$  is the concentration in the aqueous phase (mol/L).

$K_d$  and  $K_{OC}$  can be determined by laboratory studies, or calculated from the octanol–water partition coefficient ( $K_{OW}$ ) (Oliver et al 1996).

For organic species that dissociate into smaller ions, the  $K_{OC}$  can be corrected to represent sorption of the non-ionic fraction only (Kahn and Rorije 2002). The tendency of an organic compound to dissociate is indicated by the  $\text{pK}_a$  value, where the tendency to dissociate into an acidic ion increases as the  $\text{pK}_a$  decreases.

### **Volatilisation**

For chemicals subject to volatilisation, the partitioning between the gas and aqueous phases is given by the Henry's law constant, expressed as  $H$  (dimensionless) or  $K_H$  (M/atm) (equation A5.2);

$$H = \frac{C_{aq}}{C_g} \text{ and } K_H = \frac{H}{RT} \quad (\text{equation A5.2})$$

where:

- $C_{aq}$  is the concentration in the aqueous phase (mol/L)
- $C_g$  is the concentration in the gas phase (mol/L)
- $R$  is the gas constant (0.082057 L.atm/K.mol)
- $T$  is the temperature ( $^{\circ}\text{K}$ ).

Volatilisation is more significant for discharge into surface water bodies than into aquifers, but is a potential removal pathway for water recharged via infiltration basins.

### **Biodegradation**

Assuming first-order exponential decay, the concentration after a given residence time is given by equation A5.3:

$$C_t = C_0 10^{-t / \tau} \quad (\text{equation A5.3})$$

where:

- $C_0$  is the initial concentration (mol/L)
- $t$  is the residence time (days)

- $\tau$  is the time required for the initial concentration or number to be reduced to 10% of its original value (often called the 1- $\log_{10}$  removal time or T90 (ie time for 90% removal)).

The time constant for exponential decay reported in the table in Box A5.1 is the half-life, which is  $0.30\tau$ . Degradation half-lives can also incorporate the half-life of degradation byproducts.

**Box A5.1 Example of application of the environmental fate data for chloroform**

Consider the fate of chloroform, the most persistent trihalomethane, during storage for 20 days in an aquifer with either nitrate reducing or methanogenic conditions.

Starting with 380  $\mu\text{g/L}$  chloroform in the source water, and using the average half-lives for each redox state, the calculation below illustrates that storage in methanogenic conditions produces a final chloroform concentration below the guideline value; storing in nitrate reducing conditions does not. A longer storage period (>40 days) would therefore be required to reach the guideline value under nitrate reducing conditions. Note that little attenuation is expected under aerobic conditions (half-life > 120 days).

Initial concentration	380 $\mu\text{g/L}$
Guideline value	250 $\mu\text{g/L}$
Aquifer residence time	20 days
Half-life (average under nitrate reducing conditions)	70 days
Half-life (average under methanogenic conditions)	15 days
Final concentration (nitrate reducing aquifer)	312 $\mu\text{g/L}$
Final concentration (methanogenic aquifer)	150 $\mu\text{g/L}$
Residence time required to meet guideline (nitrate reducing aquifer)	42 days
Residence time required to meet guideline (methanogenic aquifer)	9 days

Table A5.2 summarises environmental fate data for transformation products exhibiting similar or greater toxicity than the parent compound.

Table A5.3 represents a broad qualitative categorisation of degradation rates for some measured trace organics recorded in soil aquifer treatment studies. These may assist in selecting reference species for risk assessments and in selecting indicator species for fate studies.

**Table A5.1 Environmental fate data for organic chemicals**

Chemical	Molar mass (g/mol)	Density (kg/m <sup>3</sup> )	pKa	Water solubility (mg/L)	K <sub>H</sub> (M/atm)	Sorption coefficients		Biodegradation half-life (days)	
						at 25°C		Aerobic	Anaerobic
Chlorinated alkanes									
<i>Chloromethanes</i>									
Bromoform	252.7	2889 [1]	–	3100 [1]	1.88 [2]	2.37 [2]	2.18 [3]	>120 [4] field trial	<1 methanogenic conditions 8–12 denitrifying conditions [5] field trial
Bromodichloromethane	163.8	1971 [6]	–	6735 [3]	0.42–4.72 [1]	1.88 [1] 2.10 [6]	1.68 [3]	>120 [4] field trial	9–29 methanogenic conditions 27–35 denitrifying conditions [5] field trial
Chloroform	119.4	1498 [6]	–	7950 [1]	0.27–0.34 [1]	1.97 [2] 2.22 [6]	1.77 [3]	>120 [4] field trial	13–18 methanogenic conditions 53–84 denitrifying conditions [5] field trial
Dibromochloromethane	208.3	2440 [1]	–	4000 [1]	0.13–1.00 [1]	2.08 [1]	1.92 [1] 1.89 [3]	>120 [4] field trial	11–36 methanogenic conditions 22–35 denitrifying conditions [5] field trial
Dichloromethane	84.9	1326 [6]	–	13200 [6]	0.31–0.44 [6]	1.25–1.30 [6]	1.00–1.25 [6]	7–28 [7] unacclimated lab test	28–112 [7] unacclimated lab test

**Table A5.1 (continued)**

Chemical	Molar mass (g/mol)	Density (kg/m <sup>3</sup> )	pKa	Water solubility (mg/L)	K <sub>H</sub> (M/atm)	Sorption coefficients		Biodegradation half-life (days)	
						at 25°C		Aerobic	Anaerobic
						Log K <sub>ow</sub>	Log K <sub>oc</sub>		
Carbon tetrachloride	153.8	1585 [8]	–	800 at 20°C [8]	0.033 [8]	2.73 [1] 2.83 [8]	2.35 [8] 2.64 [1]	168–360 [7] estimate	7–28 [7] unacclimated lab test and acclimated grab sample
<b><i>Chloroethanes</i></b>									
1,1-dichloroethane	99.0	1176 [1]	–	5060 [1]	0.17–0.23 [1]	1.78 [1]	1.48 [1] 1.60 [6]	32–154 [7] estimate	128–616 [7] estimate
1,2-dichloroethane	99.0	1253 [6]	–	8606 [6]	0.71–1.10 [6] 0.91 [1]	1.48 [1] 1.79 [6]	1.09 [6] 1.15– 1.28 [1]	100–180 [7] unacclimated grab sample	400–720 [7] estimate
1,1,1-trichloroethane	133.4	1338 [6]	–	950 [1]	0.077 [1] 0.203 [6]	2.17 [1] 2.49 [6]	1.70– 2.08 [6] 2.18 [1]	140–273 [7] estimate and grab sample	560–1092 [7] unacclimated lab test
1,1,2-trichloroethane	133.4	1440 [6]	–	4400 at 20°C [1]	1.10 [1] 1.43 [6]	2.07– 2.38 [6] 2.18 [1]	1.75 [1] 1.85 [6]	180–365 [7]	720–1460 [7] estimate
<b><i>Chlorinated alkenes</i></b>									
Chloroethene (vinyl chloride)	62.5	911 [1]	–	2763 [6]	0.013 [6]	0.60 [1] 1.00– 1.38 [6]	0.39 [1] 0.91 [6] 1.27 [9]	28–180 [7] lab test	56–2875 [7] groundwater field study of chlorinated ethenes
1,1-dichloroethene	96.9	1213 [3]	–	2250 [3]	0.0053 [1] 0.048 [6]	1.48 [1] 2.13 [6]	1.81 [1] 2.17 [6]	28–180 [7] estimate	56–173 [7]

**Table A5.1 (continued)**

Chemical	Molar mass (g/mol)	Density (kg/m <sup>3</sup> )	pKa	Water solubility (mg/L)	K <sub>H</sub> (M/atm)	Sorption coefficients		Biodegradation half-life (days)	
						at 25°C		Aerobic	Anaerobic
						Log K <sub>ow</sub>	Log K <sub>oc</sub>		
1,2-dichloroethane	99.0	1251(trans) – 1281(cis) [6]	–	3500(cis)–6260(trans) [6]	0.11–0.14 [6]	1.48 [1] 1.93 [6]	1.15 [1] 1.55 [6] 1.72 [9]	28–180 [7] estimate	112–2875 [7] estimate and unacclimated grab sample
Trichloroethene (TCE) <sup>a</sup>	131.4	1464 [1]	–	1100 [6]	0.085 [6] 0.10 at 20°C [1]	2.28 [6] 2.53–3.30 [1]	1.81 [1] 2.14 [6]	180–360 [7]	98–1653 [7] grab sample
Perchloroethene (PCE) <sup>a</sup>	165.8	1624 [1]	–	150 [1]	0.076–0.35 [1]	2.10–2.88 [1]	2.19 [9] 2.56 [1]	180–360 [7]	98–1653 [7] lab test
<b><i>Aromatic hydrocarbons</i></b>									
Benzene	78.1	877 [1]	–	1790 [1]	0.14–0.23 [6]	1.56–2.13 [1] 2.39 [6]	1.69–2.00 [1] 2.33 [6]	5–16 [7]	112–720 [7] unacclimated lab test
Toluene	92.1	867 [1]	–	524 [1]	0.12–0.20 [6]	2.10–3.00 [6] 2.50–2.80 [1]	2.06–2.18 [1] 2.85 [6]	4–22 [7] die-away test	56–210 [7] lab test and grab sample
Ethylbenzene	106.2	867 [1]	–	152 [6]	0.11–0.15 [6]	3.05 [1] 3.13–3.43 [6]	1.98–2.41 [1] 3.04 [6]	3–10 [7] die-away test data	176–228 [7] die-away test
o-xylene	106.2	880 [6]	–	175 [1]	0.18–0.20 [1]	2.73 [6] 3.13 [1]	2.11 [1] 2.73 [6]	7–28 [7] estimate	180–360 [7] acclimated grab sample
m-xylene	106.2	884 [6]	–	160 [6]	0.14–0.16 [1]	3.20 [1] 3.29 [6]	2.34 [6] 3.20 [1]	7–28 [7]	28–529 [7] unacclimated lab test

**Table A5.1 (continued)**

Chemical	Molar mass (g/mol)	Density (kg/m <sup>3</sup> )	pKa	Water solubility (mg/L)	K <sub>H</sub> (M/atm)	Sorption coefficients		Biodegradation half-life (days)	
						at 25°C		Aerobic	Anaerobic
						Log K <sub>ow</sub>	Log K <sub>oc</sub>		
p-xylene	106.2	861 [6]	–	180 [1]	0.14–0.16 [1]	3.08 [6] 3.18 [1]	2.05 [6] 2.31 [1]	7–28 [7]	28–360 [7] estimate
<i>Polycyclic aromatic hydrocarbons</i>									
Anthracene	178.2	1283 [6]	–	0.045 [1]	15.4–56.5 [1] 25.6–71.4 [6]	4.34–4.54 [1]	4.21–4.41 [1] 4.93 [6]	30–920 [7]	200–1840 [7] estimate
Fluoranthene	202.3	1252 [1]	–	0.265 [1]	18.5–779 [6] 59.2 [1]	4.70–5.22 [6]	4.00–6.38 [6] 4.62 [1]	120–880 [7]	560–1760 [7] estimate
Fluorene	166.2	1203 [1]	–	1.98 [1]	4.76 [1] 8.51–20.0 [6]	4.18 [1] 4.47 [6]	3.70 [1] 4.21 [6]	30–120 [7]	128–240 [7] estimate
Phenanthrene	178.2	1174 [6]	–	1.18 [1]	7.69–25.6 [1] 42.6 [6]	4.46 [1] 4.67 [6]	3.72–4.59 [1] 4.28 [6]	32–400 [7]	64–800 [7] estimate
Pyrene	202.3	1271 [1]	–	0.13 [6]	8.17–195 [6] 53.5–91.7 [1]	4.50–5.18 [6] 5.32 [1]	4.66–5.13 [1] 6.50 [6]	120–3800 [7]	840–7600 [7] estimate
<i>Chlorobenzenes</i>									
Chlorobenzene	112.6	1107 [6]	–	472 [1]	0.23–0.28 [1]	2.13–3.00 [6] 2.84 [10]	1.68 [1] 2.34 [9] 2.92 [6]	68–150 [7] unacclimated die-away test	261–600 [7] estimate

**Table A5.1 (continued)**

Chemical	Molar mass (g/mol)	Density (kg/m <sup>3</sup> )	pKa	Water solubility (mg/L)	K <sub>H</sub> (M/atm)	Sorption coefficients		Biodegradation half-life (days)	
						at 25°C		Aerobic	Anaerobic
						Log K <sub>ow</sub>	Log K <sub>oc</sub>		
1,2-dichlorobenzene	147.0	1306 [6]	–	156 [1]	0.42 [6]	3.38 [10] 3.55 [1] 3.90 [6]	2.27–3.23 [1] 2.79 [9]	28–180 [7] estimate	120–720 [7] estimate
1,3-dichlorobenzene	147.0	1288 [6]	–	123 [1]	0.22 [6] 0.38 [1]	3.40 [6] 3.60 [10] 3.72 [1]	2.23–3.23 [1] 3.00 [6]		
1,4-dichlorobenzene	147.0	1241 [6]	–	83 [6]	0.22 [6] 0.37 [1]	3.38 [1] 3.52 [10] 3.67 [6]	2.20 [1] 2.79 [9] 2.91 [6]		
1,2,3-trichlorobenzene	181.5	1690 [6]	–	21 [6]	0.31 [6] 0.42 [6]	3.75–4.28 [6]	2.00–3.70 [6]	28–180 [7] unacclimated grab sample	112–720 [7] estimate
1,2,4-trichlorobenzene	181.5	1454 [1]	–	35 [11]	0.23–0.37 [6]	3.93 [1] 4.02 [10] 4.10 [6]	2.70–3.09 [1] 4.30 [6]		
1,3,5-trichlorobenzene	181.5	1387 [6]	–	5.3 [6]	0.091 [6]	4.02–4.10 [6] 4.49 [10]	2.85 [6]		
<b>Phenols</b>									
2-chlorophenol	128.6	1257 [6]	–	28000 [1]	95.1–147 [6]	2.15 [10] 2.29 [6]	2.56 [1] 3.70 [6]		

**Table A5.1 (continued)**

Chemical	Molar mass (g/mol)	Density (kg/m <sup>3</sup> )	pKa	Water solubility (mg/L)	K <sub>H</sub> (M/atm)	Sorption coefficients		Biodegradation half-life (days)	
						at 25°C		Aerobic	Anaerobic
						Log K <sub>ow</sub>	Log K <sub>oc</sub>		
2,4-dichlorophenol	163.0	1383 [6]	7.9 [2]	4500 [1]	233–921 [6]	2.70–3.23 [6] 3.15 [1]	2.17 [9] 2.59 [6] 2.94 [1]	2.78–8.29 [7] aerobic die-away test data	13.5–43 [7] anaerobic die-away test
2,4,6-trichlorophenol	197.4	1490 [1]	–	800 [1]	178 [6] 1.10E+04 [1]	3.06 [1] 3.69 [6]	3.03 [1] 3.34 [6]	7–70 [7] unacclimated die-away test and soil grab sample	169–1820 [7] unacclimated grab sample
Pentachlorophenol	266.3	1978 [1]	4.7 [1]	14 [6]	294–3570 [1] 1280 [6]	3.25–5.05 [6] 5.86 [1]	2.95 [1] 4.54 [6]	23–178 [7] acclimated grab sample	42–1520 [7] unacclimated grab sample
<b>Pesticides</b>									
Aldrin	364.9	1700 at 20°C [8]	–	0.18 [8]	2.02 [8]	5.17 [1] 7.40 [8]	2.61 [1] 4.69 [8]	21–592 [7] unacclimated die-away test	1–7 [7]
Chlordane	409.8	1590 [1]	–	0.056 [8]	20.8 [8]	6.00 [8]	4.58–5.57 [8]	238–1386 [7] unacclimated die-away test	1–7 [7] grab sample
Chlorpyrifos	350.6	1398 [8]	–	1.4 [15]	240 [8]	5.2 [8]	3.41–4.49 [15]	10–81 [13]	–
DDT (Dichlorodiphenyltrichloroethane)	354.5	1560 at 15°C [8]	–	0.0012 [8]	9.71–26.3 [1]	4.89 [8] 5.76–6.19 [1]	5.15–6.26 [8] 5.38 [1]	730–5708 [7]	16–11250 [7]
Diazinon	304.3	1116 at 20°C [8]	2.5 [2]	60 [14]	8930 [8]	3.81 [8]	3.00–3.27 [8]	5–59 [16] rate increases with moisture content	–

**Table A5.1 (continued)**

Chemical	Molar mass (g/mol)	Density (kg/m <sup>3</sup> )	pKa	Water solubility (mg/L)	K <sub>H</sub> (M/atm)	Sorption coefficients		Biodegradation half-life (days)	
						at 25°C		Aerobic	Anaerobic
						Log K <sub>ow</sub>	Log K <sub>oc</sub>		
Dieldrin	380.9	1750 at 20°C [8]	–	0.2 [1]	17.2 [8]	3.69–6.20 [8] 4.55–5.48 [1]	4.08–4.55 [8]	175–1080 [7]	1–7 [7]
Endosulfan <sup>a</sup>	406.9	1745 at 20°C [8]	–	0.32 [14] 0.53 [2]	9.9 [8] 52.4 [2]	3.55 [8]	3.31 [8]	2–14 [7] unacclimated die-away test and grab sample	8–56 [7] estimate
Heptachlor <sup>a</sup>	373.3	1660 at 20°C [8]	–	0.18 [8]	0.435 [8]	4.40 [8] 5.44 [1]	4.38 [8] 6.15 [9]	15–64 [7] unacclimated grab sample	60–261 [7] unacclimated lab test
Lindane	290.8	1870 at 20°C [8]	–	7.52 [8]	503 [8]	3.20 [1] 3.89 [8]	2.38 [8] 3.52 [1]	400 [14]	–
<b><i>Herbicides and fungicides</i></b>									
Atrazine <sup>a</sup>	215.7	1187 [3]	1.6 at 20°C [2]	33 [14]	3.29E+05 [8]	2.27 [8]	1.59 (sand) – 2.19 (loam) [12]	60 average, ranging from 21–131 [17]	164–200 [13]
2,4-dichloro phenoxy acetic acid	221.0	1416 [8]	2.6–3.3 [2] 2.8 [14]	890 [14]	184–98400 [6]	0.92 [6] 1.47–4.88 [8]	1.30 [6] 1.68–2.73 [8]	10–50 [7] unacclimated die-away test 1.8–3.1 [6] with co-metabolism	28–180 [7] estimate 69–135 [6]
Diuron	233.1	1385 [8]	–1 to –2 [2]	36 [18]	1.98E+06 [15]	2.58 [8]	2.21 [8]	20–119 [16]	995 [18]

**Table A5.1 (continued)**

Chemical	Molar mass (g/mol)	Density (kg/m <sup>3</sup> )	pKa	Water solubility (mg/L)	K <sub>H</sub> (M/atm)	Sorption coefficients		Biodegradation half-life (days)	
						at 25°C		Aerobic	Anaerobic
						Log K <sub>ow</sub>	Log K <sub>oc</sub>		
Simazine	201.7	1302 [3]	1.7 at 20°C [2]	4.0 [2]	2.94E+05 at 20°C [2]	1.94 [2] 2.18 [12]	1.57 (sand) – 2.04 (sandy loam) [13]	60 average, range 10–300 [17]	–
<i>Miscellaneous organic chemicals</i>									
Bisphenol A	228.0	1200 [11]	–	120 [19]	1.00E+07 [10]	3.32 [19]	2.89 [19]	persistent [19] lab study using aquifer material at 20°C	persistent [19] lab study using aquifer material at 20°C
DEHP(Di(2-ethylhexyl) phthalate)	390.6	983 [6]	–	0.34 [3]	67.8–3570 [6] 90.9 [1]	3.58–5.11 [6] 4.20 [1]	4.00–5.00 [1]	5–23 [7] unacclimated die-away test	41–389 [7] unacclimated die-away test
4-tert-octylphenol (4-t-OP)	206.0	–	–	12.6 [19]	–	4.12 [19]	4.26 [19]	persistent [19] lab study using aquifer material at 20°C	persistent [19] lab study using aquifer material at 20°C
4-n-nonylphenol (4-n-OP)	220.0	–	–	5.43 [19]	–	4.48 [19]	4.59 [19]	7 [19] lab study using aquifer material at 20°C	persistent [19] lab study using aquifer material at 20°C
Tributyl phosphate	266.3	980 [11]	–	280 [15]	709 [15]	4.00 [15]	–	–	–
TCEP (tris-(chloroethyl)-phosphate)	285.5	1420 [22]	–	8000 at 20°C [22]	–	1.7 [22]	2.56 [22]	–	degradable [23] SAT

**Table A5.1 (continued)**

Chemical	Molar mass (g/mol)	Density (kg/m <sup>3</sup> )	pKa	Water solubility (mg/L)	K <sub>H</sub> (M/atm)	Sorption coefficients		Biodegradation half-life (days)	
						at 25°C		Aerobic	Anaerobic
						Log K <sub>ow</sub>	Log K <sub>oc</sub>		
TCIPP (tris-(chloroisopropyl)-phosphate)	327.5	1290 [22]	–	1600 at 20°C [22]	–	2.6 [22]	2.8 [22]	–	persistent [23] SAT
<b>Additional disinfection byproducts</b>									
Trichloroacet-aldehyde (chloral hydrate)	147.4	1512 [3]	9.7 at 30°C [15]	3.00E+04 [15]	3.44E+05 [15]	0.99 [15]	–	–	–
EDTA (ethylenediamine tetraacetic acid)	292.2	860 [11]	0.26 [15]	500 [11] 1000 [15]	8.55E+19 [15]	–3.86 [15]	–	–	–
Chloroacetonitrile	75.5	1193 [3]	–	1.00E+05 [15]	92.6 [15]	0.45 exp [15]	–	–	–
Chloroacetic acid	94.5	1404 [6]	2.9 [2]	1.072E+05 [2]	–	0.22 [2]	–	1–7 [7]	4–28 [7] estimate
Dichloroacetic acid	128.9	1563 [6]	1.3 [2]	86300 [6] 1.00E+06 [15]	1.19E+05 [15]	0.92 [6]	0.72 [3]	–	<1 nitrate reducing [5] field trial
Trichloroacetic acid	163.4	1620 [6]	0.52 [2]	44000 [15] 1.15E+05 [6]	74100 [15]	1.33 [6]	1.51 [3]	–	<1 nitrate reducing [5] field trial
<b>Pharmaceuticals</b>									
Amoxicillin	365.4	–	2.4 [20]	–	–	–	3 [20]	–	degradable [20] estimate
Cefaclor	367.8	–	2.4 [20]	–	–	–	3 [20]	–	partly degradable/persistent [20] estimate

**Table A5.1 (continued)**

Chemical	Molar mass (g/mol)	Density (kg/m <sup>3</sup> )	pKa	Water solubility (mg/L)	K <sub>H</sub> (M/atm)	Sorption coefficients		Biodegradation half-life (days)	
						at 25°C		Aerobic	Anaerobic
						Log K <sub>ow</sub>	Log K <sub>oc</sub>		
Carbamazepine	236.3	–	–	–	–	–	–	–	persistent [23] SAT
Cephalexin	347.4	–	2.5 [20]	1790 [15]	3.61E+13 [15]	0.65 [15]	3 [20]	–	degradable [20] estimate
Clofibric acid	214.6	–	3.2 [20]	–	–	–	2 [20]	–	persistent [20] estimate
17β-estradiol	272.4	–	–	13 at 20°C [19]	2.75E+07 [15]	3.94 [19]	3.64 [19]	2 [19] lab study using aquifer material at 20°C	107 [19] lab study using aquifer material at 20°C degradable [23] SAT
17α-ethinyl estradiol	296.4	–	–	4.8 at 20°C [19]	1.26E+08 [15]	4.15 [19]	3.68 [19]	81 [19] lab study using aquifer material at 20°C	persistent [19] lab study using aquifer material at 20°C
Gemfibrozil	250.3	–	4.8 [20]	–	–	–	3 [20]	–	degradable [20] estimate degradable [23] SAT
Ibuprofen	206.3	–	4.4 [20]	21 [15]	6.67E+03 [15]	3.97 [15]	3 [20]	–	degradable [20] estimate degradable [23] SAT
Metformin	165.6	–	2.8 [20]	–	–	–	2 [20]	–	degradable [20] estimate
Naproxen	230.3	–	4.2 [20]	16 [15]	2.95E+06 [15]	3.18 [15]	3 [20]	–	degradable [20] estimate degradable [23] SAT
Phenazone	188.2	–	–	–	–	–	–	~15 [21] lab and field studies	persistent [21] lab and field studies

**Table A5.1 (continued)**

Chemical	Molar mass (g/mol)	Density (kg/m <sup>3</sup> )	pKa	Water solubility (mg/L)	K <sub>H</sub> (M/atm)	Sorption coefficients		Biodegradation half-life (days)	
						at 25°C		Aerobic	Anaerobic
						Log K <sub>ow</sub>	Log K <sub>oc</sub>		
Primidone	218.3	–	–	–	–	–	–	–	persistent [23] SAT
Roxithromycin	-	–	–	–	–	–	–	–	degradable [20] estimate
Salicylic acid	138.1	–	3.0 [20]	2240 [15]	1.36E+05 [15]	2.26 [15]	1 [20]	–	degradable [20] estimate

– = not available; EDTA = ethylenediaminetetraacetic acid; SAT = soil aquifer treatment.

**a** Transformation product/s exhibit similar or greater toxicity (see Table A5.2 for fate data).

**References:**

- [1] Montgomery and Welkom (1991)
- [2] Dillon and Toze (2005)
- [3] Cabridgesoft Corporation (2004)
- [4] Pavelic et al (2006a)
- [5] Pavelic et al (2005)
- [6] Mackay et al (1992)
- [7] Howard (1991)
- [8] Montgomery (1997)
- [9] Illinois General Assembly (2008)
- [10] Howard (1989)
- [11] IPCS (2008)
- [12] Oliver et al (1996)
- [13] Vogel (2005)
- [14] Wauchope et al (1992)
- [15] SRC (1999)
- [16] APVMA (2007)
- [17] Barbash and Resek (1997)
- [18] DPR (2007)
- [19] Ying et al (2003)
- [20] Kahn and Rorije (2002)
- [21] Greskowiak et al (2006)
- [22] NICNAS (2001)
- [23] Amy and Drewes (2007).

**Table A5.2 Environmental fate data for transformation products exhibiting similar or greater toxicity than the parent compound**

Transformation product	Parent compound/s	Water solubility (mg/L)	Sorption coefficients		Biodegradation half-life (days)	Toxicity compared to parent compound
			Log $K_{ow}$	Log $K_{oc}$		
DDD (Dichlorodiphenyldichloroethane)	DDT	0.04 [1]	6.51 [1]	–	–	similar, measured as total DDT
DDE (Dichlorodiphenyldichloroethylene)	DDT	0.04 [1]	6.51 [1]	–	–	
DEA (Desethylatrazine)	Atrazine	2700 [2]	1.51 [1]	1.61 (sand) – 1.90 (loam) [3]	42–327 atrazine and DEA [4], aerobic conditions	slightly less toxic than atrazine
Endosulfan sulfate	Endosulfan	0.18 [5]	3.66 [5]	3.37 [6]	30–270 endosulfan and endosulfan sulfate [7], aerobic conditions	acute toxicity, similar to parent compound
Heptachlor epoxide	Heptachlor	0.28 [5]	3.65 [5]	4.32 [6]	33–552 aerobic grab sample, 1–7 anaerobic grab sample [8]	more
Vinyl chloride	Perchloroethene, trichloroethene	8800 [1]	1.62 [1]	–	persistent [9], requires deeply anaerobic conditions	more, known carcinogen

– = not available.

**References:**

- [1] SRC (1999)
- [2] Vogel (2005)
- [3] Oliver et al (1996)
- [4] Barbash and Resek (1997)
- [5] Montgomery and Welkom (1991)
- [6] Montgomery (1997)
- [7] International POPs Elimination Network (2007)
- [8] Howard (1991)
- [9] Bradley (2000).

**Table A5.3 Treatment removal categories for indicator compounds of soil aquifer treatment systems under specified conditions<sup>a</sup> (adapted from Drewes et al 2008b)**

	Good Removal	Intermediate Removal		Poor Removal
	>90%	90–50%	50–25%	<25%
Acetaminophen	Ketoprofen	Meprobamate	Chloroform	Carbamazepine
Acetyl cedrene <sup>1</sup>	Mecoprop			Primidone
Atenolol <sup>2</sup>	Methyl dihydrojasmonate <sup>2</sup>			TCEP
Atorvastatin <sup>1</sup>	Methyl ionine <sup>3</sup>			TCPP
Atorvastatin (o-hydroxy) <sup>1</sup>	Methyl salicylate <sup>2</sup>			TDCPP
Atorvastatin (p-hydroxy) <sup>1</sup>	Metoprolol			Dilantin
Benzyl acetate <sup>2</sup>	Musk ketone <sup>1</sup>			
Benzyl salicylate <sup>3</sup>	Musk xylene <sup>1</sup>			
Bisphenol A	Naproxen			
Bucinal <sup>3</sup>	NDMA			
Butylated hydroxyanisole <sup>3</sup>	Nonylphenol			
Caffeine	OTNE <sup>1</sup>			
DEET	Phenylphenol <sup>2</sup>			
Dichlorprop	Propranolol			
Diclofenac	Propylparaben <sup>2</sup>			
EDTA	Salicylic acid			
Erythromycin-H <sub>2</sub> O	Simvastatin hydroxy acid <sup>3</sup>			
Estriol	Sulfamethoxazole			
Estrone	Terpineol <sup>1</sup>			
Fluoxetine	Tonalide <sup>1</sup>			
Galaxolide <sup>1</sup>	Triclobarban <sup>1</sup>			
Gemfibrozil	Triclosan			
Hexyl salicylate <sup>3</sup>	Trimethoprim			
Hexylcinnamaldehyde <sup>1</sup>				
Hydrocodone				
Ibuprofen				
Indolebutyric acid <sup>2</sup>				
Iopromide				
Isobornyl acetate <sup>1</sup>				
Isobutylparaben <sup>3</sup>				

**a** Recycled water quality — biodegradable dissolved organic carbon concentration >3 mg/L; subsurface conditions — travel time ≥4 weeks; predominant redox conditions — oxic followed by anoxic; no dilution with native groundwater (from Drewes et al 2008b).

Note: Removal of compounds with no footnote verified through peer-reviewed literature data or experimental data generated during a study by Drewes et al (2008b).

<sup>1</sup> Removal estimated based upon  $\log K_d > 3.0$  (pH 7);

<sup>2</sup> Removal estimated as fast biodegradation based upon BioWin prediction;

<sup>3</sup> Removal estimated based upon  $\log K_d > 3.0$  (pH 7) AND fast biodegradation based upon BioWin prediction (see Drewes et al 2008b) where  $K_d$  is the distribution coefficient (equation A5.1).

DEET = N,N-diethyl-meta-toluamide; EDTA = ethylenediaminetetraacetic acid; NDMA = N-nitrosodimethylamine; OTNE = (1-(1,2,3,4,5,6,7,8-octahydro-2,3,8,8-tetramethyl-2-naphthalenyl)ethanone); TCEP = tris(2-chloroethyl) phosphate; TCPP = tris(1-chloro-2-propyl) phosphate; TDCPP = tris(1,3-dichloro-2-propyl) phosphate.

# Appendix 6 Prediction of pathogens and organic chemicals in groundwater and recovered water (informative only)

## A6.1 Managed aquifer recharge in different situations

The methods described in this appendix (derived from Dillon et al 2005b) enable prediction of the removal of pathogens and biodegradable organics:

- between injection and recovery wells
- for ASR (aquifer storage and recovery) with nearby production wells
- for simple ASTR (aquifer storage transfer and recovery) projects
- between the river bank and production wells in bank filtration projects.

The methods assume a homogeneous isotropic aquifer, of uniform thickness and porosity, with:

- uniform ambient hydraulic gradient
- uniform rate of pumping and extraction
- a constant exponential rate of biodegradation or pathogen inactivation
- a linear adsorption isotherm for organics.

In its simplest form, only two non-dimensional parameters are needed to define the number of  $\log_{10}$  reductions or biodegradation during transport through the aquifer to the recovery well. These parameters describe advective transport due to pumping wells and the regional hydraulic gradient respectively. They uniquely define the ratio of minimum travel time to the time for 1- $\log_{10}$  reduction; and therefore, define the number of  $\log_{10}$  reductions of the contaminant reaching neighbouring wells.

Although this nomogram, and the analytical models on which it is based, do not cover complex situations, they are expected to be useful as a planning tool. They will assist in designing managed aquifer recharge projects, and evaluating proposed projects at a Stage 2 assessment level, using data from Appendix 4 and Appendix 5 on 1-log removal times of pathogens and organic chemicals.

For a Stage 3 assessment, more advanced modelling methods are likely to be needed; methods that are capable of dealing with more realistic aquifer considerations, such as groundwater flow and solute transport modelling, and geochemical and reactive contaminant modelling.

### Documentation of method

First, it is assumed that the pathogens (or other trace organic contaminants) undergo first-order exponential decay with respect to residence time in the aquifer.

$$C_t = C_0 10^{-t/\tau} \quad (\text{equation A6.1})$$

where:

- $C_t$  is the concentration or number of viable pathogens per unit volume after storage time  $t$
- $C_o$  is the concentration or number in water recharged via the injection well
- $\tau$  is the time required for the initial concentration or number to be reduced to 10% of its original value, often called the 1- $\log_{10}$  removal time. This is 3.32 multiplied by the half-life, another commonly used measure of the rate of exponential decay (as used in Appendix 5).

### *Single-well systems*

The minimum residence time of injected water in the aquifer in ASR systems is simply the storage period between injection and recovery, defined here as  $t_s$ . Hence, the worst-case scenario for biodegradation or inactivation is when  $t = t_s$  in equation A6.1, neglecting the potential effect of dilution with native groundwater.

### *Dual-well systems*

For ASTR, or for ASR with a nearby pumping well that needs its water quality protected, the worst-case scenario considers that the water has travelled to the recovery well along the shortest flow path, when the injection and recovery wells are operating continuously (at the same rate). This gives the minimum travel time ( $t_{\min}$ ) over which biodegradation can occur. If the ambient groundwater velocity is small with respect to the gradients induced by the injection and recovery wells, and assuming injection and pumping rates are equal,

$$t_{\min} = \frac{\pi D n_e L^2}{3Q} \quad \text{(equation A6.2)}$$

where:

- $D$  is the aquifer thickness (m)
- $L$  is the distance between injection and recovery wells (m)
- $n_e$  is the porosity of the aquifer (-)
- $Q$  is the rate of steady-state pumping (in and out) ( $\text{m}^3 \text{d}^{-1}$ ).

The shortest travel time occurs when there is a regional hydraulic gradient in the aquifer, and the recovery well is situated directly downgradient of the injection well. Dilution with ambient groundwater is neglected, as this leads to increased contaminant attenuation. In such a two-well system,  $t_{\min}$  is given by Rhebergen and Dillon (1999) as

$$t_{\min} = \frac{n_e L}{\frac{3Q}{\pi DL} + v_{do}} \quad \text{(equation A6.3)}$$

where:  $v_{do}$  is the Darcian velocity due to ambient regional flow in the direction from the injection well towards the recovery well ( $\text{m d}^{-1}$ ).

As continuous concurrent injection and recovery rarely occur, equation A6.3 is likely to underestimate travel time, because when wells are operated intermittently, the average hydraulic effective gradient over the travel time will be less than the value that has been assumed in this equation (worst-case scenario).

Assuming that the organic chemical or pathogen of interest is also sorbed onto the aquifer matrix with a linear adsorption isotherm, then hazard transport is slowed by a constant retardation factor ( $R$ ) with respect to conservative transport of the water molecules. Thus, the minimum travel time ( $t_{\min i}$ ) of a hazard ( $i$ ) is a factor  $R$  multiplied by the travel time of conservative solutes that move at the same rate as the water, that is

$$t_{\min i} = R t_{\min} \quad (\text{equation A6.4})$$

where:  $R = 1 + K_d \rho / n_e$  (equation A6.5)

and  $K_d = f_{oc} K_{oc}$  (equation A6.6)

where:

- $K_d$  is the distribution coefficient for a linear adsorption isotherm ( $\text{m}^3/\text{kg}$ )
- $\rho$  is the dry bulk density of the porous media ( $\text{kg}/\text{m}^3$ )
- $f_{oc}$  is the weight fraction of organic carbon in the porous media (-)
- $K_{oc}$  is the adsorption coefficient related to organic carbon content ( $\text{m}^3/\text{kg}$  organic carbon).

In this model, sorption acts only to extend the travel time during which biodegradation takes place. By itself, sorption is not regarded as a sustainable attenuation process. It is also assumed that all of the water from the pumping well originates from the injection well.

#### **Bank filtration**

From image-well theory, constant head along a stream can be approximated by an injection and recovery well pair bisected by the stream (as in equation A6.2); but, substituting the distance ( $a$ ) between the stream and the pumping well ( $a = L/2$ ) and noting that the water derived from the stream has only half the travel distance of the water traveling from the image well to the pumping well. This results in equation A6.7 (Dillon et al 2002)

$$t_{\min} = \frac{2\pi D n_e a^2}{3Q} \quad (\text{equation A6.7})$$

In this instance, the rate of streambed infiltration ( $q$ ) induced by pumping from the well at a rate ( $Q$ ) at any time ( $t$ ) since the commencement of pumping is approximated by Glover and Balmer (1954) as

$$\frac{q}{Q} = \text{erfc} \left( \frac{a}{\sqrt{4\alpha t}} \right) \quad (\text{equation A6.8})$$

where  $\alpha$  is aquifer diffusivity (transmissivity/storage coefficient), and here in an unconfined system of approximately constant saturated thickness ( $D$ ) and hydraulic conductivity ( $K$ ) is  $KD/n_e$ . For steady-state pumping, the value of  $q/Q$  is 1 for a semi-infinite aquifer with an initially horizontal free surface.

A hazard originating from the stream at a steady concentration ( $C_0$ ) reaches a concentration ( $C_t$ ) in the well at time ( $t$ ) is given by equation A6.9; this is a restatement of equation A6.1 accounting for equations A6.4, A6.7 and A6.8. Dillon et al (2002) also account for the effect of conservative hazards (eg salinity) in groundwater for bank filtration design.

$$C_t = C_0 \frac{q}{Q} 10^{-R t_{\min} / \tau} \quad (\text{equation A6.9})$$

### **Other situations**

The concentration remaining at the point of discharge may be calculated wherever:

- the travel time between a constant sole source of hazard and a point of groundwater discharge can be calculated
- the relative contribution of that source to the discharge can be calculated
- retardation and degradation or inactivation rates are known.

Aquifer Storage and Recovery Risk Index (ASRRI) is a computer program developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) that uses the principles outlined above to calculate the risk of contamination for a range of single and dual-well ASR systems (Miller et al 2002). The risk indexes calculate whether specific organic chemicals or pathogens in the recovered water would reach their target attenuation ratio (log removal) or their guideline value for a given scenario.

### **Nomogram for dual-well system**

Using three non-dimensional terms (each with a physical meaning), a nomogram based on equations A6.1, A6.3 and A6.4 was produced, to define the  $\log_{10}$  removal under a range of scenarios for dual-well systems. This allows separation distances or pumping rates to be determined that will meet any required number of log removals for a given set of aquifer characteristics (eg depth, porosity, Darcian velocity, retardation factor [organic carbon fraction]). The non-dimensional terms are described below.

Term 1: Advective transport expression due to pumping wells  $\frac{n_e L^2 DR}{Q\tau}$

Term 2: Advective transport due to regional hydraulic gradient  $\frac{n_e LR}{v_{do}\tau}$

Term 3: The ratio of hazard travel time to 1- $\log_{10}$  removal time  $\frac{t_{\min}}{\tau}$

The nomogram shown in Figure A6.1 can be used in various ways.

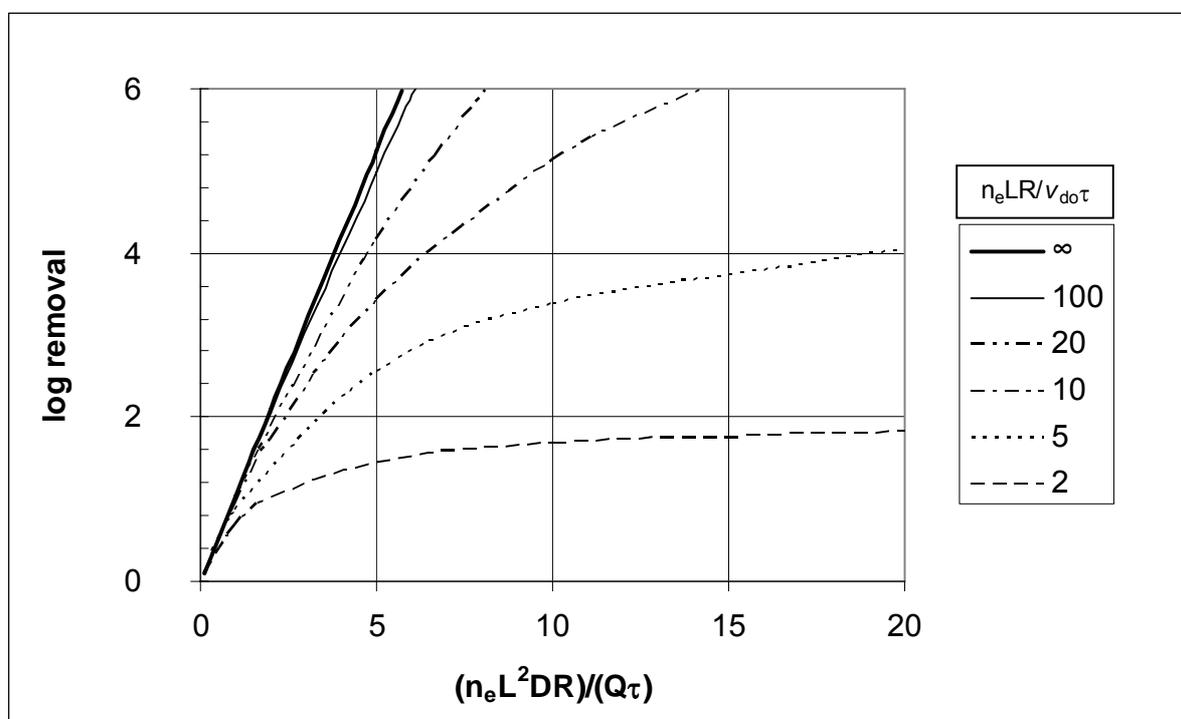
Knowing existing or planned well locations and aquifer properties, and an approximate 1- $\log_{10}$  removal time, for example, from Dillon et al (2005b), a value for Term 1 can be found on the  $x$ -axis, and a curve value for Term 2 can be used to interpolate a  $y$ -coordinate value on the nomogram. This immediately defines the value of Term 3, which also defines the  $\log_{10}$  reduction expected for that hazard.

Alternatively, if the aim is to achieve a given log removal (eg 4-log), then the curve parameter (Term 2) cannot be less than five. The curve parameter (Term 2) is composed of variables that are intrinsic to the aquifer and the hazard, and the sole control variable is the separation distance ( $L$ ). Hence,  $L$  can be increased, in principle, so that it is sufficiently large that the curve rises above the number of log removals required.

Term 1 contains two control variables. It is proportional to  $L^2$ , and inversely proportional to  $Q$ . In this case, if Term 2 had a value of 10, then Term 1 would need a value exceeding 7 to achieve the required 4-log removals. This may require reducing the pumping rate.

The nomogram shows that for some combinations of characteristics, no realistic system design will produce sufficient log removal for satisfactory performance. In those areas, ASR should be prevented unless the injected water is adequately pretreated. Conversely, higher  $n_e$ ,  $L$  and  $R$  values increase Terms 1 and 2 to give more time for biodegradation, and result in a higher log removal.

Note that the curve parameter tends towards infinity as the ambient gradient approaches zero. Fildebrandt et al (2003) also provide nomograms for recovery wells positioned upgradient of the injection well, and at various angles; however, the downgradient direction is normally expected to be the most critical case for decision making concerning water-quality impacts on the aquifer.



**Figure A6.1** Nomogram for dual-well ASR system (recovery well downgradient of injection well)

Box A6.1 contains examples of calculating attenuation zone size.

**Box A6.1 Calculation of attenuation zone size for different situations**

Aquifer properties: effective porosity,  $n_e = 0.3$ ; thickness,  $D = 20$  m

Operational properties: injection rate,  $Q = 1000$  m<sup>3</sup>/day

Hazard properties:  $\tau = T_{90} = 30$  days (in this aquifer). In this simple example, assume hazard is not sorbed on aquifer material (that is retardation factor,  $R = 1$ )

Rearranging equations A6.2, A6.3 and A6.7 allows calculation of minimum distances required for attenuation.

The examples below show the requirement for 4-log removals of a constituent.

**Single-well ASR, in an aquifer with no ambient hydraulic gradient**

- (a) minimum storage time  $t_{\min} = 4$ ;  $\tau = 120$  days
- (b) minimum attenuation zone radius = 80 m (see equation A6.10 below)
- (c) minimum radius to nearest well pumping at the same rate as the injection rate = 138 m (see equation A6.11 below).

**ASTR operation**

These requirements also apply in the case of a neighbouring downgradient well pumping at the same rate as the injection rate in an aquifer with an ambient (pre-pumping) hydraulic gradient from the injection well towards the discharging well; the minimum separation distance for the same attenuation (and travel time) depends on the ambient hydraulic gradient. In the same aquifer, the gradients and corresponding minimum separation lengths (without a Stage 3 assessment) would be:

- (a) no gradient = 0 m/year      138 m (see equation A6.11 or A6.12)
- (b) 0.1 m/day = 36 m/year      160 m (see equation A6.12)
- (c) 0.5 m/day = 183 m/year      270 m (see equation A6.12)
- (d) 1 m/day = 365 m/year      440 m (see equation A6.12).

**Bank filtration well**

For a bank filtration well pumping at the same rate near a stream or river in the same aquifer with no ambient hydraulic gradient, the minimum setback from the bank is 98 m to give 4-log removal (see equation A6.13).

In each case, there is no allowance for heterogeneity of the aquifer. All aquifers contain some horizons that convey water faster than the mean rate of flow. Therefore, minimum travel times may be shorter than the mean velocities on the shortest pathways between points of recharge and discharge or observation. Based on experience with an aquifer, a factor may be applied to travel time used in these calculations, and hence to the separation lengths, to increase confidence that attenuation will occur within the defined zone.

Down-hole electromagnetic flow metering (listed in Appendix 3) may be applied as a means to quantify this factor (eg Pavelic et al 2006b).

Equations A6.2, A6.3 and A6.7 rearranged to calculate separation distances are:

- for distance to observation well on perimeter of attenuation zone

$$L = \sqrt{(Qt_{\min} / \pi D n_e)} \quad \text{(equation A6.10)}$$

- for separation of injection and recovery wells — no ambient hydraulic gradient

$$L = \sqrt{(3Qt_{\min} / \pi D n_e)} \quad \text{(equation A6.11)}$$

- for separation of injection well from downgradient recovery well

$$L = v_{d0} t_{\min} / 2n_e + \sqrt{((v_{d0} t_{\min})^2 + 12 n_e Qt_{\min} / \pi D)} / 2n_e \quad \text{(equation A6.12)}$$

- for separation of bank filtration recovery well from edge of stream or lake

$$a = \sqrt{(3Qt_{\min} / 2\pi D n_e)} \quad \text{(equation A6.13)}$$

## A6.2 Managed aquifer recharge involving infiltration through the unsaturated zone

Aerobic attenuation rates are generally faster in the unsaturated zone than below the watertable for two reasons:

- The relative abundance of oxygen, nutrients and microbial biofilm in comparison to the saturated zone.
- The interstitial water is often associated with the grains of the media and is therefore closer to the attached microbial biofilm, which generally constitutes 99% of microbial biomass in porous media.

In an unsaturated zone, variations in infiltration rate, temperature and nutrients result in a more dynamic system than in the saturated zone. Hence, attenuation of constituents is less reliably predicted. For this reason, to assume the same rates of attenuation in the unsaturated zone as in an aerobic saturated aquifer at the same temperature is, in the absence of other data, a risk-averse assessment of attenuation.

Hence, attenuation during infiltration precedes attenuation during residence in the aquifer, before recovery or detection at nearby wells where water quality must be protected.

Soil aquifer treatment systems, which involve intermittent infiltration of treated sewage from basins, have demonstrably higher levels of attenuation of nutrients such as nitrogen (due to alternate nitrification and denitrification). Nitrogen removal rates are determined on a site-specific and operation-specific basis. Examples are listed in Section 5.4.

The travel time through the unsaturated zone has traditionally been calculated using equation A6.14

$$t_u = \frac{d_u n_e}{i} \quad (\text{equation A6.14})$$

where:

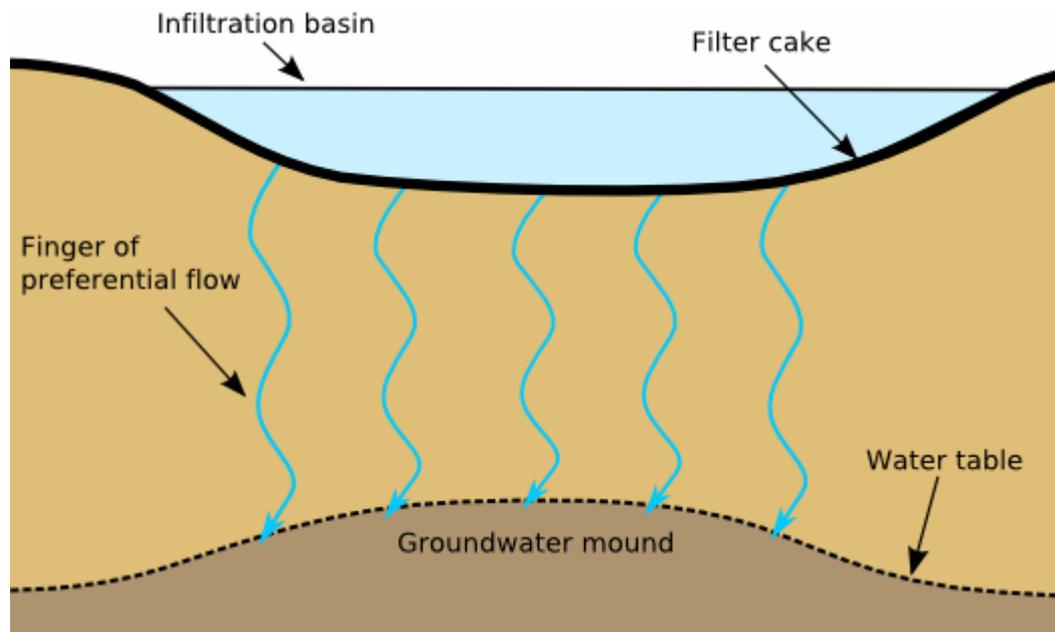
- $d_u$  is the minimum depth to the mounded watertable beneath the infiltration basin or gallery (m)
- $n_e$  is the effective porosity of the unsaturated zone (-)
- $i$  is the infiltration rate (m/day).

This equation assumes that the whole profile carries unsaturated flow to the watertable. However, when used to calculate travel time to estimate attenuation of hazards such as pathogens, equation A6.14 is likely to overestimate travel time.

A more conservative approach is to consider that a clogging layer on the floor of the infiltration basin or gallery will result in fingers of saturated flow beneath the clogging layer. These will extend to the watertable, or to the next layer of low permeability, below which the fingering process will be repeated. Hence, equation A6.15 is recommended to calculate travel time of water through the unsaturated zone to the watertable. Evidence is increasing that preferential flow (as shown in Figure A6.2) is the most common form of flow beneath infiltration basins.

$$t_u = \frac{d_u n_e}{K_s} \quad (\text{equation A6.15})$$

where  $K_s$  is the saturated hydraulic conductivity of the soil in the vertical direction (m/day). Travel time through the unsaturated zone will typically be from hours to days.



**Figure A6.2 Preferential flow beneath infiltration basins**

Fingers of saturated flow tend to occur beneath the clogging layer. This facilitates more rapid flow to the watertable than is accounted for by the traditional piston-flow assumption, in which unsaturated flow is assumed to occupy the whole domain beneath the basin or gallery.

Box A6.2 contains an example of calculating travel time in an unsaturated zone.

#### **Box A6.2 Travel time in an unsaturated zone**

Assume that:

- minimum depth ( $d_u$ ) to the watertable beneath the infiltration basin is 10 m
- effective porosity ( $n_e$ ) of the unsaturated zone is 0.3
- infiltration rate ( $i$ ) is 0.5 m/day
- saturated hydraulic conductivity ( $K_s$ ) of the soil is 5 m/day.

Travel time calculated by piston-flow assumption (equation A6.14) is 6 days.

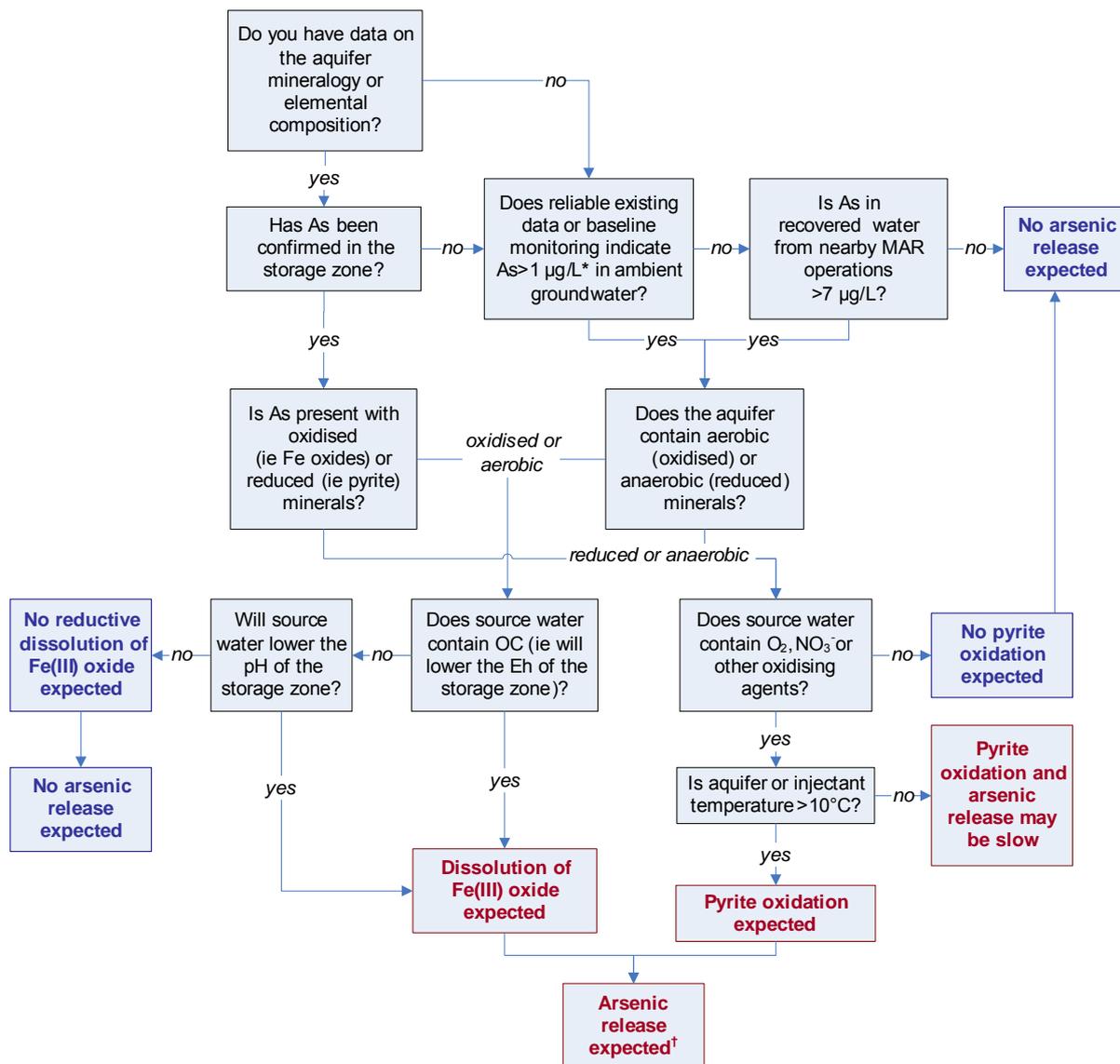
Travel time calculated assuming finger flow (equation A6.15) is 0.6 days. This is assumed to be the more reliable estimate for the purposes of calculating constituent attenuation above the watertable.

## **Appendix 7 Decision trees to identify potential arsenic and iron release in managed aquifer recharge**

Understanding the potential for hazard release through geochemical processes during managed aquifer recharge requires knowledge of the:

- source-water quality
- native groundwater quality
- composition of the aquifer matrix
  - mineralogy
  - major and minor elements
  - exchange potential
  - organic carbon content.

Figures A7.1 and A7.2 provide decision trees to support the discussion in Chapter 5 to identify the potential for release of arsenic or iron in a managed aquifer recharge scheme. The spatial distribution of arsenic within the sediments of the storage phase may vary considerably, and thus the potential for arsenic release can be difficult to predict. The decision trees do not substitute for geochemical modelling, but may be used to understand the important geochemical processes. Table A7.1 lists other metals or inorganic hazards that may in some circumstances potentially be released from aquifers during managed aquifer recharge and pose a concern for human health.



Eh = a measure of redox potential — the propensity for oxidation and reduction reactions; MAR = managed aquifer recharge; OC = organic carbon.

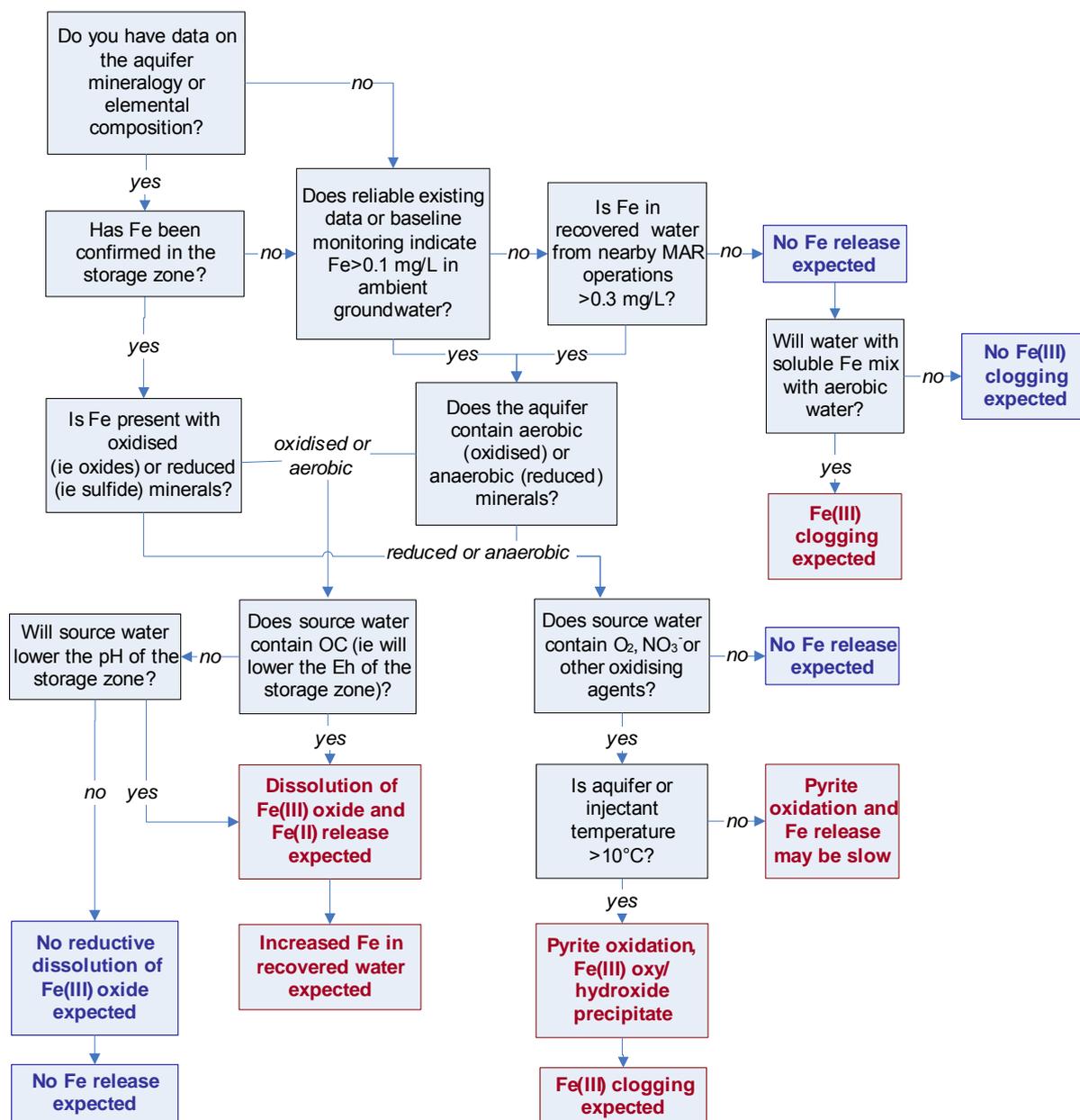
\* Arsenic (As) concentrations should be reported to 1 µg/L.

† Other trace metals (see Table A7.1) can be released concurrently.

**Figure A7.1 Decision tree for identifying arsenic mobilisation in managed aquifer recharge (from Vanderzalm et al, 2009)**

Arsenic release (Figure A7.1) may also indicate release of other hazards, such as cobalt, chromium, copper, nickel and zinc. It is recommended that groundwater arsenic concentrations, which are used as a surrogate to indicate arsenic in the sediments, be reported to a 1 µg/L detection limit. A concentration reported to a higher detection limit (ie <5 µg/L) does not preclude the potential for sufficient arsenic release to exceed guideline values.

The decision tree for iron (Figure A7.2) can be used to consider the potential for iron release and the subsequent recovery of water elevated in iron, or aquifer clogging due to the precipitation of iron oxides in the vicinity of the recharge point. As manganese exhibits similar behaviour to iron, the iron decision tree could be modified to examine the potential manganese release, if manganese is a major constituent of the aquifer.



Eh = a measure of redox potential — the propensity for oxidation and reduction reactions; MAR = managed aquifer recharge; OC = organic carbon.

**Figure A7.2 Decision tree for identifying potential for iron mobilisation or iron clogging due to redox processes in managed aquifer recharge; iron concentrations may also be affected by mineral equilibrium processes (from Vanderzalm et al, 2009)**

**Table A7.1 Trace ions posing a concern to human health or the environment that can be released during managed aquifer recharge**

Trace ion	Sources	Mechanisms	Health <sup>a</sup>	Environment <sup>b</sup>
Aluminium	<ul style="list-style-type: none"> <li>Al(III)</li> <li>gibbsite in laterites</li> <li>clay minerals</li> </ul>	<ul style="list-style-type: none"> <li>pH</li> <li>mineral equilibrium</li> </ul>	aesthetic	✓
Antimony	<ul style="list-style-type: none"> <li>sulfides</li> </ul>	<ul style="list-style-type: none"> <li>redox</li> </ul>	✓	–
Arsenic	<ul style="list-style-type: none"> <li>sulfides</li> <li>Fe(III) oxides</li> </ul>	<ul style="list-style-type: none"> <li>redox</li> <li>pH</li> <li>exchange</li> </ul>	✓	✓
Barium	<ul style="list-style-type: none"> <li>barite (barium sulfate)</li> <li>Fe(III) oxides</li> <li>carbonates</li> </ul>	<ul style="list-style-type: none"> <li>mineral equilibrium</li> <li>redox (sulfate reduction)</li> <li>pH</li> <li>exchange</li> </ul>	✓	–
Beryllium	<ul style="list-style-type: none"> <li>beryl (silicate)</li> </ul>	<ul style="list-style-type: none"> <li>mineral equilibrium</li> </ul>	–	✓
Cadmium	<ul style="list-style-type: none"> <li>sulfides</li> <li>Fe(III) oxides</li> </ul>	<ul style="list-style-type: none"> <li>redox</li> <li>pH</li> <li>exchange</li> </ul>	✓	✓
Chromium	<ul style="list-style-type: none"> <li>sulfides</li> <li>Fe(III) oxides,</li> <li>chromite in olivine inclusions in basalts</li> </ul>	<ul style="list-style-type: none"> <li>redox</li> <li>pH</li> <li>exchange</li> </ul>	✓	✓
Cobalt	<ul style="list-style-type: none"> <li>sulfides</li> <li>Fe(III) oxides</li> </ul>	<ul style="list-style-type: none"> <li>redox</li> <li>pH</li> <li>exchange</li> </ul>	–	✓
Copper	<ul style="list-style-type: none"> <li>sulfides</li> <li>Fe(III) oxides</li> </ul>	<ul style="list-style-type: none"> <li>redox</li> <li>pH</li> <li>exchange</li> </ul>	✓	✓
Fluoride	<ul style="list-style-type: none"> <li>fluorite</li> <li>apatite in igneous rocks</li> </ul>	<ul style="list-style-type: none"> <li>mineral equilibrium</li> </ul>	✓	✓
Iron	<ul style="list-style-type: none"> <li>Fe(III)</li> <li>sulfides</li> <li>carbonates</li> </ul>	<ul style="list-style-type: none"> <li>redox</li> <li>pH</li> <li>mineral equilibrium</li> </ul>	aesthetic	✓
Lead	<ul style="list-style-type: none"> <li>sulfides</li> <li>Fe(III) oxides</li> </ul>	<ul style="list-style-type: none"> <li>redox</li> <li>pH</li> <li>exchange</li> </ul>	✓	✓
Manganese	<ul style="list-style-type: none"> <li>oxides</li> <li>carbonates</li> </ul>	<ul style="list-style-type: none"> <li>redox</li> <li>pH</li> <li>mineral dissolution</li> </ul>	–	✓

**Table A7.1 (continued)**

<b>Trace ion</b>	<b>Sources</b>	<b>Mechanisms</b>	<b>Health<sup>a</sup></b>	<b>Environment<sup>b</sup></b>
Molybdenum	• sulfides	• redox	✓	✓
Nickel	• sulfides • Fe(III) oxides	• redox • pH • exchange	✓	✓
Selenium	• sulfides	• redox	✓	✓
Uranium	• phosphates • organic rich deposits	• redox	–	✓
Vanadium	• sulfides • apatite	• redox • mineral equilibrium	–	✓
Zinc	• sulfides • Fe(III) oxides	• redox • pH • exchange	aesthetic	✓

Al = aluminium; Fe = iron; pH = a measure of the acidity or alkalinity of a solution.

**a** Source: NHMRC–NRMMC (2004).

**b** Source: ANZECC–ARMCANZ (2000a).

✓ Indicates this species is included in the relevant guideline.

– Indicates this species is not included in the relevant guideline and is considered to be of less concern.



## Appendix 8 Aquifer characteristics and suitability for managed aquifer recharge

Aquifers are those parts of the subsurface that contain water that can be extracted at useful rates. They can range from unconsolidated sands and gravels, through to consolidated sandstone and limestone, and to hard rocks that convey water through cracks. In general, aquifers can be divided into two broad classes:

- unconfined — where water can infiltrate from the ground surface to a watertable below, beneath which all pore space is saturated
- confined — where locally the roof of the aquifer is relatively impermeable to water (eg clay), and infiltration from overlying land does not reach the aquifer.

Confinement therefore defines the types of recharge that are viable, as indicated in Chapter 2. Table A8.1 summarises various characteristics of aquifers and identifies their influence on potential for managed aquifer recharge with recycled and natural waters.

In any location there may be no aquifer, or one or more aquifers; for example, in the Northern Adelaide Plains there are a number of thin, unconsolidated, alluvial layers embedded within a dense Plio-Pleistocene clay down to about 100 m, underlain by three Tertiary aquifers down to 300 m composed of limestone and sandstone, with low permeability formations between them. The second Tertiary aquifer (T2) has typically been selected for managed aquifer recharge because it:

- is a moderately high-yielding consolidated limestone
- is generally brackish, so there are few existing wells
- is confined and poorly connected to other aquifers over most of its area, and therefore protected from pollution from overlying land uses
- has a groundwater gradient that is mostly gentle, so water that is injected stays close to the ASR (aquifer storage and recovery) well and is easily recovered.

Without a permeable formation, there is no opportunity for subsurface storage. In some arid locations, permeable but dry formations suggest the possibility for managed aquifer recharge. However, sometimes those formations are dry because groundwater can discharge so quickly that storage does not accumulate, and opportunities for managed recharge here are only illusory, unless use of the aquifer is regarded only as a filtration step before discharge. If there are several aquifers available, depending on how interconnected they are, it may be possible to store water of different qualities in different aquifers. Table A8.1, together with sound local hydrogeological knowledge, may help in identifying the most suitable aquifers for use in storing recycled and natural waters of different qualities for different purposes.

Table A8.1 cannot cover all possibilities because there are many subtleties. For example, many aquifers are semiconfined, with characteristics that are intermediate between those shown in the table. Semiconfined aquifers can have other effects (eg reducing recovery efficiency), if the leaky confining bed contains water that is more saline than water in the aquifer.

Because of the range of characteristics that come into play, it is difficult to use performance at one managed aquifer recharge site to predict performance at another. Unfortunately, a site-by-site approach will be necessary until the knowledge base has extended sufficiently to make predictions more reliable.

**Table A8.1 Characteristics of aquifers and their influence on potential for managed aquifer recharge**

<b>Characteristic</b>	<b>Feature and influence on managed aquifer recharge</b>	
<b>Permeability</b>	<b>Moderate to high</b> <ul style="list-style-type: none"> <li>• High rates of recharge possible</li> <li>• Recharged water can be dispersed</li> <li>• Lower capital and energy costs per unit of water recovered</li> </ul>	<b>Low to moderate</b> <ul style="list-style-type: none"> <li>• Lower rates of recharge possible</li> <li>• Recharged water more localised</li> <li>• Greater capital and energy costs per unit of water recovered</li> </ul>
<b>Confinement</b>	<b>Unconfined</b> <ul style="list-style-type: none"> <li>• Surface infiltration methods viable</li> <li>• Unprotected from surface contamination</li> <li>• Storage capacity depends on depth to watertable</li> </ul>	<b>Confined</b> <ul style="list-style-type: none"> <li>• Well injection methods only</li> <li>• Protected from surface contamination</li> <li>• Storage capacity depends on aquifer thickness</li> </ul>
<b>Thickness</b>	<b>Thick</b> <ul style="list-style-type: none"> <li>• High storage potential</li> <li>• More sensitive to salinity stratification if native groundwater is brackish</li> </ul>	<b>Thin</b> <ul style="list-style-type: none"> <li>• Low storage potential</li> <li>• May limit rate of recovery by wells</li> </ul>
<b>Uniformity of hydraulic properties</b>	<b>Homogeneous</b> <ul style="list-style-type: none"> <li>• Minimal mixing and higher recovery efficiencies if native groundwater is brackish</li> </ul>	<b>Heterogeneous</b> <ul style="list-style-type: none"> <li>• Lower recovery efficiencies if native groundwater is brackish</li> <li>• In karstic and fractured rock systems, limited ability to contain recharged water</li> </ul>
<b>Salinity of groundwater</b>	<b>Fresh</b> <ul style="list-style-type: none"> <li>• Recovery efficiency not limiting</li> <li>• Requirement to protect wider range of beneficial uses of aquifer (higher treatment costs)</li> </ul>	<b>Saline</b> <ul style="list-style-type: none"> <li>• Recovery efficiency can limit effectiveness</li> <li>• Less beneficial uses to protect, so treatment requirements less onerous</li> </ul>
<b>Lateral hydraulic gradient</b>	<b>Gentle</b> <ul style="list-style-type: none"> <li>• Recharged water contained closer to point of recharge</li> </ul>	<b>Moderate to steep</b> <ul style="list-style-type: none"> <li>• Recharged water dispersed downgradient and lower recovery efficiencies if native groundwater is brackish</li> </ul>
<b>Consolidation</b>	<b>Consolidated</b> <ul style="list-style-type: none"> <li>• Easier to complete wells</li> <li>• Easier to maintain recharge wells to prevent irrecoverable clogging</li> </ul>	<b>Unconsolidated</b> <ul style="list-style-type: none"> <li>• Screens required for injection and recovery wells</li> <li>• Land subsidence a consideration</li> </ul>
<b>Aquifer mineralogy</b>	<b>Unreactive with recharge water</b> <ul style="list-style-type: none"> <li>• Recovered water quality unaffected by geochemical reactions with aquifer matrix</li> <li>• Likelihood of clogging of injection wells is sometimes increased</li> </ul>	<b>Reactive with recharge water</b> <ul style="list-style-type: none"> <li>• Consider metal (eg As) mobilisation, Fe and H<sub>2</sub>S effects on recovered water and groundwater</li> <li>• In carbonate aquifers, less onerous treatment required to avoid clogging of injection wells</li> </ul>
<b>Redox state of native groundwater</b>	<b>Aerobic</b> <ul style="list-style-type: none"> <li>• Higher rates of inactivation of pathogens and biodegradation of some endocrine disrupting chemicals</li> </ul>	<b>Anaerobic</b> <ul style="list-style-type: none"> <li>• Higher biodegradation rates for trihalomethanes</li> </ul>

Source: Adapted from Dillon and Jimenez (2008); As = arsenic, Fe = iron ; H<sub>2</sub>S = hydrogen sulfide.



## Appendix 9 Operational performance data

Data from 14 national and international ASR (aquifer storage and recovery) sites were compiled to compare the effect of different source-water compositions on the degree of well clogging experienced in different hydrogeological environments (Table A9.1). Clogging rates were classified as either low, moderate or severe, in terms of their relative impact on well efficiency and redevelopment frequency. The data are presented in full below and the findings of the analysis are presented in Section 6.1.4.

**Table A9.1 Relationships between aquifer characteristics, source-water quality and well clogging**

Water quality <sup>a</sup>	Site	Aquifer	Transmissivity (m <sup>2</sup> /day)	Pretreatment process <sup>b</sup>	Typical water quality <sup>c</sup> (mg/L)	Main apparent form/s of clogging	Level of clogging <sup>d</sup>
M	Orange County, California	Sands and gravels	390–9900	TERT	0.1–0.7 NTU (turb) 0.2–6.1 (NH <sub>3</sub> ) 1.5–2.1 (TOC)	Biological + physical	Low
M	Palo Alto Baylands, California	Silty sand and gravel	110	A/SEC+Chl	16 (NH <sub>3</sub> ) 3 (TOC) 10 (COD)	Unknown	Low
M	Bolivar, South Australia	Sandy limestone	150	A/SEC+Chl	<6 (SS) <10 (N-total)  >6 (SS) >10 (N-total)	Biological + physical	Low–moderate
M	Willunga, South Australia	Sandy limestone (fissured)	>>80	A/SEC+Chl	<1 (SS) 4.2 (N-total) 3.5 (TOC) 4/mL (T.algae)	Physical	Low
H	Waruwi, Northern Territory	Sandstone	80	GWATER	<1 (SS) <0.1 (N-total) <0.3 (TOC)	Chemical	Low
L	Andrews Farm, South Australia	Sandy limestone	180	WET	29–169 (SS) 4–8 (TOC)	Physical	Low
M	Basós-Riera D’Horta, Spain	Coarse sands and gravels	?	SEC + Chl	3–6 (SS) 25–40 (NH <sub>4</sub> )	Physical	Moderate
L	Bay Park, New York	Fine-medium sand	?	A/SEC+Chl	23 (NH <sub>3</sub> ) 33 (SS) 2 (chlor res)	Biological	Moderate

**Table A9.1 (continued)**

Water quality <sup>a</sup>	Site	Aquifer	Transmissivity (m <sup>2</sup> /day)	Pretreatment process <sup>b</sup>	Typical water quality <sup>c</sup> (mg/L)	Main apparent form/s of clogging	Level of clogging <sup>d</sup>
H	El Paso, Texas	Alluvial sands, some gravel-silt-clay lenses	1240	TERT	0.5 NTU (turb)	Unknown	Moderate
M	Waialua, Hawaii	Coral and recemented reef rubble	2500	SEC + Chl	<5 (BOD) <5 (SS)	Biological (long-term) + physical (short-term)	Moderate
H	Sun Lakes, Arizona	Unconsolidated gravel, sand and silt	8000–44 000	TERT	<5 (BOD) <4 (N-total) 0.2 (SS) <1 NTU (turb)	Biological	Moderate
L	Waimanalo, Hawaii	Fine–medium carbonate sand	90	SEC + Chl	10–15 (BOD) 5–15 (SS) 1.5 (chlor res.)	Biological (long-term) + physical (short-term)	Moderate
L	Carrum, Victoria	Intercalated basalt	570	SEC + Chl	3.4–26 (NO <sub>3</sub> ) 20–27 (TOC)	Biological + physical	Severe
L	Urrbrae, South Australia	Unconsolidated sand	6	WET	2–110 (SS) 4–13 (TOC)	Biological + physical	Severe

**a** L = low quality (high levels, TSS>10 mg/L and TOC>10 mg/L); M = medium quality (medium levels, TSS 1–10 mg/L and TOC 1–10 mg/L); H = high quality (low levels, TSS<1 mg/L and TOC<1 mg/L).

**b** A/SEC+Chl = secondary plus advanced treatment plus chlorination; SEC+Chl = secondary treatment plus chlorination; GWATER = groundwater; TERT = tertiary treatment, including disinfection (to near-potable standards); WET = wetland treatment.

**c** BOD = biochemical oxygen demand; chlor res = chlorine residual; COD = chemical oxygen demand; NTU = nephelometric turbidity unit; SS = suspended sediment; TOC = total organic carbon; TSS = total suspended solids; turb = turbidity; T.algae = Total algal count; chlor res = chlorine residual; NH<sub>3</sub> = ammonia, NH<sub>4</sub> = ammonium; N-total = total nitrogen.

**d** Low = impact on well efficiency is low, redevelopment infrequent; Moderate = impact is moderate but manageable, redevelopment may be frequent; Severe = impact warrants termination or at least major improvement in water quality.

## A9.1 Calculation of mixing fraction of recharge water in groundwater or recovered water

The proportion of injectant present in any sampled mixture, at any time (otherwise known as the mixing fraction, *f*) can be determined from the equation A9.1

$$f = \frac{C_r - C_g}{C_i - C_g} \quad (\text{equation A9.1})$$

where:

- *f* = fraction of recharge water present in the recovered water sample (at a given time)

- $C_r$  = solute concentration in the recovered water (at a given time)
- $C_g$  = solute concentration in the ambient groundwater (assumed constant)
- $C_i$  = solute concentration in the recharge water (assumed constant)

A value for  $f$  of one (1) indicates the sampled water is composed entirely of the recharge water; a value of zero indicates no recharge water (entirely ambient groundwater).

Table A9.2 uses equation A9.1 to give the minimum fraction of recharge water present in recovered water for two maximum permissible recovered water total dissolved salt concentrations (500 mg/L and 1500 mg/L), with respect to a recharge water total dissolved salts concentration of 100 mg/L and ambient groundwater total dissolved salts concentrations ranging from 1000 mg/L to 50 000 mg/L. Because variations in ambient groundwater salinity greatly outweigh those in recharge water, groundwater quality most strongly influences the level of mixing that is acceptable in recovered water.

**Table A9.2 Examples of the minimum fraction of recharge water present in recovered water, as a function of the total dissolved salts concentration of the ambient groundwater**

Ambient groundwater TDS (mg/L)	Minimum fraction of recharge water present in recovered water for two maximum permissible recovered water TDS concentrations <sup>a</sup>	
	500 mg/L	1500 mg/L
1000	0.556	–
2000	0.789	0.263
5000	0.918	0.714
10 000	0.960	0.859
20 000	0.980	0.930
50 000	0.991	0.972

– = all water meets permissible value; TDS = total dissolved salts.

<sup>a</sup> TDS of recharge water assumed to be 100 mg/L.

## A9.2 Summary of recovery efficiencies at ASR sites

Over the past decade or so, recovery efficiency data has emerged from a number of ASR sites. Table A9.3 presents a summary of recovery efficiency data recalculated from the concentration and volumetric data for a common permissible concentration of 1500 mg/L.

A wide range of recovery efficiencies have been observed. High recovery efficiencies (ie >66%) have occurred for the three sites that have targeted the T2 aquifer: Bolivar, Andrews Farm and the Paddocks. A recovery efficiency slightly greater than 100% occurred at the Paddocks site, since the ambient groundwater was not greatly above the threshold concentration (total dissolved salts = 1900 mg/L); dispersion appears to have been beneficial in reducing the salinity in the mixing zone, thereby allowing some of the ambient groundwater to be diluted to a quality where it could be recovered.

The lowest recovery efficiencies (<2–20%) occurred at the Clayton and Scotch College sites, for different reasons. The low recovery efficiency at Clayton is due to the high transmissivity

and karstic features of the aquifer, as well as salinity and density effects. Subsequent testing has shown that by forming a large ‘sacrificial’ lens acting as a buffer and transition zone between injectant and ambient groundwater, an actual productive water supply lens can be developed and maintained. The Scotch College site, which targets a fractured rock aquifer, has relatively low recovery efficiency; Rossdale, in weathered fractured rock, has a high recovery efficiency (factors affecting recovery efficiency are described in Section 6.2).

**Table A9.3 Summary of recovery efficiencies from six ASR sites**

Site	Recovery efficiency (%) <sup>a</sup>	No. of cycles	Aquifer type	Water quality
Andrews Farm, SA	>67	1	Sandy limestone	Source: stormwater Aquifer: brackish
Bolivar, SA	61 (cycle 1) 80 (cycle 2) >80 (cycle 3)	3	Sandy limestone	Source: treated sewage Aquifer: brackish
Clayton, SA	<2	1	Sandy limestone	Source: lake water Aquifer: saline
Paddocks, SA	~110	1	Sandy limestone	Source: stormwater Aquifer: brackish
Rossdale, VIC	>92 (cycle 4)	4	Weathered bedrock	Source: stormwater Aquifer: brackish
Scotch College, SA	7 (cycle 1) 20 (cycle 3)	3	Fractured rock	Source: creek water Aquifer: brackish

SA = South Australia; VIC = Victoria.

<sup>a</sup> Recovery efficiency based on a common permissible total dissolved salts of 1500 mg/L (electrical conductivity  $\approx$  2500  $\mu$ S/cm) for comparative purposes only.

## Appendix 10 Examples of Australian managed aquifer recharge sites

Table A10.1 provides an inventory of some managed aquifer recharge case study sites. The list is not exhaustive; further information can be obtained from the references provided below.

**TableA10.1 Inventory of managed aquifer recharge case study sites**

Site (year of commencement)	Type of MAR	Aquifer type	Source of water	Infrastructure	Annual recharge volume (ML)	Further information
Angas Bremer, SA (mid-1970s)	ASR	Tertiary limestone	River flow	~30 drainage wells	1000	Gerges et al (1996)
Scotch College, SA (1989)	ASR	Fractured rock	River flow	1 injection well 1 production well	40	Gerges et al (2002)
Andrews Farm, SA (1993)	ASR	Tertiary limestone (confined)	Stormwater	Wetland 1 injection well 3 obs wells	100	Dillon et al (1997), Barry et al (2002), Pavelic et al (2006b)
Northfield, SA (1993)	ASR	Fractured rock	Stormwater	Wetland 1 drainage well 1 obs well	40	Stevens et al (1995)
Greenfields, SA (1995)	ASR	Tertiary limestone (confined)	Stormwater	Wetland 1 drainage well 1 obs. well	100	Gerges et al (1996)
Paddocks, SA (1995)	ASR	Tertiary limestone (confined)	Stormwater	Wetland 1 injection well	75	Gerges et al (1996)
Clayton, SA (1995)	ASR	Tertiary limestone (confined)	Lake water	1 injection well 7 obs wells	70	Gerges et al (1996)
Bolivar, SA (1999)	ASR	Tertiary limestone (confined)	Treated sewage	1 ASR well 16 obs wells	200	Dillon et al (1999), Dillon et al (2003)
Parafield, SA (2003)	ASR	Tertiary limestone (confined)	Stormwater	Storage basins and wetland 2 ASR wells 12 obs wells	400	Marks et al (2005)
Parafield Gardens, SA (2006)	ASTR	Tertiary limestone (confined)	Stormwater	4 injection wells 2 recovery wells 3 obs wells	400	Rinck-Pfeiffer et al (2005), Page et al (2008, 2009)

**TableA10.1 (continued)**

Site (year of commencement)	Type of MAR	Aquifer type	Source of water	Infrastructure	Annual recharge volume (ML)	Further information
Warruwi, NT (2000)	ASR	Alluvium (confined)	Ground-water	1 ASR well 1 obs well	10	Pavelic et al (2002a)
Alice Springs, NT (2008)	SAT	Alluvium (unconfined)	Treated sewage	DAF pretreatment 5 sub-basins <sup>#</sup>	600	Knapton et al (2004)
Jandakot, WA (2000)	ASR	Alluvium (confined)	Mains-water	1 injection well	40–180	Martin et al (2002)
Halls Head, WA (2000)	SAT	Fractured limestone (unconfined)	Treated sewage	4 sub-basins 2 recovery wells 13 obs wells	400	Toze et al (2002)
Floreat Park, WA (2006)	Infiltration galleries	Limestone (unconfined)	Treated sewage	2 galleries 1 recovery well 20 obs wells	10	Bekele et al (2008)
Burdekin Delta, Qld (1970s)	Basins	Alluvium (unconfined)	River water	Pumps, weirs, infiltration basins and channels and sand dams	45 000	Charlesworth et al (2002)
Little Para River, SA (1979)	Re-charge releases from dam	Alluvium	River water	Release valve at dam. 53 obs wells, 12 gauging stations	1500	Dillon (1984)

DAF = dissolved air flotation; MAR = managed aquifer recharge; NT = Northern Territory; obs = observation; Qld = Queensland; SA = South Australia; SAT = soil aquifer treatment; WA = Western Australia.

## Appendix 11 Case study of assessment of risks in relation to preventive measures

Table A11.1 presents a retrospective assessment of the maximal and residual risk for each of the managed aquifer recharge hazards, in relation to the preventive measures and monitoring that were established at the Andrews Farm stormwater ASR (aquifer storage and recovery) case study site (referenced in Appendix 10). Recovered water is used for irrigation. The native groundwater in the storage zone was initially brackish. For each relevant hazard the residual risk was assessed to be acceptable (low or negligible).

**Table A11.1 Assessment of risks for hazards at Andrews Farm stormwater ASR site**

Specific hazard	Inherent risk	Preventive measures and monitoring	Residual risk
Pathogens	Low	<ul style="list-style-type: none"> <li>Residence time in wetland+100 micron prefilter+aquifer+non-potable usage of the recovered water</li> <li>Irrigation scheduling of public open space to minimise exposure to aerosols</li> </ul>	Negligible
Inorganic chemicals	Low	<ul style="list-style-type: none"> <li>Treatment by wetland+100 micron prefilter+aquifer</li> </ul>	Negligible
Salinity and sodicity	Medium <sup>a</sup>	<ul style="list-style-type: none"> <li>Aquifer targeted with brackish groundwater and low–moderate regional velocity</li> <li>Recovery efficiency was found to be acceptable from ASR commissioning tests</li> </ul>	Negligible
Nutrients	Low	<ul style="list-style-type: none"> <li>Treatment by wetland+100 micron prefilter+aquifer</li> <li>Monitoring revealed minimal biofilm growth around injection well</li> </ul>	Low
Organic chemicals	Medium <sup>b</sup>	<ul style="list-style-type: none"> <li>Treatment by wetland+100 micron prefilter+aquifer</li> <li>Monitoring revealed no trace organic compound in recovered water that would inhibit irrigation use</li> </ul>	Negligible
Turbidity	Medium <sup>c</sup>	<ul style="list-style-type: none"> <li>Treatment by wetland+100 micron prefilter</li> <li>Clogging found to be manageable</li> <li>High turbidity backwash water recycled through wetland</li> </ul>	Low
Radionuclides	Negligible	<ul style="list-style-type: none"> <li>Geological media and measurements at other sites in the same target aquifer show that this is not an issue in this aquifer</li> </ul>	Negligible
Hydraulics	Low	<ul style="list-style-type: none"> <li>Pump selected so as not to overpressurise the aquifer; modelling used to estimate spatial changes in pressure</li> <li>These were verified by monitoring groundwater pressures; no other wells close enough to be adversely affected</li> </ul>	Negligible

**Table A11.1 (continued)**

<b>Specific hazard</b>	<b>Inherent risk</b>	<b>Preventive measures and monitoring</b>	<b>Residual risk</b>
Aquifer dissolution and aquitard stability	Medium	<ul style="list-style-type: none"> <li>• Open interval of well completed several metres below base of aquitard</li> <li>• Rates of aquifer dissolution monitored and found to be low</li> </ul>	Negligible
Fractured rock, karstic and unconfined aquifers	Low	<ul style="list-style-type: none"> <li>• Preferential flow observed in confined limestone aquifer targeted. No local users of groundwater in this aquifer which is brackish over a wide area.</li> </ul>	Negligible
Aquifer ecosystems and groundwater-dependent ecosystems	Negligible	<ul style="list-style-type: none"> <li>• Site located remote from groundwater-dependent ecosystems, and no stygofauna found in this aquifer at other sites</li> </ul>	Negligible
Energy and greenhouse gas considerations	Low	<ul style="list-style-type: none"> <li>• Commissioning trials found energy consumption per kL water produced from ASR is substantially less than that of all alternative supplies (pumping from River Murray or desalination)</li> </ul>	Negligible

**a** Risk considers mixing in subsurface, and is higher than if due to source concentration alone.

**b** Assigned on the basis of the characteristics and land uses within the surface water catchment.

**c** Medium risk since source water has high turbidity.

# Glossary

activated carbon	Adsorptive carbon particles or granules that have a high capacity to remove trace and soluble components from solution.
algae	Comparatively simple chlorophyll-bearing plants, most of which are aquatic and microscopic.
anaerobic	Conditions where oxygen is lacking; organisms not requiring oxygen for respiration.
analyte	An analyte is a substance or chemical constituent that is determined in an analytical procedure.
aquatic ecosystem	Any water environment from small to large, from pond to ocean, in which plants and animals interact with the chemical and physical features of the environment.
aquifer	A geological formation or group of formations capable of receiving, storing and transmitting significant quantities of water. Aquifer types include confined, unconfined and artesian.
aquifer storage and recovery (ASR)	The recharge of an aquifer via a well for subsequent recovery from the same well.
aquifer storage transfer and recovery (ASTR)	The recharge of an aquifer via a well for subsequent recovery from another well, to allow a minimum residence time in the aquifer before recovery.
aquitard	A geological layer that has low permeability and confines or separates aquifers.
artesian	When the piezometric surface (hydraulic head) of a confined aquifer is above the ground surface. An uncontrolled artesian well will spurt water out of the ground.
attenuation	The reduction in contaminant or pathogen concentration as a result of treatment processes, including passive subsurface treatment. These guidelines focus on sustainable treatment processes such as biodegradation. Adsorption is another attenuating process; however, when sorption sites are exhausted, breakthrough of contaminants will occur. In these guidelines, adsorption is only relied on to the extent that it extends the time available for biodegradation.

attenuation zone	The area surrounding the zone of recharge where natural attenuation takes place; all the pre-existing environmental values of the aquifer are continually met beyond this zone. After any managed aquifer recharge project ceases, the attenuation zone will shrink and disappear as all groundwater conforms to pre-existing environmental values. Verification monitoring would normally be undertaken on the perimeter of the attenuation zone, and in the recharge zone when the operation ceases.
Becquerel (Bq)	Unit to measure radioactivity, where 1 Bq = 1 disintegration per second.
beneficial use	The value of water in sustaining ecological systems, as well as the economic uses of water (eg drinking water, irrigation, industrial and mining water supplies). Water-quality requirements are determined by the class of beneficial use.
biochemical oxygen demand	Decrease in oxygen content in a sample of water caused by the bacterial breakdown of organic matter.
biodiversity, biological diversity	The variety of life forms, including plants, animals and microorganisms; the genes they contain; and the ecosystems and ecological processes of which they are a part.
biofilm	Microbial populations that grow on the inside of pipes and other surfaces.
biomass	The living weight of a plant or animal population, usually expressed on a unit area basis.
biota	All of the organisms found in a given area, including animals, fungi and microorganisms.
bloom	An unusually large number of organisms of one or a few species, usually algae, per unit of water.
boron	An inorganic chemical that is a micronutrient for plants; there is a narrow concentration range between boron deficiency and boron toxicity. Water softeners are an important source of boron in wastewaters. The main impact of boron is toxicity to plants after soil accumulation, especially on finer textured, higher pH soils.
cadmium	A metal that can accumulate in soils and be taken up through the food chain in plants and animals. Concentrations in recycled waters are generally low; however, saline water and changes in soil pH can release cadmium stored in the soil for uptake by plants.

caisson	Exclosure in soil that allows infiltration of water( eg from roof runoff). May be filled with sand or gravel to facilitate infiltration. Perforated caissons may also be used below the watertable in river beds as horizontal collectors of infiltrated river water.
<i>Campylobacter</i>	A genus of bacteria that is a major cause of diarrhoeal illness.
catchment	Area of land that collects rainfall and contributes to surface water (eg streams, rivers, wetlands) or to groundwater.
cation exchange capacity	The sum of exchangeable cations that a soil can absorb at a specific pH. It is usually expressed in centimoles of charge per kilogram of exchanges (cmolc/kg).
chloride	Chloride in recycled waters comes from a variety of salts (including detergents) and is present as an ion (Cl <sup>-</sup> ). In addition to chloride's role in salinity, it can be toxic to plants (especially if applied directly to foliage) and aquatic biota.
coagulation	Clumping together of very fine particles into larger particles using chemicals (coagulants) that neutralise the electrical charges of the fine particles and destabilise the particles.
coliform bacteria	A group of bacteria whose presence in drinking water and wastewater can be used as an indicator for operational monitoring.
conductivity or electrical conductivity (EC)	A measure of the conduction of electricity through water; can be used to determine the total dissolved soluble salts content. EC is measured in $\mu\text{S}/\text{cm}$ .
confined aquifer	A type of aquifer with a low permeability formation as its upper boundary; its storage is increased by raising the pore pressure in the aquifer, causing elastic compression of aquifer materials and water.
confining layer	A rock unit impervious to water; forms the upper bound of a confined aquifer.
contaminant	Biological or chemical substance or entity not normally present in a system, or any unusually high concentration of a naturally occurring substance, capable of producing an adverse effect in a biological system, seriously injuring structure or function.
corrective action	Procedures to be followed when monitoring results indicate that a deviation occurs from acceptable criteria.

critical control point	A step or procedure at which controls can be applied and a hazard can be prevented, eliminated or reduced to acceptable (critical) levels.
critical limit	A prescribed tolerance that must be met to ensure that a critical control point effectively controls a potential health hazard; a criterion that separates acceptability from unacceptability.
crop plants	Plants grown for harvest as food, feed or forage.
<i>Cryptosporidium</i>	Microorganism that is highly resistant to disinfection; commonly found in lakes and rivers. <i>Cryptosporidium</i> has caused several large outbreaks of gastrointestinal illness with symptoms such as diarrhoea, nausea and stomach cramps. People with severely weakened immune systems are likely to have more severe and more persistent symptoms than healthy individuals (adapted from United States Environmental Protection Agency).
disability adjusted life years (DALY)	DALYs are used to set health-based targets and assess risks for human health in relation to pathogens. The Phase 1 guidelines (NRMCC–EPHC–AHMC 2006) set the tolerable risk at $10^{-6}$ DALYs per person per year. DALYs are used to convert the likelihood of infection or illness into burdens of disease; one DALY represents the loss of one year of equivalent full health.
disinfectant	An oxidising agent (eg chlorine, chlorine dioxide, chloramines, ozone) that is added to water in any part of the treatment or distribution process to kill or inactivate pathogenic microorganisms.
disinfection	The process designed to kill most microorganisms, including essentially all pathogenic bacteria. There are several ways to disinfect; chlorine is most frequently used in water treatment.
disinfection byproduct	Product of reactions between disinfectants, particularly chlorine, and naturally occurring organic material.
distribution system	A network of pipes leading from a treatment plant to customers' plumbing systems.
drinking water	Water intended primarily for human consumption (for the purposes of these guidelines, excludes bottled water).
<i>E. coli</i>	<i>Escherichia coli</i> ; bacterium found in the gut. Used as an indicator of faecal contamination of water.
effluent	The outflow water or wastewater from any water processing system or device.

Eh	A measure of redox potential — the propensity for oxidation and reduction reactions.
enteric	Intestinal; found in the gut.
environmental flows	Environmental allocation for surface water rivers, streams or creeks.
environmental values	Particular values or uses (sometimes called beneficial uses) of the environment that are important for a healthy ecosystem or for public benefit, welfare, safety or health, and that require protection from the effects of contaminants, waste discharges and deposits. Several environmental values may be designated for a specific water body.
eutrophication	Degradation of water quality due to enrichment by nutrients such as nitrogen and phosphorus, resulting in excessive algal and plant growth and decay, and often low dissolved oxygen in the water.
exchangeable sodium percentage (ESP)	The proportion of sodium adsorbed on a soil–clay mineral surface, as a percentage of total cation exchange capacity (used as a measure of soil sodicity).
flocculation	Process in which small particles are agglomerated into larger particles (which can settle more easily) through gentle stirring, by hydraulic or mechanical means.
Gantt chart	A Gantt chart is a type of bar chart that illustrates a project schedule. Gantt charts illustrate the start and finish dates of the elements of a project.
grab sample	Single sample collected at a particular time and place that represents the composition of the water only at that time and place.
groundwater	Water contained in rocks or subsoil.
groundwater-dependant ecosystem (GDE)	A diverse and important component of biological diversity; takes into account ecosystems that use groundwater as part of survival. GDEs can potentially include wetlands, vegetation, mound springs, river baseflows, cave ecosystems, playa lakes and saline discharges, springs, mangroves, river pools, billabongs and hanging swamps.
groundwater recharge	Replenishing of groundwater naturally, by precipitation or runoff; or artificially, by spreading or injection.

guideline	Numerical concentration limit or narrative statement recommended to support and maintain a designated water use.
guideline value	The concentration or measure of a water quality characteristic that, based on present knowledge, either does not result in any significant risk to the health of the consumer (health-related guideline value), or is associated with good-quality water (aesthetic-guideline value).
hazard	A biological, chemical, physical or radiological agent that has the potential to cause harm.
hazard control	The application or implementation of preventive measures that can be used to control identified hazards.
hazard identification	The process of recognising that a hazard exists and defining its characteristics.
hazardous event	An incident or situation that can lead to the presence of a hazard (what can happen, and how it can happen).
helminth	A worm-like invertebrate of the order Helminthes; a parasite of humans and other animals.
heterogeneity	Having different properties at different locations within an aquifer.
hyporheic	Living in the interface between groundwater and surface water bodies.
impact	Having an effect on endpoints such as people, plants, soil, biota, water or a part of the environment.
indicator	Measurement parameter or combination of parameters that can be used to assess the quality of water; a specific contaminant, group of contaminants or constituent that signals the presence of something else.
indicator organisms	Microorganisms whose presence is indicative of pollution or of more harmful microorganisms (eg <i>E. coli</i> indicates the presence of pathogenic bacteria).
injectant	The water injected (pumped or fed by gravity) into an ASR or ASTR injection well.
injection well	A well that admits water into an aquifer, by pumping or under gravity.

irrigation	Provision of sufficient water for the growth of crops, lawns, parks and gardens; can be by flood, furrow, drip, sprinkler or subsurface water application to soil.
karstic aquifer	Irregular limestone containing fissures, sinkholes, underground streams and caverns produced by dissolution and erosion.
labile	A labile compound is one that is prone to change, such as an organic carbon compound that is easily biodegraded.
Langelier Index	The Langelier Saturation Index (LSI) is an indicator of the degree of saturation of water with respect to calcium carbonate. It depends on temperature, pH, alkalinity and calcium hardness. Positive values indicate potential for calcite precipitation and negative values can indicate corrosion potential.
log reduction or removal	<p>Logarithmic (base 10) concentration reductions, effectively reduction by a factor of 10.</p> <p>Used in reference to the physical–chemical treatment of water to remove, kill, or inactivate microorganisms such as bacteria, protozoa and viruses.</p> <ul style="list-style-type: none"> <li>• 0.5 log reduction = 68% reduction</li> <li>• 1 log reduction = 90% reduction</li> <li>• 1.5 log reduction = 97% reduction</li> <li>• 2 log reduction = 99% reduction</li> <li>• 2.5 log reduction = 99.7% reduction</li> <li>• 3 log reduction = 99.9% reduction.</li> </ul>
mainswater	Potable water from a reticulated water supply (eg town water supply).
managed aquifer recharge	The intentional recharge of water to aquifers for subsequent recovery or environmental benefit..
maximal risk	The level of risk in the absence of preventive measures; also referred to as inherent or unmitigated risk.
mean	The arithmetic average obtained by adding quantities and dividing the sum by the number of quantities.

membrane filtration index (MFI)	An index of clogging in injection wells. A sample of water is pressurised at a standardised pressure, and passed through a standardised filter membrane; the cumulative flow versus time is then recorded. Plotting the inverse of the instantaneous flow rate versus cumulative volume generally gives a linear slope before filter-cake compression occurs. This slope is known as the MFI. Low values (in $s^2/L$ ) indicate low potential for physical clogging (Dillon et al 2001).
metals and metalloids	Metallic elements (eg mercury, chromium, cadmium, arsenic and lead) that can cause damage to living organisms at very low concentrations and tend to accumulate in the food chain.
microorganism	Organism too small to be visible to the naked eye (eg bacteria, viruses, protozoa, some fungi and algae).
monitoring	Systematically keeping track of something, including sampling or collecting and documenting information.
multiple barriers	Use of more than one preventive measure as a barrier against hazards.
native groundwater	Groundwater that was present before recharge operations.
nephelometric turbidity unit	A measure of turbidity.
nitrification	The oxidation of ammonia nitrogen to nitrate nitrogen in wastewater by biological means.
nitrogen	An important nutrient originating from human and domestic wastes; found in high concentrations in recycled waters. A useful plant nutrient that can also cause off-site eutrophication problems in lakes, rivers and estuaries; it can also contaminate groundwater.
nomogram	A nomogram is a two-dimensional diagram designed to allow the approximate graphical computation of a function.
nutrient	A substance that provides nourishment for an organism. The key nutrients in stormwater runoff are nitrogen and phosphorus.
nutrient imbalance	Unbalanced supply of plant mineral nutrients, resulting in plant deficiencies and toxicities.
observation well	A narrow bore, well or piezometer; its sole function is to permit measurement of water level and water quality.

oligotroph	An organism that can live in water with a very low carbon concentration.
operational monitoring	The planned sequence of measurements and observations used to assess and confirm that individual barriers and preventive strategies for controlling hazards are functioning properly and effectively.
osmosis	The process where water flows from a low salinity environment through a membrane to a higher salinity environment to balance the salt concentration on both sides of the membrane.
overburden	Geological strata overlying an aquifer or aquitard.
PAHs (polycyclic aromatic hydrocarbons)	Chemical compounds that are formed by incomplete combustion of carbon-containing fuels such as petrol, wood, fat or tobacco. One of the most widespread organic pollutants from non-point sources (eg atmospheric deposition) or point sources (eg oil spills). Some PAHs are known or suspected carcinogens.
passive treatment	Treatment technologies that can function with little or no operation or maintenance over long periods of time. They can function for weeks, years, or even decades with little human interference. Examples include: grassed swales, ponds, wetlands, unsaturated zone infiltration systems and aquifer storage.
pathogen	A disease-causing organism (eg bacteria, viruses, protozoa).
pH	Value representing acidity or alkalinity of an aqueous solution; expressed as the logarithm of the reciprocal of the hydrogen ion activity in moles per litre at a given temperature.
phosphorus	An important nutrient found in high concentrations in recycled waters; originates principally from detergents, but also from other domestic wastes. A useful plant nutrient that can also cause off-site eutrophication problems in water bodies.
phreatophytic vegetation	Deep-rooted plants (typically trees) that use groundwater.
piezometer	A short-screened observation well used to determine pressure or water quality at a particular depth interval within an aquifer.
pK <sub>a</sub>	Value representing the tendency of a compound to dissociate to form acidic ions; expressed as the negative logarithm of the acid-ionisation constant (K <sub>a</sub> ).

pollutant	Substance that damages the quality of the environment.
potable (drinking) water	Alternative term for drinking water.
pretreatment	Any treatment (eg detention, filtration) that improves the quality of water before injection.
preventive measure	Any planned action, activity or process that is used to prevent hazards from occurring, or reduce them to acceptable levels of risk.
protozoa	A phylum of single-celled, free-living animals; found mostly in water and soil.
quality	The totality of characteristics of an entity that bear on its ability to satisfy stated and implied needs; the term 'quality' should not be used to express a degree of excellence.
quality assurance	All the planned and systematic activities implemented within the quality system, and demonstrated as needed, to provide adequate confidence that an entity will fulfil requirements for quality.
quality control	Operational techniques and activities that are used to fulfil requirements for quality.
radionuclide	An isotope of an element that is unstable and undergoes radioactive decay.
reclaimed water	Alternative (but less accurate) term for treated sewage. Recycled water is the preferred term.
recovery efficiency	The volume of recovered water that meets the salinity criteria for its intended uses; expressed as a percentage of the volume of fresh water injected into a brackish aquifer. Usually evaluated on an annual basis.
recycled water	Water generated from sewage, grey water or stormwater systems and treated to a standard that is appropriate for its intended use.
residual risk	The risk remaining after consideration of existing preventive measures.
retardation	Ion exchange processes in aquifers, which can effectively slow the movement of a solute front relative to the rate of groundwater flow.

reuse	Using water that would otherwise be discharged to wastewater or stormwater systems, for domestic, commercial, agricultural or industrial purposes.
reverse osmosis	An advanced method of wastewater treatment that relies on a semipermeable membrane to separate water from its impurities.
risk	The likelihood of a hazard causing harm to exposed populations in a specified timeframe; includes the magnitude of that harm.
risk assessment	The overall process of using available information to predict how often (likelihood) hazards or specified events may occur and the magnitude of their consequences (adapted from AS/NZS 4360: 2004).
risk management	The systematic evaluation of the water supply system, the identification of hazards and hazardous events, the assessment of risks, and the development and implementation of preventive strategies to manage the risks.
roofwater	Water collected from the roofs of buildings.
runoff	Surface overland flow of water resulting from rainfall or irrigation that exceeds the soil's infiltration capacity.
salinity	The presence of soluble salts in soil or water. Electrical conductivity and total dissolved salts are measures of salinity.
saturation index (SI)	Indicates the state of saturation of a groundwater sample for any mineral, by comparing the activities of ions in the sample to the activities at equilibrium.  SI = 0 indicates equilibrium; SI > 0 indicates supersaturation and possible precipitation; SI < 0 indicates subsaturation and possible dissolution.
screen	Slotted tube or wire-wound tubular frame in a well; permits the flow of groundwater to the well while maintaining the well's integrity.
secondary porosity	Any porosity that develops after deposition, especially due to tectonic or dissolution processes (as opposed to primary or intergranular porosity).
sediment	Unconsolidated mineral and organic particulate material that has settled to the bottom of aquatic environments.

sewage or wastewater	Material collected from internal household and other building drains; includes faecal waste and urine from toilets, shower and bath water, laundry water and kitchen water.
sewer mining	Process of extracting wastewater directly from a sewer (either before or after a sewage treatment plant) for reuse as recycled water.
shandyng	Addition of one water source to another to modify the quality of the water.
sievert (Sv)	Unit to measure the effective dose of radiation that takes into account the equivalent dose received by all tissues or organs, weighted to account for their different sensitivities to radiation.
sodicity	A condition in which positively charged sodium ions cause the soil particles to repel each other, resulting in soil swelling, dispersion and reduced soil permeability.
sodium	An element endemic to the environment. High concentrations of sodium in soil relative to calcium and magnesium cause sodicity (exchangeable sodium percentage [ESP] >6 or sodium adsorption ratio [SAR] >3).
source water	Water as harvested, before any treatment and before recharge.
species	A group of organisms that resemble each other to a greater degree than members of other groups, and that form a reproductively isolated group that will not normally breed with members of another group.
stakeholder	A person or group (eg an industry, a government jurisdiction, a community group, the public) that has an interest or concern in something.
standard (eg water-quality standard)	An objective that is recognised in environmental control laws enforceable by a level of government.
storage	A natural or artificial impoundment used to hold water before its treatment or distribution (eg dam, reservoir, aquifer).
stormwater	Rainwater that runs off all urban surfaces such as roofs, pavements, car parks, roads, gardens and vegetated open space.

stratification	The layering within an aquifer caused by density contrasts; for example, induced by salinity or temperature differences between recharged water and native groundwater.
stygofauna	All animals that occur in subsurface waters.
surface water	All water naturally open to the atmosphere (eg rivers, streams, lakes, reservoirs).
surrogate	Surrogate analytes are used to improve monitoring cost efficiency or reliability for classes of hazards for which representative surrogates are easier to measure or have lower detection levels.
suspended solids	Solids in suspension in water that can be removed by laboratory filtering, usually by a filter of nominal pore size of about 1.2 $\mu\text{m}$ .
target criteria	Quantitative or qualitative parameters established for preventive measures to indicate performance; performance goals.
tertiary treatment	Includes treatment processes, beyond secondary or biological processes, that further improve effluent quality. Tertiary treatment processes include detention in lagoons and conventional filtration via sand, dual media or membrane filters, which may include coagulant dosing and land-based or wetland processes.
thermotolerant coliforms	Coliform bacteria that originate from the gut of warm-blooded animals and whose presence in drinking water can be used as an indicator for operational monitoring.
total dissolved salts	A measurement of the total dissolved salts in a solution. Major salts in recycled water typically include: sodium, magnesium, calcium, carbonate, bicarbonate, potassium, sulfate and chloride. Used as a measure of soil salinity with the units of mg/L.
toxicity	The extent to which a compound is capable of causing injury or death, especially by chemical means.
toxicology	Study of poisons and their effects, antidotes and detection.
tracer	Any distinctive substance that can be used to quantitatively or qualitatively ‘fingerprint’ water.
transmissivity	A parameter indicating the ease of groundwater flow through a metre width of aquifer section; taken perpendicular to the direction of flow.

turbidity	The cloudiness of water caused by the presence of fine suspended matter.
unconfined aquifer	A type of aquifer that has the watertable as its upper boundary; is usually recharged by infiltration from the surface.
validation of processes	The substantiation, by scientific evidence (investigative or experimental studies), of existing or new processes and operational criteria to ensure capability to effectively control hazards.
virus	Protein-coated molecules of nucleic acid (genetic material) unable to grow or reproduce outside a host cell.
waterlogging	Saturation of soil with water.
water recycling	A generic term for water reclamation and reuse. Can also describe a specific type of reuse where water is recycled and used again for the same purpose (eg recirculating systems for washing and cooling), with or without treatment in between.
watertable	Groundwater near the soil surface, with no confining layers between the groundwater and soil surface.

# Tables, figures and boxes

## Tables

Table 1.1	Resource management and environmental protection policies invoked by managed aquifer recharge operations .....	8
Table 2.1	Components of a managed aquifer recharge system.....	15
Table 2.2	Examples of unintentional, unmanaged and managed aquifer recharge.....	21
Table 4.1	Assessment stages and objectives .....	35
Table 4.2	Issues addressed at each stage of investigations .....	37
Table 4.3	Entry-level assessment Part 1 — viability assessment .....	43
Table 4.4	Entry-level assessment Part 2 — degree of difficulty assessment.....	45
Table 5.1	Summary of key hazards in source water, groundwater and aquifer materials for managed aquifer recharge projects, with examples of specific hazards and preventive methods.....	54
Table 5.2	Examples of hazardous byproducts of managed aquifer recharge operations .....	55
Table 5.3	Summary of preventive measures and critical control points for managed aquifer recharge .....	56
Table 5.4	Maximum inactivation times, in days, observed for microorganisms in situ in Australian aerobic and anoxic aquifers, using diffusion chambers <sup>a</sup> .....	61
Table 5.5	Criteria, controls and monitoring to mitigate pathogen hazards in relation to the stages of risk assessment .....	63
Table 5.6	Criteria, controls and monitoring to mitigate inorganic chemical hazards in relation to the stages of risk assessment .....	69
Table 5.7	Criteria, controls and monitoring to mitigate salinity and sodicity hazards in relation to the stages of risk assessment .....	71
Table 5.8	Nitrogen removal efficiencies in different soil aquifer treatment operations.....	74
Table 5.9	Criteria, controls and monitoring to mitigate nutrient hazards in relation to the stages of risk assessment.....	75
Table 5.10	Criteria, controls and monitoring to mitigate organic chemical hazards in relation to the stages of risk assessment .....	79
Table 5.11	Criteria, controls and monitoring to mitigate turbidity hazards in relation to the stages of risk assessment .....	82
Table 5.12	Criteria, controls and monitoring to mitigate radionuclide hazards in relation to the stages of risk assessment .....	84

Table 5.13	Criteria, controls and monitoring to mitigate pressure, flow or volume-related hazards in confined and semiconfined aquifers in relation to the stages of risk assessment.....	88
Table 5.14	Criteria, controls and monitoring to mitigate pressure, flow or volume-related hazards in unconfined aquifers in relation to the stages of risk assessment.....	92
Table 5.15	Criteria, controls and monitoring to mitigate contaminant migration in fractured rock and karstic aquifers in relation to the stages of risk assessment.....	97
Table 5.16	Criteria, controls and monitoring to mitigate aquifer dissolution and well and aquitard stability hazards in relation to the stages of risk assessment.....	101
Table 5.17	Criteria, controls and monitoring for groundwater-dependent ecosystem protection in relation to the stages of risk assessment.....	108
Table 5.17	(continued).....	109
Table 5.18	Criteria, controls and monitoring to address energy and greenhouse gas considerations in relation to the stages of risk assessment.....	112
Table 6.1	Operational issues specific to managed aquifer recharge and examples of their impact.....	114
Table 6.2	Clogging types, causes, diagnosis and methods for management.....	118
Table 6.2	(continued).....	119
Table 6.3	Rates of clogging at 14 ASR sites according to aquifer type and quality of source water.....	121
Table 7.1	Examples of subsurface validation monitoring for managing health and environmental risks in managed aquifer recharge systems.....	139
Table 7.3	Examples of subsurface operational monitoring and supporting programs for managing health and environmental risks and clogging.....	142
Table 7.4	Examples of verification monitoring and supporting programs for managing health and environmental risks.....	143
Table 7.5	Example of sampling program for operational, validation and verification monitoring of health and environment protection in stages of system development.....	144
Table A1.1	References for water-quality requirements for environmental values of water.....	147
Table A1.2	Entry-level assessment, indicating relative degree of difficulty in relation to specific environmental values of the aquifer and intended uses of recovered water.....	148
Table A3.1	Examples of the tools available for a Stage 3 assessment.....	153
Table A4.1	1 log <sub>10</sub> reduction times (T <sub>90</sub> ) of enteric microorganisms.....	158
Table A4.2	Brief descriptions of enteric microorganisms used in Table A4.1.....	159
Table A5.1	Environmental fate data for organic chemicals.....	164

Table A5.2	Environmental fate data for transformation products exhibiting similar or greater toxicity than the parent compound .....	175
Table A5.3	Treatment removal categories for indicator compounds of soil aquifer treatment systems under specified conditions <sup>a</sup> (adapted from Drewes et al 2008b) .....	176
Figure A7.1	Decision tree for identifying arsenic mobilisation in managed aquifer recharge (from Vanderzalm et al, 2009) .....	186
Table A7.1	Trace ions posing a concern to human health or the environment that can be released during managed aquifer recharge .....	188
Table A8.1	Characteristics of aquifers and their influence on potential for managed aquifer recharge .....	193
Table A9.1	Relationships between aquifer characteristics, source-water quality and well clogging .....	195
Table A9.2	Examples of the minimum fraction of recharge water present in recovered water, as a function of the total dissolved salts concentration of the ambient groundwater .....	197
Table A9.3	Summary of recovery efficiencies from six ASR sites .....	198
Table A10.1	Inventory of managed aquifer recharge case study sites .....	199
Table A11.1	Assessment of risks for hazards at Andrews Farm stormwater ASR site .....	201

## Figures

Figure 1.1	National Water Quality Management Strategy guidelines and documents .....	2
Figure 1.2	Relationship between managed aquifer recharge guidelines and other water recycling guidelines .....	5
Figure 1.3	How to use the managed aquifer recharge guidelines to assess and manage risk .....	11
Figure 2.1	Two examples of managed aquifer recharge, showing the seven components of the system .....	14
Figure 2.2	Schematic of types of managed aquifer recharge .....	18
Figure 3.1	Elements of the framework for managing water quality and use .....	23
Figure 3.2	Attenuation zone in an aquifer .....	27
Figure 4.1	Risk assessment stages in managed aquifer recharge project development .....	34
Figure 4.2	Indicative Gantt chart for development of a typical managed aquifer recharge project requiring risk assessment .....	38
Figure 4.3	A schematic for entry-level viability assessment for managed aquifer recharge projects .....	41
Figure 6.1	Change in salinity of pumped water during recovery stage .....	125

Figure 7.1	Schematic showing zones of influence of a managed aquifer recharge operation .....	137
Figure A4.1	Decay of enteric bacteria and virus in an aquifer at Floreat Park where infiltration galleries recharge secondary treated sewage effluent.....	157
Figure A6.1	Nomogram for dual-well ASR system (recovery well downgradient of injection well) .....	181
Figure A6.2	Preferential flow beneath infiltration basins .....	184
Figure A7.2	Decision tree for identifying potential for iron mobilisation or iron clogging due to redox processes in managed aquifer recharge; iron concentrations may also be affected by mineral equilibrium processes (from Vanderzalm et al, 2009).....	187

## Boxes

Box 1.1	Summary of Australia's existing and planned water recycling guidelines .....	1
Box 1.2	Principles of sustainable use of recycled water .....	4
Box 1.3	Relationship between the national guidelines and state and territory guidelines .....	6
Box 3.1	Example of managed aquifer recharge system assessment for a stormwater ASTR system .....	26
Box 3.2	Attenuation zone in an aquifer .....	27
Box 3.3	Examples of preventive measures and critical control points for a stormwater ASTR system .....	28
Box 3.4	Examples of operational procedures and process control for a stormwater ASTR system .....	29
Box 4.1	Example of a simplified assessment .....	40
Box 4.2	Examples of entry-level assessment for two managed aquifer recharge projects.....	51
Box 5.1	Arsenic release .....	66
Box 5.2	Optimising nitrogen removal through soil aquifer treatment .....	74
Box 5.3	Fate of THMs during ASR.....	78
Box 5.4	Radon increase during ASR testing .....	84
Box 5.5	Height of groundwater mound beneath infiltration basins .....	91
Box 5.6	Homogeneous porous media (a), fractured rock (b) and karst (c) aquifer characteristics, showing the opportunity for rapid migration of constituents in recharged water.....	96
Box 5.7	Effect of calcite dissolution on well stability.....	100
Box 5.8	Discharge to marine ecosystems.....	106
Box 6.1	Identification and management of chemical clogging.....	119
Box 6.2	Reduction in salinity of recovered water with successive cycles .....	124

Box 6.3	Burdekin Delta saline water intrusion barrier .....	130
Box 6.4	Example of managed aquifer recharge for environmental protection .....	130
Box 6.5	Backwashing performance in relation to purge water management.....	131
Box 7.1	Use of integrated passive samplers to assess pesticides in recharge water.....	134
Box 7.2	Examples of validation monitoring for a treated sewage aquifer storage and recovery scheme.....	135
Box 7.3	Examples of indicators and surrogates .....	136
Box 7.4	Groundwater sampling as an integrator of variable source-water quality .....	139
Box A5.1	Example of application of the environmental fate data for chloroform.....	163
Box A6.1	Calculation of attenuation zone size for different situations .....	181
Box A6.2	Travel time in an unsaturated zone .....	184



## References

- Alvarez ME, Aguilar M, Fountain A, Gonzalez N, Rascon O and D Saenz (2000). Inactivation of MS-2 phage and poliovirus in groundwater. *Canadian Journal of Microbiology* 46(2):159–165.
- Amy G and Drewes J (2007). Soil aquifer treatment (SAT) as a natural and sustainable wastewater reclamation/reuse technology: fate of wastewater effluent organic matter (EfOM) and trace organic compounds. *Environmental Monitoring and Assessment* 129:19–26.
- ANZECC–ARMCANZ (2000a). *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*. National Water Quality Management Strategy Paper no. 4. Australian and New Zealand Environmental and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand, Canberra.
- ANZECC–ARMCANZ (2000b). *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*. National Water Quality Management Strategy Paper no. 7. Australian and New Zealand Environmental and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand, Canberra.
- Appelo CAJ and Postma D (1999). *Geochemistry, Groundwater and Pollution*, AA Balkema Publishers, Leiden, the Netherlands.
- Appelo CAJ and Postma D (2005). *Geochemistry, Groundwater and Pollution*, 2<sup>nd</sup> edition, AA Balkema Publishers, Leiden, the Netherlands.
- APVMA (2007). *Chemical Reviews*, Australian Pesticides and Veterinary Medicines Authority. <http://www.apvma.gov.au/chemrev/chemrev.shtml>
- ARMCANZ–ANZECC (1994). *National Water Quality Management Strategy: Policies and Principles — A Reference Document*. Paper no. 2, April 1994, Agriculture and Resource Management Council of Australia and New Zealand and Australian and New Zealand Environment and Conservation Council, Canberra.
- ARMCANZ–ANZECC (1995). *Guidelines for Groundwater Protection in Australia*, National Water Quality Management Strategy, Agriculture and Resource Management Council of Australia and New Zealand and Australian and New Zealand Environment and Conservation Council, Canberra.
- Arthur JD, Dabous AA and Cowart JB (2003). Water-rock geochemical considerations for aquifer storage and recovery: Florida case studies southwest Florida. In: *2<sup>nd</sup> International Symposium on Underground Injection Science and Technology*, Berkley, California, 22–25 October 2003.
- AS/NZS (2004). Risk management. Australian Standard/New Zealand Standard 4360. Standards Australia. <http://www.saiglobal.com/shop/script/search.asp>
- Australian Water Resources Council (1982). Guidelines for the use of reclaimed water for aquifer recharge. Water Management Series No 2. Department of National Development and Energy. Australian Government Publishing Service, Canberra.

- Barbash JE and Resek EA (1997). *Pesticides in Groundwater: Distribution, Trends and Governing Factors*, Lewis Publishers, USA.
- Barry K, Pavelic P, Dillon P, Rattray K, Dennis K and Gerges N (2002). *Aquifer Storage and Recovery of Stormwater, Andrews Farm South Australia: Compilation of Data from the 1993–1998 Trial*, CSIRO Technical Report 17/02. <http://www.clw.csiro.au/publications/technical2002/tr17-02.pdf> (accessed 18 June 2009).
- Bekele E, Sklorz S, Douglas G and Prommer H (2007). *Batch Experiments Using Reverse Osmosis Water and Sands from the Swan Coastal Plain*, CSIRO Water for a Healthy Country National Research Flagship. [http://www.clw.csiro.au/publications/waterforahealthycountry/2007/wfhc\\_BatchExperimentsReverseOsmosis.pdf](http://www.clw.csiro.au/publications/waterforahealthycountry/2007/wfhc_BatchExperimentsReverseOsmosis.pdf)
- Bekele E, Toze S, Higginson S, Patterson B, Blair P, Heitz A, Browne A, Leviston Z, Po M, Nancarrow B, Tucker D, Porter N, McGuinness N, Rodriguez C and Devine C (2008). *Determining Requirements for Managed Aquifer Recharge in Western Australia: Progress Report*, CSIRO Water for a Healthy Country Flagship. <http://www.clw.csiro.au/publications/waterforahealthycountry/2008/wfhc-DeterminingRequirementsManagingAquiferRechargeWA.pdf> (accessed 18 June 2009).
- Berry KA and Armstrong D (1997). Olympic Dam Project Water Supply — environmental constraints. In: *Proceedings of the 6<sup>th</sup> International. Mine Water Association Congress*, Bled, Slovenia, 1:261–271.
- Blair PM and Turner N (2004). Groundwater — a crucial element of water recycling in Perth, Western Australia. In: *Proceedings of the International Water Sensitive Urban Design Symposium*, Adelaide, 21–25 November 2004, 451–460.
- Blanc R and Nasser A (1996). Effect of effluent quality and temperature on the persistence of viruses in soil. *Water Science and Technology* 33(10–11):237–242.
- Boulton AJ, Humphreys WF and Eberhard SM (2003). Imperiled subsurface waters in Australia: biodiversity, threatening processes and conservation. *Aquatic Ecosystem Health and Management* 6:41–45.
- Bouwer H (1978). *Groundwater Hydrology*, McGraw-Hill Inc, New York.
- Bouwer H (2002). Artificial recharge of groundwater: hydrogeology and engineering. *Hydrogeology Journal* 10(1):121–142.
- Bouwer H, Pyne, RDG, Brown J, St Germain D, Morris TM, Brown CJ, Dillon P and Rycus MJ (2008). Design, operation and maintenance for sustainable underground storage facilities. American Water Works Association Research Foundation Report. Denver, USA.
- Bradley PM (2000). Microbial degradation of chloroethenes in groundwater systems. *Hydrogeology Journal* 8:104–111.
- Bureau of Rural Sciences (2007). *Connected Water: Managing the Linkages between Surface Water and Groundwater*, Bureau of Rural Sciences. <http://www.connectedwater.gov.au/> (accessed 18 June 2009)

- Cambridgesoft Corporation (2004). *Chemfinder Reference Database*, Cambridgesoft Corporation. <http://chemfinder.cambridgesoft.com> (accessed 18 June 2009).
- Cavé LC (2000). Geochemical modelling and laboratory batch experiments to test the feasibility of an artificial recharge scheme. In: *Groundwater: Past Achievements and Future Challenges*, Sililo O et al (eds), Proceedings of the XXX Congress of the International Association of Hydrogeologists, Cape Town, South Africa, 26 November–1 December 2000, AA Balkema, Rotterdam, 465–470.
- Charlesworth PB, Narayan KA, Bristow KL, Lowis B, Laidlow G and McGowan R (2002). The Burdekin Delta — Australia's oldest artificial recharge scheme. In: *Management of Aquifer Recharge for Sustainability*, PJ Dillon (ed), Proceedings of the 4<sup>th</sup> International Symposium on Artificial Recharge (ISAR4), Adelaide, 22–26 September 2002, Swets and Zeitlinger, Lisse, 347–352.
- City of Melbourne (2007). *Climate Neutral Water Saving Schemes*. [http://www.melbourne.vic.gov.au/rsrc/PDFs/EnvironmentalPrograms/Climate\\_neutral\\_water\\_saving\\_schemes.DOC](http://www.melbourne.vic.gov.au/rsrc/PDFs/EnvironmentalPrograms/Climate_neutral_water_saving_schemes.DOC) (accessed 19 June 2009)
- Clark JF, Hudson GB and Avisar D (2005). Gas transport below artificial recharge ponds: Insights from dissolved noble gases and a dual gas (SF<sub>6</sub> and <sup>3</sup>He) tracer experiment. *Environmental Science and Technology* 39:3939–3945.
- Clinton T. (2007). Reclaimed water aquifer storage and recovery – potential changes in water quality. WateReuse Foundation Report of Project WRF-03-009.
- Collins KE, Cronin AA, Rueedi J, Pedley S, Joyce E, Humble PJ and Tellam JH (2006). Fate and transport of bacteriophage in UK aquifers as surrogates for pathogenic viruses. *Engineering Geology* 85:33–38.
- Cook PG and Herczeg AL (2000). *Environmental Tracers in Subsurface Hydrology*, Kluwer Publishers, USA.
- Cook S, Vanderzalm J, Burn S, Dillon P and Page D (2006). A karstic aquifer system: Mount Gambier South Australia. In: *AISUWRS Urban Water Resources Toolbox — Models for Sustainability Assessment*, Chapter 3.4, Wolf L, Morris B and Burn S (eds), IWA Publishing, London.
- Crites RW (1985). Micropollutant removal in rapid infiltration. In: *Artificial Recharge of Groundwater*, Asano T (ed), Butterworth, Boston, 597–608.
- Danielopol DL (1976). The distribution of the fauna in the interstitial habitats of riverine sediments of the Danube and the Pisting (Australia). *International Journal of Speleology* 8:23–51.
- Danielopol DL (1989). Groundwater fauna associated with riverine aquifers. *Journal of the North American Benthological Society* 8(1):18–35.
- DSE–DHS Victoria (2006). Discussion Paper — A Framework for Alternative Urban Water Supplies: Managed Aquifer Recharge (MAR). December 2006. Department of Sustainability and Environment and Department of Human Services, Victorian Government <http://www.epa.vic.gov.au/water/reuse/default.asp> (accessed 18 June 2009)

Dillon, PJ (1984). Ephemeral stream–aquifer interaction. PhD thesis, Faculty of Engineering, University of Adelaide.

Dillon P (ed) (2002). *Management of Aquifer Recharge for Sustainability*, AA Balkema, Leiden, Netherlands, 567.

Dillon PJ (2005). Future management of aquifer recharge. *Hydrogeology Journal* 13(1)313–316.

Dillon P and Jimenez B (2008). Water reuse via aquifer recharge: intentional and unintentional practices. Chapter 14 in: *Water Reuse: An International Survey of Current Practice, Issues and Needs*, Jimenez B and Asano T (eds), International Water Association, Scientific and Technical Report no. 20.

<http://www.iwaponline.com/wio/2008/05/wio200805RF1843390892.htm> (accessed 18 June 2009).

Dillon P and Molloy R (2006). *Technical Guidance for ASR*. Report to Smart Water Fund, CSIRO Land and Water Science Report 4/06, March 2006, 24.

[http://www.smartwater.com.au/downloaddocs/Technical\\_Guidelines\\_for\\_ASR.pdf](http://www.smartwater.com.au/downloaddocs/Technical_Guidelines_for_ASR.pdf) (accessed 18 June 2009).

Dillon PJ and Pavelic P (1996). *Guidelines on the quality of stormwater and treated wastewater for injection into aquifers for storage and reuse*. Urban Water Research Association of Australia Research Report no. 109.

Dillon P and Toze S (eds) (2005). *Water Quality Improvements during Aquifer Storage and Recovery, Volume 1: Water quality improvement processes. Volume 2: Compilation of Information from Ten Sites*. American Water Works Assoc Research Foundation Report 91056F.

Dillon PJ, Pavelic P, Sibenaler X, Gerges NZ and Clark RDS (1997). Aquifer storage and recovery of stormwater runoff. *Australian Water and Wastewater Association Journal, Water* 24(4):7–11.

Dillon P, Pavelic P, Toze S, Ragusa S, Wright M, Peter P, Martin R, Gerges N and Rinck-Pfeiffer S (1999). Storing recycled water in an aquifer: benefits and risks. *Australian Water and Wastewater Association Journal, Water* 26(5):21–29.

Dillon P, Pavelic P, Massmann G, Barry K and Correll R (2001). Enhancement of the membrane filtration index (MFI) method for determining the clogging potential of turbid urban stormwater and reclaimed water used for aquifer storage and recovery. *Desalination* 140(2)153–165.

Dillon PJ, Miller M, Fallowfield H and Hutson J (2002). The potential of riverbank filtration for drinking water supplies in relation to microcystin removal in brackish aquifers. *Journal of Hydrology* 266(3–4):209–221.

Dillon P, Martin R, Rinck-Pfeiffer S, Pavelic P, Barry K, Vanderzalm J, Toze S, Hanna J, Skjemstad J, Nicholson B and Le Gal La Salle C (2003). Aquifer storage and recovery with reclaimed water at Bolivar, South Australia. In: *Proceedings of the Australian Water Association 2nd Australian Water Recycling Symposium*, Brisbane, 1–2 September 2003.

Dillon P, Toze S, Pavelic P, Vanderzalm J, Barry K, Ying G-G, Kookana R, Skjemstad J, Nicholson B, Miller R, Correll R, Prommer H, Greskowiak J and Stuyfzand P (2005a). Water quality improvements during aquifer storage and recovery at ten sites. In: *Recharge systems for protecting and enhancing groundwater resources*, UNESCO (eds), Proceedings of the 5<sup>th</sup> International Symposium on Management of Aquifer Recharge (ISMAR5), Berlin, 11–16 June 2005, 85–94. <http://unesdoc.unesco.org/images/0014/001492/149210e.pdf> (accessed 18 June 2009).

Dillon P, Pavelic P, Barry K, Fildebrandt S and Prawoto N (2005b). Nomogram to predict water quality improvement for managed recharge of aquifers. In: *Recharge systems for protecting and enhancing groundwater resources*, UNESCO (eds), Proceedings of the 5<sup>th</sup> International Symposium on Management of Aquifer Recharge (ISMAR5), Berlin, Germany, 11–16 June 2005. <http://unesdoc.unesco.org/images/0014/001492/149210e.pdf> (accessed 18 June 2009).

Dillon P, Page D, Vanderzalm J, Pavelic P, Toze S, Bekele E, Sidhu J, Prommer H, Higginson S, Regel R, Rinck-Pfeiffer S, Purdie M, Pitman C and Wintgens T (2008). A critical evaluation of combined engineered and aquifer treatment systems in water recycling. *Water Science and Technology* 57(5):753-762.

Dillon P, Pavelic P, Page D, Beringen H and Ward J (2009a). Managed Aquifer Recharge: An Introduction, Waterlines Report No 13, Feb 2009. <http://www.nwc.gov.au/www/html/996-mar--an-introduction---report-no-13--feb-2009.asp>

Dillon P, Kumar A, Kookana R, Leijes R, Reed D, Parsons S and Ingleton G (2009b). Managed Aquifer Recharge — Risks to Groundwater Dependent Ecosystems — A Review. *CSIRO Water for a Healthy Country Report to Land and Water Australia*. <http://www.clw.csiro.au/publications/waterforahealthycountry/2009/wfhc-managed-aquifer-recharge-risks.pdf> (accessed 13 Aug 2009)

DPR (2007). *Fate reviews*, Department of Pesticide Regulation, California. <http://www.cdpr.ca.gov/docs/emppm/pubs/envfate.htm> (accessed 18 June 2009).

Drewes JE, Hoppe C, Oldham G, McCray J and Thompson K (2008a). *Evaluation of River Bank Filtration Systems to Optimize Removal of Bulk Organic Matter, Emerging Organic Micropollutants, and Nutrients*. Final Report. AWWA Research Foundation, Denver, Colorado.

Drewes JE, Sedlak D, Snyder S and Dickenson E (2008b). *Indicator and surrogates to assess removal of wastewater-derived contaminants in wastewater treatment and reclamation*. Final Report. WateReuse Foundation, Alexandria, Virginia.

Dudding M, Evans R, Dillon P and Molloy R (2006). *Report on Broad Scale Map of ASR Potential in Melbourne*. SKM and CSIRO Report to Smart Water Fund, March 2006, 49. [http://www.smartwater.com.au/downloaddocs/Broad\\_Scale\\_Mapping\\_Report\\_for\\_Melbourne.pdf](http://www.smartwater.com.au/downloaddocs/Broad_Scale_Mapping_Report_for_Melbourne.pdf) (accessed 18 June 2009).

Eamus D, Hatton T, Cook P and Colvin C (2006). *Ecohydrology: Vegetation function, water and resource management*. CSIRO Publishing, Melbourne.

Eber R (1983). Nematoden aus dem Interstitial der Dnau bei Fischamend (Niederosterreich). *Archiv fur Hydrobiologie Supplement* 68:100–113.

Environment Protection Authority (SA). (2004). Code of Practice for Aquifer Storage and Recovery. 14p. Adelaide. [http://www.epa.sa.gov.au/pdfs/cop\\_aquifer.pdf](http://www.epa.sa.gov.au/pdfs/cop_aquifer.pdf) (accessed 18 June 2009).

Escalante AEF, Rodríguez MG and Gil FV (2005). Use of environmental indicators in a multi-criteria analysis of the impact of MAR on groundwater dependent wetlands. In: *Recharge systems for protecting and enhancing groundwater resources*, UNESCO (eds), Proceedings of the 5<sup>th</sup> International Symposium on Management of Aquifer Recharge (ISMAR5), Berlin, Germany, 11–16 June 2005, IHP-VI series on groundwater, 799–806. <http://unesdoc.unesco.org/images/0014/001492/149210e.pdf>

European Commission (2001). Artificial recharge of groundwater. Final Report of EC Project ENV4-CT95-0071. Directorate General for Research, EUR 19400.

EWRI/ASCE (2001). Standard Guidelines for Artificial Recharge of Ground Water. EWRI/ASCE 34-01. Artificial Recharge of Ground Water Committee, Standards Development Council, Environmental and Water Resources Institute, American Society of Civil Engineers.

Fies MW, Renken RA and Komlos SB (2002). Considerations for regional ASR in restoring the Florida Everglades, USA. In: *Management of Aquifer Recharge for Sustainability*, PJ Dillon (ed), AA Balkema Publishing, Leiden, the Netherlands, 341–346.

Fildebrandt S, Pavelic P, Dillon P and Prawoto N (2003). *Recharge Enhancement Using Single or Dual Well Systems for Improved Groundwater Management in the Bandung Basin, Indonesia*. CSIRO Technical Report 29/03, May 2003, CSIRO Land and Water, Adelaide. <http://www.clw.csiro.au/publications/technical2003/tr29-03.pdf> (accessed 18 June 2009).

Foppen JWA and Schijven JF (2006). Evaluation of data from the literature on the transport and survival of *Escherichia coli* and thermotolerant coliforms in aquifers under saturated conditions. *Water Research* 40:401–426.

Fox P (2002). Soil aquifer treatment: an assessment of sustainability. In: *Management of Aquifer Recharge for Sustainability*, PJ Dillon (ed), AA Balkema Publishers, Exton, Pennsylvania, 21–26.

Fox P (2007). *Management of Aquifer Recharge for Sustainability*, Acacia Publishing, Phoenix. <http://www.iah.org/recharge/> (accessed 18 June 2009).

Fox P, Narayanaswamy K, Genz A and Drewes JE (2001). Water quality transformations during soil aquifer treatment at the Mesa Northwest Water Reclamation Plant, USA. *Water, Science and Technology* 43(10):343–350.

Freeze RA and Cherry JA (1979). *Groundwater*, Prentice-Hall Inc, Englewood Cliffs, New Jersey.

Gale I (2005). *Strategies for MAR in Semi-Arid Areas*, UNESCO IHP Publication, 30. <http://www.iah.org/recharge/> (accessed 18 June 2009).

- Gerges, NZ, Dillon PJ, Sibenaler XP, Martin RR, Pavelic P, Howles SR and Dennis K. (2002). South Australian experience in aquifer storage and recovery. In *Management of Aquifer Recharge for Sustainability*, (ed PJ Dillon), 453-458. AA Balkema.
- Gerges NZ, Sibenaler XP and Howles SR (1996). South Australian experience in aquifer storage and recovery. *Proceedings of the International Symposium on Artificial Recharge of Groundwater*, Helsinki, Finland, 3-5 June 1996, Report no. 38, Nordic Hydrological Program.
- Gilbert J and Deharveng L (2002). Subterranean ecosystems: a truncated functional biodiversity. *Bioscience* 52(6):473-481.
- Glover RE and Balmer GG (1954). River depletion resulting from a well pumping near a river. *Transactions American Geophysical Union* 35:468-470.
- Gordon C and Toze S (2003). Influence of groundwater characteristics on the survival of enteric viruses. *Journal of Applied Microbiology* 95:536-544.
- Greskowiak J, Prommer H, Vanderzalm J, Pavelic P and Dillon PJ (2005). Modelling of carbon cycling and biogeochemical changes during injection and recovery of reclaimed water at Bolivar, South Australia. *Water Resources Research* 41(10):W10418, 16.
- Greskowiak J, Prommer H, Massmann G and Nützmann G (2006). Modeling seasonal redox dynamics and the corresponding fate of the pharmaceutical residue phenazone during artificial recharge of groundwater. *Environmental Science and Technology* 40:6615-6621.
- Gundersen LCS and Wanty RB (eds) (1993). *Field Studies of Radon in Rocks, Soils, and Water*, CRC Press, Boca Raton, Florida.
- Hantush MS (1967). Growth and decay of groundwater mounds in response to uniform percolation. *Water Resources Research* 3(1):227-234.
- Herczeg AL and Dighton JC (1998). Radon-222 concentrations in potable groundwater in Australia. *Water* (journal of the Australian Water Association) 28 (May-June):37.
- Herczeg AL, Rattray KJ, Dillon PJ, Pavelic P and Barry KE (2004). Geochemical processes during five years of Aquifer Storage Recovery. *Ground Water* 42(3):438-445.
- Hijnen WAM and van der Kooij D (1992). The effect of low concentrations of assimilable organic carbon (AOC) in water on biological clogging of sand beds. *Water Research* 26(7):963-972.
- Hodgkin T (2005). *Aquifer Storage Capacities of the Adelaide Region*, South Australian Government Department of Water, Land and Biodiversity Conservation, Report 2004/47.
- Howard P (1989). *Handbook of Environmental Fate and Exposure Data for Organic Chemicals*, Lewis Publishers, USA.
- Howard P (1991). *Handbook of Environmental Degradation Rates*, Lewis Publishers, USA.

Humphreys W (2006). *Groundwater Fauna*, paper prepared for the 2006 Australian State of the Environment Committee, Australian Government Department of the Environment, Water, Heritage and the Arts, Canberra, <http://www.environment.gov.au/soe/2006/publications/emerging/fauna/index.html> (accessed 18 June 2009),

Hutchinson A and Randall R (1995). Estimation of injection well clogging with modified fouling index (MFI). In: *Artificial Recharge of Groundwater II*, Johnson AI and Pyne RDG (eds), Proceedings of the 2<sup>nd</sup> International Symposium on Artificial Recharge of Groundwater, Orlando, Florida, 17–22 July 1994, ASCE, New York, 710–719.

Ibison MA, Sanders FA, Glanzman RK and Dronfield DG (1994). Manganese in recovered water from an ASR well. In: *Artificial Recharge of Groundwater II*, Johnson AI and Pyne RDG (eds), Proceedings of the 2<sup>nd</sup> International Symposium on Artificial Recharge of Groundwater, Orlando, Florida, 17–22 July 1994, ASCE, New York, 539–547.

Illinois General Assembly (2008). *Joint Committee on Administrative Rules Administrative Code, Title 35 Environmental Protection, Part 742: Tiered Approach to Corrective Action Objectives*, Illinois General Assembly, Illinois. <http://www.ilga.gov/commission/jcar/admincode/titles.html> (accessed 18 June 2009).

Ingleton, G. (2009). Strategies for assessing potential impacts of Aldinga Reclaimed Water ASR Scheme. Appendix 7 in Dillon et al (2009b). *Managed Aquifer Recharge — Risks to Groundwater Dependent Ecosystems — A Review*. CSIRO *Water for a Healthy Country Report to Land and Water Australia*.

International POPs Elimination Network (2007). *Endosulfan*. Web-published by International Persistent Organic Pollutants Elimination Network. [http://www.oztoxics.org/poprc/CandidatePOPs/proposals\\_1.html](http://www.oztoxics.org/poprc/CandidatePOPs/proposals_1.html) (accessed 18 June 2009).

IPCS (International Programme on Chemical Safety) (2008). *International Chemical Safety Cards*. <http://www.inchem.org/pages/icsc.html> (accessed 18 June 2009).

Jansons J, Edmonds LW, Speight B and Bucens MR (1989). Survival of viruses in groundwater. *Water Research* 23:301–306.

Jimenez B (2003). Health risk in aquifer recharge with recycled water. In: *State of the Art Report: Health Risks in Aquifer Recharge Using Reclaimed Water*, Aertgeerts R and Angelakis A (eds), World Health Organisation, Report SDE/WSH/03.08.

John DE and Rose JB (2005). Review of factors affecting microbial survival in groundwater. *Environmental Science and Technology* 39(19):7345–7356.

Jones MA, Harris SJ, Baxter KM and Anderson M (2005). The Streatham groundwater source: an analogue for the development of recharge enhanced groundwater resource management in the London basin. In: *Recharge Systems for Protecting and Enhancing Groundwater Resources*, UNESCO (eds), Proceedings of the 5<sup>th</sup> International Symposium on Management of Aquifer Recharge (ISMAR5), Berlin, Germany, 11–16 June 2005, IHP-VI series on groundwater, 819–824, <http://unesdoc.unesco.org/images/0014/001492/149210e.pdf> (accessed 18 June 2009).

Kahn SJ and Rorije E (2002). Pharmaceutically active compounds in aquifer storage and recovery. In: *Management of Aquifer Recharge for Sustainability*, Dillon PJ (ed), Proceedings of the 4<sup>th</sup> International Symposium on Artificial Recharge of Groundwater (ISAR4), Adelaide, 22–26 September 2002, Swets and Zeitlinger, Lisse, 169–174.

Knapton A, Jolly P, Pavelic P, Dillon P, Barry K, Mucha M and Gates W (2004). *Feasibility of a pilot 600 ML/yr Soil Aquifer Treatment Plant at the Arid Zone Research Institute*, Department of Infrastructure, Planning and Environment, Alice Springs, Report no. 29/2004A.

Komarova T, Bartkow ME, Müller JF, Carter S and Vanderzalm J (2006). Field evaluation of passive samplers: monitoring polycyclic aromatic hydrocarbons (PAHs) in stormwater. *Polycyclic Aromatic Compounds* 26:221–236.

Kumar, A. (2009). Review of ecotoxicological monitoring methods for groundwater dependent ecosystems. Appendix 6 in Dillon et al (2009b).: *Managed Aquifer Recharge — Risks to Groundwater Dependent Ecosystems — A Review*. CSIRO *Water for a Healthy Country Report to Land and Water Australia*.

Le Gal La Salle C, Vanderzalm J, Hutson J, Dillon P, Pavelic P and Martin R (2005). Isotope evolution and contribution to geochemical investigations in aquifer storage and recovery: a case study using reclaimed water at Bolivar, South Australia. *Hydrological Processes* 19:3395–3411.

Leijs R (2009). Potential effects on stygofauna communities of managed aquifer recharge. Appendix 3 in Dillon et al (2009b). *Managed Aquifer Recharge — Risks to Groundwater Dependent Ecosystems — A Review*. CSIRO *Water for a Healthy Country Report to Land and Water Australia*.

Leviston Z, Nancarrow BE, Tucker DI and Porter NB (2006). *Predicting Community Behaviour: Indirect Potable Reuse of Wastewater Through Managed Aquifer Recharge*, CSIRO Land and Water Science Report 29/06, Australia.  
<http://www.clw.csiro.au/publications/science/2006/sr29-06.pdf>

Mackay D, Shiu WY and May KC (1992). *Illustrated Handbook of Physical-Chemical Properties and Environmental Fate for Organic Chemicals*, vols I–III, Lewis Publishers, USA.

Marks R, Chapman F, Lane S and Purdie M (2005). Parafield urban stormwater harvesting facility, *Water* 32:42–45.

Martin MW, Xu C and Rattray KJ (2002). Management of physical clogging during ASR at Jandakot, Perth, Western Australia. In: *Management of Aquifer Recharge for Sustainability*, Dillon PJ (ed), Proceedings of the 4<sup>th</sup> International Symposium on Artificial Recharge of Groundwater (ISAR4), Adelaide, 22–26 September 2002, Swets and Zeitlinger, Lisse, 199–202.

- Miller R, Correll R, Dillon P and Kookana R (2002). ASRRI: a predictive model of contaminant attenuation during aquifer storage and recovery. In: *Management of Aquifer Recharge for Sustainability*, Dillon PJ (ed) Proceedings of the 4<sup>th</sup> International Symposium on Artificial Recharge of Groundwater (ISAR4), Adelaide, 22–26 September 2002, Swets and Zeitlinger, Lisse, 69–74.
- Montgomery J (1997). *Agrochemicals Desk Reference*, 2<sup>nd</sup> edition, Lewis Publishers, USA.
- Montgomery J and Welkom L (1991). *Groundwater Chemicals Desk Reference*, Lewis Publishers, USA.
- NHMRC–NRMMC (2004). *Australian Drinking Water Guidelines*, National Health and Medical Research Council and Natural Resource Management Ministerial Council, Canberra. <http://www.nhmrc.gov.au/publications/synopses/eh19syn.htm>
- NICNAS (2001). *Triphosphates: Priority Existing Chemicals Assessment Report No 17*, June 2001. National Industrial Chemicals Notification and Assessment Scheme, Commonwealth of Australia, Canberra. <http://www.nicnas.gov.au/Publications/CAR/PEC/PEC17.asp> (accessed 18 June 2009).✓
- NRC (1994). *Ground Water Recharge Using Waters of Impaired Quality*, National Research Council, National Academies Press, Washington DC.
- NRC (2008). *Prospects for Managed Underground Storage of Recoverable Water*, National Research Council, National Academies Press, Washington DC.
- NRMMC (2004). Guidelines for sewerage systems — biosolids management. National Water Quality Management Strategy Paper 13. Natural Resource Management Ministerial Council, Canberra, Australia.
- NHMRC–NRMMC (2004). *Australian Drinking Water Guidelines*, National Health and Medical Research Council and Natural Resource Management Ministerial Council, Canberra. <http://www.nhmrc.gov.au/publications/synopses/eh19syn.htm>
- NRMMC–EPHC–AHMC (2006). *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 1)*, Natural Resources Ministerial Management Council, Environment Protection and Heritage Council and Australian Health Ministers' Conference, Canberra.
- NRMMC–EPHC–NHMRC (2008). *Australian Guidelines for Water Recycling: Augmentation of Drinking Water Supplies (Phase 2)*, Natural Resource Ministerial Management Council, Environment Protection and Heritage Council and National Health and Medical Research Council, Canberra.
- NRMMC–EPHC–NHMRC (2009). *Australian Guidelines for Water Recycling: Stormwater Harvesting and Reuse (Phase 2)*, Natural Resource Ministerial Management Council, Environment Protection and Heritage Council and National Health and Medical Research Council, Canberra.
- Oliver YM, Gerritse RG, Dillon PJ and Smettem KRJ (1996). Fate and mobility of stormwater and waster contaminants in aquifers. Centre for Groundwater Studies Report no. 67, CGS, South Australia.

Olsthoorn TN (1982). *The Clogging of Recharge Wells*, Netherlands Waterworks' Testing and Research Institute KIWA Research Communications 72, 150.

Page D, Barry K, Pavelic P, Dillon P and Chassagne A (2008). Preliminary quantitative risk assessment for the Salisbury stormwater ASTR Project, CSIRO: Water for a Healthy Country National Research Flagship, ISSN: 1835-095X.

Page D, Vanderzalm J, Barry K, Levett K, Ayuso-Gabella M, Dillon P, Toze S, Sidhu J, Shackelton M, Purdie M and Regel R. (2009). Operational residual risk assessment for the Salisbury stormwater ASTR project. CSIRO Water for A Healthy Country report series. CSIRO: Water for a Healthy Country Flagship Report, April 2009.

<http://www.clw.csiro.au/publications/waterforahealthycountry/2009/wfhc-salisbury-ASTR-risk-assessment.pdf> (accessible from 28 Sept 2009)

Parsons S (2009). Effects on groundwater dependent vegetation of groundwater level changes induced by managed aquifer recharge. Appendix 5 in Dillon et al (2009b). Managed Aquifer Recharge — Risks to Groundwater Dependent Ecosystems — A Review. *CSIRO Water for a Healthy Country Report to Land and Water Australia*.

Pavelic P, Ragusa SR, Flower RL, Rinck-Pfeiffer SM and Dillon PJ (1998). Diffusion chamber method for in situ measurement of pathogen inactivation in groundwater. *Water Research* 32(4):1144–1150.

Pavelic P, Dillon P, Martin R, Traegar B and Simmons C (2001). Multi-scale permeability characterisation of a confined carbonate aquifer targeted for aquifer storage and recovery. In: *New Approaches to Characterising Groundwater Flow*, Seiler KP and Wohnlich S (eds), Proceedings of the International Association of Hydrogeologists XXXI Congress, Munich, 10–14 September 2001, AA Balkema Publishers, 2:859–862.

Pavelic P, Dillon P, Toze S, Barber C, Yin Foo D, Knapton A and Jolly PB (2002a). Water banking in the Australian tropics: results from a trial on South Goulburn Island, Northern Territory. In: *Management of Aquifer Recharge for Sustainability*, Dillon PJ (ed), Proceedings of the 4<sup>th</sup> International Symposium on Artificial Recharge (ISAR4), Adelaide, 22–26 September 2002, Swets and Zeitlinger, Lisse, 441–446.

Pavelic P, Dillon PJ and Simmons CT (2002b). Lumped parameter estimation of initial recovery efficiency during aquifer storage and recovery. In: *Management of Aquifer Recharge for Sustainability*, Dillon PJ, (ed), Proceedings of the 4<sup>th</sup> International Symposium on Artificial Recharge (ISAR4), Adelaide, 22–26 September 2002, Swets and Zeitlinger, Lisse, 285–290.

Pavelic P, Nicholson BC, Dillon PJ and Barry KE (2005). Fate of disinfection by-products in groundwater during aquifer storage and recovery with reclaimed water. *Journal of Contaminant Hydrology* 77:351–373.

Pavelic P, Dillon PJ and Nicholson BC (2006a). Comparative evaluation of the fate of disinfection byproducts at eight aquifer storage and recovery sites. *Environmental Science and Technology* 40(2):501–508.

Pavelic P, Dillon PJ and Simmons CT (2006b). Multi-scale characterization of a heterogeneous aquifer using an ASR operation. *Ground Water* 44(2):155–164.

- Pavelic P, Dillon PJ, Barry KE and Gerges NZ (2006c). Hydraulic evaluation of aquifer storage and recovery (ASR) with urban stormwater in a brackish limestone aquifer. *Hydrogeology Journal* 14(2):1544–1555.
- Pavelic P, Dillon PJ, Barry KE, Vanderzalm JL, Correll RL and Rinck-Pfeiffer SM (2007a). Water quality effects on clogging rates during reclaimed water ASR in a carbonate aquifer. *Journal of Hydrology* 334:1–16.
- Pavelic P, Dillon P and Barry K (2007b). Management of clogging for reclaimed water ASR in a carbonate aquifer. In: *Management of Aquifer Recharge for Sustainability*, Fox P (ed), Proceedings of the 6<sup>th</sup> International Symposium on Artificial Recharge (ISMAR6), Phoenix, Arizona, 28 October to 2 November 2007. <http://www.iah.org/recharge> (accessed 18 June 2009).
- Pedley S, Yates MV, Schijven JF, West J, Howard G and Barrett M (2006). Pathogens: health relevance, transport and attenuation. In: *Protecting Groundwater for Health: Managing the Quality of Drinking-Water Sources*, Schmoll O, Howard G, Chilton J and Chorus I (eds), WHO, IWA Publishing, London.
- Pérez-Paricio A and Carrera J (1998). A conceptual and numerical model to characterize the clogging of artificial groundwater recharge systems. In: *Proceedings of the 3<sup>rd</sup> International Symposium on Artificial Recharge of Groundwater (TISAR'98)*, Amsterdam, 21–25 September 1998, AA Balkema, Rotterdam, 55–60.
- Pérez-Paricio A and Carrera J (1999). Clogging handbook. EU Project on Artificial Recharge of Groundwater, Research program on Environment and Climate, Contract ENV-CT95–0071.
- Popit A, Vaupotic J and Kukar N (2004). Systematic radium survey in spring waters of Slovenia. *Journal of Environmental Radioactivity* 76:337–347.
- Pyne RDG (1995). *Groundwater recharge and wells: a guide to aquifer storage recovery*, Lewis Publishers, CRC Press, 376.
- Pyne RDG (2006). *Groundwater Recharge and Wells*, 2<sup>nd</sup> edition, ASR Systems, Florida.
- Radcliffe J (2004). *Water Recycling in Australia*, Australian Academy of Technological Sciences and Engineering. <http://www.atse.org.au/index.php?sectionid=597> (accessed 18 June 2009).
- Reed DA (2007). Spatial and temporal biogeochemical changes of groundwater associated with managed aquifer recharge in two different geographical areas. PhD Thesis, Department of Microbiology and Immunology, University of Western Australia, Perth, Australia.
- Reed D. (2009). Effects on aquifer microbial communities of managed aquifer recharge. Appendix 4 in: Dillon et al (2009b). Managed Aquifer Recharge — Risks to Groundwater Dependent Ecosystems — A Review. *CSIRO Water for a Healthy Country Report to Land and Water Australia*.
- Reed DA, Toze S and Chang B (2007). Spatial and temporal changes in sulfate-reducing groundwater bacterial community structure in response to managed aquifer recharge. In: *Proceedings of the International Water Association 6<sup>th</sup> Conference on Wastewater Reclamation and Reuse for Sustainability*, Antwerp, Belgium, 9–11 October 2007.

Rhebergen W and Dillon P (1999). *Riverbank Filtration Models for Assessing Viability of Water Quality Improvement*, Centre for Groundwater Studies Report no. 90, Glen Osmond, South Australia.

Rinck-Pfeiffer SM, Ragusa SR, Sztajn bok P and Vandeveld T (2000). Interrelationships between biological, chemical and physical processes as an analog to clogging in Aquifer Storage and Recovery (ASR) wells. *Water Research* 34(7):2110–2118.

Rinck-Pfeiffer S, Pitman C and Dillon P (2005). Stormwater ASR in practice and ASTR (Aquifer Storage Transfer and Recovery) under investigation in Salisbury, South Australia. In: *Recharge Systems for Protecting and Enhancing Groundwater Resources*, UNESCO (eds), Proceedings of the 5<sup>th</sup> International Symposium on Management of Aquifer Recharge (ISMAR5), Berlin, Germany, 11–16 June 2005, IHP-VI series on groundwater, 151–159, <http://unesdoc.unesco.org/images/0014/001492/149210e.pdf> (accessed 18 June 2009).

Runnels DR (1969). Diagenesis, chemical sediments, and the mixing of natural waters. *Journal of Sedimentary Petrology* 39(3):1188–1201.

Scatena MC and Williamson DR (1999). *A Potential Role for Artificial Recharge in the Perth Region: A Pre-feasibility Study*, Centre for Groundwater Studies Report no. 84, Glen Osmond, South Australia.

Schijven JF and Hassanizadeh SM (2000). Removal of viruses by soil passage: overview of modeling, processes and parameters. *Critical Reviews in Environmental Science and Technology* 31:49–125.

Schijven JF, Mülschlegel JHC, Hassanizadeh SM, Teunis PFM and de Roda Husman AM (2006). Determination of protection zones for Dutch groundwater wells against virus contamination — uncertainty and sensitivity analysis. *Journal of Water and Health* 4(3):297–312.

Syracuse Research Corporation (1999). *Physical Properties Database*, USA. <http://www.syrres.com/esc/physprop.htm> (accessed 18 June 2009).

Stevens R, Emmett AJ and Howles S (1995). Stormwater re-use at Regent Gardens residential development, Northfield, South Australia. In: Proceedings of the 2<sup>nd</sup> International Symposium on Urban Stormwater Management, 11–13 July 1995, Melbourne, National. Comm. Water Engin. and Inst. Engin. Aust. Publication NCP 95/03, Vol. 2, (supplementary paper).

Stormwater Management Authority (2009). Urban stormwater harvesting options study. Wallbridge & Gilbert. <http://www.waterforgood.sa.gov.au/2009/06/urban-stormwater-harvesting-options-study/> (accessed 18 July 2009).

Stuyfzand PJ, Vogelaar, AJ and Wakker J (2002). Hydrogeochemistry of prolonged deep well injection and subsequent aquifer storage in pyritiferous sands; DIZON pilot, Netherlands. In: *Management of Aquifer Recharge for Sustainability*, Dillon PJ (ed), Proceedings of the 4<sup>th</sup> International Symposium on Artificial Recharge of Groundwater (ISAR4), Adelaide, 22–26 September 2002, AA Balkema Publishing, Leiden, the Netherlands, 107–110.

Taylor SW and Jaffe PR (1990). Biofilm growth and the related changes in the physical properties of a porous medium I: Experimental investigation. *Water Resources Research* 26(9):2153–2159.

Toze S (2004). Pathogen survival in groundwater during artificial recharge. In: *Wastewater Re-use and Groundwater Quality*, Proceedings of IUGG2003 Symposium HS04, Sapporo, July 2003. IAHS Publication 285:70–84.

Toze S, and Bekele E (in press). Determining requirements for managed aquifer recharge in Western Australia. A report to the Water Foundation. CSIRO Water for a Healthy Country National Research Flagship.

<http://www.clw.csiro.au/publications/waterforahealthycountry/index.html#reports>

Toze S and Hanna J (2002). The survival of enteric microbial pathogens in a reclaimed water ASR project. In: *Management of Aquifer Recharge for Sustainability*, Dillon PJ (ed), Proceedings of the 4<sup>th</sup> International Symposium on Artificial Recharge of Groundwater (ISAR4), Adelaide, 22–26 September 2002, AA Balkema Publishing, Leiden, the Netherlands, 139-142.

Toze S, Hanna J, Smith A and Hick W (2002). Halls Head indirect treated wastewater reuse scheme. CSIRO Report to Water Corporation, Western Australia, October 2002.

Toze S, Hanna J, Smith T, Edmonds L and McCrow A (2004). Determination of water quality improvements due to the artificial recharge of treated effluent. *Wastewater Re-use and Groundwater Quality*. IAHS Publication 285:53–60.

Tufenkji N, Dixon DR, Considine R and Drummond CJ (2006). Multi-scale *Cryptosporidium* / sand interactions in water treatment. *Water Research* 40:3315–3331.

UNESCO IHP (2003). *Management of Aquifer Recharge and Subsurface Storage*, Netherlands National Committee of the International Association of Hydrogeologists, 86. <http://www.iah.org/recharge> (accessed 18 June 2009).

UNESCO IHP (2006). *Recharge Systems for Protecting and Enhancing Groundwater Resources*. Proceedings 5<sup>th</sup> International Symposium on Management of Aquifer Recharge, ISMAR5, Berlin, Germany, 11–16 June 2005. [http://www.iah.org/recharge/downloads/Recharge\\_systems.pdf](http://www.iah.org/recharge/downloads/Recharge_systems.pdf) (accessed 18 June 2009).

Vanderzalm JL (2004). Hydrogeochemical processes during aquifer storage and recovery (ASR) with reclaimed water in a carbonate aquifer. PhD thesis, Flinders University.

Vanderzalm JL, Le Gal La Salle C and Dillon PJ (2006). Fate of organic matter during aquifer storage and recovery (ASR) of reclaimed water in a carbonate aquifer. *Applied Geochemistry* 21:1204–1215.

Vanderzalm J, Sidhu J, Bekele E, Ying G-G, Pavelic P, Toze S, Dillon P, Kookana R, Hanna J, Barry K, Yu XY, Nicholson B, Morran J, Tanner S and Short S (2009). *Water Quality Changes During Aquifer Storage and Recovery*. Water Research Foundation, Denver, USA.

Vogel M (2005). Contaminant attenuation of urban water resources and systems in a carbonate aquifer — Gambier Limestone Aquifer (South Australia). Projektarbeit (Project work), Technical University of Berlin.

- Wall K, Toze S and O'Hara G (2004). The fate of enteric pathogens in artificial recharge schemes. In: Proceedings of the IWA 6th International Specialised Conference on Small Water and Wastewater Systems and 1st International Specialised Conference on Onsite Wastewater Treatment and Recycling, 11-13 February 2004, Fremantle, Western Australia. Mathew K and Ho G (eds), International Water Association Publication, London, UK, 53–60.
- Ward, J and Dillon, P (2009). Robust Design of Managed Aquifer Recharge Policy in Australia. CSIRO Water for a Healthy Country Report to National Water Commission.
- Ward JD, Simmons CT, Dillon PJ, and Pavelic P (2009). Integrated assessment of lateral flow, density effects and dispersion in aquifer storage and recovery. *Journal of Hydrology* 370: 83-99.
- Wauchope RD, Buttler TM, Hornsby AG, Augustijn-Beckers PWM, and Burt JP (1992). The SCS/ARS/CES pesticide properties database for environmental decision making. *Reviews of Environmental Contamination and Toxicology* 123:1–164. ✓
- Environmental Protection Authority of Western Australia (2005). Strategic advice on managed aquifer recharge using treated wastewater on the Swan Coastal Plain. Bulletin 1199, Western Australia.
- WHO (2006). *Guidelines for Drinking Water Quality*, 3<sup>rd</sup> edition, World Health Organization, Geneva. [http://www.who.int/water\\_sanitation\\_health/dwq/gdwq3rev/en/](http://www.who.int/water_sanitation_health/dwq/gdwq3rev/en/) (accessed 18 June 2009).
- Williams JB, Cowart JB and Arthur JD (2002). Florida aquifer storage and recovery geochemical study: year one and year two progress report. Florida Geological Survey Open File Report 82.
- Wood M, Le Gal La Salle C, Dillon PJ, Hutson J, Fallowfield H and Rinck-Pfeiffer SM (2005). Effect of grain size on biological clogging in porous media leached with synthetic nutrient solutions. In: *Recharge systems for protecting and enhancing groundwater resources*, UNESCO (eds), Proceedings of the 5<sup>th</sup> International Symposium on Management of Aquifer Recharge (ISMAR5), Berlin, 11–16 June 2005. <http://unesdoc.unesco.org/images/0014/001492/149210e.pdf> (accessed 18 June 2009).
- Water Services Association of Australia (2007). Sustainability framework. Report prepared by University of NSW.
- Yahya MT, Galsomies L, Gerba CP and Bales RC (1993). Survival of bacteriophages MS-2 and PRD-1 in Ground Water. *Water Science and Technology*, 27(3–4):409–412.
- Yates MV, Gerba CP and Kelley LM (1985). Virus persistence in groundwater. *Applied and Environmental Microbiology* 49(4):778–781.
- Ying G-G, Kookana RS and Dillon PJ (2003). Sorption and degradation of five selected endocrine disrupting chemicals in aquifer material. *Water Research* 37:3785–3791.
- Zhou X and Li C (1992). Hydrogeochemistry of deep formation brines in central Sichuan basin, China. *Journal of Hydrology* 138:1–15.