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Managed aquifer recharge case study risk assessments

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December 2010

A document supporting the Australian Guidelines for Managed Aquifer Recharge.
This is a report of the NWC Raising National Water Standards project:
Facilitating recycling of stormwater and reclaimed water via aquifers.

Australian Government
National Water Commission

Water for a Healthy Country Flagship Report series ISSN: 1835-095X

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Citation: Page, D, Dillon, P, Vanderzalm, J, Bekele, E, Barry, K, Miotlinski, K and Levett, K. 2010. Managed aquifer recharge case study risk assessments. CSIRO: Water for a Healthy Country National Research Flagship

Cover Photographs:

Sites described in this report (photographer in parentheses): Top row - Kingswood Domestic ASR (Peter Dillon); Sampling at Andrews Farm ASR site (Paul Pavelic); Rossdale Golf Club ASR site showing stormwater dam (Peter Dillon); Construction of infiltration gallery at CSIRO Floreat Park (Elise Bekele). Bottom row - Bolivar recycled water ASR well head (Greg Rinder, CSIRO ScienceImage photo BU4239); Filling a recharge basin at Alice Springs SAT site (Karen Barry); Warruwi ASR well head (Paul Pavelic); Salisbury ASTR hutches covering wellheads in a reserve (Kerry Levett); aerial view of Blue Lake, in the City of Mount Gambier (Willem Van Aken, CSIRO ScienceImage photo BU5984); © 2010 CSIRO

EXECUTIVE SUMMARY

This set of case studies of risk assessments at a variety of Australian managed aquifer recharge projects was compiled as a supporting document to the *Australian Guidelines for Water Recycling: Managed Aquifer Recharge* (NRMMC–EPHC–NHMRC 2009a).

The Managed Aquifer Recharge Guidelines were published on the website of Environment Protection and Heritage Council in August 2009 as part of Phase 2 of the Australian Guidelines for Water Recycling (http://www.ephc.gov.au/taxonomy/term/39). The guidelines apply to all source waters including recycled waters, rainwater, treated drinking water, and natural waters.

The guidelines are the first risk-based guidelines for managed aquifer recharge. They also take specific account of water quality changes in aquifers, based on scientific evidence. They encourage a prudent staged approach to investment in any project where uncertainties need to be resolved by proponents to establish that human health and the environment are protected.

While the guidelines give numerous small examples within the text, during public consultations with the draft guidelines in May-June 2008 it was requested at meetings in various states that some worked case studies be documented showing what is needed for the various stages of risk assessment for projects of different types.

This companion document to the Managed Aquifer Recharge Guidelines is intended to do that with the aim of making the guidelines as easy as possible to understand and use by proponents and regulators. It provides 'model' risk assessments and descriptions of the investigations to support them, which could be used as conceptual templates for several types of projects.

The case studies are assembled in a sequence from simplest to more complicated and generally with non-potable projects at the beginning and potable projects at the end. The latter case studies also invoke other guidelines including Augmentation of Drinking Water Supplies (NRMMC-EPHC–NHMRC 2008) and Stormwater Harvesting and Reuse (NRMMC-EPHC–NHMRC–2009b). At the beginning of the document is a summary of the case studies and the issues they examine.

The case studies were all developed before the guidelines, and so the investigations and risk assessments undertaken are reconstituted here to address the requirements of the guidelines in a consistent format. Nevertheless, site development was generally logical and followed the sequence described by the guidelines. These case studies also take account of all relevant National Water Quality Management Strategy guidelines, as would be expected by state jurisdictions.

Sections of a draft of this document were used in workshops held in May 2010 in Adelaide, Canberra, Melbourne, Perth and Brisbane to familiarise proponents and assessors of managed aquifer recharge projects with the application of the guidelines.

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ACKNOWLEDGMENTS

This compilation of risk assessments of Managed Aquifer Recharge (MAR) projects was supported by the National Water Commission as part of its project ‘Facilitating Recycling of Stormwater and Reclaimed Water via Aquifers in Australia’ under the Raising National Water Standards Program. Each MAR project was undertaken by partner organisations of CSIRO who are acknowledged in the relevant sections. The authors are grateful for reviews of this document undertaken by Warish Ahmed and Jatinder Sidhu (CSIRO).

OVERVIEW OF RISK ASSESSMENT FOR MANAGED AQUIFER RECHARGE

How to use this document

For those interested in developing a managed aquifer recharge project, the *Australian Guidelines for Water Recycling: Managed Aquifer Recharge* ('MAR Guidelines'; NRMMC–EPHC–NHMRC 2009a) are used to undertake a risk assessment for the purposes of ensuring that human health and the environment are protected. This document presents case studies of example projects, and can be used to assist in clarifying what the MAR Guidelines require for projects of various types.

The diversity and geographic spread of MAR in Australia has increased in recent years and most states and territories have operational MAR projects. In this section, Table I - 1 provides a brief summary of nine example projects, summarising MAR methods, source waters, hydrogeological settings, end-uses of recovered water and associated issues; each project is described in more detail in the individual case studies. Project locations are shown in Figure I - 1. Each of the documented case study sites has progressed to a differing level of completeness and operation at the time of writing. Although many have been operating, one for more than 130 years (Mount Gambier, SA), by May 2010 only the Bolivar, SA site has progressed all the way to Stage 4 and the development of a risk management plan.

If your intended project has features that match one of these case study projects you can go straight to that chapter. If the intended project has features of several projects you may need to read all relevant chapters.

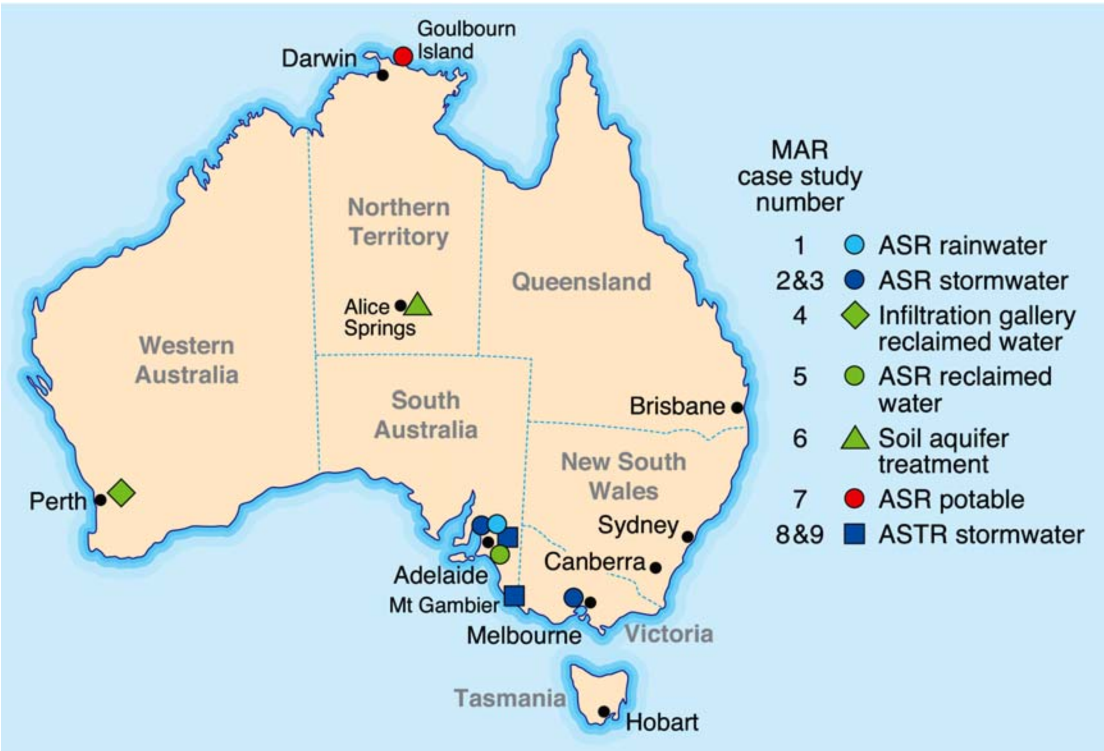

Figure I - 1 Map of Australia showing case study risk assessment sites

Table I - 1 Overview of MAR projects in this report

Chapter	Project	Source Water	Aquifer	Recharge method	End use	Project stages covered
1	Kingswood, SA	Domestic roof runoff	Unconfined alluvial	ASR	Irrigation - landscape	1
2	Andrews Farm, SA	Urban stormwater	Confined limestone	ASR	Irrigation - landscape	2
3	Rossdale, Vic	Urban stormwater	Fractured rock	ASR	Irrigation - landscape	2
4	Perry Lakes, WA	Reclaimed water	Unconfined sandstone	Infiltration gallery	Ecosystem protection, Irrigation - landscape	2
5	Bolivar, SA	Reclaimed water	Confined limestone	ASR	Irrigation - horticultural	4
6	Alice Springs, NT	Reclaimed water	Unconfined alluvial	SAT	Irrigation - horticultural	2
7	Warruwi, NT	Groundwater	Confined sandstone	ASR	Drinking	2
8	ASTR Salisbury, SA	Urban stormwater	Confined limestone	ASTR	Toilet-flushing, irrigation - landscape, drinking	3
9	Mount Gambier, SA	Urban stormwater	Unconfined karstic limestone	Drainage wells	Drinking	3

Table I - 2 Overview of Stage 2 maximal risks of MAR projects presented in these case studies

Project	Pathogens	Inorganic chemicals	Salinity and sodicity	Nutrients	Organic Chemicals	Turbidity and particulates	Radio-nuclides	Pressure	Contaminant migration	Aquifer dissolution	Groundwater dependant ecosystems	Energy considerations
Kingswood, SA*												
Andrews Farm, SA	●		●					●	●	●		●
Rossdale, Vic			●					●	●	●		●
Perry Lakes, WA	●	●		●	●			●	●	●	●	●
Bolivar, SA		●	●	●	●		●	●	●	●	●	●
Alice Springs, NT	●		●	●	●			●			●	●
Warruwi, NT		●				●		●		●		
ASTR Salisbury, SA	●	●	●		●	●		●		●		
Mt Gambier, SA	●	●		●	●	●			●	●	●	

* Simplified assessment only, Stage 2 risk assessment not performed

● indicates that the hazard was assessed as uncertain or high in the maximal risk assessment for any endpoint.

For any projects which have low inherent risk and meet the MAR Guidelines' requirements for Simplified Assessments (e.g. Kingswood domestic scale ASR), there is no need to identify hazards and assess their risks. All other projects will require the assessment of the 12 hazards considered in the MAR Guidelines (Table I - 2).

Each of the MAR projects described in these case studies have a different mix of potential hazards which can cause risks to human health and the environment; these hazards have been assessed to differing extents depending upon the level of risk assessed at each project development stage. Table I - 2 presents an overview of the maximal risks assessed at each MAR case study site during the Stage 2 pre-commissioning risk assessment. This highlights the hazards that are relevant to each site and hence where additional information on the investigations addressing those risks can be obtained in this document.

If you are unsure of the recharge method or require only basic information on MAR, refer to National Water Commission Waterlines report #13 – *Managed Aquifer Recharge: An Introduction* (Dillon *et al*. 2009), which also addresses a wide range of issues associated with MAR, such as planning, economics and water allocation policies.

References

Dillon, P, Pavelic, P, Page, D, Beringen, H and Ward, J (2009) Managed Aquifer Recharge: An Introduction, Waterlines Report Series No. 13, National Water Commission, Canberra, Australia, http://www.nwc.gov.au/www/html/996-mar--an-introduction---no-13.asp

NRMMC–EPHC–NHMRC (2009a). Australian Guidelines for Water Recycling (Phase 2): Managed Aquifer Recharge, Natural Resource Ministerial Management Council, Environment Protection and Heritage Council and National Health and Medical Research Council, Canberra, www.ephc.gov.au/taxonomy/term/39

1 RAINWATER ASR DOMESTIC SCALE, KINGSWOOD, SOUTH AUSTRALIA

The Kingswood ASR (Aquifer Storage and Recovery) project aimed to harvest rainwater from the roof runoff of a residential property for garden irrigation on a domestic/household scale. The native groundwater was too saline to be used for irrigation and the project intended to dilute it with fresh water to provide an alternative source of water to reduce consumption of mains water.

The project meets the requirements for Simplified Assessment as specified in the MAR Guidelines (section 4.2):

- *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.*

The local authorities at the time of establishment of the project were the Department of Water, Land and Biodiversity Conservation (DWLBC), the Patawalonga Catchment Water Management Board (PCWMB) and the SA Environment Protection Authority. Between them they agreed that DWLBC would issue a permit with a set of permit conditions for discharging water to a prescribed water body. Those permit conditions were:

(a) the drilling of any wells was to be undertaken by a licensed driller (an existing requirement)

(b) meters were installed to record cumulative volume of injection and recovery

(c) a 100 micron filter be installed in the injection line between the rainwater tank and the ASR well.

The project was also used as a research and demonstration site; an observation well was drilled 5 m from the ASR well, and frequent monitoring, sampling and reporting was undertaken for research purposes. This provided assurances to the regulators that unexpected outcomes or problems from this first-of-breed project would be reported and that maintenance would be performed to ensure protection of human health and the environment. The site was on private property owned and occupied by a CSIRO researcher.

Although the project meets the Simplified Assessment criteria, and therefore according to the MAR Guidelines does not require an Entry Level Assessment (section 4.3) it was thought that documenting the project establishment process, doing an Entry Level Assessment and reporting results very briefly here would help prospective proponents see that the Entry Level Assessment can be very simple and easy to do, especially when inherent risks are low.

1.1 Site description

In June 2003 a domestic scale ASR demonstration trial commenced in the rear garden of a residential dwelling at Kingswood, South Australia, 6 km south-east of the city of Adelaide (Figure 1-1).

Figure 1-1 Location of Kingswood ASR site (marked with dot) (aerial photo ©2010 Google – Imagery ©2010 DigitalGlobe, GeoEye, Map data ©2010 MapData Sciences Pty Ltd, PSMA)

1.1.1 Initial evaluation

The site was considered to be viable only with a shallow well (less than ~40 m depth), hence DWLBC provided a map showing the locations of existing wells within proximity of the proposed ASR site, and a table that listed for all wells shallower than 40 m, the unit number, depth of well, depth to water table, year of construction, well yield determined by the driller, and the electrical conductivity (EC) of the groundwater. This showed about 15 wells within a distance of 2 km completed at depths between 15 and 35 m with yields between 0.2 and 2 L/s and EC between 2500 and 6000 µS/cm. For several wells driller's logs were available, and beneath the surficial clay material was reported as a mixture of clay, silt and sand with occasional thin bands of gravel or calcrete.

It appeared that yields in this Quaternary alluvium (0.5 – 1 L/s) would likely be adequate for garden irrigation and for an acceptable rate of injection; however, the variable and high salinity suggested that unless recovered water contained a sufficient proportion of rainwater it would be too saline for garden irrigation (Pavelic *et al*. 1992). The owner decided to proceed with the demonstration project including an ASR well and a monitoring well. After obtaining permits, two bores were drilled to a depth of 24 m in 2002. They were located 5 m apart with respective PVC casing diameters of 125 mm for the southern well (A) and 100 mm for the northern well (B). The wells were completed as slotted PVC from 12 m below ground surface (bgs) for well A and from 9 m bgs for well B, to the bottom of the drilled hole, and the annulus gravel packed over this interval with a bentonite seal to the surface. Initially the higher yielding well B was used as the ASR well and well A was an observation well (Barry and Dillon 2005a; 2005b). Depth to water table was 12 m.

A permit to discharge roof runoff to the aquifer was obtained from DWLBC, which required a 100 micron filter to be placed in the injection line. Run-off from the rooftop of 285 m^2 was plumbed to the ASR well under gravity feed via a 4 m^3 tank (with 3 m^3 active storage). The recovery line was connected to a pump installed to a depth of 18 m.

145 m^3 of rainwater was injected into well B in the first year and of 0.6 m^3 of water was recovered monthly during pumping to purge any suspended solids. Purging events showed the salinity of water was still close to ambient level and not suitable for garden irrigation. In July 2004 after a second set of aquifer pump tests, the injection line was moved to the lower yielding, less permeable well A, to determine if the reduced aquifer permeability would retain the fresh injectant closer to the well and thereby improve recovery efficiency.

Downhole electromagnetic flowmeter metering was performed in May 2005, which revealed a low hydraulic conductivity section below 20 m depth in well A (the ASR well at the time). Salinity profiling revealed a layer of more saline groundwater at the same depth (below 20 m). Consequently the ASR well was partially backfilled to 19.7 m in September 2005, in an attempt to further increase the recovery efficiency.

1.1.2 Site configuration

The Kingswood ASR recycled water system components are summarised in Figure 1-2 and Table 1-1.

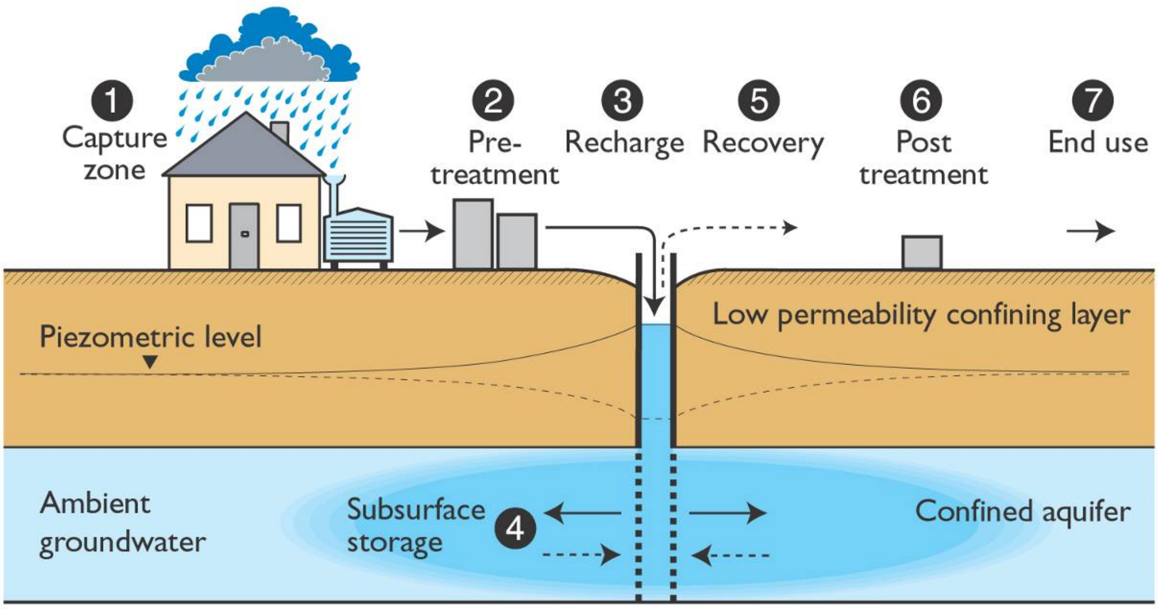

Figure 1-2 Kingswood domestic ASR system schematic of water flow

Table 1-1 Components of the Kingswood ASR system

Component	Kingswood ASR system
1. Capture zone	Domestic rooftop of 285 m^2
2. Pre-treatment	Tank strainer and 100 μm filter
3. Recharge	ASR well; open interval 12-24 m
4. Subsurface storage	Quaternary alluvial aquifer
5. Recovery	ASR well
6. Post-treatment	nil
7. End use	Garden irrigation

1.1.3 Aquifer description

The target aquifer was the upper Quaternary alluvial aquifer, located below surficial clay with an average hydraulic gradient of ~ 0.007. Pumping tests indicated well yields of 34 m^3/d (0.4 L/s) in well A and 95 m^3/d (1.1 L/s) in well B. The profile was largely a mixture of clay with occasional layers of sand and gravel up to 2 m thick to 21 m depth underlain by a stiff clay base. Aquifer material recovered during a pump out event in August 2005 consisted mostly of quartz (40%) and smectite (33%) with smaller amounts of albite (10%), mica (7%), orthoclase (6%), kaolin (3%), goethite (1%) and calcite (<1%).

The ambient groundwater was brackish (~4,500 µS/cm) with low organic carbon (2.3 mg/L) and phosphorus (<0.025 mg/L) but had significant concentrations of nitrate (5.8 mg-N/L).

1.1.4 Source water description

The source rainwater was fresh (25 µS/cm), oxygenated and with low nutrient levels (total nitrogen = 0.69 mg/L, total phosphorous = 0.03 mg/L), but contained detectable levels of zinc (0.14 mg/L) as a result of the galvanized steel roof. The nutrient content of the source water was controlled by regular gutter cleaning.

Over the 39 month period of operations a total volume of 487 m^3 was injected and 38 m^3 was recovered, leaving a net increase in storage of 449 m^3.

Figure 1-3 Kingswood domestic ASR site, showing point of rainwater runoff from house roof, rainwater tank, logger unit, ASR well and observation well.

1.2 Stage 1 Entry level risk assessment

Table 1-2 and Table 1-3 show the completed entry-level risk assessment for the Kingswood ASR project, as per section 4.3 of the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a). Table 1-3 also provides a summary of Stage 2 investigations required as identified in the Stage 1 assessment.

Table 1-2 Kingswood ASR entry level assessment part 1 – Viability

	Attribute	Answer
1	Intended water use	
	• Is there an ongoing local demand or clearly defined environmental benefit for recovered water that is compatible with local water management plans?	✓ Recovered water is intended for garden irrigation, to replace irrigation by mains water
2	Source water availability and right of access	
	• Is adequate source water available, and is harvesting this volume compatible with catchment water management plans?	✓ Source water is roof runoff that is otherwise discharged to a soakage pit on-site
3	Hydrogeological assessment	
	• Is there at least one aquifer at the proposed managed aquifer recharge site capable of storing additional water?	✓ Storage capacity identified within the Quaternary aquifer (Pavelic *et al.* 1992)
	• Is the project compatible with groundwater management plans?	✓ The project was undertaken with the support of the PCWMB which is responsible for groundwater management plans. A permit was obtained from DWLBC.
4	Space for water capture and treatment	
	• Is there sufficient land available for capture and treatment of the water?	✓ Capture zone is the existing roof area and tank thus does not require additional land area
5	Capability to design, construct and operate	
	• Is there a capability to design, construct and operate a managed aquifer recharge project?	✓ Project supported by the PCWMB and CSIRO. A licensed driller constructed the wells. Operator of site was a CSIRO scientist who has experience in design, construction and operation of ASR schemes. DWLBC provided geophysical services. →Continue to entry level assessment (Table 1-3)

Table 1-3 Kingswood ASR entry level assessment part 2 – degree of difficulty

Question	Kingswood ASR answers	Investigations required
1 Source water quality with respect to groundwater environmental values		
Does source water quality meet the requirements for the environmental values of ambient groundwater?	Yes – ambient groundwater is too brackish for irrigation.	No
2 Source water quality with respect to recovered water end use environmental values		
Does source water quality meet the requirements for the environmental values of intended end uses of water on recovery?	Yes – source water meets irrigation requirements	No
3 Source water quality with respect to clogging		
Is source water of low quality, for example: total suspended solids, total organic carbon or total nitrogen >10 mg/L, And is soil or aquifer free of macropores?	No - source water is high quality, relatively low risk of clogging	No
4 Groundwater quality with respect to recovered water end use environmental values		
Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery?	No – ambient groundwater is too saline for the garden.	Recovery efficiency may not be adequate
5 Groundwater and drinking water quality		
Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?	No – target aquifer is not used for drinking water supply and no connected ecosystems nearby.	No
6 Groundwater salinity and recovery efficiency		
Does the salinity of native groundwater exceed: (a) 10000 mg/L, or (b) the salinity criterion for uses of recovered water?	Yes to (b) – ambient groundwater salinity is too high for irrigation.	Recovery efficiency may not be adequate
7 Reactions between source water and aquifer		
Is redox status, pH, temperature, nutrient status and ionic strength of source water and groundwater similar?	No – but impact of reactions not expected to breach irrigation quality targets	No
8 Proximity of nearest existing groundwater users, connected ecosystems and property boundaries		
Are there other groundwater users, groundwater–connected ecosystems or a property boundary near (within 100–1000 m) the MAR site?	Small scale project will not impact on other groundwater users. None within 100 m.	No
9 Aquifer capacity and groundwater levels		
Is the aquifer confined and not artesian? Or is it unconfined, with a watertable deeper than 4 m in rural areas or 8 m in urban areas?	Yes - semi-confined and not artesian, water table >12m	No
10 Protection of water quality in unconfined aquifers		
Is the aquifer unconfined, with an intended use of recovered water being drinking water supplies?	No – semi-confined for irrigation use	No
11 Fractured rock, karstic or reactive aquifers		
Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?	No – unlikely to be reactive, alluvial sand and gravel	No
12 Similarity to successful projects		
Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?	No – but is of a small scale and can be easily managed	No

Question	Kingswood ASR answers	Investigations required
13 Management capability		
Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty, or with water treatment or water supply operations involving a structured approach to water quality risk management?	Yes – CSIRO operator has experience in complex ASR schemes	No
14 Planning and related requirements		
Does the project require development approval? And is it in a built up area; on public, flood-prone or steep land; close to a property boundary; contain open water storages or engineering structures; likely to cause public health, safety or nuisance issues, or adverse environmental impacts?	No – Drilling approval obtained. System 3 m from property boundary but operation is silent. Any overflow goes into existing soakage pit. Screens used to prevent mosquitoes breeding in tank.	No

This MAR case study qualifies for a simplified assessment and as such no further project stages are required in managing the system for human health and environment.

1.3 Concluding remarks

The Kingswood ASR project was developed as a research project to assess small scale ASR viability. Due to the small scale nature of the project, quality of injectant, and aquifer used, an Entry Level assessment was found to be suitable for assessing the risks to human health and the environment. Ultimately the project was decommissioned as the quality of recovered water was found to be too saline for use as irrigation water. This was due to relatively steep hydraulic gradient at the site and the small volume of injected water in relation to lateral flows (Barry *et al*. 2007; Ward *et al*. 2009).

1.4 References

Barry, K and Dillon, P (2005a). 'Domestic-scale ASR with rainwater at Kingswood, South Australia', *Proceedings of the 5th International Symposium on Management of Aquifer Recharge*, ISMAR5, 11-16 June 2005, Berlin, Germany.

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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.

2 STORMWATER ASR AT ANDREWS FARM, SOUTH AUSTRALIA

The stormwater ASR (Aquifer Storage and Recovery) project at Andrews Farm evaluated the technical, environmental and economic viability of injecting winter stormwater flows into a brackish limestone aquifer, for the purposes of recovering irrigation supplies during summer months.

2.1 Site description

The Andrews Farm ASR site is situated in a residential subdivision approximately 25 km north of the centre of Adelaide, within the Northern Adelaide Plains (NAP) prescribed groundwater region (Figure 2-1). The stormwater catchment covers 55 km^2 and its land use is largely comprised of dryland agriculture but also contains an expanding residential area.

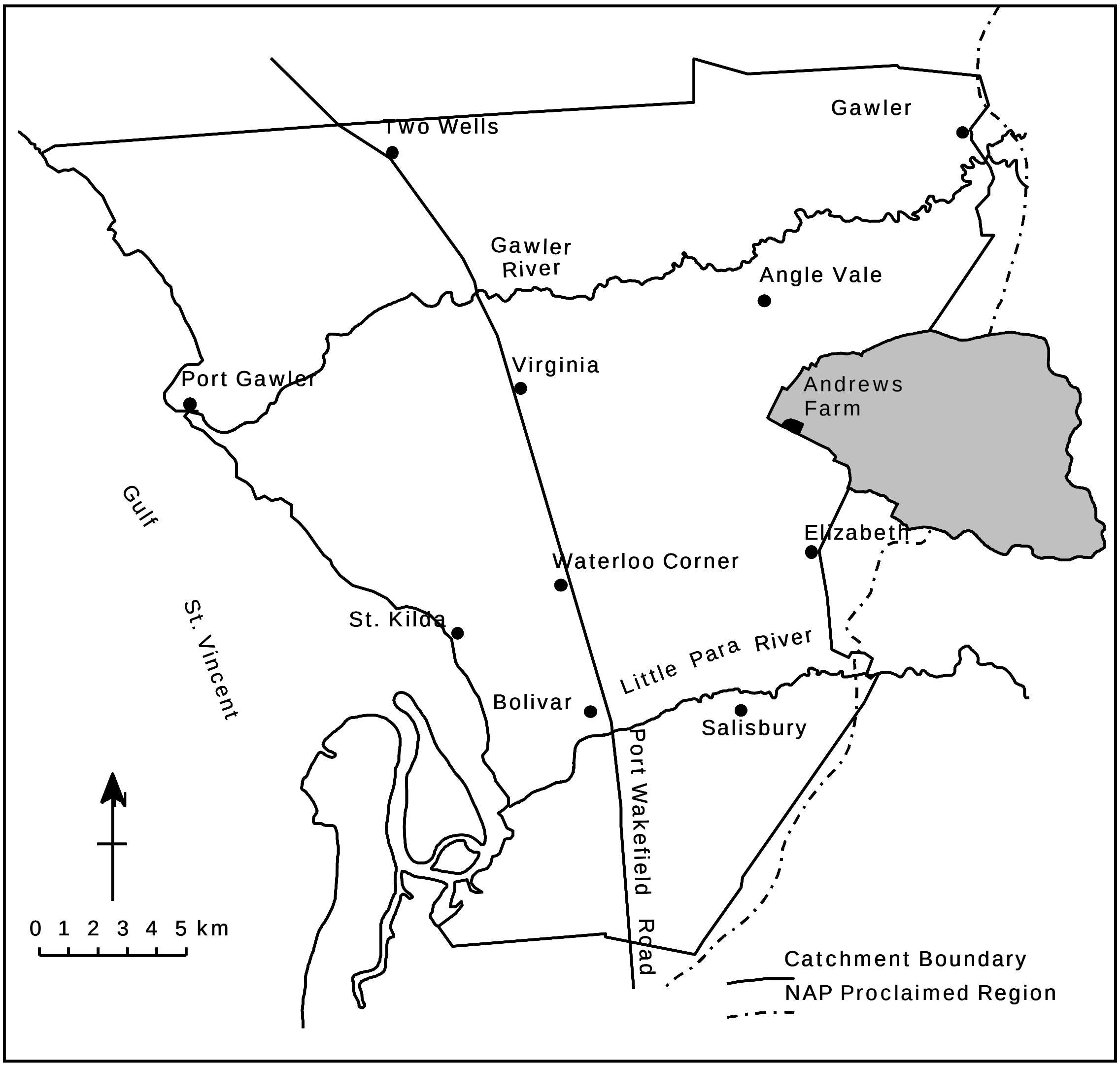

Figure 2-1 Map of the Northern Adelaide Plains region showing the location of the Andrews Farm ASR site and stormwater catchment.

2.1.1 Sequence of development

The Andrews Farm ASR trial commenced in 1992, when a residential housing development provided an opportunity to assess the potential for urban stormwater ASR to replenish an over exploited aquifer on the Northern Adelaide Plains (Gerges *et al*. 2002). A series of three

stormwater detention basins with a combined capacity of 52 ML were constructed within the residential development to provide environmental amenity and stormwater detention and treatment. The practice of using open earth channels for stormwater drainage within the catchment area, combined with soil erosion in the upland areas resulted in highly turbid runoff waters. All surface flow was routed through the three stormwater detention basins in series in order to reduce the particulate loading in the source water. Also, stormwater detention was a mandatory requirement for the subdivision so that peak stormwater flows downstream were not increased.

The developer, Hickinbotham Group, recognised the potential for ASR to bank the detained water and create irrigation supplies to irrigate parks and school playing fields and thereby increase land value. As this was the first urban ASR site in Australia, approval for a trial was given by the Department of Mines and Energy based on management of the trial by the state government (Department of Mines and Energy) and required that investigations be performed to demonstrate the effects of ASR on the aquifer.

An ASR well and three observation wells were drilled within the target aquifer, the second of two confined Tertiary confined aquifers known locally as the 'T2' aquifer (Figure 2-3). The uppermost 19 m of the aquifer (108 - 127 m below ground surface) was targeted for injection, and this interval was completed as 'open hole'. The observation wells were drilled at radial distances of 25, 65 and 325 m from the ASR well. The 25 m well had an open interval comparable to the ASR well while the 65 and 325 m wells had open intervals in the upper 13 to 15 m of the aquifer. The observation wells were steel cased.

Ephemeral stormwater runoff was stored in the detention basin/wetland system before being pumped under pressure from a floating intake attached to a pontoon in the downstream basin, overland to the ASR well via a stainless steel filter (100 μm).

2.1.2 Site configuration

The Andrews Farm ASR system components are summarised in Figure 2-2 and Table 2-1.

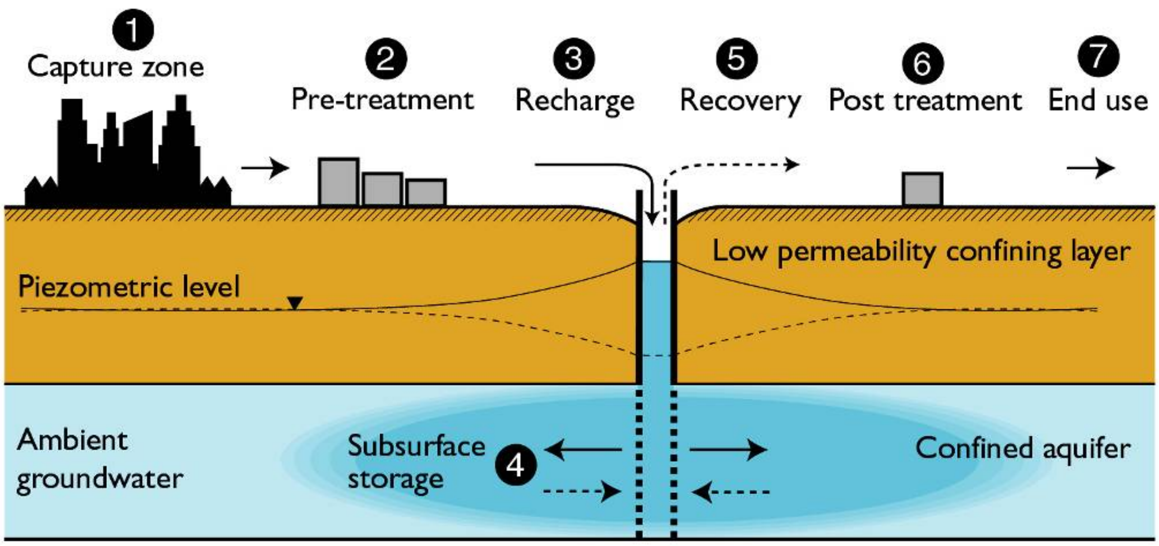

Figure 2-2 Andrews Farm ASR system schematic of water flow

Table 2-1 Components of the Andrews Farm ASR system

Component	Andrews Farm ASR system
1. Capture zone	Effective area contributing to stormwater runoff is approximately 55 km^2
2. Pre-treatment	Passive treatment through three detention basins and passage through geotextile fabric and 100 µm stainless steel filter
3. Recharge	ASR well; open interval 108 - 127 m
4. Subsurface storage	T2 aquifer – confined limestone Tertiary aquifer
5. Recovery	ASR well
6. Post-treatment	nil
7. End use	Green space irrigation

2.1.3 Aquifer description

The aquifer targeted for ASR, known locally as the 'T2' aquifer, is the second of a series of confined Tertiary marine sediments underlying the 60 m thick surficial Plio-Pleistocene Hindmarsh Clay formation (Figure 2-3). It is intersected locally at a depth of 105 m and underlies 9 m of highly plastic clay. Heterogeneous in nature, the aquifer locally consists of an interbedded sequence of variably cemented limestone and sand (Gerges *et al.* 1995).

Pump test analysis indicated that the aquifer has a transmissivity of 180 m^2/day and a storage coefficient of 2 - 6×10^{-4}. The vertical hydraulic conductivity of the confining clay between the T1 and T2 aquifers ranges from 4×10^{-6} to 4×10^{-5} m/day.

The ambient groundwater is brackish, with a measured salinity of between 1,900 - 2,500 mg/L TDS, and a temperature of 22 °C.

2.1.4 Source water description

Characteristically, the stormwater is colder, has higher concentrations of dissolved oxygen, suspended solids, nitrogen, organic carbon, coliforms and higher pH and turbidity than the brackish ambient groundwater, but has lower concentrations of iron and total dissolved solids (Pavelic *et al.* 2006a).

2.2 Stage 1 Entry level risk assessment

Table 2-2 and Table 2-3 show the completed entry-level risk assessment for the Andrews Farm ASR project, as per section 4.3 of the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a). Table 2-3 also provides a summary of Stage 2 investigations required as identified in the Stage 1 assessment.

Table 2-2 Andrews Farm ASR entry level assessment part 1 – Viability

	• **Attribute**	• **Answer**
1	Intended water use	
	• Is there an ongoing local demand or clearly defined environmental benefit for recovered water that is compatible with local water management plans?	✓ Recovered water is intended for landscape irrigation, to replace irrigation by mains water.
2	• Source water availability and right of access	
	• Is adequate source water available, and is harvesting this volume compatible with catchment water management plans?	✓ Source water is stormwater that is otherwise discharged to waste, and requires detention for flood mitigation and sedimentation.
3	Hydrogeological assessment	
	• Is there at least one aquifer at the proposed managed aquifer recharge site capable of storing additional water?	✓ Based on existing wells in the area, storage capacity was identified within the Tertiary ‘T2’ aquifer (Gerges *et al.* 1995).
	• Is the project compatible with groundwater management plans?	✓ Experimental licence granted to Department of Mines and Energy (DME) to operate the site
4	Space for water capture and treatment	
	• Is there sufficient land available for capture and treatment of the water?	✓ Stormwater harvesting facility already exists.
5	• Capability to design, construct and operate	
	• Is there a capability to design, construct and operate a managed aquifer recharge project?	✓ Project operated by DME with scientific input from CSIRO. →Continue to entry level assessment (Table 2-3)

Table 2-3 Andrews Farm ASR entry level assessment part 2 – degree of difficulty

Question	Andrews Farm answers	Investigations required
1 Source water quality with respect to groundwater environmental values		
Does source water quality meet the requirements for the environmental values of ambient groundwater?	Yes – ambient groundwater is too brackish for irrigation.	None
2 Source water quality with respect to recovered water end use environmental values		
Does source water quality meet the requirements for the environmental values of intended end uses of water on recovery?	Yes – source water meets irrigation requirements	None
3 Source water quality with respect to clogging		
Is source water of low quality, for example: total suspended solids, total organic carbon and total nitrogen each >10 mg/L, And is soil or aquifer free of macropores?	Yes - Turbidity > 10 NTU Require Stage 2 investigations to assess clogging potential and pre-treatment options.	Clogging evaluation (Sections 2.3.1, 2.3.2)
4 Groundwater quality with respect to recovered water end use environmental values		
Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery?	No – ambient groundwater salinity is above irrigation standards Require Stage 2 investigations to assess recovery efficiency.	Groundwater mixing evaluation (Section 2.3.3)
5 Groundwater and drinking water quality		
Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?	No – target aquifer is not used for drinking water supply and is of negligible environmental value	None
6 Groundwater salinity and recovery efficiency		
Does the salinity of native groundwater exceed: (a) 10000 mg/L, or (b) the salinity criterion for uses of recovered water?	Yes to (b) – ambient groundwater salinity is above irrigation standards Require Stage 2 investigations to assess recovery efficiency.	Groundwater mixing evaluation (Section 2.3.3)
7 Reactions between source water and aquifer		
Is redox status, pH, temperature, nutrient status and ionic strength of source water and groundwater similar?	No – but impact of reactions unlikely to breach irrigation quality targets Require Stage 2 investigations to assess the impact of reactions on recovered water quality and aquifer integrity.	Geochemical evaluation (Section 2.3.4)
8 Proximity of nearest existing groundwater users, connected ecosystems and property boundaries		
Are there other groundwater users, groundwater–connected ecosystems or a property boundary near (within 100–1000 m) the MAR site?	No – nearest pumping centre is 2 km north	None
9 Aquifer capacity and groundwater levels		
Is the aquifer confined and not artesian? Or is it unconfined, with a watertable deeper than 4 m in rural areas or 8 m in urban areas?	Yes - target aquifer confined and not artesian. However, injection may cause aquifer to become artesian. Require Stage 2 investigations to assess artesian zone.	Hydrogeological evaluation (Section 2.3.1)
10 Protection of water quality in unconfined aquifers		
Is the aquifer unconfined, with an intended use of recovered water being drinking water supplies?	No – confined and recovered water intended for irrigation use	None
11 Fractured rock, karstic or reactive aquifers		
Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?	Yes – potential for dissolution of carbonates Require Stage 2 investigations to assess the impact of aquifer dissolution.	Geochemical evaluation (Section 2.3.4)

Question	Andrews Farm answers	Investigations required
12 Similarity to successful projects		
Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?	No, first of its kind	All (see Section 2.3)
13 Management capability		
Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty, or with water treatment or water supply operations involving a structured approach to water quality risk management?	No – operator (DME) has experience in ASR schemes with rural runoff	None
14 Planning and related requirements		
Does the project require development approval? And is it in a built up area; on public, flood-prone or steep land; close to a property boundary; contain open water storages or engineering structures; likely to cause public health, safety or nuisance issues, or adverse environmental impacts?	No – ASR project does not require development approval. Open water storages on public land already exist.	None

In summary of the Stage 1 assessment the following investigations were identified in proceeding to Stage 2 (Table 2-4).

Table 2-4 Summary of Stage 2 investigations required at Andrews Farm

Issue		Investigations required at stage two	Discussed in section
3	Source water quality with respect to clogging	Clogging evaluation	2.3.1, 2.3.2
4	Groundwater quality with respect to recovered water end use environmental values	Groundwater mixing evaluation	2.3.3
6	Groundwater salinity and recovery efficiency	Groundwater mixing evaluation	2.3.3
7	Reactions between source water and aquifer	Geochemical evaluation	2.3.4
9	Aquifer capacity and groundwater levels	Hydrogeological evaluation	2.3.1
11	Fractured rock, karstic or reactive aquifers	Geochemical evaluation	2.3.4
12	Similarity to successful projects	None, first of its kind in the region	2.3

2.3 Stage 2 Pre-commissioning investigations

A series of studies were performed in support of the Stage 2 pre-commissioning risk assessment. They are described below, followed by the maximal and residual risk assessments. Figure 2-3 shows the layout that was adopted for the Andrews Farm site and a cross section of the geology. The hydrogeology and geochemical investigations and their results are described in Dillon and Pavelic (1996).

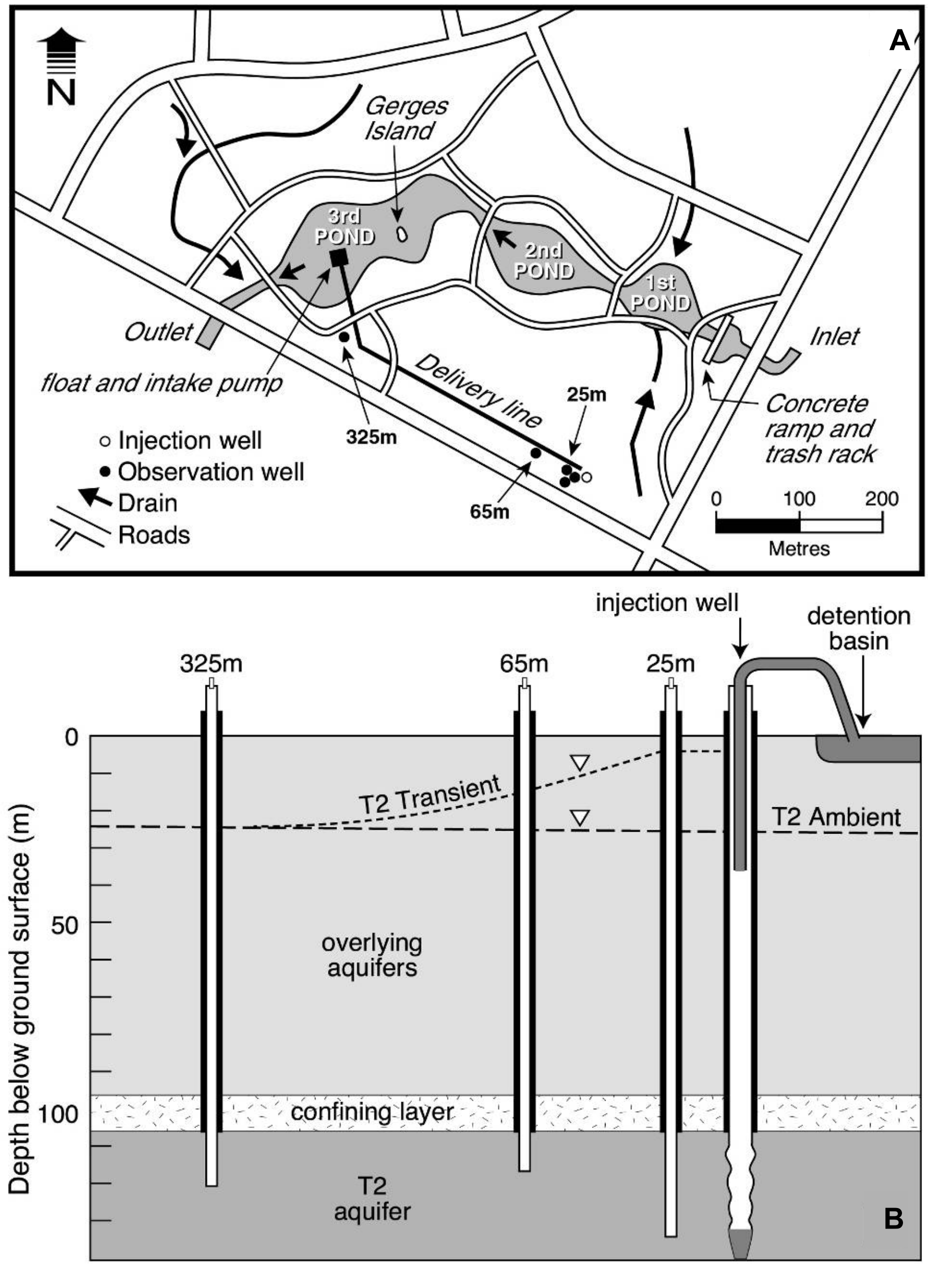

Figure 2-3 Andrews Farm experimental ASR site layout (A) and a schematic vertical cross-section of the Andrews Farm site showing ASR and observation wells (B) (Herczeg *et al.* 2004).

2.3.1 Clogging and hydrogeological evaluation

Physical clogging was identified as a key issue for the Andrews Farm ASR site due to the potential for high particulate loading in the source stormwater. Initially a mains water injection test was undertaken to establish the performance of the ASR well and the hydraulic response of the aquifer to injection without the impact of physical clogging (Gerges *et al.* 1995). This indicated minor clogging in the immediate vicinity of the injection well only, due to mobilisation of fine material from the aquifer and degassing due to temperature differences. Zooplankton in the source water also led to rapid clogging of the inline 100 µm filter and of the aquifer; preventing zooplankton from entering the injection line was achieved by shielding the pump intake with geotextile fabric (Pavelic *et al.* 2006a). Subsequent stormwater injection trials indicated it was possible to manage physical clogging by well redevelopment after each 40 ML of injection, despite high suspended solids in the source water (on average 62 mg/L but up to 160 mg/L) (Gerges *et al.* 2002).

During the initial mains water injection test, water levels increased by 9.1 m in the injection well and 2.1 m at the 325 m radius well, so the aquifer had not become artesian (Gerges *et al.* 1995; Barry *et al.* 2002). Head rises continued to be monitored during each stormwater injection season and redevelopment events to unclog the ASR well occurred whenever piezometeric head approached the ground surface and at the end of each injection season (Pavelic *et al*. 2006a).

2.3.2 Water quality assessment

Water quality assessments were performed for the urban stormwater source water, the ambient groundwater and the recovered water quality (Table 2-5).

Table 2-5 Andrews Farm ASR water quality data

	LTV Irrigation	STV Irrigation	Injectant		Ambient		Recovered	
			n	**mean**	**n**	**mean**	**n**	**mean**
Physical characteristics								
Temperature (°C)			**20**	14.1			**3**	20.1
pH	6-8.5	6-8.5	**16**	8.1			**3**	7.0
Conductivity (µS/cm)	2,500 [1]	2,500 [1]	**22**	280	**2**	3,570	**2**	1,640
Total Dissolved Solids (mg/L)	1,500 [1]	1,500 [1]	**22**	155	**2**	2,050	**4**	630
Dissolved Oxygen (mg/L)			**19**	8.2			**3**	0.6
Redox Potential (mV SHE)			**15**	348			**3**	-41
Suspended Solids (mg/L)			**18**	62			**3**	24
Turbidity (NTU)			**13**	94			**2**	26
Carbon dioxide (mg/L)							**1**	10
Major ions (mg/L)								
Alkalinity as $CaCO_3$			**9**	96			**2**	216
Bicarbonate			**21**	96	**2**	204	**4**	241
Sulfate			**21**	12	**2**	321	**4**	74
Chloride	175 [2]	175 [2]	**22**	30	**2**	1,010	**4**	210
Fluoride	1	2	**12**	0.29			**3**	0.22
Calcium			**21**	22	**2**	138	**4**	64
Magnesium			**21**	7.7	**2**	79	**4**	22
Potassium			**21**	5.1	**2**	10	**4**	5.9
Sodium	115 [2]	115 [2]	**22**	24	**2**	630	**4**	143
Microbiological								
Thermotolerant coliforms (cfu/100 mL)			**18**	790			**3**	0
Cryptosporidium (oocysts/L)			**5**	<0.10			**1**	<0.1
Giardia (cysts/L)			**5**	0.7			**1**	<0.1
Enteric virus (PDU/L)			**2**	0				
Nutrients (mg/L)								
Nitrate + Nitrite as N			**21**	0.27	**1**	<0.01	**4**	0.01
Ammonia as N			**19**	0.04			**3**	0.31
Total Kjeldahl Nitrogen	5 [3]	25-125 [3]	**21**	0.62			**3**	0.73
Filterable Reactive Phosphorus			**12**	0.02				
Total Phosphorus	0.05	0.8-12	**21**	0.11			**3**	0.11
Dissolved Organic Carbon			**20**	5.5			**3**	3.8
Total Organic Carbon			**20**	5.2			**3**	4.2
Biological Oxygen Demand			**2**	2.5				
Silica			**8**	5.5			**4**	10.5

	LTV Irrigation	STV Irrigation	Injectant		Ambient		Recovered	
			n	mean	n	mean	n	mean
Metals and metalloids (mg/L)								
Arsenic - Soluble			**13**	0.001				
Arsenic - Total	0.1	2	**21**	0.001			**3**	0.018
Boron - Soluble	0.5 [4]	0.5 [4]	**21**	0.11			**3**	0.15
Cadmium - Total	0.01	0.05	**11**	<0.0002				
Chromium - Total	0.1	1	**12**	0.007				
Copper - Total	0.2	5	**21**	0.010			**3**	0.424
Iron - Total	0.2	10	**21**	1.96	**1**	0.45	**4**	3.94
Iron - Soluble			**10**	0.23				
Lead - Total	2	5	**20**	0.006			**3**	0.026
Manganese - Soluble			**10**	<0.005				
Manganese - Total	0.2	10	**20**	0.030			**3**	0.094
Nickel - Total	0.2	2	**1**	0.027				
Zinc - Total	2	5	**18**	0.042			**3**	0.12
Organic chemicals (µg/L)								
Total Halogenated Phenols			**8**	<1.5			**3**	<1.5
Pentachlorophenol			**5**	<0.5			**3**	<0.50
Tetrachlorophenol			**4**	<0.5			**3**	<0.50
Trichlorophenol			**5**	<0.5			**3**	<0.50
Total Insecticides			**12**	0.015				
Total Herbicides			**12**	2.4				
Atrazine			**10**	2.3			**3**	<1.2
Simazine			**4**	3.1			**3**	<1.2
Chlorthal Dimethyl (Dacthal)							**2**	<0.05
Total Polychlorinated Biphenols (PCBs)			**3**	<0.1				

LTV = long term irrigation trigger value; STV = short term irrigation trigger value; [1] Threshold considered to be locally accepted criteria for irrigated agriculture. See ANZECC-ARMCANZ (2000) guidelines for a detailed tolerance of different crops; [2] A value less than this can cause foliar damage in sensitive crops; [3] Guideline is for Total Nitrogen; [4] For very sensitive crops; sensitive 0.5-1, moderately sensitive 1-2.

Analysis of the physical parameters and nutrients reveal the potential for clogging (suspended solids = 66 mg/L; Total P = 0.11 mg/L; Total N = 1.0 mg/L) and geochemical changes (recovered water total arsenic = 0.018 mg/L). Analysis of the major ions suggest a degree of mixing between stormwater and groundwater (recovered water TDS = 630 mg/L, sulphate = 74 mg/L and calcium = 64 mg/L). Microbial analysis of the source stormwater suggests potential for pathogen and organic chemical contamination with thermotolerant coliforms of 790 cfu/100mL, simazine 3.1 µg / L and atrazine 2.3 µg/L. However neither pathogens nor organic chemicals were observed in the recovered water. Note that no drinking water guidelines were considered as this was not an intended use of the recovered water.

2.3.3 Groundwater mixing evaluation

Injection occurred in winter and spring in each of the four years from 1993 to 1996. A net total of 256 ML of water was injected at average rates of injection between 1,300 and 1,700 m^3/day (15-20 L/s). Injections occurred on a discontinuous basis subject to the availability of detained stormwater (Barry *et al.* 2002). Progressively larger volumes in each year reflect only the succession of winter rainfall amounts and the capacity of the active storage of the detention system. A major recovery phase was conducted in the following year (July 1997 to July 1998) when a total of volume of 151 ML was extracted, leaving a net increase in storage of 100 ML.

Salinity variations in the storage zone and in the recovered water were indicative of heterogeneous movement of stormwater in the aquifer (Dillon *et al*. 1995; Herczeg *et al.* 2004). Salinity increases in between injection cycles were greater than expected under the ambient hydraulic gradient (1:500), but possible under the higher temporary gradient induced by pressure injection with the variably cemented nature of the aquifer providing a conduit for rapid horizontal flow (Herczeg *et al.* 2004). Similar preferential flow produced irregular amounts of mixing in the recovered water with pulses of freshening evident (Dillon *et al*. 1995). The impact of mixing with the brackish ambient groundwater on the salinity of the recovered water can be managed through operational procedures and monitoring.

2.3.4 Geochemical evaluation

A geochemical evaluation found that the major effects on water quality were carbonate dissolution and sulfide mineral oxidation (Herczeg *et al.* 2004). Neither process impacted on the utility of the recovered water for irrigation. Calcite dissolution counteracted aquifer clogging in the vicinity of the ASR well and increased the aquifer transmissivity at the ASR well over the five year trial period (Gerges *et al.* 2002). The amount of calcite dissolution per injection event was unlikely to lead to well stability concerns during the project.

2.4 Stage 2 Pre-commissioning risk assessment

2.4.1 Maximal risk assessment

The risk assessment is presented in the order of the twelve key hazards outlined in the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a). A semi-quantitative risk assessment was performed for each of the hazards for human health and environmental endpoints, with green, orange and red indicating low (acceptable), uncertain and high (unacceptable) risks respectively (Table 2-6). The white boxes indicate that that hazard does not apply to that endpoint (hazards 8 to 12 for the human and irrigation endpoints).

The maximal risk assessment for the human health end point was conducted by comparing the water quality data for untreated stormwater and native groundwater for hazards 1 to 7 to the Stormwater Harvesting and Reuse Guidelines (NRMMC–EPHC–NHMRC 2009b) for irrigation exposure. For the irrigation end point, hazards 1 to 7 were compared to the short term values (STV) for irrigation guidelines (ANZECC–ARMCANZ 2000). For the aquifer endpoint, the aquifer's beneficial use was conservatively assumed to be for irrigation supplies (even though the salinity of the groundwater would not support irrigation), and for hazards 1 to 7 the quality of raw stormwater was compared to the irrigation guidelines (ANZECC–ARMCANZ 2000).

For hazards 8 to 12, the risks were assessed based on their potential impacts on the aquifer or biosphere as described in the MAR Guidelines.

Table 2-6 Maximal risk assessment summary for Andrews Farm ASR

	MAR Hazards	Human endpoint – ingestion of sprays	Environmental endpoint – green space irrigation	Environmental endpoint – aquifer
1.	Pathogens – pathogens present in untreated stormwater	H	L	L
2.	Inorganic chemicals – none likely present at levels of concern for irrigation	L	L	L
3.	Salinity and sodicity – potential for mixing with native groundwater if not managed appropriately	L	U	L
4.	Nutrients: nitrogen, phosphorous and organic carbon – none likely present at levels of concern for irrigation	L	L	L
5.	Organic chemicals – none likely present at levels of concern for irrigation	L	L	L
6.	Turbidity and particulates – not present at levels of concern for irrigation but may cause clogging (operational risk)	L	L	L
7.	Radionuclides - none likely present at levels of concern for irrigation	L	L	L
8.	Pressure, flow rates, volumes and groundwater levels – potential for artesian wells			U
9.	Contaminant migration in fractured rock and karstic aquifers – potential for karstic features unknown			U
10.	Aquifer dissolution and stability of well and aquitard – aquifer and well stability unknown			U
11.	Aquifer and groundwater-dependent ecosystems – none present in the target aquifer which is saline and anoxic			L
12.	Energy and greenhouse gas considerations – unknown compared to other options			U

L low risk; **U** unknown risk; **H** high risk.

The maximal risk assessment shows an unacceptable risk to human health from pathogens in the absence of preventative measures such as restricting access during irrigation. The scheme was considered low risk for the presence of radionuclides, either in the stormwater or released from the aquifer sediments. Salinity risks could present a problem but can be managed if mixing of the injectant and groundwater are controlled. Risks from upward leakage need to be monitored, as well as well stability and effects of the ASR operation on groundwater levels. Energy considerations were not fully assessed and so remain uncertain.

2.4.2 Residual risk assessment

Following the maximal risk assessment a semi-quantitative residual risk assessment was performed including all preventive measures identified in the Stage 2 investigations: control the timing of irrigation to limit exposure to pathogens, as per the Stormwater Harvesting and

Reuse Guidelines (NRMMC–EPHC–NHMRC 2009b); and mixing of native groundwater with stormwater. The residual risk assessment compares recovered water quality to that required for irrigation of the public green spaces. The residual risk assessment was found to be acceptable for all end points for all of the twelve hazards. Monitoring of salinity of the recovered water showed that it was acceptable for irrigation due to the large residual buffer of fresh water in the aquifer. Inorganic chemicals such as arsenic were observed to be released during recovery at concentrations much less than irrigation requirements. Although calcium, magnesium, sodium, silica and bicarbonate were released from the aquifer matrix (Table 2-5) the well remained stable during the operation and Herczeg *et al*. (2004) showed that dissolution of the matrix would not reduce the stability of the well. There was no evidence of excessive upward leakage at the site and energy use was minimised by pumping and treating stormwater on demand.

2.5 Stage 3 Operational residual risk assessment

Changes of management arrangements at the ASR site on completion of the successful commissioning of the project led to change in the economic drivers for the project and operations were deferred. Excessive leakage from a detention basin (Santich 1996) also diminished the amount of water available for recharge. As such as operational residual risk assessment has not been completed at this time.

2.6 Concluding remarks

The Andrews Farm ASR project was developed to assess viability of injecting low salinity turbid stormwater into a brackish limestone aquifer. Before the trial commenced it was anticipated that injecting turbid water would quickly clog the well. It also seemed unlikely that the recovered blend of injected stormwater and ambient groundwater would be of an acceptable salinity for irrigation use. The study proved that these problems were manageable and its success as a trial has led to a series of ASR projects being established in the Northern Adelaide Plain region (Martin and Dillon, 2002). It also initiated the first guidance on the storage of stormwater in aquifers at a national level (Dillon and Pavelic 1996) which was a forerunner for the current national MAR Guidelines (NRMMC–EPHC–NHMRC 2009a).

2.7 References

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3 STORMWATER ASR AT ROSSDALE GOLF CLUB, VICTORIA

The Rossdale ASR (aquifer storage and recovery) project provides supplementary irrigation water to the Rossdale Golf Club in summer (Figure 3-1). Restrictions on use of mains water for irrigation led to the golf club harvesting stormwater from an adjacent drain and storing it in dams. The ASR system effectively expands storage without occupying additional valuable land.

Figure 3-1 Rossdale ASR site, showing the main stormwater dam and enclosures housing the irrigation pump, stormwater treatment unit (foreground) and ASR well (right background).

3.1 Site description

The ASR site is at the Rossdale Golf Club in Aspendale, south-eastern suburb of Melbourne, Victoria (Figure 3-2).

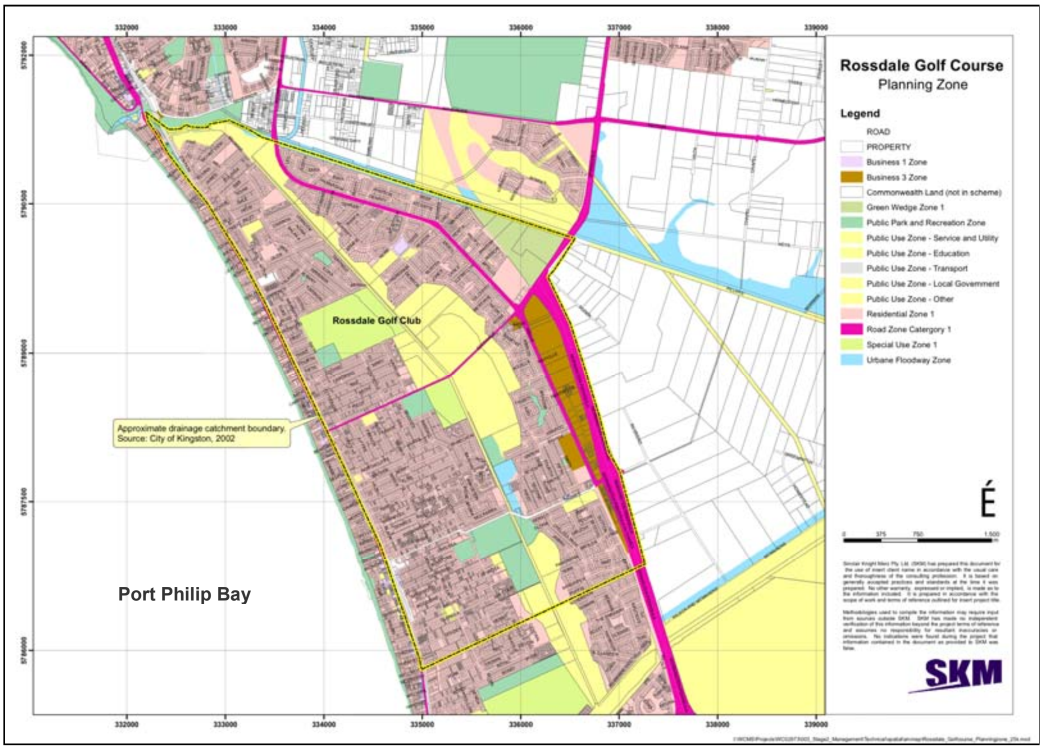


Figure 3-2 Map of Aspendale area and catchment showing Rossdale golf course (after Molloy 2006).

3.1.1 Sequence of development

A 10 ML stormwater dam was constructed at Rossdale Golf Club in 2004, and a permit was granted for the golf club to harvest 40 ML of water per annum from the Centre Swamp Drain (Figure 3-3). In 2005 Rossdale was selected as an ASR demonstration site for “Developing ASR Opportunities in Melbourne”, a Smart Water Fund (SWF) project. A hydrogeological assessment was undertaken and two wells (BH1 and BH2) were drilled in the Werribee Formation in 2005, but were found to be unsuitable for ASR due to low yields. The aquifer expected at the site based on regional hydrogeological information (Dudding *et al*. 2006) was not found.

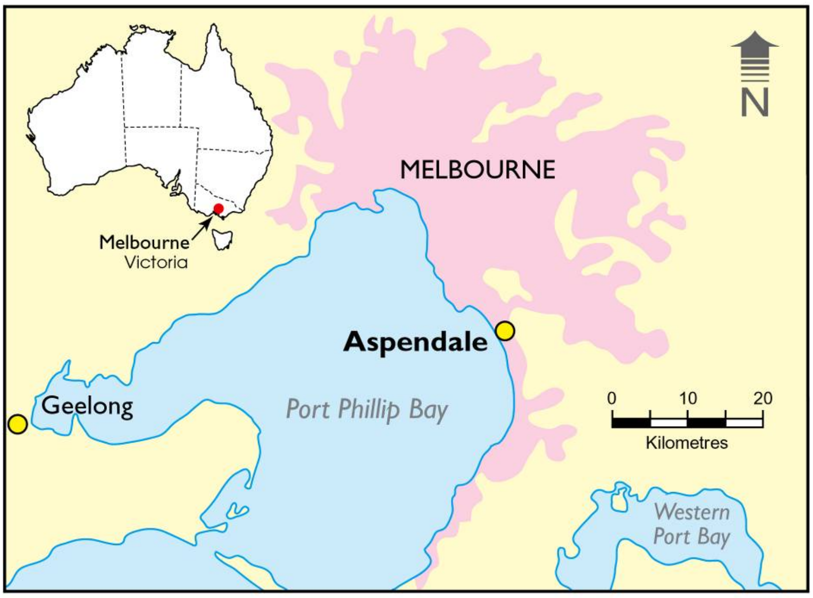
BH3 and BH4 were drilled in the bedrock in December 2005 and June 2006 to depths of 127 m and 146 m respectively. Both wells had pressure cemented casing and were completed as open-hole (i.e. without a screen) in the confined hard rock formation. Pumping tests and water quality sampling and analyses were performed. The best well yield (BH3) was 1.1 L/s, transmissivity 0.85-1.3 m^2/day, and hydraulic conductivity of storage zone was 4.1×10^{-6} m/d. Ambient groundwater salinity was ~1,500 mg/L TDS and standing water level was at ground surface level.

BH3 was identified as the most appropriate ASR well, with BH4 and BH2 becoming observation wells. Construction of well-head infrastructure and instrumentation occurred in 2006, and an injection and recovery trial with mains water occurred from December 2006 to April 2007 (Dillon *et al*. 2007).

Stormwater pre-treatment studies were performed in 2007 and 2008 to determine the most appropriate method of treating the stormwater prior to injection to avoid clogging of the ASR well. An Ultrafiltration and Granular Activated Carbon treatment unit was installed in October 2008, and after a successful two month field trial, the treatment unit was connected to the injection line, and injection of treated stormwater began in December 2008. Two cycles of injection and recovery have taken place up to March 2010.

3.1.2 Site configuration

The Rossdale ASR system is located near the eastern boundary of the Rossdale Golf Club approximately 1 km from Port Phillip Bay. The system consists of a stormwater drain, an off-take pumping system, a dam (10 ML capacity), an Ultra-Filtration Granular Activated Carbon (UF-GAC) pre-treatment unit, an ASR well (BH3) and two observation wells (BH2 and BH4) (Figure 3-3). Water is pumped from the dam, through the UF-GAC unit, and into the ASR well. Water is recovered from the ASR well back into the stormwater dam.



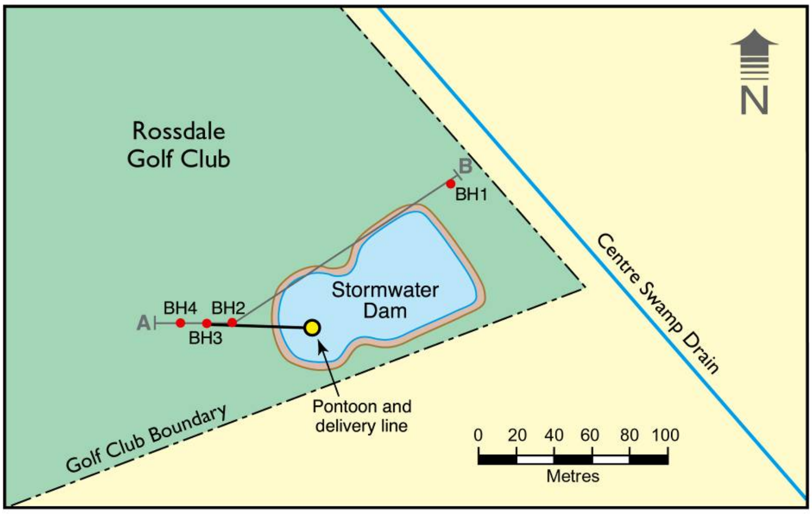


Figure 3-3 Map of Greater Melbourne area (pink) showing location of Aspendale (top), and Rossdale ASR site schematic, showing location of stormwater dam, ASR well (BH3) and observation wells (BH2 and BH4) in south-eastern corner (bottom).

The Rossdale ASR system components are summarised in Figure 3-4 and Table 3-1.

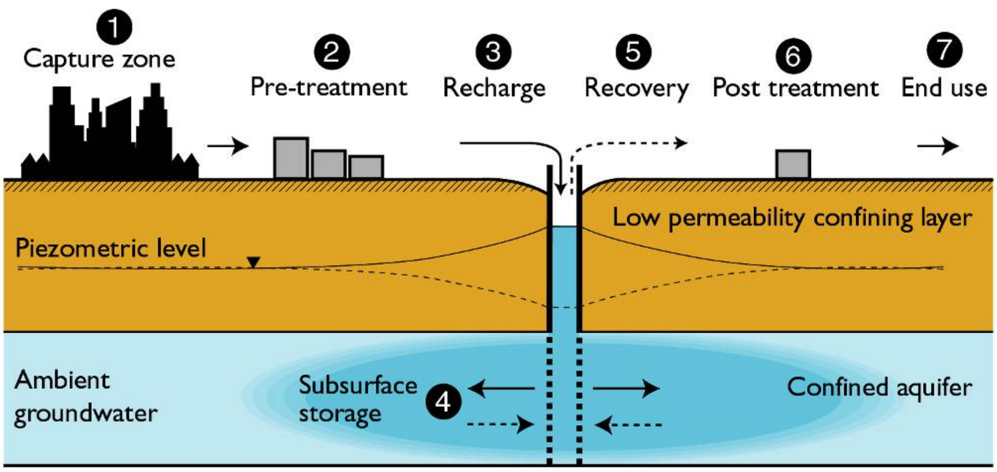


Figure 3-4 Rossdale ASR system schematic of water flow

Table 3-1 Rossdale ASR system components

Component	Rossdale ASR system
1. Capture zone	Stormwater from Centre Swamp Drain pumped into a dam
2. Pre-treatment	Ultrafiltration and Granular Activated Carbon filtration
3. Recharge	ASR well (BH3), open interval 93 – 123.5 m
4. Subsurface storage	Confined weathered Silurian bedrock
5. Recovery	ASR well (BH3)
6. Post-treatment	Water recovered to dam and mixed with fresh stormwater
7. End use	Irrigation of golf course

On-line flow rate, pressure and water quality data (electrical conductivity, turbidity, temperature and water level) is received via a web-based telemetry system and supplemented by daily manual readings by on-site personnel from the Rossdale Golf Course.

3.1.3 Aquifer description

The target aquifer is the Bedrock Sandstone Formation of Silurian age and consists of interbedded siltstone and fractured sandstone layers and with sub-vertical bedding planes (Figure 3-5). The aquifer was chosen as the target for ASR after previous investigations of the Werribee Formation identified that aquifer to be absent (Lennon *et al.* 2006, Pavelic *et al.* 2008a).

The aquifer is confined and exhibits transmissivities in the range 0.85 - 1.3 m^2/day. The low transmissivity, small fracture apertures and small pore sizes in the matrix suggest a high potential for clogging unless stormwater is treated to near-potable standards prior to injection (Pavelic *et al.* 2008a).

The ambient groundwater is brackish (~2800 µS/cm) and anoxic (redox potential from -90 to -60 mV). The mineralogy of the Bedrock Formation is dominated by quartz. Minor mineral phases include kaolinite, muscovite, siderite, chlorite and pyrite (Pavelic *et al.* 2008a).

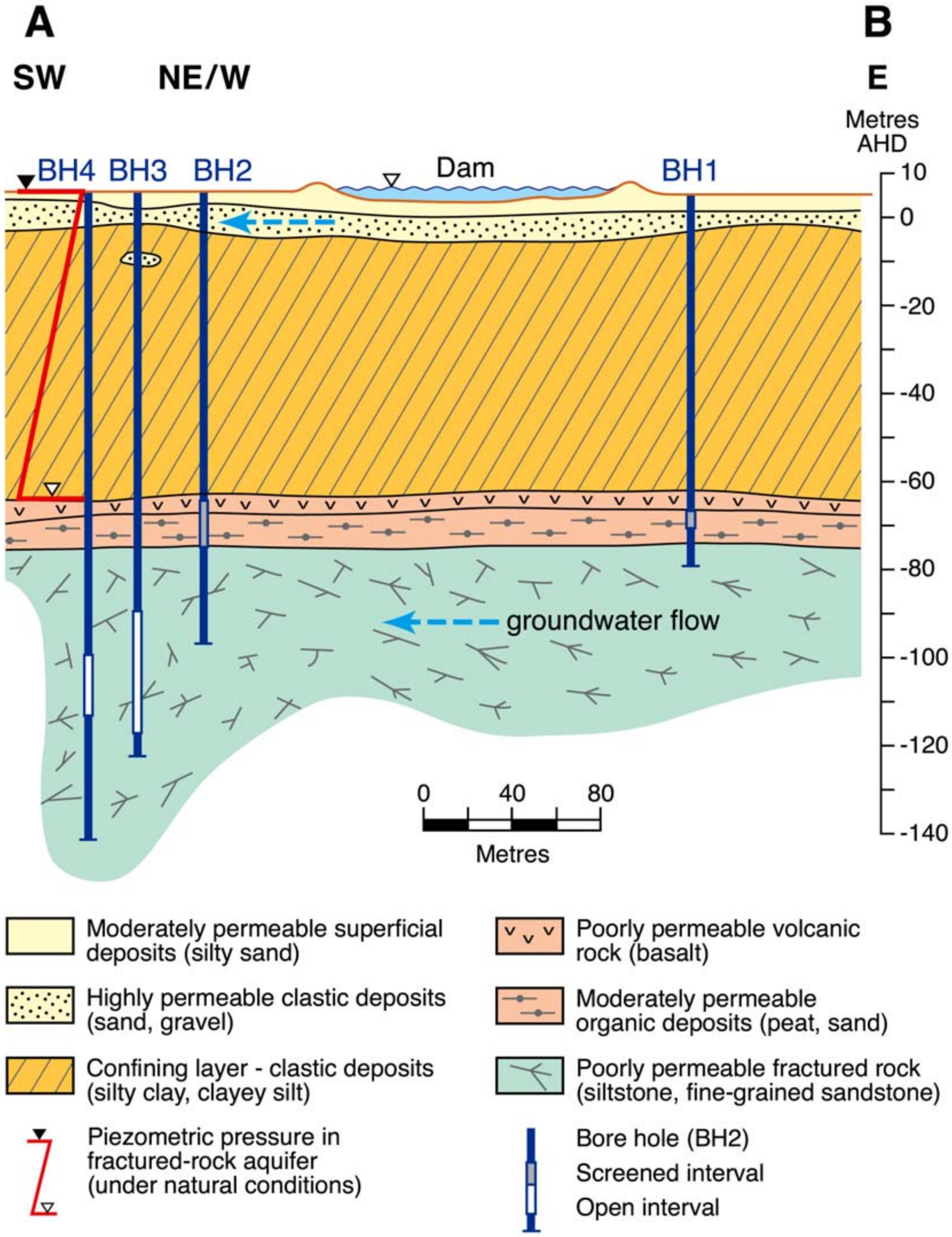


Figure 3-5 Geological cross section for the Rossdale ASR site

3.1.4 Source water description

The source water is stormwater from the Centre Swamp Drain in the main Mordialloc Creek catchment (Figure 3-2) and is owned, maintained and operated by Melbourne Water. Molloy (2006) reported that the catchment area had been assessed and noted that with the exception of a few point sources, the potential threats to stormwater quality in the drainage catchment are typical urban stormwater pollutants. The only potential point source pollutant in the drainage catchment was the Sixth Avenue Industrial Area (located within the 'Business 3 Zone' on Figure 3-2). Molloy (2006) reported that there were no current development proposals in the catchment that could pose a threat to stormwater quality.

Being stormwater, the quality is variable, but is generally fresh with low electrical conductivity (330 µS/cm). After settling in the dam particulate concentrations are relatively low (mean total suspended solids = 6.4 mg/L). Nutrient concentrations are similar to natural catchments (mean dissolved organic carbon = 8.3 mg/L).

Rossdale Golf Club has a licence to pump stormwater from the drain, and the raw stormwater is currently used for irrigation of the golf course, generally at night.

3.2 Stage 1 Entry level risk assessment

Table 3-2 and Table 3-3 show the completed entry-level risk assessment for the Rossdale ASR project, as per section 4.3 of the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a). Table 3-3 also provides a summary of Stage 2 investigations required as identified in the Stage 1 assessment.

Table 3-2 Rossdale ASR entry level assessment part 1 – Viability

	Attribute	Answer
1	Intended water use	
	• Is there an ongoing local demand or clearly defined environmental benefit for recovered water that is compatible with local water management plans?	✓ Recovered water intended for irrigation of golf course, to replace irrigation by mains water.
2	Source water availability and right of access	
	• Is adequate source water available, and is harvesting this volume compatible with catchment water management plans?	✓ Rossdale Golf Course has licence to harvest an adequate quantity of stormwater from Centre Swamp Drain.
3	Hydrogeological assessment	
	• Is there at least one aquifer at the proposed managed aquifer recharge site capable of storing additional water?	✓ Site is in area with moderate ASR potential according to regional mapping.
	• Is the project compatible with groundwater management plans?	✓ Licence to inject and recover up to 10 ML per annum granted by Southern Rural Water.
4	Space for water capture and treatment	
	• Is there sufficient land available for capture and treatment of the water?	✓ Existing dam on golf course to be used for harvesting stormwater.
5	Capability to design, construct and operate	
	• Is there a capability to design, construct and operate a managed aquifer recharge project?	✓ Through SWF, CSIRO to plan and design project. SKM to oversee drilling and pumping tests. Orica assisted with treatment plant. Rossdale Golf Club use programmable logic controllers in managing their irrigation systems so have potential for managing the ASR pre-treatment and injection and recovery systems and field supervisor received training in operating, monitoring and maintaining system. →Continue to entry level assessment (Table 3-3)

Table 3-3 Rossdale ASR entry level assessment part 2 – degree of difficulty

Question	Rossdale answers	Investigations required
1 Source water quality with respect to groundwater environmental values		
Does source water quality meet the requirements for the environmental values of ambient groundwater?	Yes – environmental values of ambient groundwater exclude drinking or irrigation due to high salinity.	None
2 Source water quality with respect to recovered water end use environmental values		
Does source water quality meet the requirements for the environmental values of intended end uses of water on recovery?	Yes – source water meets current irrigation requirements (before ASR).	None
3 Source water quality with respect to clogging		
Is source water of low quality, for example: total suspended solids, total organic carbon or total nitrogen >10 mg/L, And is soil or aquifer free of macropores?	Yes – source water has moderate TSS (5 mg/L) and high TOC (10 mg/L). Require Stage 2 investigations to assess clogging potential and pre-treatment options.	Clogging evaluation (Section 3.3.2)
4 Groundwater quality with respect to recovered water end use environmental values		
Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery?	No – ambient groundwater salinity is above irrigation standards. Require Stage 2 investigations into recovery efficiency.	Recovery efficiency evaluation (Section 3.3.4)
5 Groundwater and drinking water quality		
Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?	No – target aquifer is too saline for use as a drinking water supply, and does not support aquatic ecosystems with high conservation value. At least 1 km from coast with shallow hydraulic gradient and thick confining layer.	None
6 Groundwater salinity and recovery efficiency		
Does the salinity of native groundwater exceed: (a) 10000 mg/L, or (b) the salinity criterion for uses of recovered water?	Yes to (b) – ambient groundwater salinity above irrigation standards. Require Stage 2 investigations into recovery efficiency.	Water quality assessment (Section 3.3.3)
7 Reactions between source water and aquifer		
Is redox status, pH, temperature, nutrient status and ionic strength of source water and groundwater similar?	No – redox status, nutrient status and ionic strength of source water and groundwater are different. Require Stage 2 investigations to assess impacts of reactions on recovered water quality and aquifer integrity.	Geochemical evaluation (Section 3.3.1)
8 Proximity of nearest existing groundwater users, connected ecosystems and property boundaries		
Are there other groundwater users, groundwater–connected ecosystems or a property boundary near (within 100–1000 m) the MAR site?	No other groundwater users exist within 1000 m of the site. Groundwater is not suitable for stock and domestic use.	None
9 Aquifer capacity and groundwater levels		
Is the aquifer confined and not artesian? Or is it unconfined, with a watertable deeper than 4 m in rural areas or 8 m in urban areas?	Yes – target aquifer is confined and not artesian, however expected to become locally artesian during injection. Requires stage 2 investigations to assess artesian zone.	Evaluate potential for upward leakage (Section 3.4)
10 Protection of water quality in unconfined aquifers		
Is the aquifer unconfined, with an intended use of recovered water being drinking water supplies?	No – target aquifer is confined and recovered water intended for irrigation uses.	None
11 Fractured rock, karstic or reactive aquifers		
Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?	Yes – target aquifer is fractured rock, and contains pyrite and siderite. Require Stage 2 investigations to evaluate migration and hydrogeochemical reactions.	Recovery efficiency evaluation (Section 3.3.4)

Question	Rossdale answers	Investigations required
12 Similarity to successful projects		
Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?	No, first of its kind. Require Stage 2 investigations.	All (Section 3.3)
13 Management capability		
Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty, or with water treatment or water supply operations involving a structured approach to water quality risk management?	Yes – Rossdale Golf Club has experience with programmable logic controllers in managing irrigation systems and will manage the ASR and pre-treatment systems with training and service contracts.	None
14 Planning and related requirements		
Does the project require development approval? And is it in a built up area; on public, flood-prone or steep land; close to a property boundary; contain open water storages or engineering structures; likely to cause public health, safety or nuisance issues, or adverse environmental impacts?	No – project site approval granted by Rossdale Golf Club. Site set back from property boundary and screened with brush fencing. Met low acceptable noise level from players and neighbours. Avoid well construction and transport of treatment unit on site in winter to prevent wheel ruts in soft soil. Uses a pre-existing dam.	None

In summary of the Stage 1 assessment the following investigations were identified in proceeding to Stage 2 (Table 3-4).

Table 3-4 Summary of Stage 2 investigations required for Rossdale ASR

Issue		Investigations required at stage two	Discussed in section
3	Source water quality with respect to clogging	Clogging evaluation	3.3.2
4	Groundwater quality with respect to recovered water end use environmental values	Recovery efficiency evaluation	3.3.4
6	Groundwater salinity and recovery efficiency	Water quality assessment	3.3.3
7	Reactions between source water and aquifer	Geochemical evaluation	3.3.1
9	Aquifer capacity and groundwater levels	Evaluate potential for upward leakage	3.4
11	Fractured rock, karstic or reactive aquifers	Recovery efficiency evaluation	3.3.4
12	Similarity to successful projects	None, first of its kind in the region	3.3

3.3 Stage 2 Pre-commissioning investigations

A series of studies were performed in support of the Stage 2 pre-commissioning assessment and they are described below followed by the maximal and residual risk assessments.

3.3.1 Geochemical evaluation

The geochemical evaluation was undertaken by considering the reaction scenarios that could occur when the source stormwater is injected into the aquifer storage zone. It was based on evaluation of the end-members involved in reactions – the aquifer sediments, the ambient groundwater and the source water. A geological cross section is presented in Figure 3-5.

Using the decision trees in the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a), there is potential for release of both arsenic and iron at the Rossdale site when stormwater (with and without UF-GAC pre-treatment) is injected into the siliceous aquifer. Iron can be released through oxidation of pyrite soon after injection, and also through equilibrium with iron-bearing carbonate minerals (siderite). Pyrite oxidation can lead to the release of arsenic, as was evident in the mains water trial where the arsenic concentration reached a peak of 49 µg/L

(Dillon *et al.* 2007), but this is not likely to breach the short term irrigation quality guidelines (Arsenic < 2 mg/L) after return to the dam. Following mobilisation from the aquifer sediments, the fate of the iron will depend upon the prevailing pH and redox conditions, either remaining as soluble Fe(II) or precipitating as Fe(III) oxide. The effects of iron precipitates on well clogging are discussed in the following Section 3.3.2.

The impact of aquifer dissolution on the stability of the well was also evaluated. Water in contact with a mineral phase will tend toward equilibrium with that phase, either through dissolution or precipitation of that phase. The mineral saturation index of a solution can indicate if mineral equilibrium processes are expected. In this system, injection of water that is not in equilibrium with carbonate minerals may lead to dissolution soon after injection. Dissolution may serve to offset the effect of precipitation of iron oxides; however, it may also enhance the erosion of aquifer sediments and lead to well instability problems.

Dilution of recovered water with the dam water is a preventative measure. Monitoring should be undertaken for arsenic to verify concentrations remain low and monitoring of piezometric pressure and flow rate can be undertaken to evaluate any change in specific capacity of the well.

3.3.2 Clogging evaluation

The major clogging risks at the Rossdale site were investigated by Pavelic *et al.* (2008a). These issues were related to physical, chemical and biological clogging.

The risk of physical clogging is primarily related to the turbidity of the injected water which is exacerbated by the low transmissivity of the target aquifer (0.85 - 1.3 m^2/day). Pavelic *et al.* (2008a) reported that the extensive clogging by particulates is a risk as raw stormwater is characterised by high Membrane Filtration Index (MFI) values (>150 s/L^2). Pavelic *et al.* (2008a) recommended decreasing the MFI value of injected water to ≤5 s/L^2 with a view to achieving viable injection rates and in order to avoid frequent backflushing operations.

The risk of chemical clogging is mostly associated with the possibility of iron oxyhydroxide precipitation (Pavelic *et al.* 2008a). Preliminary geochemical modelling using PHREEQC (Parkhurst and Appelo 1999) indicates that pyrite oxidation will occur after injection of stormwater, which would subsequently lead to iron oxyhydroxide precipitation in the borehole and aquifer. This would require regular backwashing of the ASR well. Nevertheless, the acquisition of additional geochemical data is necessary to confirm this hypothesis. For the same reason it is not possible to evaluate the rate of precipitation of iron phases (Pavelic *et al.* 2008a). The characterisation of the aquifer performed by Pavelic *et al*. (2008a) implied that clogging due to swelling or dispersion of reactive clays is unlikely to be an issue due to the lower sodicity of the recharge water than the moderately brackish ambient groundwater.

The risk of biological clogging can be an issue as high concentrations of biodegradable dissolved organic carbon (BDOC) are present in the untreated stormwater that may support biofilm development in the borehole and in the aquifer around the ASR well (Page *et al*. 2008a). Therefore, some pre-treatment of injected water would be required to reduce these risks.

With a view to determining the possibility and rate of clogging development during site operation, a trial injection using mains water as the source water was performed (Dillon *et al.* 2007). The trial was conducted over four cycles of injection, storage and recovery, which increased in duration from three hours, three days, three weeks to three months. During the trial, no major clogging issues were observed, notably due to the low levels of particulate matter and BDOC. Dillon *et al.* (2007) concluded that the use of stormwater as a recharge water requires the removal of suspended solids and turbidity as well as reduction of BDOC to be sustainable. Without the time or budget to run column tests with cores of aquifer material the average quality of the mains water of turbidity (0.6 NTU); DOC (1.7 mg/L) and BDOC (0.2 mg/L) was therefore adopted as the treatment target for the stormwater to avoid clogging (Levett *et al*. 2009). A containerised Ultrafiltration and Granular Activated Carbon

(UF-GAC) plant was obtained from Orica for use as a pre-treatment method capable of meeting these water quality targets (Levett *et al*. 2009).

3.3.3 Water quality assessment

A water quality assessment was performed and data is given in the following table for untreated and treated stormwater and the ambient groundwater quality (Table 3-5).

Table 3-5 Rossdale ASR water quality data

	LTV Irrigation	STV Irrigation	Raw stormwater		Ambient Groundwater		Treated stormwater	
			n	mean	n	mean	n	mean
Physical characteristics								
pH (pH units)	6-8.5	6-8.5	**3**	8.7	**1**	7.7		
Electrical Conductivity (µS/cm)	800 [1]	800 [1]	**3**	333	**1**	2800	**3**	313
Total Dissolved Solids (mg/L)			**3**	181	**1**	1600		
True Colour (HU)								
Total Suspended Solids (mg/L)			**11**	6.4	**1**	73	**7**	1.3
Turbidity (NTU)			**7**	3.1			**10**	1.0
Major ions (mg/L)								
Bicarbonate			**3**	62	**1**	287		
Sulphate			**3**	22.3	**1**	116		
Chloride	175 [2]	175 [2]	**3**	49	**1**	690		
Fluoride			**3**	0.27				
Calcium			**3**	20.1	**1**	89		
Magnesium			**3**	5.7	**1**	27		
Potassium			**3**	3.1	**1**	5.5		
Sodium	115 [2]	115 [2]	**3**	34	**1**	465		
Nutrients (mg/L)								
Nitrate + Nitrite Nitrogen			**9**	1.719	**1**	<0.005	**5**	0.1
Ammonia			**4**	0.012	**1**	0.272		
Total Kjeldahl Nitrogen			**9**	0.86	**1**	0.33	**5**	0.5
Total Nitrogen	5	25-125	**9**	2.6		0.34	**5**	0.5
Filterable Reactive Phosphorus			**4**	0.0049		0.044		
Total Phosphorus	0.05	0.8-12	**9**	0.139	**1**	0.181	**5**	0.2
Biodegradable DOC			**2**	5.5			**8**	0.6
Dissolved Organic Carbon (DOC)			**9**	8.3	**1**	5.1	**11**	1.9
Total Organic Carbon			**9**	10.2	**1**	5.2	**6**	1.8
Silica			**3**	1	**1**	11		
Metals and metalloids (mg/L)								
Aluminium - Total	5	20	**2**	0.366	**1**	0.226		
Arsenic - Total	0.1	2	**4**	0.002	**1**	0.003		
Boron - Soluble	0.5 [3]	0.5 [3]	**4**	0.051	**1**	0.105		
Cadmium - Total	0.01	0.05	**4**	<0.0005	**1**	<0.0005		
Chromium - Total	0.1	1	**4**	<0.030	**1**	0.003		
Copper - Total	0.2	5	**1**	0.0045	**1**	<0.03		
Iron - Total	0.2	10	**3**	0.253	**1**	0.676		
Iron - Soluble			**4**	0.176	**1**	<0.005		
Lead - Total	2	5	**4**	0.0007	**1**	0.005		
Manganese - Total	0.2	10	**4**	0.0160	**1**	0.0673		
Nickel - Total	0.2	2	**4**	0.0020	**1**	0.0011		
Zinc - Total	2	5	**4**	0.022	**1**	0.004		

LTV = long term irrigation trigger value; STV = short term irrigation trigger value; [1] Threshold considered to be locally accepted criteria for irrigation of golf course; [2] A value greater than this can cause foliar damage in sensitive crops; [3] For very sensitive crops; sensitive 0.5-1, moderately sensitive 1-2.

3.3.4 Recovery efficiency evaluation

Recovery efficiency (RE) is defined as the proportion of water injected into a brackish aquifer that can be recovered at an acceptable quality for its intended use (800 µS/cm is the limit for irrigation of the golf course). With a view to evaluating REs of the ASR site at Rossdale, the injection and extraction trials with mains water were performed (Dillon *et al.* 2007). There were four cycles of injection with durations of 1 hour, 1 day, 1 week and 1 month, and equivalent periods of storage and recovery. During the four cycles 1,378 m^3 was injected and 1,401 m^3 was recovered. The calculations of RE were performed on the basis of measurements of electrical conductivity (EC) of injected and recovered water during trials. Three thresholds of recovered water salinity were used: 800 µS/cm (local irrigation criteria), 1,500 µS/cm and 2,000 µS/cm. The two higher criteria were also considered since the 800 µS/cm limit applies to the water quality within the dam and some account could be made for blending recovered water with fresher water in the dam.

For the 800 µS/cm criterion, REs were only 2-5% (neglecting the cycle 1 data due to the small scale of the test). Higher RE values of 17-30% were achieved for the 1,500 µS/cm criterion, and values were higher again for the 2,000 µS/cm criterion at 61-99% (Dillon *et al.* 2007).

Recovery efficiency was relatively poor when considered against the local irrigation criteria of 800 µS/cm for the extracted water, however blending within dam water allowed 90% of the injected volume to be recovered during the largest cycle. If the stormwater ASR does proceed then acceptably high recovery efficiencies are envisaged unless the initial storage volume in the dam is extremely low and there is an absence of stormwater inflow during recovery (Dillon *et al.* 2007).

As the level of mixing between the pumped water and stormwater within the holding dam would ultimately refine the RE, calculations were made on the final water quality within the dam at the end of an ASR pumping cycle in relation to the initial volume stored in the dam for recovered volumes ranging from 1 ML to 7 ML. The results indicated that a RE of >86% (i.e. >6 ML) is feasible where the initial storage volume on commencement of recovery exceeds 15% of dam capacity. If the initial storage exceeds 40% then a RE of 100% can be achieved (Dillon *et al.* 2007).

3.4 Stage 2 Pre-commissioning risk assessment

3.4.1 Maximal risk assessment

The risk assessment is presented in the order of the twelve key hazards outlined in the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a). A semi-quantitative risk assessment was performed for each of the hazards for human health and environmental endpoints, with green, orange and red indicating low (acceptable), uncertain and high (unacceptable) risks respectively (Table 3-6). The white boxes indicate that that hazard does not apply to that endpoint (hazards 8 to 12 for the human and irrigation endpoints).

The maximal risk assessment for the human health end point was conducted by comparing the water quality data for untreated stormwater and native groundwater for hazards 1 to 7 to the Stormwater Harvesting and Reuse Guidelines (NRMMC–EPHC–NHMRC 2009b) for irrigation exposure. For the irrigation end point, hazards 1 to 7 were compared to the short term values (STV) for irrigation guidelines (ANZECC–ARMCANZ 2000). For the aquifer endpoint, the aquifer's beneficial use was conservatively assumed to be for irrigation supplies (even though the salinity of the groundwater would not support irrigation), and for hazards 1 to 7 the quality of raw stormwater was compared to the irrigation guidelines (ANZECC–ARMCANZ 2000).

For hazards 8 to 12, the risks were assessed based on their potential impacts on the aquifer or biosphere as described in the MAR Guidelines.

Table 3-6 Maximal risk assessment summary for Rossdale ASR

	MAR Hazards	Human endpoint – ingestion of sprays	Environmental endpoint – golf course irrigation	Environmental endpoint – aquifer
1.	Pathogens – already approved for green space irrigation by the health department	L	L	L
2.	Inorganic chemicals – unlikely to be present at levels unsuitable for irrigation	L	L	L
3.	Salinity and sodicity – potential for mixing with native groundwater if not managed appropriately	L	U	L
4.	Nutrients: nitrogen, phosphorous and organic carbon – unlikely to be present at levels unsuitable for irrigation	L	L	L
5.	Organic chemicals – unlikely to be present at levels unsuitable for irrigation	L	L	L
6.	Turbidity and particulates – unlikely to be present at levels unsuitable for irrigation but may cause clogging (operational risk)	L	L	L
7.	Radionuclides – unlikely to be present at levels unsuitable for irrigation	L	L	L
8.	Pressure, flow rates, volumes and groundwater levels – potential for upward leakage			U
9.	Contaminant migration in fractured rock and karstic aquifers – potential migration via fractures			U
10.	Aquifer dissolution and stability of well and aquitard – potential for well stability issues			U
11.	Aquifer and groundwater-dependent ecosystems – none in the anoxic aquifer			L
12.	Energy and greenhouse gas considerations – unknown			U

L low risk; **U** unknown risk; **H** high risk.

The maximal risk assessment shows a low risk to human health from pathogens and organic chemicals if used for irrigation. There were no high levels of inorganic chemicals, nutrients, turbidity or radionuclides likely to be present in the stormwater based on the catchment risk assessment (Molloy 2006). Salinity risks could present a problem but can be managed if mixing of the injectant and groundwater are controlled. Risks from upward leakage will need to be monitored, as well as well stability and effects of the ASR operation on groundwater levels. Energy considerations were not fully assessed and so remain uncertain.

3.4.2 Residual risk assessment

Following the maximal risk assessment a semi-quantitative residual risk assessment was performed including all preventive measures identified in the Stage 2 investigations: pre-treatment of stormwater using the UF-GAC system; control of timing of irrigation to limit exposure to pathogens, as per the Stormwater Harvesting and Reuse Guidelines (NRMMC–EPHC–NHMRC 2009b); and mixing recovered water with stormwater in the dam. The residual risk assessment compares the recovered stormwater quality to the environmental values; in this case, irrigation of the golf course green spaces. The residual risk assessment was found to be acceptable for all of the twelve hazards. The stormwater pre-treatment system (UF-GAC) was a suitable pre-treatment for removal of turbidity and nutrients such as BDOC which could cause clogging.

Monitoring of salinity of the recovered water showed that it could be managed by blending with the dam water. No inorganic chemicals such as arsenic were observed to be released during recovery and the well remained stable throughout the operation. There was no evidence of excessive upward leakage at the site and energy use was minimised by pumping and treating stormwater on demand.

3.5 Stage 3 Operational residual risk assessment

The Rossdale ASR site is currently at Stage 2. Stage 3 assessment will begin when water is recovered for irrigation in the summer of 2009-2010, additional monitoring of recovered water will be required to ensure recovered water meets irrigation standards. Well efficiencies will also be monitored to ensure clogging is limited and this information used to verify that the residual risk assessment remains a low risk for an operational site. Results of commissioning are documented in Dillon *et al*. (2010).

3.6 Stage 4 Operation-refined risk management plan

There is currently no risk management plan in place for operating the Rossdale ASR site. Based on the identified risks in the Stage 3 operational residual risk assessment, the key components required within a risk management plan for the Rossdale ASR site are outlined in Table 3-7. Additional details on all of the elements required within a risk management plan are available in the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a).

Table 3-7 Key components required within the Rossdale ASR risk management plan likely to arise from the Stage 3 operational residual risk assessment

Element and key components
Element 3: Preventative measures for recycled water management
• Document UF-GAC pre-treatment procedures and validate performance of pre-treatment • Assess CCP and QCP limits and trigger values (e.g. conductivity of recovered water) and link to operational procedures
Element 4: Operational procedures and process control
• Define operational procedures for operation of the source water pre-treatment, back-washing of the injection well and cessation of recovery upon reaching the salinity limit • Operational monitoring is required to ensure source water quality meets target values • Operational monitoring is required to ensure no well clogging occurs • Corrective actions required if operational procedures are not met • Establish a program for regular inspection and maintenance of all equipment • Establish documented procedures for evaluating chemicals, materials and suppliers • Establish reporting requirements for EPA.
Element 5: Verification of recycled water quality and environmental performance
• Monitor volumes injected and recovered • Monitor recovered water quality to ensure it meets irrigation quality guidelines • Monitor impacts on receiving environment; hydraulic head in target aquifer and in overlying aquifer and groundwater quality
Element 7: Operation, contractor and end user awareness and training
• Ensure that operators, contractors and end users maintain the appropriate experience and qualifications • Identify training needs and ensure resources are available to support training • Document training and maintain records of training
Element 9: Validation, research and development
• Validation of CCPs and QCPs related to the control of clogging

3.7 Concluding remarks

While this irrigation MAR project would not normally be especially complex, the particular hydrogeology at the project site has required some advanced water treatment to ensure well clogging is not an issue. The treatment required to avert clogging is much more onerous than would be required for aquifer protection or ensuring adequate quality of recovered water.

3.8 References

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4 RECLAIMED WATER INFILTRATION AT PERRY LAKES, WESTERN AUSTRALIA

The Perry Lakes groundwater replenishment scheme is a proposal to replenish the superficial aquifer near two shallow water table lakes to save the lakes from drying out due to decreased recharge due to climate change and excessive groundwater pumping. It may also allow the Town of Cambridge in Western Australia to continue irrigating the adjacent parks and ovals. The proposal is to recharge reclaimed water using a series of infiltration galleries located hydraulically down-gradient from the lakes.

As this project is prospective, the majority of information describing the project is from unpublished sources, including the Water Corporation's *Perry Lakes Groundwater Management Project Brochure* (Water Corporation 2007), and the *Perry Lakes Aquifer Replenishment Proposal* (McFarlane *et al*. 2007) submitted by CSIRO and the Water Corporation to the Town of Cambridge and WA Government Regulators. McFarlane *et al*. (2009) outlines the infiltration gallery system design and describes the environmental, social and economic benefit of augmenting the groundwater in the area to maintain the wetlands. Tapsuwan *et al*. (2009) discuss preliminary economic cost estimates for the proposed scheme as well as economic and environmental benefits. Bekele *et al.* (2008) and Toze and Bekele (2009) describe the nearby Floreat Infiltration Galleries trial and monitoring results at the CSIRO Floreat Park site and provide insights on using this type of scheme in the superficial aquifer.

4.1 Site description

The Perry Lakes Reserve is in the suburb of Floreat, 7 km west of Perth (Figure 4-1). Perry Lakes consists of a series of shallow wetlands above an unconfined aquifer. These are referred to as West Lake and East Lake, which cover areas of approximately 5.2 ha and 6.9 ha, respectively (Rich 2004). The lakes are flowthrough lakes, whereby groundwater enters from the northeast and discharges to the southwest. However, they are also highly dynamic as they receive storm water inputs and lake levels are maintained during the summer using groundwater to offset evaporational losses (Rich 2004).

Figure 4-1 Location of the proposed infiltration galleries for the Perry Lakes aquifer replenishment scheme (McFarlane, personal communication).

4.1.1 Sequence of development

The replenishment of the Perry Lakes aquifer project remains a proposal at this stage. A formal proposal was submitted to the Town of Cambridge in March 2008. While the proposal was supported in principle, financial support had not been obtained. The annual operating costs are a major concern for the Town of Cambridge and thus, they have sought state and federal support for additional funding. To date, there has been no investment in investigative drilling or construction directly related to Perry Lakes.

The proposal includes results from a small scale MAR trial operating nearby (Floreat Infiltration Galleries) to provide an indication of potential groundwater quality changes that would result from the scheme. Also included were results from a small set of water samples collected at the site; a groundwater flow model for the proposed scheme at Perry Lakes; and a risk register, documenting the risks, their likelihood, impact and mitigation (McFarlane *et al*. 2007 *Appendix 1*).

The Floreat Infiltration Galleries (FIG) study was a CSIRO trial that operated approximately 500 metres south of Perry Lakes Reserve from 4 October 2005 to 23 December 2008. During this time, ~37 ML of secondary treated wastewater from the Subiaco WWTP was recharged to the same unconfined aquifer as proposed for the Perry Lakes aquifer replenishment scheme. The wastewater received additional polishing via passage through Amiad® multi-media filters before recharging the aquifer.

Water sampling was conducted by Water Corporation from two bores and from East Lake on 1 March 2007 to obtain additional data on nitrogen species and total dissolved solid concentrations for comparison with results from the FIG study.

A critical component of the proposal was a groundwater flow model produced by Dr Tony Smith (CSIRO, personal communication), which involved a steady-state model of the aquifer to assess the impact of a 1.3 km long infiltration gallery down-gradient from the lakes and a 0.65 km gallery up-gradient of the lakes in the redevelopment area (McFarlane *et al*. 2007). The model was able to reproduce the groundwater contours for 1997 that are documented in Rich (2004). Simulations were conducted to demonstrate the sensitivity to infiltrating different quantities of wastewater. Model results reveal that most of the impact is up-gradient and is likely due to impeding groundwater flow, rather than the addition of wastewater (McFarlane *et al*. 2007).

4.1.2 Site configuration

A design for the aquifer replenishment scheme was proposed for indicative and costing purposes. The proposed source water is secondary treated wastewater from the Subiaco WWTP, which would receive additional polishing via passage through rapid Amiad® multi-media filters. The reclaimed water would be pumped to a series of infiltration galleries (Figure 4-2) located hydraulically down-gradient from the lakes at the Perry Lakes Reserve. The MAR scheme is intended to produce a water table mound that would ultimately reduce the rate of groundwater outflow from the lakes, thereby providing a means to better manage lake levels using groundwater from up-gradient. It requires a continuous supply of regional groundwater flow to prevent back flow of treated effluent into the lakes.

Figure 4-2 Construction of infiltration galleries at CSIRO Floreat Park

A further pre-treatment step may include filling the infiltration galleries with wood chips to provide a carbon source to assist nitrogen removal. This has not yet been tested in a trial.

The infiltration galleries would be approximately 1 m wide x 1 m deep, and would run in series approximately 1,300 m long, as depicted in Figure 4-1. The system would use a parallel delivery main on the contour above top lake water level. The main would have connections to the galleries every 50 m for infiltration control.

The proposal suggests a possible connection with the irrigation ring main, but this would require chlorination, which is not planned for the galleries at this time. It is anticipated that treated wastewater could not be extracted by private bores downgradient for at least 10 years as the flow direction is under Bold Park nature reserve (Water Corporation 2007).

A schematic of the Perry Lakes aquifer replenishment project is given in Figure 4-3 and a description of the components is provided in Table 4-1.

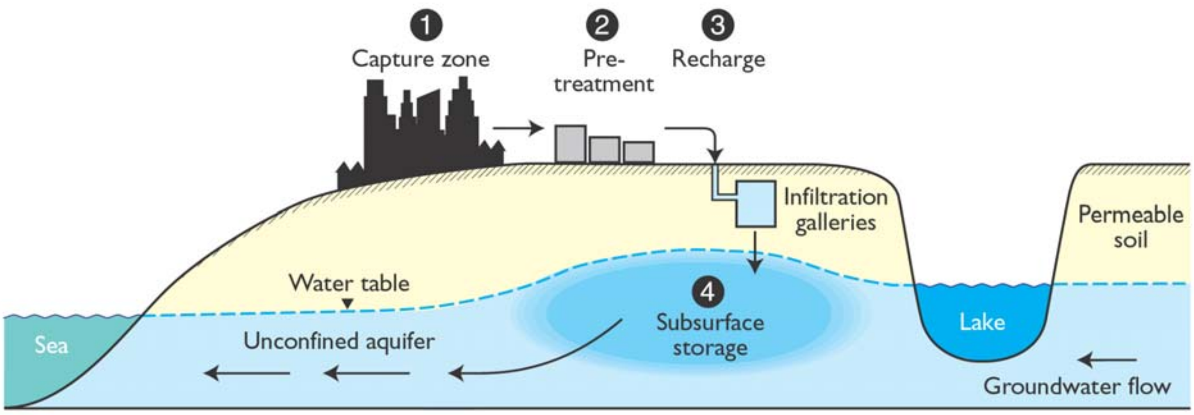

Figure 4-3 Perry Lakes aquifer replenishment scheme schematic of water flow

Table 4-1 Perry Lakes aquifer replenishment scheme proposed components

Component	Perry Lakes aquifer replenishment scheme
1. Capture zone	Secondary treated wastewater from the Subiaco WWTP
2. Pre-treatment	Passage through rapid sand filters (Amiad® AGF media filters) at the Subiaco WWTP. Proposal to fill the infiltration galleries with wood chips to provide a carbon source to assist nitrogen removal.
3. Recharge	Infiltration galleries ~ 1 m wide x 1 m deep x 1,300m long
4. Subsurface storage	Spearwood sand and the unconfined Tamala Limestone
5. Recovery	Aquifer replenishment only to increase storage and compensate for evaporative losses from the lakes and increased flow down gradient. However, ultimately water will reach irrigation wells.
6. Post-treatment	Nil
7. End use	Environmental benefit: Increase and maintain lake levels in Perry Lakes

4.1.3 Aquifer description

The managed aquifer recharge proposal is concentrated upon the superficial Spearwood sands and the underlying unconfined Tamala Limestone Formation. Both the Spearwood sands and the Tamala Limestone are of Pleistocene age (Tapsell *et al.* 2003). Tracer tests reveal that the horizontal hydraulic conductivity of the sands is 10 - 30 m/d, and up to 100 m/day for the limestone. The transmissivity values of the entire aquifer vary from 700 - 2,200 m^2/day. The aquifer is unconfined and the hydraulic gradient is around 0.0014.

Groundwater in the aquifer is aerobic with salinity in the range of 800 - 870 mg/L TDS. Quartz with carbonate minerals dominate the aquifer matrix.

4.1.4 Source water description

The reclaimed water source is from the Subiaco Wastewater Treatment Plant operated by the Water Corporation of Western Australia. The majority of secondary treated wastewater is currently discharged at an ocean outfall. The Perry Lakes scheme would use secondary treated wastewater with additional polishing using Amiad® AGF media filters (rapid sand filtration). This filtered recycled water has been used, with the additional treatment step of chlorine disinfection, to irrigate sporting grounds at McGillivray Oval for several years (McFarlane *et al*. 2007).

An assessment of the performance of the Amiad® AGF filters with regard to physical, chemical and biological parameters of the filtered water was conducted as part of a McGillivray Oval study (Toze *et al*. 2005). The average characteristics of the secondary treated wastewater after rapid sand filtration based on six sampling events are as follows: pH (7.4), electrical conductivity (1,309 µS/cm), dissolved oxygen (8.6 ppm), turbidity (24 NTU), temperature (27 ºC), total suspended solids (6 mg/L), total dissolved solids (655 mg/L), DOC (10 mg/L), total nitrogen (4.7 mg/L) and total phosphate (8 mg/L) (Toze *et al*. 2005).

The Floreat Infiltration Galleries (FIG) study offers additional information about the source water; water quality was monitored for a wider range of parameters (see Section 4.3.1).

4.2 Stage 1 Entry level risk assessment

Table 4-2 and Table 4-3 show the completed entry-level risk assessment for the Perry Lakes proposal, as per section 4.3 of the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a). Table 4-3 also provides a summary of Stage 2 investigations required as identified in the Stage 1 assessment.

Table 4-2 Perry Lakes entry level assessment part 1 – Viability

	Attribute	Answer
1	Intended water use	
	• Is there an ongoing local demand or clearly defined environmental benefit for recovered water that is compatible with local water management plans?	Yes – lake water level management is needed to prevent loss of existing wetland habitat and associated flora and fauna. The current maintenance of artificial lake level by pumping groundwater into lakes is unsustainable due to a falling regional water table. An Environmental Management Plan commissioned by the Town of Cambridge (PPK 2000) recommended an investigation into the use of treated wastewater as a solution.
2	Source water availability and right of access	
	• Is adequate source water available, and is harvesting this volume compatible with catchment water management plans?	Yes – about 7 ML/day is available from the Amiad® AGF media filter plant at the Subiaco WWTP. Recharging this would reduce volume of secondary treated wastewater discharged at ocean outfalls.
3	Hydrogeological assessment	
	• Is there at least one aquifer at the proposed managed aquifer recharge site capable of storing additional water?	Yes – the Tamala Limestone is regionally known for its high transmissivity. The overlying Spearwood sand is generally less transmissive; hydraulic properties below and around the lakes require further investigation.
	• Is the project compatible with groundwater management plans?	Yes –The Perry Lakes proposal had a conceptual review by the Department of Water (Water Corporation 2007). As part of the regional groundwater plan the Town of Cambridge aims to reduce its reliance on pumping from the aquifer (Town of Cambridge 2008).
4	Space for water capture and treatment	
	• Is there sufficient land available for capture and treatment of the water?	Yes – uses existing treatment plant and preliminary design plan indicates sufficient land is available.
5	Capability to design, construct and operate	
	• Is there a capability to design, construct and operate a managed aquifer recharge project?	Yes – Water Corporation experienced in wastewater treatment and CSIRO has experience in design and operation of infiltration galleries. Organisation to construct and manage project is yet to be determined. →Continue to entry level assessment (Table 4-3)

Table 4-3 Perry Lakes entry level assessment part 2 – degree of difficulty

Question	Perry Lakes answers	Investigations required
1 Source water quality with respect to groundwater environmental values		
Does source water quality meet the requirements for the environmental values of ambient groundwater?	Uncertain – there has been limited sampling of ambient groundwater. Total nitrogen in the source water is higher than ambient groundwater. More sampling is needed to determine the extent of seasonal variation.	Water quality evaluation, particularly to assess seasonal variations in nutrients and ascertain water quality targets for ecosystem support. (Section 4.3.1)
2 Source water quality with respect to recovered water end use environmental values		
Does source water quality meet the requirements for the environmental values of intended end uses of water on recovery?	No – concentrations of iron, total nitrogen and fluoride exceed irrigation long term trigger values; measured phosphorus has exceeded the short-term trigger value. Would need to ensure that no water discharges to the lakes as it does not meet ecosystem support criteria.	Source water quality evaluation (Section 4.3.1)
3 Source water quality with respect to clogging		
Is source water of low quality, for example: total suspended solids, total organic carbon or total nitrogen >10 mg/L, And is soil or aquifer free of macropores?	Yes – average concentrations of TSS (7.5 mg/L) and TOC (9.9 mg/L) indicate low quality; TN (4.3 mg/L) is less problematic. The potential for macropores has not been assessed, but likely given the variable amount of carbonate cement in the sands and Tamala Limestone. Stage 2 investigations required.	Clogging evaluation
4 Groundwater quality with respect to recovered water end use environmental values		
Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery?	Yes – the Town of Cambridge artificially maintains lake levels in the summer by pumping groundwater into the lakes. Groundwater also supports irrigation.	None
5 Groundwater and drinking water quality		
Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?	Yes – protection of ecological values is a concern. The lakes support a variety of water fowl, turtles and other species (PPK 2000). There are long-necked turtles as reported in Dames and Moore (1992a) and Guyot and Kuchling (1998). Groundwater also discharges to coast. Stage 2 investigations required.	Groundwater quality evaluation to assess risk to connected high-value ecosystems
6 Groundwater salinity and recovery efficiency		
Does the salinity of native groundwater exceed: (a) 10000 mg/L, or (b) the salinity criterion for uses of recovered water?	No	None
7 Reactions between source water and aquifer		
Is redox status, pH, temperature, nutrient status and ionic strength of source water and groundwater similar?	No – not enough information to fully assess redox status and ionic strength; pH and temperature are similar. Nutrients are similar, except for higher P in the source water.	Geochemical evaluation; fate of recycled water trace organics

Question	Perry Lakes answers	Investigations required
8 Proximity of nearest existing groundwater users, connected ecosystems and property boundaries		
Are there other groundwater users, groundwater-connected ecosystems or a property boundary near (within 100–1000 m) the MAR site?	Yes – Stage 2 investigations required to assess impacts to groundwater-connected ecosystems.	Groundwater flow and mass transport modelling
9 Aquifer capacity and groundwater levels		
Is the aquifer confined and not artesian? Or is it unconfined, with a watertable deeper than 4 m in rural areas or 8 m in urban areas?	No – unconfined and the water table is shallower than 8m (urban area). Stage 2 investigations required to assess risk of waterlogging and excessive groundwater mound height.	Evaluate potential for waterlogging and excessive groundwater mound height
10 Protection of water quality in unconfined aquifers		
Is the aquifer unconfined, with an intended use of recovered water being drinking water supplies?	No	None
11 Fractured rock, karstic or reactive aquifers		
Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?	Numerous caves have been documented within the Tamala Limestone in the Perth metro area. A "buried pinnacle landscape" (solution pipes filled and re-cemented) was revealed from drilling the south side of Perry Lakes (Rich 2004), but no fractures or karst have been identified yet at Perry Lakes. Stage 2 investigations required to determine presence of reactive minerals or karst features.	Geochemical evaluation
12 Similarity to successful projects		
Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?	Yes – Floreat Infiltration Gallery trial undertaken at small scale. Larger scale trial warranted.	Larger scale trial
13 Management capability		
Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty, or with water treatment or water supply operations involving a structured approach to water quality risk management?	An operator/manager of the scheme has not been identified. Water Corporation and CSIRO are assisting and do have this experience.	Identify manager with competencies or train them at other MAR sites and on water quality risk management.
14 Planning and related requirements		
Does the project require development approval? And is it in a built up area; on public, flood-prone or steep land; close to a property boundary; contain open water storages or engineering structures; likely to cause public health, safety or nuisance issues, or adverse environmental impacts?	Yes – the project will need approvals. It is located in a park/reserve area on public land, adjacent to an area to be extensively redeveloped for residential properties. Public heath, safety and nuisance issues will need to be considered, but resident surveys demonstrate a strong demand for open water (McFarlane *et al*. 2007 – *Risk Register*).	As required by legal approval processes

In summary of the Stage 1 assessment the following investigations were identified in proceeding to Stage 2 (Table 4-4).

Table 4-4 Summary of Stage 2 investigations required at Perry Lakes

Issue		Investigations required at stage two	Discussed in section
1	Source water quality with respect to groundwater environmental values	Water quality evaluation, particularly to assess seasonal variations in nutrients and ascertain water quality targets for ecosystem support.	4.3.1
2	Source water quality with respect to recovered water end use environmental values	Source water quality evaluation	4.3.1
3	Source water quality with respect to clogging	Clogging evaluation	
5	Groundwater and drinking water quality	Groundwater quality evaluation to assess risk to connected high-value ecosystems	
7	Reactions between source water and aquifer	Geochemical evaluation; fate of recycled water trace organics	
8	Proximity of nearest existing groundwater users, connected ecosystems and property boundaries	Groundwater flow and mass transport modelling	
9	Aquifer capacity and groundwater levels	Evaluate potential for waterlogging and excessive groundwater mound height	
11	Fractured rock, karstic or reactive aquifers	Geochemical evaluation	
12	Similarity to successful projects	Conduct trial to determine how to operate effectively.	
13	Management capability	Identify manager with competencies or train them at other MAR sites and on water quality risk management.	
14	Planning and related requirements	As required by legal approval processes	

4.3 Stage 2 Pre-commissioning investigations

The initial water quality assessment performed to support the Stage 2 pre-commissioning assessment is described below; other proposed Stage 2 investigations have not been performed to date.

4.3.1 Water quality assessment

Water quality data from the recycled water system (secondary treated reclaimed water and groundwater); the extracted data was used for the maximal risk assessment, are shown in Table 4-5.

Table 4-5 Initial water quality assessment for Perry Lakes groundwater replenishment trial, using ambient groundwater from the proposed site, and source water from Floreat Infiltration Galleries (FIG) as indicative source water.

	LTV Irrigation	STV Irrigation	Source water (FIG)		Ambient groundwater	
			n	mean	n	mean
Physical characteristics						
Temperature (°C)			**53**	24.0		
pH	6-8.5	6-8.5	**40**	7.3	**13**	7.3
Conductivity (μS/cm)	800 [1]	800 [1]	**53**	1468	**13**	1572
Total Dissolved Solids (mg/L)			**20**	755		
Dissolved oxygen (mg/L)			**49**	2.2		
Redox potential (mV SHE)			**49**	385		
Suspended Solids (mg/L)			**8**	7.5		
Turbidity (NTU)			**19**	2.8		
Major ions (mg/L)						
Alkalinity as $CaCO_3$			**36**	145		
Bicarbonate			**42**	174	**13**	387
Bromide			**20**	0.62		
Sulfate			**42**	64	**13**	68
Chloride	175 [2]	175 [2]	**63**	245	**13**	277
Fluoride			**15**	0.73		
Calcium			**42**	29	**13**	110
Magnesium			**42**	12	**13**	25.3
Potassium			**60**	23	**13**	11.3
Sodium	115 [2]	115 [2]	**42**	194	**13**	176
Microbiological						
Thermotolerant coliforms (cfu/100 mL)			**46**	TNC [3]		
Enterococci faecalis (cfu/100 mL)			**48**	TNC [4]		
FRNA phage (positive/negative)			**40**	39 / 40 positive		
Adenovirus (present/absent)			**19**	13 / 19 present		
Coxsackie (present/absent)			**6**	1 / 6 present		
Nutrients (mg/L)						
Nitrate as N			**42**	2.16	**13**	0.07
Ammonia as N			**20**	0.64		
Total Kjeldahl Nitrogen			**20**	1.86		
Total Nitrogen	5	25-125	**22**	4.28	**13**	4.1
Filterable Reactive Phosphorus			**42**	6.3		
Total Phosphorus	0.05	0.8-12			**13**	1.28
Dissolved Organic Carbon			**14**	10.9		
Total Organic Carbon			**41**	10.0		
Silica			**22**	13.2		
Biological Oxygen Demand			**6**	<5		
Metals and metalloids (mg/L)						
Aluminium - Total	5	20	**42**	0.016		
Antimony - Total			**10**	0.0003		
Arsenic - Total	0.1	2	**20**	<0.001		
Barium - Total			**14**	0.033		
Boron - Soluble	0.5 [5]	0.5 [5]	**60**	0.204		
Cadmium - Total	0.01	0.05	**25**	<0.0001		
Cobalt - Total			**18**	<0.005		
Chromium - Total			**14**	<0.002		

	LTV Irrigation	STV Irrigation	Source water (FIG)		Ambient groundwater	
Copper - Total	0.2	5	**20**	0.005		
Iron - Total	0.2	10	**42**	0.140	**13**	1.566
Lead - Total	2	5	**25**	0.0003		
Manganese - Total	0.2	10	**25**	0.036		
Mercury - Total	0.002	0.002	**24**	<0.0005		
Molybdenum - Total	0.01	0.05	**14**	<0.02		
Nickel - Total	0.2	2	**25**	0.003		
Selenium - Total	0.02	0.05	**14**	<0.001		
Silver - Total			**14**	<0.005		
Uranium - Total	0.01	0.1	**14**	<0.0001		
Vanadium - Total			**14**	<0.005		
Zinc - Total	2	5	**25**	0.058		
Organic chemicals (µg/L)						
Temazepam			**25**	0.31		
Oxazepam			**25**	0.31		
Diazepam			**25**	<0.10		
Phenytoin			**25**	<0.10		
Carbamazepine			**25**	0.21		

LTV = long term irrigation trigger value; STV = short term irrigation trigger value; [1] Threshold considered to be locally accepted criteria for irrigation. See ANZECC-ARMCANZ (2000) guidelines for a detailed tolerance of different crops; [2] A value less than this can cause foliar damage in sensitive crops; [3] TNC = too numerous to count. Mean of 29 quantifiable thermotolerant results = 1,300 cfu/100 mL; [4] Mean of 23 quantifiable *Enterococci faecalis* results = 1,657 cfu/100 mL based on raw counts; [5] For very sensitive crops; sensitive 0.5-1, moderately sensitive 1-2.

4.4 Stage 2 Pre-commissioning risk assessment

4.4.1 Maximal risk assessment

The risk assessment is presented in the order of the twelve key hazards outlined in the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a). A semi-quantitative risk assessment was performed for each of the hazards for human health and environmental endpoints, with green, orange and red indicating low (acceptable), uncertain and high (unacceptable) risks respectively (Table 4-6). The white boxes indicate that that hazard does not apply to that endpoint (hazards 8 to 12 for the human and irrigation endpoints).

The maximal risk assessment for the human health end point was conducted by comparing the water quality data for secondary treated reclaimed water for hazards 1 to 7 to the Australian Guidelines for Water Recycling (NRMMC–EPHC–AHMC 2006) for irrigation exposure. For the irrigation end point, hazards 1 to 7 were compared to the short term values (STV) for irrigation guidelines (ANZECC–ARMCANZ 2000). For the other environmental endpoint, the aquifer's beneficial use was assumed to be for maintenance of groundwater dependent ecosystems, and for hazards 1 to 7 the quality of secondary treated effluent was conservatively compared to ambient conditions in the aquifer.

For hazards 8 to 12, the risks were assessed based on their potential impacts on the aquifer or biosphere as described in the MAR Guidelines.

Table 4-6 Maximal risk assessment summary for Perry Lakes groundwater replenishment trial

	MAR Hazards	Human endpoint – ingestion of sprays	Environmental endpoint – green space irrigation	Environmental endpoint – GDE
1.	Pathogens – pathogens known to be present in source water	H	U	U
2.	Inorganic chemicals – potential effect of nitrogen species on the aquatic ecosystem	L	L	U
3.	Salinity and sodicity – low, both source water and lake are fresh	L	L	L
4.	Nutrients: nitrogen, phosphorous and organic carbon – potential for eutrophication of the lakes	L	U	U
5.	Organic chemicals – chemicals present but unknown effects	U	U	U
6.	Turbidity and particulates – unlikely to cause effects for irrigation and ecosystem support but may cause clogging (operational risk)	L	L	L
7.	Radionuclides	L	L	L
8.	Pressure, flow rates, volumes and groundwater levels – effects of infiltrated plume and groundwater levels needs to be assessed		U	U
9.	Contaminant migration in fractured rock and karstic aquifers – potential for travel via preferential flow paths		U	U
10.	Aquifer dissolution and stability of well and aquitard – potential for calcite dissolution		U	U
11.	Aquifer and groundwater-dependent ecosystems – unknown risk		U	U
12.	Energy and greenhouse gas considerations – unknown at present compared to other options		U	U

L low risk; **U** unknown risk; **H** high risk; **GDE** = groundwater dependent ecosystem (i.e. aquifer, Perry Lakes)

Pathogen risks to human health need to be verified as low prior to commencement of the project. High levels of inorganic chemicals, salinity, turbidity, or radionuclides are not likely to be present in the source water. Nutrient risks could potentially present a problem to the connected aquatic ecosystems but could be managed with treatment such that groundwater dependent ecosystems are protected. As the aquifer is karstic in places there is potential for more rapid movement of contaminants to environmental receptors. There is potential for dissolution of calcite in the limestone aquifer. Energy and greenhouse gas emissions will be addressed by minimising energy requirements and using renewable energy where possible. Energy costs would be compared with those from ongoing groundwater pumping.

The Perry Lakes aquifer replenishment scheme is still currently at Stage 2 investigations. Additional water chemistry and quality monitoring of ambient groundwater and the source

water from the AGF media filters that supply the source water will enable a more accurate assessment of the risks. Although the rapid sand filtration used at FIG and proposed for Perry Lakes are similar, monitoring of the AGF media filter water should be conducted to determine whether the long-term source water data from the Floreat Infiltration Galleries study is directly relevant.

An ecotoxicological assessment is needed to determine whether pharmaceuticals and other organic compounds will impact negatively on the flora and fauna of the lake and groundwater system, if the source water discharges via groundwater flow into the lakes. An ecological survey may be needed to obtain an accurate picture of the current presence, abundance and distribution of aquatic species. Ambient concentrations of organic compounds in the lakes and groundwater should be monitored.

Sufficient sustainable infiltration will need to be demonstrated. Dr Tony Smith's groundwater flow model suggests an infiltration rate of the order of 4 m/day at Perry Lakes (McFarlane *et al*. 2007). Although recharge to FIG was increased to 3 - 4 m/d over two months after completion of the FIG study, it may not be possible to sustain this rate in the long-term without clogging. McFarlane *et al*. (2007) suggest strategies that may help to overcome potential clogging, but they would need to be tested and ongoing maintenance may be costly. The mitigation for this risk is to design the galleries so that a hydraulic barrier can be maintained while the galleries are rested and oxidized or cleaned. A hybrid/split system, relying on an engineered filter/reactor bed may be needed to achieve infiltration capacity as recommended by Dr Jeff Turner (CSIRO, *personal communication*).

4.5 Stage 3 Operational residual risk assessment

A Stage 3 assessment can only be performed once the Perry Lakes aquifer replenishment scheme is in operation. Verification of the adopted preventative measures, hydrology and effect on lake levels will be a fundamental component of this stage.

4.6 Stage 4 Operation-refined risk management plan

A Risk Register produced as part of the Perry Lakes proposal describes the risks, their likelihoods, impacts and mitigation strategies (Table 4-7).

Table 4-7 Risk management plan key components for Perry Lakes groundwater replenishment scheme (Adapted from the risks identified in Appendix 1 of McFarlane *et al*. (2007))

Element and key components
Element 3: Preventative measures for recycled water management
• Assess CCP and QCP limits and trigger values (e.g. nitrogen concentrations and flow of water under Bold Park) and link to operational procedures of the plan
Element 4: Operational procedures and process control
• Define operational procedures for operation of the infiltration galleries to enhance denitrification and hydraulic considerations. • Operational monitoring is required to ensure source water quality meets target values • Operational monitoring is required to ensure no well clogging occurs • Corrective actions required if operational procedures are not met • Establish a program for regular inspection and maintenance of all equipment • Establish reporting requirements for EPA.
Element 5: Verification of recycled water quality and environmental performance
• Monitor volumes injected and recovered • Monitor recovered water quality to ensure it meets aquatic ecosystem protection guidelines • Monitor impacts on receiving environment; hydraulic head in target aquifer and in overlying aquifer and groundwater quality
Element 7: Operation, contractor and end user awareness and training
• Ensure that operators, contractors and end users maintain the appropriate experience and qualifications • Identify training needs and ensure resources are available to support training • Document training and maintain records of training
Element 9: Validation, research and development
• Validation of CCPs and QCPs related to the control of clogging

4.7 Concluding remarks

The Perry Lakes aquifer replenishment proposal is for a scheme intended to improve the environmental, social and economic values of the wetlands. A Ph.D. thesis dissertation by Rich (2004) assists in understanding the Perry Lakes water balance and groundwater-lake interactions and dynamics. There remain a number of issues to investigate to ensure the successful production of an underground groundwater barrier and additional investigative drilling will likely be required. To date, a steady-state groundwater flow model has been produced, but a transient model would be necessary to consider the seasonal recharge and pumping in the area.

The Town of Cambridge currently maintains water in the lakes by pumping groundwater into them during the summer, but this is increasingly energy intensive due to declines in the regional water table. Secondary treated wastewater currently discharged to an ocean outfall could be more beneficially applied to increase the water table near the lakes. Understandably there are also concerns for aquatic species, if in the worst case, treated wastewater were to flow back into the lakes. An ecotoxicological assessment of the environmental receptor species and potential impacts from interactions with organic compounds present in the wastewater needs to be conducted.

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5 RECLAIMED WATER ASR AT BOLIVAR, SOUTH AUSTRALIA

The horticultural activities in the Northern Adelaide Plains (NAP) have traditionally used groundwater supplies for irrigation. Expansion of horticulture in the area needed additional water supplies and Bolivar WWTP effluent was identified as a potential new source of irrigation water. Use of reclaimed water for irrigation required a tertiary treatment (Dissolved Air Flotation/Filtration; DAFF) and chlorination upgrade. Since 1999, the water produced by these treatments is supplied for irrigation via the Virginia Pipeline Scheme (VPS). However, the water demand in the NAP increases during summer, and the water produced by the DAFF plant is not sufficient to meet demand at this time. Storing the surplus water produced during winter in an aquifer was seen as a feasible possibility to meet demand year round, which initiated the Bolivar ASR (aquifer storage and recovery) project.

The Bolivar ASR project aimed to determine whether tertiary-treated wastewater can be stored in an aquifer and be recovered later for irrigation purposes.

5.1 Bolivar site description

The Bolivar ASR system is 25 km north of the centre of Adelaide (South Australia) within the northern boundary of the Bolivar wastewater treatment plant (WWTP) (Figure 5-1 and Figure 5-2).

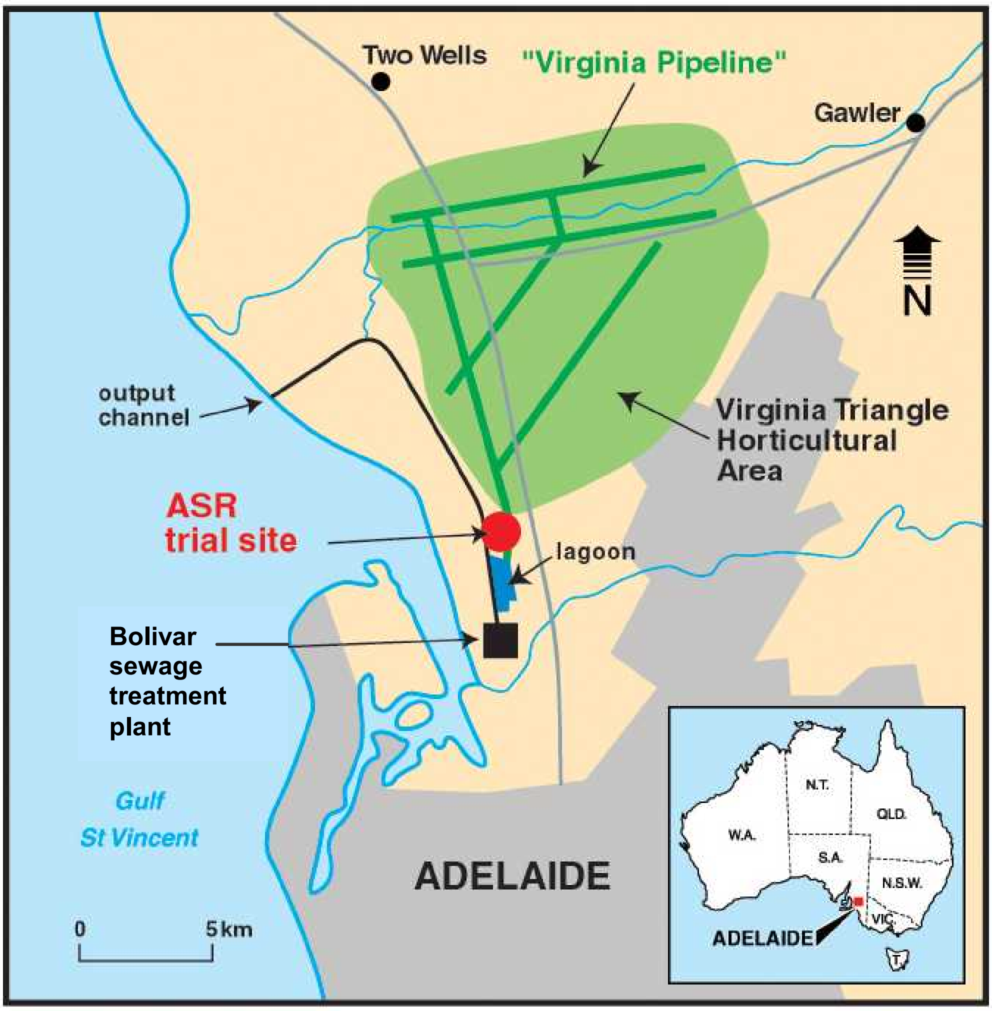

Figure 5-1 Location of Bolivar ASR trial site near the Northern Adelaide Plains horticultural area (from Dillon *et al.* 1999; 2003).

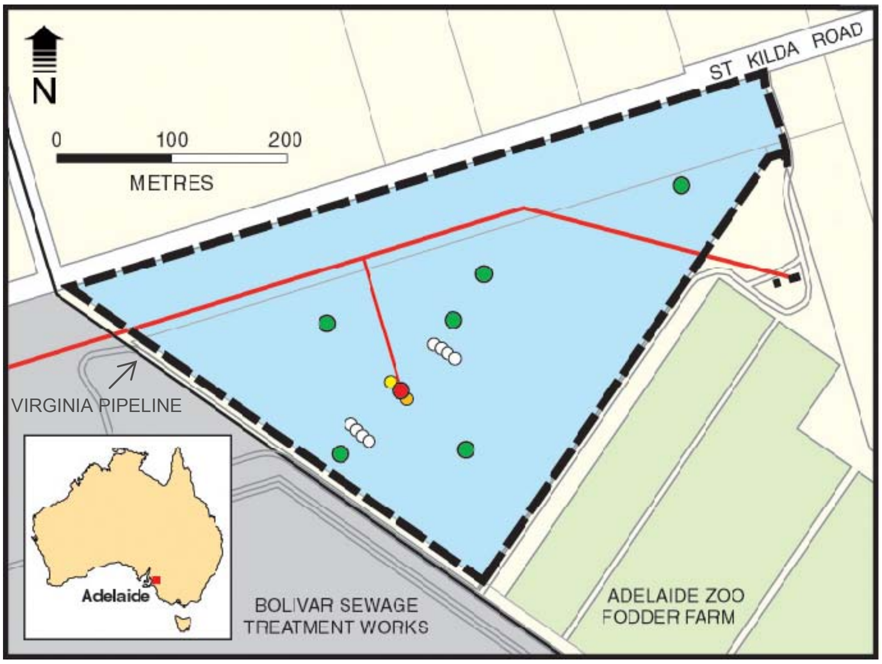

Figure 5-2 Location of wells and piezometers at the Bolivar site. The red dot represents the ASR well (#18777), the orange dot is the observation well at 4 m (#19450), the yellow dot is the T1 aquifer well (#19179), the white dots are piezometers at 50 m, and green dots are observation wells at 75 m, 120 m and 300 m (after Dillon *et al.* 2003). The red line represents the reclaimed water supply line to the Bolivar ASR and Adelaide Zoo sites from the main Virginia Pipeline.

5.1.1 Sequence of development

The project was undertaken in three phases. The first phase involved construction of a test well at Bolivar in 1997 and a series of laboratory and desk-top studies (Dillon *et al.* 1999) to determine if the risks associated with the injection of reclaimed water into the aquifer, such as aquifer clogging (Rinck-Pfeiffer *et al.* 2000), could be adequately managed (Martin and Dillon 2005). Activities included collection of aquifer core material for analysis and use in laboratory studies, undertaking down-hole geophysical logs, performing aquifer pumping tests and sampling the ambient groundwater quality.

The second phase was the establishment of the Bolivar ASR field trial to continue the investigation of the public health, environmental and technical viability of the use of nutrient-rich source water for ASR and to ensure there were no adverse impacts on the aquifer or water quality. In 1999 the Bolivar ASR well system was established and a pipe was connected from the ASR well to the Virginia pipeline (Figure 5-2). During this testing, a discharge pipe was established to the Bolivar outfall channel to take water recovered during the early phase of the trial, or whenever recovery took place when demand for the pipeline water supply was low. In addition, a scour pond was constructed near the ASR well to accept water purged from the well during back-flushing. The first cycle of injection at Bolivar commended in October 1999, since then there have been three subsequent injection and recovery cycles (Barry *et al*. in prep).

Finally the third phase of the project focused on identifying the economic viability of reclaimed water ASR on a larger scale (5-10 GL/year), to determine the storage capacity of suitable aquifers for reclaimed water and the preliminary design of a larger scale well field (Dillon *et al.* 2003; Martin and Dillon 2005).

5.1.2 Site configuration

Briefly, wastewater from Salisbury and Adelaide trunk mains is pumped to the Bolivar WWTP, where it undergoes solid removal, grit removal and pre-aeration. The wastewater undergoes primary treatment (sedimentation) followed by secondary treatment (an activated sludge process which replaced trickling filters in January 2001). The treated wastewater is then sent to the stabilisation lagoons for approximately 30 days. Finally tertiary treatment occurs at the DAFF plant, where the treatment follows a process of flocculation, dissolved air flotation and filtration. The tertiary treated effluent is then chlorinated and stored in the VPS open storage lagoon, from where pumps can send it through the VPS pipeline network to the irrigators and/or to the ASR injection well (Figure 5-3).

Figure 5-3 Bolivar ASR site showing ASR well on the right, and container housing online sensors on the left.

Both the DAFF-treated and chlorinated water and the recovered water from the ASR well can be used for VPS crop irrigation. The DAFF-treated and chlorinated water is also blended with urban stormwater from other MAR operations for use at Mawson Lakes for urban irrigation and toilet flushing (SA Water 2009), but the supply to the Bolivar ASR system is separate from the Mawson Lakes supply.

The ASR well targets the lower of the two Tertiary limestone aquifers known locally as the T2 aquifer. The ASR well is equipped with a turbine pump and the pipework is configured to prevent cavitation of water injected into the well. The delivery line has a number of taps to allow water sampling, a flow meter, and on-line water quality sensors including electrical conductivity (EC), pH, dissolved oxygen (DO), temperature, and oxidation reduction potential (ORP). An ISCO auto-sampler unit is installed to enable integrated sampling of injectant or recovered water. A supervisory control and data acquisition (SCADA) system enables automatic shut down of injection if any water quality parameter goes outside its tolerable range; automated periodic or event-based back-flushing of the ASR well to control clogging and maintain injection rates; and remote access to all data recorded.

The Bolivar ASR recycled water system components are summarised in Figure 5-4 and Table 5-1.

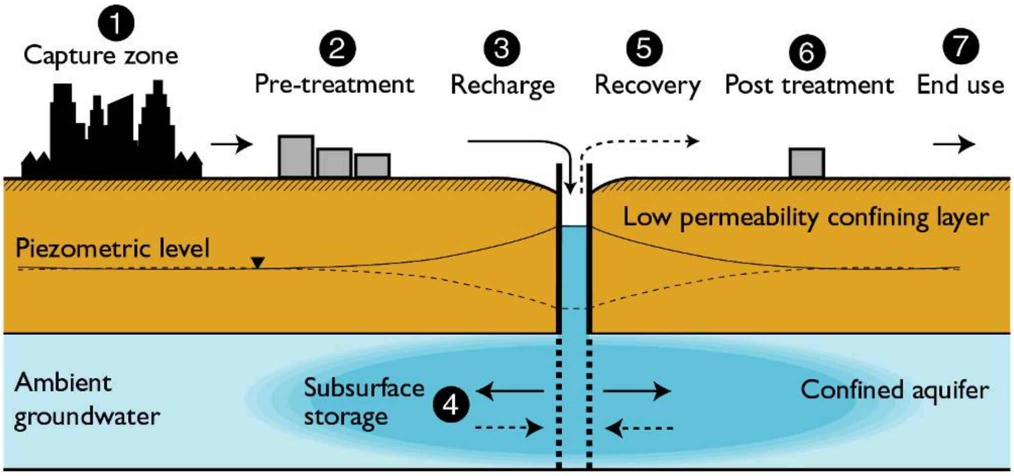

Figure 5-4 Bolivar ASR recycled water system schematic of water flow

Table 5-1 Components of the Bolivar ASR system

Component	Bolivar ASR system
1. Capture zone	Salisbury and Adelaide wastewater
2. Pre-treatment	Primary treatment (sedimentation), secondary treatment (activated sludge process), stabilisation lagoons, tertiary treatment (Dissolved Air Flotation/Filtration; DAFF), chlorination and pond storage.
3. Recharge	ASR well; open interval 103-160 m
4. Subsurface storage	T2 aquifer – confined limestone Tertiary aquifer
5. Recovery	ASR well
6. Post-treatment	None
7. End use	Irrigation

5.1.3 Aquifer description

The Bolivar ASR site is located within the Adelaide Embayment which is a section of the St Vincent Basin. The area is underlain by a thick sequence of sedimentary deposits of Quaternary and Tertiary age which in turn overlay the Precambrian basement.

The target aquifer is known locally as the 'T2' – Lower Port Willunga aquifer. The lithology of the aquifer ranges from fossiliferous and marly limestones to siliceous calcarenite (Pavelic *et al*. 2006b).

The aquifer is confined and is moderately transmissive (180 m^2/day). Groundwater flow is dominated by matrix flow and the average porosity is 0.45 (Pavelic *et al.* 2006b). The aquifer is composed of layers of differing permeability and is relatively homogeneous in the horizontal direction (Pavelic *et al.* 2006b). Regional ambient groundwater gradient is 0.002 towards the N-NE, induced by the area of greatest pumping demand at Virginia (Martin and Dillon 2005).

The ambient groundwater in the T2 aquifer at Bolivar is brackish with a salinity of ~2,100 mg/L TDS and is anoxic. The salinity of the ambient groundwater in this location renders it unsuitable for irrigation use and also limits the portion of native groundwater that can be recovered from the ASR site. The mineralogy of the aquifer is dominated by calcite and quartz, with minor contributions from ankerite, hematite and the feldspars microcline and albite (Vanderzalm *et al*. 2006).

5.1.4 Source water description

The source of recycled water supplied to the Bolivar ASR scheme is the wastewater treated in Bolivar WWTP and DAFF plant. The DAFF-treated and chlorinated source water is deemed suitable for unrestricted irrigation use, based on compliance with Class A irrigation quality guidelines (Martin and Dillon 2005).

The source water is lower in salinity than the ambient groundwater (~1,100 mg/L TDS) but is also dominated by sodium and chloride; on average neutral in pH; oxygenated; and relatively nutrient rich.

5.2 Stage 1 Entry level risk assessment

The Stage 1 entry level assessment for the Bolivar ASR system is given in Table 5-2 and Table 5-3. This risk assessment is based on the quality of source water supplied to the Bolivar ASR scheme (post-DAFF). An extended version of this risk assessment, including the untreated wastewater, was performed by Ayuso Gabella *et al*. (2010; in prep). Table 5-3 also provides a summary of Stage 2 investigations required as identified in the Stage 1 assessment.

Table 5-2 Bolivar ASR entry level assessment part 1 – Viability

	Attribute	Answer
1	Intended water use	
	• Is there an ongoing local demand or clearly defined environmental benefit for recovered water that is compatible with local water management plans?	✓ Recovered water is intended to meet contracted demand for crop irrigation water.
2	Source water availability and right of access	
	• Is adequate source water available, and is harvesting this volume compatible with catchment water management plans?	✓ Adequate volume of treated wastewater is available; the treated wastewater not used for irrigation in winter would otherwise be discharged to sea.
3	Hydrogeological assessment	
	• Is there at least one aquifer at the proposed managed aquifer recharge site capable of storing additional water?	✓ T2 aquifer is capable of storing additional water.
	• Is the project compatible with groundwater management plans?	✓ The project is compatible with groundwater management plans. The aquifer is too brackish for irrigation in this area.
4	Space for water capture and treatment	
	• Is there sufficient land available for capture and treatment of the water?	✓ The Bolivar WWTP and the DAFF plant are already treating the wastewater for crop irrigation.
5	Capability to design, construct and operate	
	• Is there a capability to design, construct and operate a managed aquifer recharge project?	✓ Capability exists between project partners DWLBC, CSIRO, United Water and SA Water to design, construct and operate project. → Go to Table 5-3

Table 5-3 Bolivar ASR entry level assessment part 2 – degree of difficulty

Question	Bolivar ASR answers	Investigations required
1 Source water quality with respect to groundwater environmental values		
Does source water quality meet the requirements for the environmental values of ambient groundwater?	Yes – ambient groundwater is too saline to be used for irrigation in this area. However overlying aquifer is fresh and used for drinking water supplies. Require Stage 2 investigations to confirm no connection through aquitard or any local leaky wells.	Operational performance evaluation - connection between target aquifer and overlying T1 aquifer used for drinking water supply (Section 5.3.5)
2 Source water quality with respect to recovered water end use environmental values		
Does source water quality meet the requirements for the environmental values of intended end uses of water on recovery?	Yes – the water to be injected already meets the requirements for unrestricted irrigation and is monitored to confirm compliance.	None
3 Source water quality with respect to clogging		
Is source water of low quality, for example: total suspended solids, total organic carbon or total nitrogen >10 mg/L, And is soil or aquifer free of macropores?	Yes – source water is of low quality (TOC > 10 mg/L), and should lead to a high rate of clogging in the limestone aquifer. Require Stage 2 investigations to assess the clogging risk.	Clogging studies (Sections 5.3.1, 5.3.2)
4 Groundwater quality with respect to recovered water end use environmental values		
Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery?	No – ambient groundwater salinity is above crop irrigation standards. Require Stage 2 investigations to evaluate recovery efficiency.	Salinity and recovery efficiency investigation (Section 5.3.4)
5 Groundwater and drinking water quality		
Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?	No – target aquifer is too saline for use as drinking water supply; target aquifer does not support aquatic ecosystems with high conservation value.	None
6 Groundwater salinity and recovery efficiency		
Does the salinity of native groundwater exceed: (a) 10000 mg/L, or (b) the salinity criterion for uses of recovered water?	Yes to (b) only – ambient groundwater salinity above crop irrigation standards. Require Stage 2 investigations to assess recovery efficiency.	Salinity and recovery efficiency investigation (Section 5.3.4)
7 Reactions between source water and aquifer		
Is redox status, pH, temperature, nutrient status and ionic strength of source water and groundwater similar?	No – redox status, nutrient status, and ionic strength of source water is different to that of groundwater. Require Stage 2 investigations to assess geochemical reactions.	Geochemical evaluation (Section 5.3.3)

Question	Bolivar ASR answers	Investigations required
8 Proximity of nearest existing groundwater users, connected ecosystems and property boundaries		
Are there other groundwater users, groundwater–connected ecosystems or a property boundary near (within 100–1000 m) the MAR site?	Yes – wells used for crop irrigation within 1000 m of MAR site, but in T1 aquifer. Require Stage 2 investigations to assess leakage through aquitard (see Question 1).	Operational performance evaluation - connection between target aquifer and overlying T1 aquifer used for drinking water supply (Section 5.3.5)
9 Aquifer capacity and groundwater levels		
Is the aquifer confined and not artesian? Or is it unconfined, with a watertable deeper than 4 m in rural areas or 8 m in urban areas?	Yes – target aquifer confined and not artesian. However, injection may cause aquifer to become artesian. Require Stage 2 investigations to assess extent of artesian zone.	Operational performance evaluation - extent of artesian zone identified (Section 5.3.3)
10 Protection of water quality in unconfined aquifers		
Is the aquifer unconfined, with an intended use of recovered water being drinking water supplies?	No – target aquifer is confined.	None
11 Fractured rock, karstic or reactive aquifers		
Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?	Yes – target aquifer contains reactive minerals, and dissolution of carbonate minerals and mobilisation of metals (arsenic and iron) is possible. Require Stage 2 investigations to assess potential for aquifer dissolution, migration of recharge water, and clogging.	Geochemical evaluation of the dissolution of calcite and reactivity (Section 5.3.3)
12 Similarity to successful projects		
Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?	No – Andrews Farm and other stormwater ASR schemes have been operating successfully in the same aquifer, but this is the first application of reclaimed water ASR. Stage 2 investigations are required to assess risks from injecting wastewater.	Clogging studies and geochemical evaluation (Sections 5.3.1, 5.3.2)
13 Management capability		
Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty, or with water treatment or water supply operations involving a structured approach to water quality risk management?	Yes – proponents have experience with similar MAR operations and wastewater treatment.	None
14 Planning and related requirements		
Does the project require development approval? And is it in a built up area; on public, flood-prone or steep land; close to a property boundary; contain open water storages or engineering structures; likely to cause public health, safety or nuisance issues, or adverse environmental impacts?	No – project is situated on SA Water land near DAFF plant, within paddock and visibility is buffered from road by trees.	None

A summary of the Entry level Stage 1 risk assessment studies requiring to be performed for Bolivar for the Stage 2 pre-commissioning assessment is shown in Table 5-4.

Table 5-4 Summary of Stage 2 investigations required for Bolivar ASR

Issue		Investigations required at stage two	Discussed in section
1	Source water quality with respect to groundwater environmental values	Operational performance evaluation - connection between target aquifer and overlying T1 aquifer used for drinking water supply	5.3.5
3	Source water quality with respect to clogging	Clogging studies	5.3.1, 5.3.2
4	Groundwater quality with respect to recovered water end use environmental values	Salinity and recovery efficiency investigation	5.3.4
6	Groundwater salinity	Salinity and recovery efficiency investigation	5.3.4
7	Reactions between source water and aquifer	Geochemical evaluation	5.3.3
8	Proximity of nearest existing groundwater users, connected ecosystems and property boundaries	Operational performance evaluation - connection between target aquifer and overlying T1 aquifer used for drinking water supply	5.3.5
9	Aquifer capacity and groundwater levels	Operational performance evaluation - extent of artesian zone identified	5.3.3
11	Fractured rock, karstic or reactive aquifers	Geochemical evaluation of the dissolution of calcite and reactivity	5.3.3
12	Similarity to successful projects	Clogging studies and geochemical evaluation	5.3.1, 5.3.2

5.3 Stage 2 Pre-commissioning investigations

During the Stage 2 pre-commissioning assessment the receptors for the environmental and human health risk assessments were identified and a series of targeted studies performed. For the Bolivar site, the intended uses of the water were crop irrigation in the Northern Adelaide Plains (NAP), hence this risk assessment focuses on the use of the water for crop irrigation, delivered by the Virginia Pipeline Scheme (VPS). Parameters were considered according to the twelve hazards described in the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a).

For the human health end points, the routes of exposure considered were crop consumption and accidental ingestion of irrigation water.

For the environmental end points, the following routes of exposure were identified:

- Aquifer receiving the recycled water following DAFF-treatment and chlorination.
- Irrigated crops: the crops are directly affected by water quality, especially nutrients and salinity. Different methods of water application to the soil or plant may result in a different level of risk for the crop. The application method considered in this report is irrigation via sprinklers.
- Soil beneath the crops: soil can be affected by the water quality, especially salinity. Again, different methods of application may result in a different level of risk for the soil.

While the risk to human and environmental health (via the latter two routes of environmental exposure) may be considered acceptable for reclaimed water supplied from the VPS as it has been approved for unrestricted irrigation use, this assessment also considers the potential for hazards to be introduced through aquifer storage.

A number of studies identified as necessary by the Stage 1 risk assessment (Table 5-3) were performed in support of the Stage 2 pre-commissioning risk assessment and are described below followed by the maximal and residual risk assessments. The Stage 2 studies include: assessment of the source water quality; evaluation of clogging potential; geochemical investigations; salinity and recovery efficiency investigation and an operational performance evaluation to assess local effects on the T1 aquifer and the extent of the artesian zone.

Stage 2 field studies utilise a number of observation wells and piezometers within the storage zone (Figure 5-5) for observation of pressure and water quality. The ASR well has a 203 mm internal diameter, fibre reinforced plastic casing to 103 m and the remaining depth was completed as open hole to ~160 m. Observation wells at radial distances of 4, 75, 120 and 300 m fully penetrate the T2 (102-160 m), and the four piezometers 50 m up gradient (NE) and four 50 m down gradient (SW) of the ASR well were completed over four distinct intervals of the aquifer each with an open interval of 5 m, corresponding to alternating layers of high and low permeability.

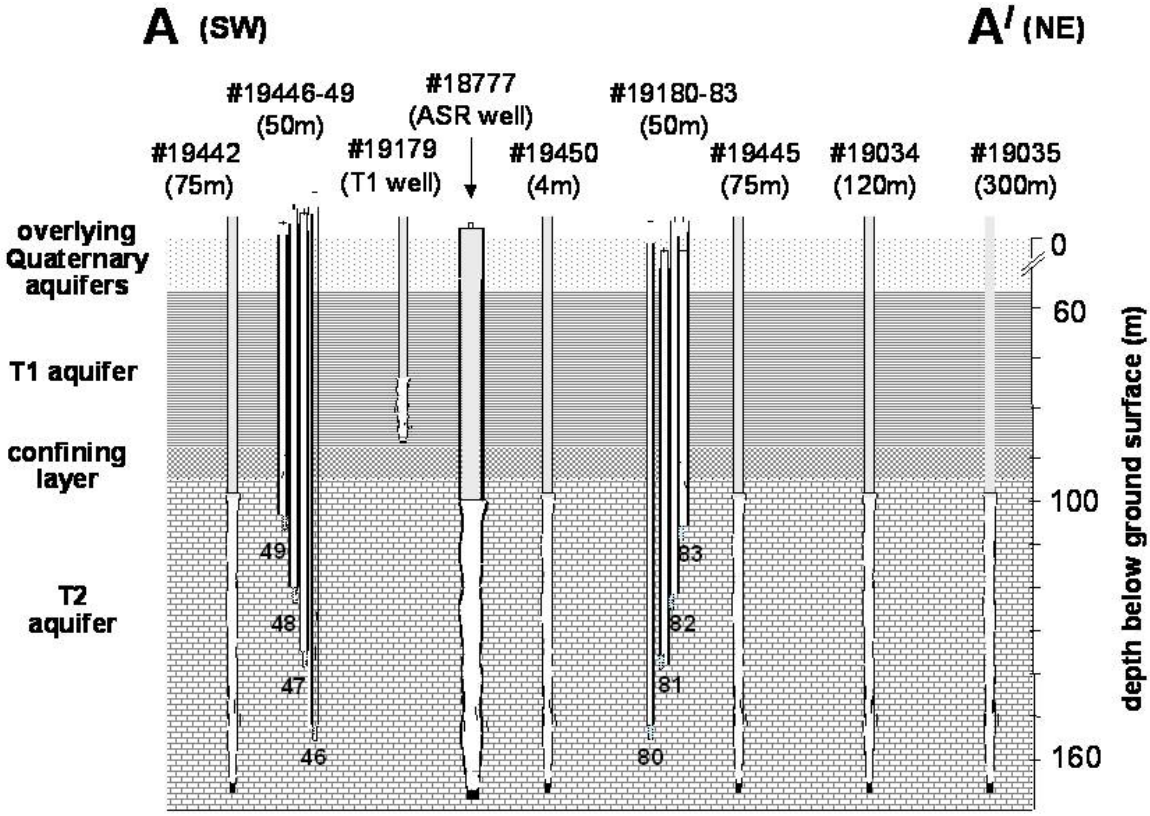

Figure 5-5 Simplified vertical section along a SW-NE transect (A-A´) showing location of ASR well, observation wells and piezometers (Martin and Dillon 2005).

5.3.1 Source water quality assessment

The quality of source water, ambient groundwater and water recovered from the Bolivar ASR scheme is shown in Table 5-5. Water quality data from the recycled water system including the untreated wastewater has been previously summarised by Ayuso Gabella *et al*. (2010).

Table 5-5 Bolivar ASR water quality summary

	LTV Irrigation	STV Irrigation	Injectant		Ambient Groundwater		Recovered Water	
			n	mean	n	mean	n	mean
Physical characteristics								
Temperature (°C)			**14**	17	**10**	25	**6**	18
pH (pH units)	6-8.5	6-8.5	**1139**	7.1	**10**	7.0	**17**	7.8
Conductivity (µS/cm)			**1133**	1900	**10**	3700	**25**	2200
Total Dissolved Solids (mg/L)	1500 [1]	1500 [1]	**1133**	1057	**10**	2009	**25**	1230
SAR	2 [2]	2 [2]	**18**	8.4	**6**	8.1	**25**	7.4
Dissolved Oxygen (mg/L)			**12**	7.1	**10**	0.3	**6**	<0.1
Redox Potential (mV SHE)			**12**	662	**10**	65	**6**	56
Suspended Solids (mg/L)			**299**	<1	**2**	5		
Turbidity (NTU)			**1075**	0.93	**3**	12	**25**	2.7
Major ions (mg/L)								
Alkalinity as $CaCO_3$			**10**	125	**3**	305	**2**	202
Bicarbonate			**10**	153	**6**	325	**25**	275
Bromide			**33**	0.49	**10**	3.7	**14**	1.5
Sulfate			**34**	181	**6**	297	**25**	196
Chloride	175 [2]	175 [2]	**16**	404	**10**	976	**25**	467
Cyanide as CN			**2**	<0.05			**2**	<0.05
Fluoride	1	2	**17**	0.79	**6**	0.24	**2**	0.72
Calcium			**18**	36	**6**	150	**25**	69
Magnesium			**18**	32	**6**	85	**25**	41
Potassium			**17**	36	**6**	13	**25**	43
Sodium	115 [2]	115 [2]	**18**	285	**6**	503	**25**	313
Microbiological								
Algae – Total (cells/mL)			**167**	2737				
Cyanobacteria – Total (cells/mL)			**73**	<1				
Thermotolerant coliforms (cfu/100mL)			**2**	13			**2**	<1
E. coli – Presumptive (cfu/100mL)			**244**	<1	**2**	0	**2**	<1
Enterococci (cfu/100mL)			**1**	0			**2**	<1
Faecal Streptococci (cfu/100mL)			**1**	0			**2**	<1
Cryptosporidium - Presumptive [3] (oocysts/L)			**72**	<1			**2**	<1
Giardia - Presumptive [3] (cysts/L)			**72**	<1			**2**	<1
Chlorine - Free			**436**	1.6				
Chlorine - Total			**436**	2.5				
Nutrients (mg/L)								
Nitrate as N			**76**	8.6	**2**	0.0005	**12**	0.32
Nitrite as N			**59**	<0.005	**2**	<0.005	**9**	0.26
Ammonia as N			**34**	1.1	**4**	0.06	**19**	1.7
Total Kjeldahl Nitrogen as N	5 [4]	25-125 [4]	**11**	3	**4**	0.06	**25**	2.4
Filterable Reactive Phosphorous			**22**	2.2			**14**	0.90
Total Phosphorus	0.05	0.8-12	**10**	2.2	**4**	0.02	**25**	0.86
Dissolved Organic Carbon			**22**	17	**5**	2.9	**14**	13
Total Organic Carbon			**34**	16	**4**	0.48	**25**	11
Metals and metalloids (mg/L)								
Aluminium - Total	5	20	**17**	0.11	**1**	0.028		
Arsenic - Soluble			**3**	0.0023	**3**	0.0043		
Arsenic - Total	0.1	2	**17**	0.0017	**3**	0.0047	**13**	0.014
Barium - Total			**18**	0.0032			**2**	0.0096
Beryllium - Total	0.1	0.5	**17**	<0.0005				
Boron - Soluble	0.5 [5]	0.5 [5]	**18**	0.29	**2**	0.1	**2**	0.31
Cadmium - Total	0.01	0.05	**16**	0.00058	**1**	<0.0002	**2**	<0.0002
Chromium - (VI) Soluble			**19**	<0.01				

	LTV Irrigation	STV Irrigation	Injectant		Ambient Groundwater		Recovered Water	
			n	**mean**	**n**	**mean**	**n**	**mean**
Chromium - Total	0.1	1	**16**	0.0031	**1**	<0.003		
Cobalt - Total	0.05	0.1	**16**	0.00077				
Copper - Total	0.2	5	**16**	0.011	**1**	<0.001	**2**	<0.001
Iron - Soluble			**3**	<0.03	**3**	0.93		
Iron - Total	0.2	10	**8**	0.036	**4**	1.3	**25**	0.31
Lead - Total	2	5	**16**	0.00058	**1**	<0.0005	**2**	<0.0005
Lithium - Total	2.5 [6]	2.5 [6]	**17**	0.0096	**1**	<0.001		
Manganese - Soluble			**3**	0.031	**3**	0.052		
Manganese - Total	0.2	10	**8**	0.015	**3**	0.05		
Mercury - Total	0.002	0.002	**18**	<0.0005	**1**	<0.0005	**2**	<0.0005
Molybdenum - Total	0.01	0.05	**17**	0.0072				
Nickel - Total	0.2	2	**16**	0.008	**2**	0.0011		
Selenium - Total	0.02	0.05	**17**	0.0031				
Strontium - Total			**14**	0.36	**3**	1.1	**12**	0.43
Uranium - Total	0.01	0.1	**3**	<0.0006	**1**	<0.0006	**2**	0.0010
Vanadium - Total	0.1	0.5	**17**	0.0038				
Zinc - Total	2	5	**16**	0.034	**2**	0.042		
Disinfection by-products (µg/L)								
Bromoacetic acid			**1**	5			**2**	<1
Bromochloroacetic acid			**1**	25			**2**	<1
Bromodichloroacetic acid			**1**	39			**2**	<1
Bromodichloromethane			**2**	78	**1**	<1	**2**	<1
Bromoform			**2**	26	**1**	<1	**2**	<1
Chloroacetic acid			**1**	<5			**2**	<5
Chlorodibromomethane			**2**	91	**1**	<1	**2**	<1
Chloroform			**2**	40	**1**	<1	**2**	<1
Dibromoacetic Acid			**1**	13			**2**	<1
Dichloroacetic Acid			**1**	23			**2**	<1
Trichloroacetic acid			**1**	26			**2**	<1
VOCs (µg/L)								
1,2-dibromo-3-chloropropane			**2**	4				
Radionuclides (mBq/L)								
Gross alpha							**2**	76
Gross beta (excluding K-40)							**1**	<10

DWG = drinking water guideline, taken from Australian Drinking Water Guidelines or Augmentation of Drinking Water Supplies guidelines; LTV = long term irrigation trigger value; STV = short term irrigation trigger value; [1] Salinity threshold set for Virginia Pipeline Scheme. See ANZECC-ARMCANZ guidelines for a detailed tolerance of different crops; [2] A value less than this can cause foliar damage in sensitive crops; [3] Samples for protozoa are taken after the DAFF treatment but before the chlorination; [4] Guideline is for Total Nitrogen; [5] For very sensitive crops; sensitive 0.5-1, moderately sensitive 1-2; [6] The guideline value is 0.075 for *Citrus* crops.

5.3.2 Clogging studies

Rinck-Pfeiffer *et al.* (2000) and Pavelic *et al*. (2007) utilised laboratory column and field studies to investigate the mechanisms and rates of physical, chemical and biological clogging at Bolivar. The rates of clogging, defined by changes in the relative intrinsic permeability of the aquifer, were particularly dependent on turbidity, total nitrogen concentration and pH value of the injected water due to their resultant effects on particle entrapment, microbial growth, and calcite dissolution, respectively. Acceptably low rates of short- and long-term clogging development were achieved for turbidity < 3 NTU, total nitrogen < 10 mg/L and pH < 7.2 (Pavelic *et al.* 2007). On average, these injectant quality targets were achieved following commissioning of the activated sludge process at the Bolivar WWTP.

5.3.3 Geochemical evaluation

The Bolivar ASR trial was the first application of source water with DOC > 10 mg/L in ASR and thus reactions between the source water and the aquifer were considered a potential risk to this system. Injecting source water with such a high nutrient loading was likely to induce redox reactions which could impact on the recovered water quality and also lead to associated chemical and biological clogging processes. Calcite dissolution was expected to occur and to exceed that previously observed for the Andrews Farm stormwater ASR scheme in the same aquifer system (Chapter 2; Herczeg *et al.* 2004) in order to buffer the carbon dioxide produced *in situ* by redox processes.

Approximately 20% DOC removal was evident during ASR and attributed to aerobic oxidation and denitrification, utilising oxygen and nitrate present in the source water (Vanderzalm *et al.* 2006). Redox reactions also produced a slight increase, on average 11 µg/L, in arsenic concentration resulting in a concentration of approximately 14 µg/L in the recovered water (*c.f.* long term irrigation guideline value of 100 µg/L) (Vanderzalm *et al.* 2009c). More reducing conditions were evident around the ASR well itself due to the accumulation of organic matter around the point of injection. This resulted in deleterious water quality changes affecting the first 100 m^3 of recovered water. This could be managed by discarding the first volume recovered and treating it in the same manner as an injection cycle backwash.

A small amount of calcite dissolution was evident in the near well zone and varied in response to the quality of the source water (Le Gal La Salle *et al.* 2005). Dissolution served to counteract clogging around the ASR well and was not considered as a risk to the stability of the ASR well under typical injection scenarios.

5.3.4 Salinity and recovery efficiency investigation

Salinity of the recovered water dictates the recovery efficiency (RE) of the Bolivar ASR site. The salinity limit for recovered water to re-enter the Virginia pipeline is a TDS of 1,500 mg/L and this constrained the RE for the site. Fundamental to understanding the physical movement of the injectant plume is an understanding of the heterogeneity of the hydrogeological properties of the storage zone.

Multi-scale permeability testing was undertaken to characterize aquifer heterogeneity (Pavelic *et al*. 2006b). The small scale core sample analyses provided information on the lower estimates of hydraulic conductivity (*K*), intermediate scale down-hole flow metering was used to understand the variation of *K* with depth, and large scale pumping test data gave an integrated measure of the effective *K* useful to define bulk properties.

The studies on heterogeneity of the aquifer in conjunction with flow and solute transport modelling (Martin and Dillon 2005) and reactive transport modelling (Greskowiak *et al*. 2005) have broadened the knowledge on distribution of the injectant plume in the aquifer and allowed optimisation of the system to predict the future changes in chemistry of recovered water and recovery efficiency of the site (Martin and Dillon 2005). In the first cycle the RE was reported as > 60%, increasing to > 80 % in subsequent cycles (Martin and Dillon 2005), due to the volume of injected water that remains in the aquifer as a salinity ‘buffer’ in between cycles.

5.3.5 Operational performance – effect on overlying aquifer and extent of artesian zone

During the ASR trial there was no correlation between pressures in the T1 and T2 aquifers, based on the piezometric pressures in observations wells located approximately 4 m from the ASR well in the T1 aquifer (T1 well; #19179) and the T2 aquifer (4 m well; #19450) (Figure 5-5). Groundwater quality monitoring in the T1 well showed no change in water quality due to the ASR operation, aside from natural variation over repeated sampling

events. Thus it was concluded that the Bolivar ASR operation had no effect on pressure or water quality in the overlying T1 aquifer (Martin and Dillon 2005).

Injection of the reclaimed water through the ASR well increased piezometric pressure in the T2 aquifer by up to 30 metres, including the effects of clogging in and around the well (Martin and Dillon 2005) but long-lasting artesian pressure has never been reported. On recovery, typical drawdown was about 12 m in the injection well.

5.4 Stage 2 Pre-commissioning risk assessment

5.4.1 Maximal risk assessment

The risk assessment is presented in the order of the twelve key hazards outlined in the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a). A semi-quantitative risk assessment was performed for each of the hazards for human health and environmental endpoints, with green, orange and red indicating low (acceptable), uncertain and high (unacceptable) risks respectively (Table 5-6). The white boxes indicate that that hazard does not apply to that endpoint.

The maximal risk assessment for the human health end point was conducted by comparing the water quality data for the reclaimed source water and native groundwater for hazards 1 to 7 to the Australian Guidelines for Water Recycling (NRMMC–EPHC–AHMC 2006) for crop consumption and irrigation exposure. For the environmental end points, hazards 1 to 7 were compared to the short term values (STV) for irrigation guidelines (ANZECC–ARMCANZ 2000) for irrigation risks to crops and soil.

For the aquifer endpoint, the native groundwater quality, obtained from the observation well 300 m from the injection well where no mixing with the injected water has occurred, serve as a reference value for hazards 1 to 7 (Ayuso Gabella *et al.* 2010) as there were no beneficial uses or ecosystem support requirements identified for the brackish native groundwater in this locale.

For hazards 8 to 12, the risks were assessed based on their potential impacts on the aquifer or biosphere as described in the MAR Guidelines.

The maximal risk assessment found that the only hazards with potential to be released through aquifer storage that could pose a risk to human health were inorganic chemicals, salinity and sodicity, and radionuclides. Similarly, the environmental risk assessment found only inorganic chemicals and sodicity may pose a risk to the environment via irrigation. However, most of the hazards were potentially a risk to the aquifer if preventative measures were not in place. Pathogens were not considered a risk to the aquifer given the low number in the reclaimed water source water.

Table 5-6 Maximal risk assessment summary for Bolivar ASR

MAR Hazards		Human endpoints – Crop consumption	Human endpoints – Ingestion of sprays	Environmental endpoints – Irrigation – Crops	Environmental endpoints – Irrigation – Soil	Environmental endpoints – Aquifer
1.	Pathogens – currently assessed as suitable for irrigation by SA Department of Health, MAR does not increase the risk	L	L	L	L	L
2.	Inorganic chemicals – potential for mixing with native groundwater may increase the risk	U	U	U	U	H
3.	Salinity and sodicity – potential for mixing with native groundwater may increase the risk	L	L	U	U	L
4.	Nutrients: nitrogen, phosphorous and organic carbon	L	L	L	L	H
5.	Organic chemicals – potential effect of organic chemicals in the source water on the groundwater dependant ecosystems	L	L	L	L	H
6.	Turbidity and particulates – unlikely to be present at levels unsuitable for irrigation but may cause clogging (operational risk)	L	L	L	L	L
7.	Radionuclides – unknown	U	U	L	L	U
8.	Pressure, flow rates, volumes and groundwater levels – potential for artesian conditions and aquitard rupture					H
9.	Contaminant migration in fractured rock and karstic aquifers – aquifer has known karstic features					U
10.	Aquifer dissolution and stability of well and aquitard – stability of well and aquifer needs to be assessed					H
11.	Aquifer and groundwater-dependent ecosystems – unknown presence of groundwater dependant ecosystems					U
12.	Energy and greenhouse gas considerations – currently unknown compared to potential other options.					U

L low risk; **U** unknown risk; **H** high risk.

5.4.2 Residual risk assessment

The pre-commissioning residual risk assessment includes the findings from the Stage 2 investigations and indicates that all risks can be considered low, if the ASR scheme is operated appropriately. For example, extraction and recovery volumes must be appropriately managed to control the amount of mixing with the brackish ambient groundwater and ensure the recovered water quality is acceptable. Similarly, the quality of the injectant must meet target values to ensure the risk of aquifer clogging is acceptable.

5.5 Stage 3 Operational residual risk assessment

The Stage 3 operational residual risk assessment confirms the findings of the Stage 2 residual risk assessment by examining the recovered water quality data (Table 5-5).

Pathogen risks were quantitatively assessed to be acceptable ($<1\times10^{-6}$ DALYs) (Ayuso Gabella *et al*. 2010). The risk from using recovered water for irrigation was less than calculated for use of reclaimed water directly from the pipeline and reported as 4.4×10^{-7} DALYs via crop consumption and 2.2×10^{-7} DALYs via aerosol inhalation. The results obtained are in accordance with reported risks for pathogens in the literature, with Rotavirus being the pathogen that entails the most risk, followed by *Cryptosporidium* and *Campylobacter* (Hamilton *et al.* 2006; Haavelar and Melse 2003; Petterson and Ashbolt, 2001).

For inorganic chemicals the potential release of arsenic and iron from the aquifer was considered a risk when using the recovered water for irrigation. In the case of arsenic, the levels in the recovered water for the first three ASR cycles were acceptable for crop irrigation. However, further monitoring of arsenic and iron will verify continued safety.

An increase in iron concentration was evident through aquifer storage, which may be due to mixing with ambient groundwater. The concentration of iron in the recovered water for the first three cycles of injection (0.31 mg/L total iron) was higher than the recommended long-term value for irrigation (0.2 mg/L), and also higher than the average injected concentration (0.036 mg/L). The long-term guideline is set to prevent blocking of the irrigation equipment. The irrigation guidelines state that concentrations of iron in the range of 0.2–1.5 mg/L will cause only minor problems with clogging of trickle or drip irrigation systems, while concentrations above 1.5 mg/L may cause severe problems (ANZECC–ARMCANZ 2000). Thus, the concentration in the recovered water may cause minor problems to the irrigation system.

Both DAFF-treated water and water recovered from the aquifer have high salinities, with mean TDS values of 1,057 and 1,230 mg/L respectively (corresponding to mean conductivity values of 1.9 and 2.2 dS/cm). Irrigation guidelines recommend that the water used for irrigation has conductivity less than 0.65 dS/cm (ANZECC–ARMCANZ 2000). Thus, some of the crops grown in the NAP could be affected by the high salinity of the DAFF-treated water and the recovered water.

Although the salinity of the DAFF-treated water and the recovered water is much higher than recommended in the irrigation guidelines, United Water and SA Water have a contractual agreement in which United Water ensures that the water delivered to the VPS has a TDS ≤1,500 mg/L. Data available from the DAFF-treated water and the recovered water show that the salinity has always been under the contractual level. The water delivered from the VPS to the irrigators is mixed with mains water to reduce TDS to 900-1,200 mg/L. The contractual agreement with the irrigators states that the maximum daily value should not exceed 1,200 mg/L, with a mean value of 900 mg/L.

However, these mean and maximum values for the irrigation water are still higher than the recommended value in the irrigation guidelines. To ameliorate the impact of the saline water on the crops, SA Water has produced a booklet on good irrigation practices and crops most suitable to be grown in NAP, also considering the nature of the soils in the area.

The irrigators/growers are prepared to accept the higher than ideal salinity of the recycled water to address the increased demand for water in the NAP, as any alternative source has a higher financial cost.

5.6 Stage 4 Operation-refined risk management plan

A draft risk management plan has been prepared as part of the on-going operation of the Bolivar ASR site (details can be found in Ayuso-Gabella *et al*. in prep). The plan, entitled the *Bolivar Aquifer Storage and Recovery recycled water management plan* (BAMP), aims to set the basis for future management to improve the performance of the Bolivar ASR scheme and support the transition of the system from a trial case study to a fully operational site.

The present draft BAMP (Ayuso-Gabella *et al*. in prep) was developed using two documents: the Australian Guidelines for Water Recycling (NRMMC–EPHC–AHMC 2006) and the MAR guidelines (NRMMC–EPHC–NHMRC 2009a).

The format of the BAMP has been set out to follow site-relevant elements listed in the guidelines as recommended by SA Department of Health and the SA Environmental Protection Agency (EPA), key elements of the BAMP are shown in Table 5-7.

Table 5-7 Key components required within the Bolivar Aquifer Storage and Recovery risk management plan likely to arise from the Stage 3 operational residual risk assessment

Element and key components
Element 3: Preventative measures for recycled water management
• Assess CCP and QCP limits and trigger values (e.g. conductivity of injectant and recovered water) and link to operational procedures
Element 4: Operational procedures and process control
• Define operational procedures for operation of the back-washing of the injection well and cessation of recovery upon reaching the salinity limit • Operational monitoring is required to ensure source water quality meets target values • Operational monitoring is required to ensure no well clogging occurs • Corrective actions required if operational procedures are not met • Establish a program for regular inspection and maintenance of all equipment • Establish documented procedures for evaluating chemicals, materials and suppliers • Establish reporting requirements for EPA
Element 5: Verification of recycled water quality and environmental performance
• Monitor volumes injected and recovered • Monitor recovered water quality to ensure it meets irrigation quality guidelines • Monitor impacts on receiving environment; hydraulic head in target aquifer and in overlying aquifer and groundwater quality
Element 7: Operation, contractor and end user awareness and training
• Ensure that operators, contractors and end users maintain the appropriate experience and qualifications • Identify training needs and ensure resources are available to support training • Document training and maintain records of training
Element 9: Validation, research and development
• Validation of CCPs and QCPs related to the control of clogging and metal mobilisation

5.7 Conclusions

A risk assessment of the Bolivar ASR system was performed through four stages and can be summarised as follows:

- The effectiveness of the treatment barriers – the human health Stage 3 risk assessment results show that the different barriers are robust and capable of

reducing the pathogens present in the wastewater. These barriers can also reduce nutrients, particles, inorganic and organic chemicals.

- The appropriateness of the whole recycling system for producing water for crop irrigation – the results of the risk assessment show that the risk was acceptable to reuse the recovered water for crop irrigation.
- In general, with the exception of metals and salinity, the recovered water was of better quality than the source water for ASR.

5.8 References

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6 RECLAIMED WATER SAT AT ALICE SPRINGS, NORTHERN TERRITORY

Soil Aquifer Treatment (SAT) is a technique for augmentation of groundwater resources with reclaimed wastewater via infiltration basins that are used intermittently. This method of MAR is possible where aquifers are unconfined and do not contain groundwater of a potable quality. SAT is favoured due to the simplicity of construction and maintenance. The enhancement in water quality during percolation through the unsaturated zone can be due to many different mechanisms including oxidation and reduction, biological decay, physical adsorption, ion exchange and chemical precipitation. In arid and semi-arid climate zones like Alice Springs, where shallow ambient groundwater is usually saline or brackish due to evaporative concentration of soil water, SAT operations can decrease the salinity of groundwater making it more suitable for reuse in the future.

The SAT project in Alice Springs, Northern Territory (Figure 6-1), is Australia's first purposefully constructed SAT scheme and was initiated with a view to reducing environmental impacts associated with overflows from wastewater stabilisation ponds to the adjacent Ilparpa swamp. Since Alice Springs relies on largely non-renewable groundwater reserves from deep aquifers, the commencement of MAR operations also provide this fast developing town with ancillary water resources that can be utilised in the future for agricultural purposes and substitute for non-potable uses of water.

Figure 6-1 Soil aquifer treatment basin #1 at the Arid Zone Research Institute, NT.

6.1 Site description

The study area is located at the Arid Zone Research Institute (AZRI) approximately 7.5 km south of Alice Springs, NT (Figure 6-2). The area is characterised by an arid to semi-arid climate with an average annual rainfall of 303 mm and potential annual evaporation of 3400 mm. In the summer months the daily temperature will typically fluctuate between 20 °C and 36 °C, whereas in the winter months it is in the range of 4–20 °C.

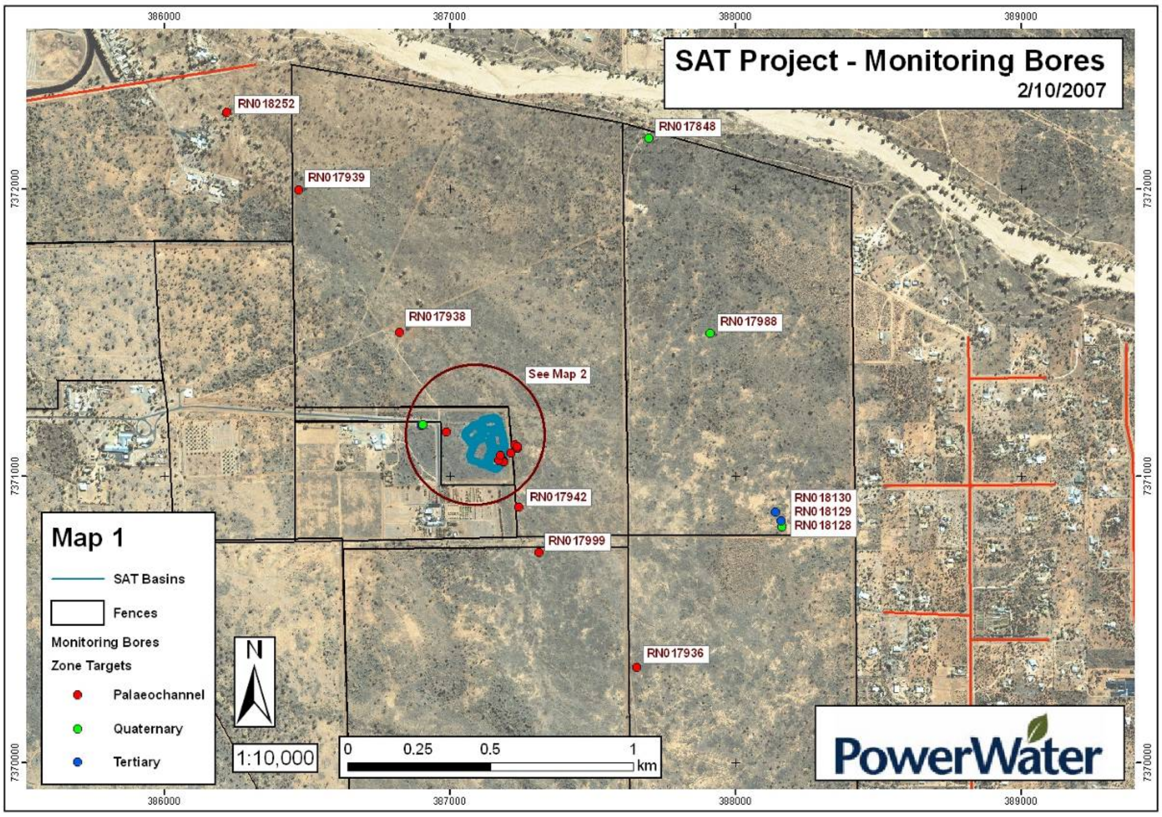

Figure 6-2 Location of the AZRI study site (after Pavelic *et al*. 2008b). The dry valley of the Todd River is located about 2 km north-east from the AZRI site

6.1.1 Sequence of development

The Alice Springs SAT project was conceived at a workshop in 2000 to address overflows from the sewage treatment plant into Ilparpa Swamp while augmenting recharge to groundwater resources to secure additional water supplies. The feasibility studies of the Alice Springs area for SAT operation were performed by Knapton *et al*. (2004). By 2004 the hydrogeological investigations had been undertaken to select a site suitable for the SAT operation. The studies at the AZRI site involved geophysical investigations, a field trial using potable water, as well as setting up a predictive numerical groundwater model. The investigations were followed by a public consultation phase, and construction of the pipeline, Dissolved Air Flotation (DAF) plant and basins was completed in early 2008. After commissioning of the DAF plant, four infiltration basins were first operated from 3 June 2008. The fifth and largest basin came on-line on 10 December 2009.

Geochemical characterisation of sediments was performed by Gates *et al*. (2009). Miotlinski *et al*. (2009a, 2010) presented a preliminary assessment of the site operation and its impacts on groundwater resources.

6.1.2 Site configuration

Wastewater is treated to a primary standard in the Alice Springs Wastewater Treatment Plant and to a secondary standard by the Dissolved Air Flotation (DAF) reclamation plant, and then stored in a 2.5 ML storage tank at the DAF plant. Since AZRI is at an elevation approximately 10 m below the DAF plant, treated wastewater flows 6 km by gravity from the DAF plant to the SAT site at AZRI via a 375 mm PVC pipeline. There is a set of pumps to pressurise the line but they have never been commissioned.

The SAT site comprises five infiltration basins (Figure 6-3). The delivery lines for each basin are fitted with actuating valves so that each basin may be filled independently, allowing

greater flexibility in operation. Total flow rate to the basins is continuously measured. Potential impacts to groundwater from the site are monitored via a set of observation wells (Figure 6-3).

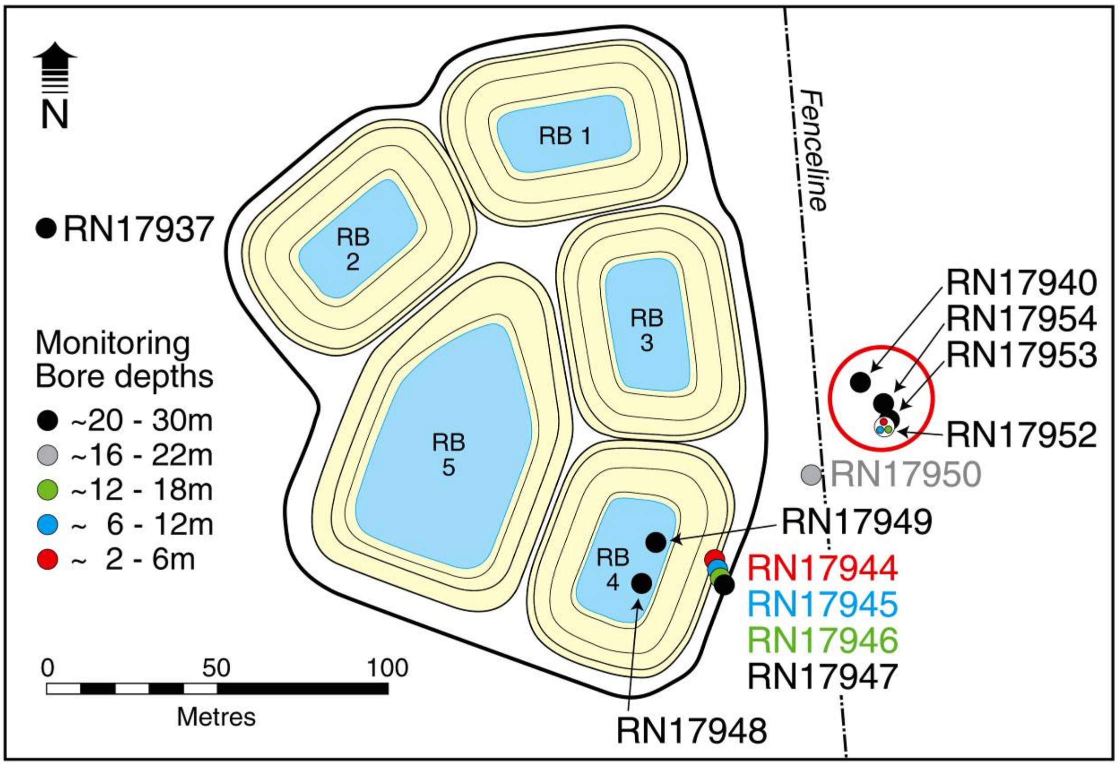

Figure 6-3 Location of the infiltration basins and the monitoring wells at the AZRI site

The components of the SAT water reuse system in Alice Springs are presented in Figure 6-4, and are summarised in

Table 6-1.

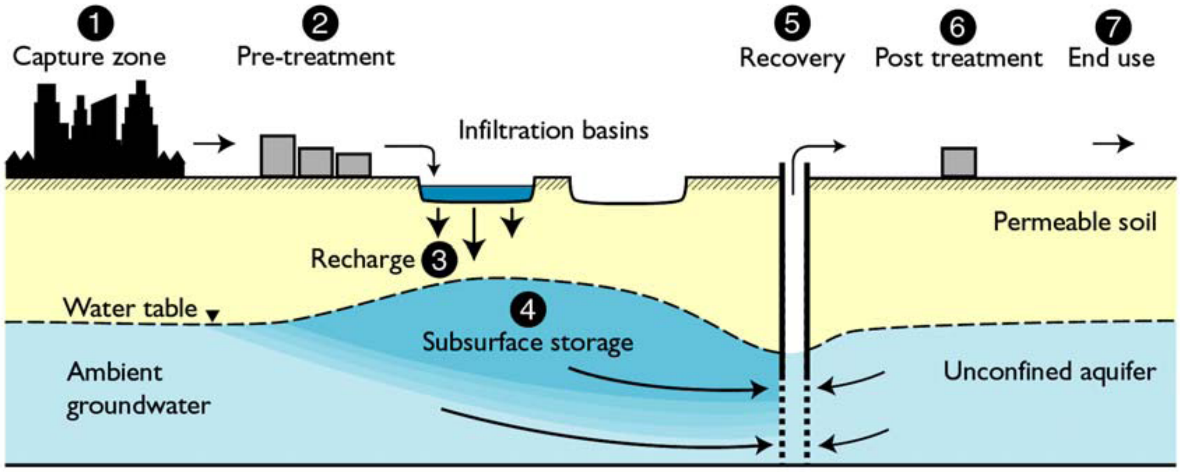

Figure 6-4 Alice Springs SAT system schematic of water flow

Table 6-1 Components of the Alice Springs SAT system

Component	Alice Spring SAT system
1. Capture zone	Wastewater from Alice Springs WWTP
2. Pre-treatment	Secondary treatment by dissolved air floatation (DAF) plant
3. Recharge	Via infiltration basins
4. Subsurface storage	Sandy unconfined alluvial aquifer of Quaternary age
5. Recovery	Intended to be via wells. Not yet commenced (planned for 2011)
6. Post-treatment	None
7. End use	Irrigation for agriculture

6.1.3 Aquifer description

SAT operations target a siliceous buried valley of Quaternary age. This structure is comprised of a series of silts, sands and gravels of alluvial origin, which vary up to 30 m in thickness within the axis of the valley and to 5 – 10 m in the lateral extensions within lower permeability silts and clays. The aquifer exhibits hydraulic conductivity from 10 to 45 m/day and specific yield of 0.07 (Quinlan and Woolley 1969; Knapton *et al*. 2004). It is recharged by the Todd River, infiltration of precipitation, as well as artificial irrigation via application of effluent in Blatherskite Park (Berry 1991) and now also the SAT basins at the AZRI site. The target aquifer is isolated from the underlying aquifers due to the extensive intervening low permeability clays of Neogene age. The aquifer is generally unconfined; although a relatively consistent formation of sandy silts to 1 – 2 m below ground surface is apparent. The water table occurs at a depth of 17 – 19 m and exhibits natural seasonal fluctuations in the range of 1 – 2 m.

Native groundwater in the target aquifer is brackish with electrical conductivity of 1,340 – 3,400 µS/cm. Ambient groundwater is mostly of a Ca-Na-Cl-SO_4 water type. Concentration of dissolved oxygen varies from 0.1 – 5 mg/L and nitrate from 5 – 50 mg-N/L (Jeuken 2004). Infrared spectra data indicate that quartz, smectite and kaolinite are abundant among the mineral phases (Gates *et al*. 2009). Carbonate minerals occur from the depth 20 m downwards. The extraction of the sediment derived from both unsaturated and saturated zones implied the abundance of iron minerals, and also the existence of aluminium oxides.

6.1.4 Source water description

The source water for Alice Springs SAT is secondary treated wastewater from the Alice Springs DAF plant, and is characterised by the dominance of sodium and bicarbonate (Table 6-5). Electrical conductivity is in the range of 1,200 – 3,100 µS/cm (average = 1,680 µS/cm), with peak salinity in summer. There are substantial concentrations of nutrients in the source water. Total nitrogen has an average concentration of 14.8 mg/L and concentration of total organic carbon (TOC) varies between 32 – 50 mg/L (Miotlinski *et al*. 2010). Relatively low BOD_5 values (< 10 mg/L) indicate that much of the organic carbon is not readily biodegradable (Miotlinski *et al*. 2009b). The concentration of oxygen measured in the infiltration basins is variable (4.3 – 13 mg/L) and is dependent on microbial activity during the recharge cycle. Apart from dissolved oxygen and nitrogen, the comparison of other parameters of source water quality indicates no large variations over time (Miotlinski *et al*. 2009a). Data on the concentration of pathogens is not available yet but the median concentration of the indicator organisms *E. coli* is 0 cfu/100 mL (maximum concentration 3 cfu/100 mL).

6.2 Stage 1 Entry level risk assessment

The Stage 1 entry level assessment for the Alice Springs SAT system is given in Table 6-2 and Table 6-3, as per section 4.3 of the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a). Table 6-3 also provides a summary of Stage 2 investigations required as identified in the Stage 1 assessment.

Table 6-2 Alice Springs SAT entry level assessment part 1 – Viability

	Attribute	Answer
1	Intended water use	
	• Is there an ongoing local demand or clearly defined environmental benefit for recovered water that is compatible with local water management plans?	✓ Recovered water is intended to be used for agriculture, as the major source of potable water (the Amadeus aquifer) is overexploited.
2	Source water availability and right of access	
	• Is adequate source water available, and is harvesting this volume compatible with catchment water management plans?	✓ Adequate volume of treated wastewater is available. Management of the overflows of reclaimed sewage water into the Ilparpa Swamp is another benefit of the SAT operation.
3	Hydrogeological assessment	
	• Is there at least one aquifer at the proposed managed aquifer recharge site capable of storing additional water?	✓ The Quaternary aquifer within the buried valley is capable of storing large quantities of water.
	• Is the project compatible with groundwater management plans?	✓ The target aquifer does not have direct hydraulic connections with underlying groundwater bodies. Thus, the MAR operation does not pose a risk of contaminating potable groundwater resources.
4	Space for water capture and treatment	
	• Is there sufficient land available for capture and treatment of the water?	✓ Treated wastewater is stored in existing stabilisation ponds and in the closed water tank prior to sending to the recharge basins.
5	Capability to design, construct and operate	
	• Is there a capability to design, construct and operate a managed aquifer recharge project?	✓ Some capability exists between the project partners (Power and Water Corporation, CSIRO) to design, construct and operate the project. Additional help was sought from Dr Peter Fox, Arizona State University. →Continue to entry level assessment (Table 6-3)

Table 6-3 Alice Springs SAT entry level assessment part 2 – degree of difficulty

Question	Alice Springs SAT answers	Investigations required
1 Source water quality with respect to groundwater environmental values		
Does source water quality meet the requirements for the environmental values of ambient groundwater?	Yes – local ambient groundwater is generally too brackish to be used for agricultural purposes.	None
2 Source water quality with respect to recovered water end use environmental values		
Does source water quality meet the requirements for the environmental values of intended end uses of water on recovery?	Yes – wastewater will be treated to meet local standards for irrigation supplies directly.	None
3 Source water quality with respect to clogging		
Is source water of low quality, for example any of: total suspended solids, total organic carbon and total nitrogen >10 mg/L, And is soil or aquifer free of macropores?	Yes – due to high concentrations of pollutants (organic carbon, nitrogen) there is a potential for clogging of the soil and shallow subsurface matrix. Require Stage 2 investigations to assess potential for clogging.	Clogging evaluation (Sections 6.3.3, 6.3.4)
4 Groundwater quality with respect to recovered water end use environmental values		
Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery?	No – local ambient groundwater salinity is too high for crop irrigation. Require Stage 2 investigations to assess recovery efficiency.	Groundwater flow and solute transport modelling (Section 6.3.1)
5 Groundwater and drinking water quality		
Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?	No – ambient groundwater in the aquifer is locally too saline for potable use, and does not have high ecological value.	None
6 Groundwater salinity and recovery efficiency		
Does the salinity of native groundwater exceed: (a) 10,000 mg/L, or (b) the salinity criterion for uses of recovered water?	Yes to (b) only – low recovery efficiency is possible. Stage 2 investigations are required, including detailed hydrogeological studies with a view to choosing the location of recovery wells.	Groundwater flow and solute transport modelling (Section 6.3.1)
7 Reactions between source water and aquifer		
Is redox status, pH, temperature, nutrient status and ionic strength of source water and groundwater similar?	Yes – within reasonable limits. However, the abundance of iron and the presence of carbonate minerals lead to redox and pH buffering during recharge of reclaimed water. Increases in iron concentration in groundwater may occur unless the site is well managed (if the drying cycles are too short to induce re-precipitation)	Geochemical investigations (Section 6.3.1)
8 Proximity of nearest existing groundwater users, connected ecosystems and property boundaries		
Are there other groundwater users, groundwater–connected ecosystems or a property boundary near (within 100–1000 m) the MAR site?	No – there are no users of groundwater from the same aquifer in the proximity of the site.	None

Question	Alice Springs SAT answers	Investigations required
9 Aquifer capacity and groundwater levels		
Is the aquifer confined and not artesian? Or is it unconfined, with a watertable deeper than 4 m in rural areas or 8 m in urban areas?	Yes – the aquifer is unconfined and the water table occurs at a depth of ~18 metres. However, a basic groundwater study would estimate the expected rise in the groundwater table.	Basic groundwater study to predict height of groundwater mound (Section 6.3.2)
10 Protection of water quality in unconfined aquifers		
Is the aquifer unconfined, with an intended use of recovered water being drinking water supplies?	No – the aquifer is unconfined but there is no intention to use groundwater from the target aquifer for drinking purposes.	None
11 Fractured rock, karstic or reactive aquifers		
Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?	Uncertain. Stage 2 investigations are required.	Mineralogical investigations (Section 6.3.2)
12 Similarity to successful projects		
Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?	No – there are no other projects in the same aquifer with similar source water.	All - monitoring the site as a national demonstration project for SAT (Section 6.3)
13 Management capability		
Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty, or with water treatment or water supply operations involving a structured approach to water quality risk management?	Yes – the proponent has experience running wastewater treatment and water supply operations. Expert help brought in (CSIRO and Dr Peter Fox, Arizona State University).	None
14 Planning and related requirements		
Does the project require development approval? And is it in a built up area; on public, flood-prone or steep land; close to a property boundary; contain open water storages or engineering structures; likely to cause public health, safety or nuisance issues, or adverse environmental impacts?	Yes – project required aboriginal heritage development approvals. Require Stage 2 investigations to provide additional information.	As required by planning approval processes

In summary of the Stage 1 assessment the following investigations were identified in proceeding to Stage 2 (Table 6-4).

Table 6-4 Summary of Stage 2 investigations required for SAT project in Alice Springs

Issue		Investigations required at stage two	Discussed in section
3	Source water quality with respect to clogging	Clogging evaluation	6.3.3, 6.3.4
4	Groundwater quality with respect to recovered water end use environmental values	Groundwater flow and solute transport modelling	6.3.1
6	Groundwater salinity and recovery efficiency	Groundwater flow and solute transport modelling	6.3.1
7	Reactions between source water and aquifer	Geochemical investigations	6.3.1
9	Aquifer capacity and groundwater levels	Basic groundwater study to predict height of groundwater mound	6.3.2
11	Fractured rock or karstic aquifer	Mineralogical investigations	6.3.2
12	Similarity to successful projects	None - this suggests monitoring the site as a national demonstration project for SAT.	6.3
14	Planning and related requirements	As required by planning approval processes	

6.3 Stage 2 Pre-commissioning investigations

During the Stage 2 pre-commissioning stage the issues identified in Table 6-3 were further assessed, each of them is further detailed below.

6.3.1 Groundwater studies

Drilling and geophysical studies were performed to evaluate: the capacity of the aquifer to store recharge water; and the ability to recover water at an acceptable quality.

Drilling revealed the thickness and the extent of the aquifer, the hydraulic gradient and groundwater quality. Pumping tests were conducted to determine the transmissivity of the aquifer. A simple analytical model was used to predict the height of the groundwater mound. Subsequent numerical modelling was used to predict the evolution of the plume of recharged water in the aquifer. Results reported in Knapton *et al*. (2004) demonstrated that based on this information there was adequate storage capacity and that water could be recovered at a suitable salinity for irrigation. The modelling simulations included the calculations of water table build-up under a high rate of source water infiltration and simulation of source water transport in the saturated zone (Knapton *et al*. 2004). The results revealed that the rise in water level with the expected infiltration rate is unlikely to exceed several metres. Solute transport simulations indicated the velocity of the plume to be in the range of 300 to 1,000 m/year depending of the heterogeneity of hydraulic conductivity.

Regional groundwater flow in the aquifer is towards south-east (Figure 6-5).

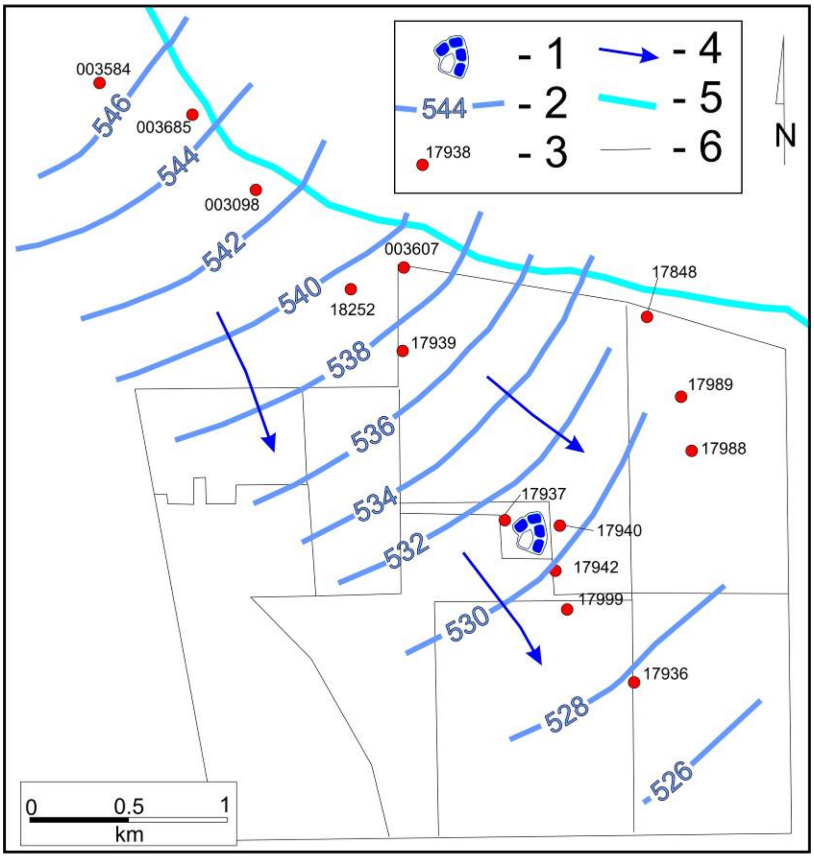

Figure 6-5 Hydrogeological sketch of the Quaternary aquifer in the area of SAT site. 1 – infiltration basins, 2 – water level contours (2 metre interval), 3 – monitoring wells, 4 – directions of groundwater flow, 5 – Todd river, 6 – AZRI paddocks. Water level contours are not relevant for flooding events (after Knapton *et al*. 2004).

6.3.2 Geochemical investigations

Mineral composition of samples from soil investigations and drilling were analysed using conventional analytical methods as well as a new infrared technique (Gates *et al*. 2009). The abundance of iron oxides in both unsaturated and saturated zones provides a substantial oxidation buffer for recharge water (Gates *et al*. 2009; Miotlinski *et al*. 2009a). Both carbonate minerals and aluminium oxides act as a pH buffer while source water is percolated through the unsaturated zone. The mass of leachable salt stored in the unsaturated zone was found to be small enough that recovered water uses would not be impaired.

6.3.3 Evaluation of clogging

Although clogging is not an issue for public health and environment protection at the SAT site, the longevity of operation could be adversely affected or operating costs increased if infiltration rates become too low. The size of the basins is also determined by infiltration rate hence studies were undertaken to determine the likely extent of clogging. The studies involved initial soil investigation and characterisation. This was followed by pilot infiltration tests in pits with Alice Springs mains water. Finally, laboratory column infiltration studies were undertaken using two soil types and four water types to bracket the expected composition of source water at the SAT site. In conclusion, clogging constitutes a major operational risk for the Alice Springs SAT site. However, in considering the residual risk assessment this risk can be controlled through operational fine-tuning.

6.3.4 Water quality assessment

The quality of source water, ambient groundwater and groundwater affected by MAR operation (both above the regional groundwater table at times unsaturated and the saturated zones) is shown in Table 6-5. It must be noted that the mixed water is not representative of the final quality of recovered water, since the recovery operations have yet to commence.

Table 6-5 Alice Springs SAT water quality assessment

	LTV Irrigation	STV Irrigation	Recharge water		Ambient groundwater		Above regional water table		Saturated zone – after SAT	
			n	mean	n	mean	n	mean	n	mean
Physical characteristics										
Temperature (°C)					**5**	25.86				
pH	6-8.5 [1]	6-8.5 [1]	**9**	7.9	**21**	7.2	**15**	7.7	**14**	7.4
Conductivity (µS/cm)			**19**	1624	**21**	2559	**15**	1645	**14**	1654
Dissolved oxygen (mg/L)					**5**	1.6				
Turbidity (NTU)			**13**	4.7			**15**	4.9	**6**	9.1
Major ions (mg/L)										
Alkalinity as $CaCO_3$			**9**	360	**16**	6917	**4**	316	**6**	299
Bicarbonate			**9**	442	**21**	340	**4**	385	**6**	371
Bromide			**23**	0.7	**11**	3.3	**12**	0.64	**6**	1.28
Sulfate			**5**	128	**21**	508	**15**	190	**14**	206
Chloride	175 [2]	175 [2]	**5**	210	**21**	470	**15**	250	**14**	267
Fluoride			**3**	0.6	**21**	0.6	**4**	0.2	**10**	0.6
Calcium			**12**	50	**21**	217	**15**	140	**14**	163
Magnesium			**12**	31	**21**	56	**15**	20	**14**	35
Potassium			**5**	20	**21**	7.9	**15**	12	**14**	6.5
Sodium	115 [2]	115 [2]	**5**	208	**21**	283	**15**	224	**14**	163
Microbiological										
Thermotolerant coliforms (cfu/100 mL)					**5**	0				
E.coli (cfu/100 mL)					**5**	0				
Clostridium spores (cfu/L)^					**3**	0				
Nutrients (mg/L)										
Nitrate as N			**22**	3.00	**21**	4.2	**2**	2.8	**2**	9.9
Nitrite as N			**22**	0.64	**5**	<0.005	**13**	0.071	**10**	<0.02
Ammonia as N			**22**	10.6	**5**	<0.01	**11**	<0.1	**9**	<0.1
Total Nitrogen	5	25-125	**22**	14.8	**3**	1.1	**12**	4.1	**9**	12
Filterable Reactive Phosphorus			**22**	1.1			**13**	0.175	**10**	0.02
Total Phosphorus	0.05	0.8-12	**22**	1.6	**5**	0.017	**12**	<0.3	**9**	<0.3
Dissolved Organic Carbon					**5**	1.46				
Total Organic Carbon			**3**	22			**11**	32	**9**	21
Silica										
Metals and metalloids (mg/L)										
Aluminium - Total	5	20	**20**	0.147	**12**	0.607	**15**	0.556	**14**	0.563
Antimony - Total			**20**	<0.0005	**10**	<0.0002	**6**	0.0002	**7**	<0.0002
Arsenic - Total	0.1	2	**20**	<0.0005	**10**	<0.0005	**4**	0.0006	**6**	<0.0005
Barium Total			**20**	0.039	**10**	<0.05	**13**	0.179	**14**	0.058
Beryllium - Total	0.1	0.5	**20**	<0.0005	**10**	<0.001	**4**	<0.001	**6**	<0.001
Boron - Soluble	0.5 [3]	0.5 [3]	**20**	0.232	**15**	0.099	**15**	0.190	**14**	0.282
Cadmium - Total	0.01	0.05	**20**	<0.0002	**10**	<0.0002	**6**	<0.0002	**7**	<0.0002
Chromium - Total			**20**	<0.001	**10**	<0.005	**6**	0.006	**7**	0.006

	LTV Irrigation	STV Irrigation	Recharge water		Ambient groundwater		Above regional water table		Saturated zone – after SAT	
			n	mean	n	mean	n	mean	n	mean
Copper - Total	0.2	5	**20**	0.027	**10**	<0.01	**15**	0.188	**14**	<0.05
Iodine - Total			**20**	0.135	**10**	0.277	**4**	0.155	**6**	0.250
Iron - Soluble					**10**	0.084				
Iron - Total	0.2	10	**20**	0.187	**10**	0.646	**15**	0.49	**14**	0.37
Lead - Total	2	5	**20**	<0.001	**10**	<0.001	**15**	0.002	**14**	<0.002
Manganese - Soluble					**10**	<0.005				
Manganese - Total	0.2	10	**20**	<0.005	**10**	<0.005	**15**	0.007	**14**	<0.005
Mercury - Total	0.002	0.002	**20**	<0.0001	**10**	<0.0001	**4**	<0.0001	**6**	<0.0001
Molybdenum - Total	0.01	0.05	**20**	<0.005	**10**	<0.005	**6**	<0.005	**7**	<0.005
Nickel - Total	0.2	2	**20**	<0.002	**10**	<0.002	**15**	0.023	**14**	0.023
Selenium - Total	0.02	0.05	**20**	<0.002	**10**	<0.001	**6**	0.001	**7**	0.002
Silver - Total			**20**	<0.0005			**4**	<0.01	**5**	<0.01
Tin - Total			**20**	<0.01	**10**	<0.01	**4**	<0.01	**7**	<0.01
Uranium - Total	0.01	0.1	**20**	0.006	**10**	0.111	**4**	0.021	**6**	0.010
Zinc - Total	2	5	**20**	0.016	**10**	<0.01	**15**	0.086	**14**	<0.03

LTV = long term irrigation trigger value; STV = short term irrigation trigger value; [1] See ANZECC-ARMCANZ (2000) guidelines for a detailed tolerance of different crops; [2] A value less than this can cause foliar damage in sensitive crops; [3] For very sensitive crops; sensitive 0.5-1, moderately sensitive 1-2.

6.4 Stage 2 Pre-commissioning risk assessment

6.4.1 Maximal risk assessment

The risk assessment is presented in the order of the twelve key hazards outlined in the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a). A semi-quantitative risk assessment was performed for each of the hazards for human health and environmental endpoints, with green, orange and red indicating low (acceptable), uncertain and high (unacceptable) risks respectively (Table 6-6). The white boxes indicate that that hazard does not apply to that endpoint (hazards 8 to 12 for the human and irrigation endpoints).

The maximal risk assessment for the human health end point was conducted by comparing the water quality data for reclaimed wastewater and native groundwater for hazards 1 to 7 to the Australian Guidelines for Water Recycling (NRMMC–EPHC–AHMC 2006) for irrigation exposure. For the irrigation end point, hazards 1 to 7 were compared to the short term values (STV) for irrigation guidelines (ANZECC–ARMCANZ 2000). For the aquifer endpoint, the aquifer's beneficial use was conservatively assumed to be for irrigation supplies (even though the salinity of the groundwater would not support irrigation), and for hazards 1 to 7 the quality of reclaimed wastewater was compared to the irrigation guidelines (ANZECC–ARMCANZ 2000).

For hazards 8 to 12, the risks were assessed based on their potential impacts on the aquifer or biosphere as described in the MAR Guidelines.

Table 6-6 Maximal risk assessment summary for SAT in Alice Springs

	MAR Hazards	Human endpoint – ingestion of sprays	Environmental endpoint – irrigation	Environmental endpoint – aquifer
1.	Pathogens – pathogens known to be present in the source water	H	L	L
2.	Inorganic chemicals – not likely to be present at levels of concern for irrigation	L	L	L
3.	Salinity and sodicity – potential for mixing with native groundwater may exceed irrigation guideline	L	U	L
4.	Nutrients: nitrogen, phosphorous and organic carbon – potential for accumulation of nutrients	L	U	U
5.	Organic chemicals – unknown	U	L	U
6.	Turbidity and particulates – not likely to be present at levels of concern for irrigation but may cause clogging (operational risk)	L	L	L
7.	Radionuclides – not likely to be present at levels of concern for irrigation	L	L	L
8.	Pressure, flow rates, volumes and groundwater levels – potential for plume migration needs to be assessed			U
9.	Contaminant migration in fractured rock and karstic aquifers – aquifer has no karstic features			L
10.	Aquifer dissolution and stability of well and aquitard – unlikely to be a concern due to aquifer matrix			L
11.	Aquifer and groundwater-dependent ecosystems – unknown at present			U
12.	Energy and greenhouse gas considerations – unknown at present			U

L low risk; **U** unknown risk; **H** high risk.

The maximal risk assessment shows an unacceptable risk to human health from pathogens in the absence of preventative measures such as restricting access during irrigation. There were no high levels of inorganic chemicals, nutrients turbidity or radionuclides likely to be present in the reclaimed wastewater. Organic chemicals are present in the reclaimed water; however, no guidelines exist for irrigation water. Salinity risks could present a problem but can be managed if mixing of the injectant and groundwater can be controlled. Infiltration rates will need to be monitored, as well as effects of the SAT operation on groundwater levels and any dependent ecosystems. Energy considerations were not fully assessed and so remain uncertain.

6.5 Stage 3 Operational residual risk assessment

The Alice Springs SAT site is currently at Stage 2. Stage 3 assessment will begin when water is recovered for irrigation, and monitoring of recovered water will be required to ensure recovered water meets irrigation standards. SAT basin infiltration rates will also be monitored to assess clogging and the need for basin cleaning or preventative measures for an operational site.

6.6 Stage 4 Operation-refined risk management plan

There is currently no risk management plan in place for operating the Alice Springs SAT site, however key risks and their management were identified in Technical Appendix 3 of Knapton *et al*. (2004). Based on the identified risks, the key components required within a risk management plan for the Alice Springs SAT site are outlined in Table 6-7. Additional details on all of the elements required within a risk management plan are available in the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a).

Table 6-7 Key components required within the Alice Springs SAT management plan likely to arise from the Stage 3 operational residual risk assessment

Element and key components
Element 3: Preventative measures for recycled water management
• Document DAF pre-treatment procedures and validate performance of pre-treatment • Assess CCP and QCP limits and trigger values (e.g. conductivity of recovered water) and link to operational procedures
Element 4: Operational procedures and process control
• Define operational procedures for operation of the source water pre-treatment and scraping of SAT infiltration basins. • Operational monitoring is required to ensure source water quality meets target values • Operational monitoring is required to ensure no SAT basin clogging occurs • Operational monitoring is required to ensure mosquitoes do not breed in the basins • Corrective actions required if operational procedures are not met • Establish protocols to deal with flooding events • Establish a program for regular inspection and maintenance of all equipment • Establish documented procedures for evaluating chemicals, materials and suppliers • Establish reporting requirements for EPA.
Element 5: Verification of recycled water quality and environmental performance
• Monitor volumes injected and recovered, to ensure recycled water plume does not move off-site • Monitor recovered water quality to ensure it meets irrigation quality guidelines • Monitor impacts on receiving environment; hydraulic head in target aquifer and in overlying aquifer; and groundwater quality.
Element 7: Operation, contractor and end user awareness and training
• Ensure that operators, contractors and end users maintain the appropriate experience and qualifications • Identify training needs and ensure resources are available to support training • Document training and maintain records of training
Element 9: Validation, research and development
• Validation of CCPs and QCPs related to the control of clogging of basins

6.7 Concluding remarks

The risk assessment of the Alice Springs SAT site is to date still in the pre-commissioning phase (Stage 2). The major risks identified include the formation of a clogging layer which deteriorates the infiltration capacity of the site and the potential for organic chemicals to be introduced to the groundwater. An operational residual risk assessment (Stage 3) should be

undertaken once water is recovered to verify the risks are low before proceeding to the development of a risk management plan (Stage 4).

6.8 References

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7 SHALLOW GROUNDWATER ASR AT WARRUWI, NORTHERN TERRITORY

The Warruwi ASR (aquifer storage and recovery) project aims to supplement potable supplies to the Warruwi indigenous community at the end of the dry season by banking excess groundwater from the shallow laterite aquifer during the wet season in a deeper aquifer, the Marligur sandstone. The project was demonstrated to be viable and is awaiting investment in control system and power supply infrastructure before operational use for drinking water supplies.

7.1 Site description

Warruwi is located on South Goulburn Island, near the coast of Arnhem Land in the Northern Territory (Figure 7-1). The selected ASR trial site borders the airstrip on the southern part of the island where the Marligur sandstone is most prominent.

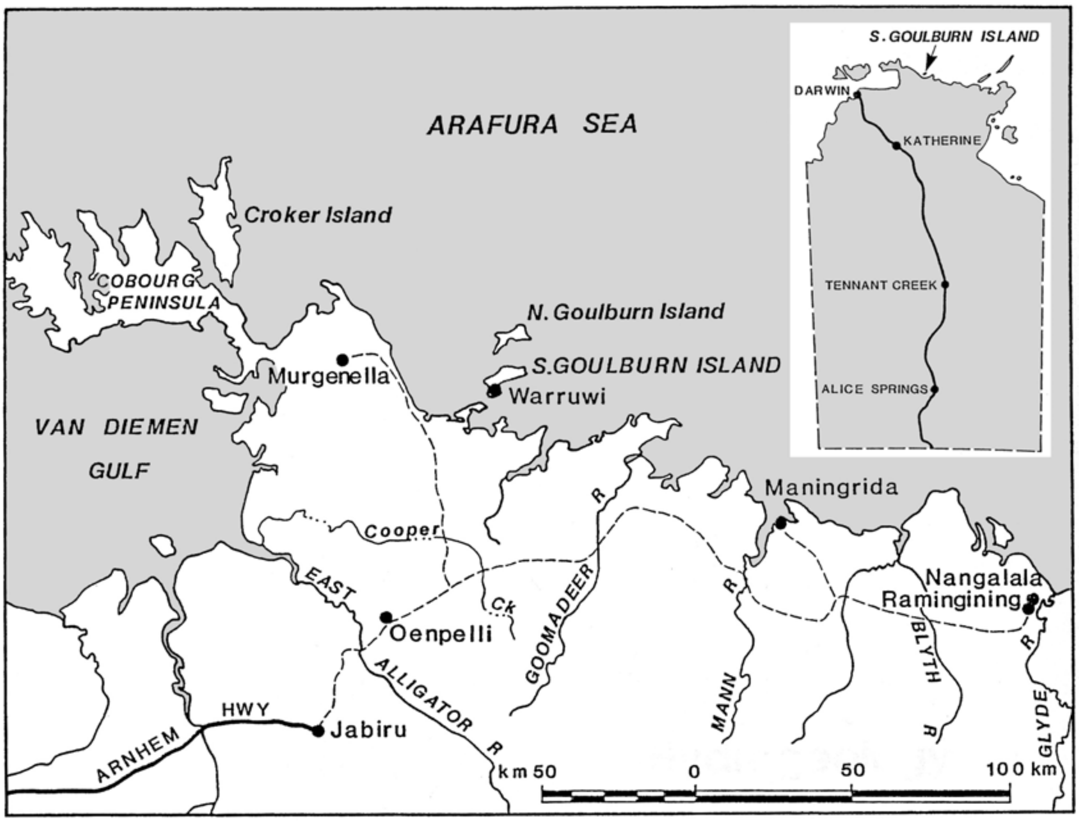

Figure 7-1 Location of South Goulburn Island, Northern Territory.

7.1.1 Sequence of development

In October and November 2000, five wells were drilled by Department of Land Planning and Environment (DLPE), Northern Territory, including one ASR well (32931) and four observation wells (32578, 32932, 32759 & 32930). Hydraulic testing of the ASR well revealed an airlift yield of 20 L/s of water of 2,500 µS/cm (Knapton 2002). Source water quality testing occurred in November and December 2000.

An injection line from the source water well field mixing tanks to the injection well was constructed in 2000. This was modified in 2001 to come from the 3 km well field only, with the town’s water supply coming from the 8 km and 10 km fields (Figure 7-2). Instrumentation was installed in 2001 and the first injection trial commenced in 2002. No recovery has taken place to date.

7.1.2 Site configuration

The ASR site has six wells, including one ASR well (32931) with an open interval of 119.8 – 128.0 m bgs, and four observation wells: 32758, 32932, 32930 and 32759 positioned at radial distances of 12, 100, 460 and 1060 m respectively (Figure 7-2). These augment an existing well at 260 m which is completed at 96 m (23972).

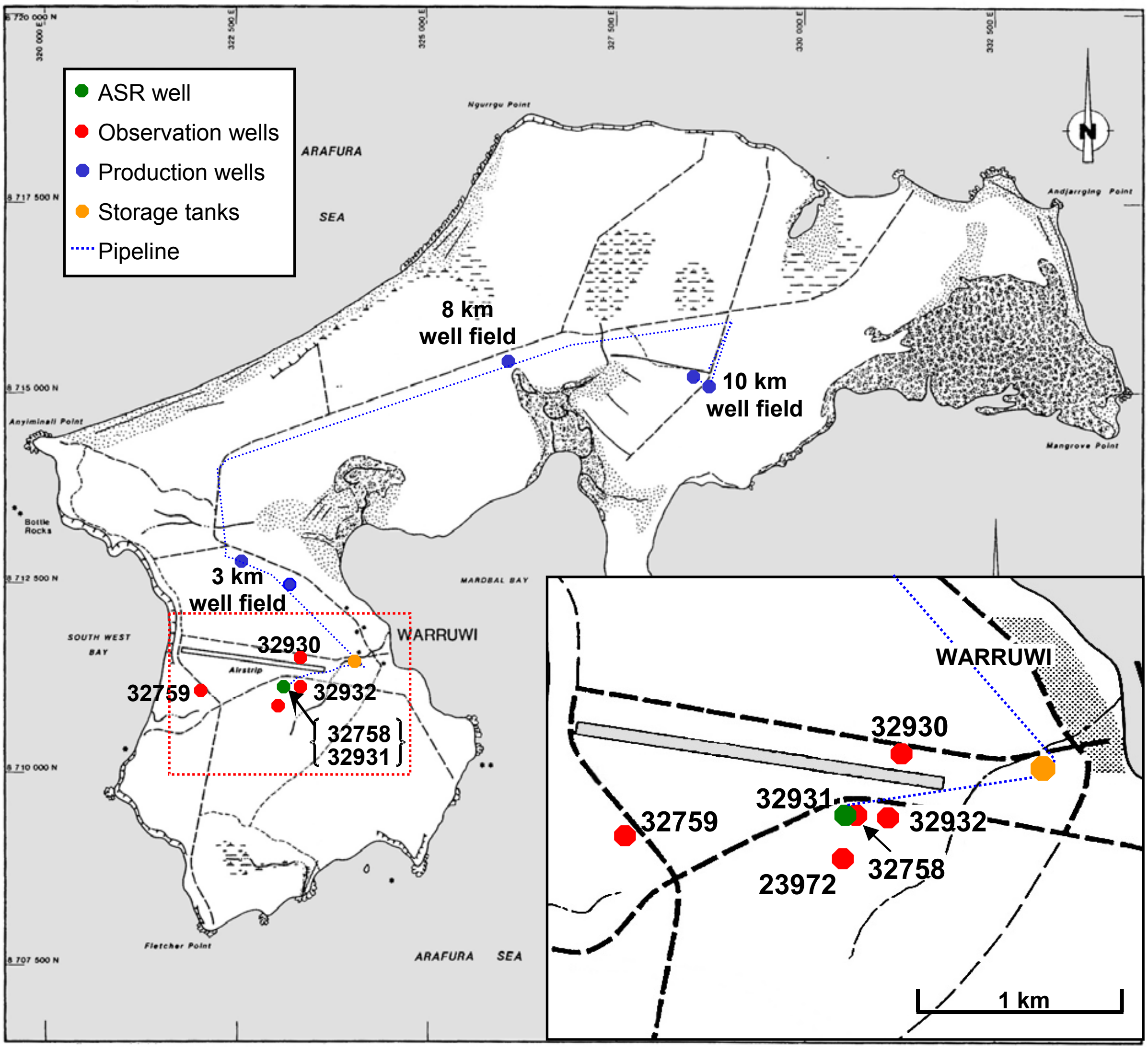

Figure 7-2 Location of ASR well (32931), five observation wells, storage tanks and production well fields on South Goulburn Island

The source water for the Warruwi ASR system is fresh groundwater from the shallow lateritic aquifer. Groundwater is extracted from the production wells at the 3 km well-field and transferred to the ASR site via a polypipe delivery line. From the pipe-line the water is injected into the deep Marligur sandstone aquifer via the ASR well (Figure 7-3). A submersible pump installed within the storage tank delivers 2.3 L/s. Near the ASR well, the polypipe is coupled to a 50 mm stainless steel piping system. The incoming water is fed through ~3 m tall vertical pipe which serves as a sediment trap and bleeds entrained air via a relief valve at the top. Within the well, a 40 mm lay-flat pipe was installed to 30 m depth as the downhole injection pipe (15 m below the depth to the initial water level). A narrower nozzle has been fitted at the discharge end. This injection system provides a cheap but effective means of minimising cascading as cross-sectional area of the pipe can adjust to the flow rate (Pavelic *et al*. 2002c).

Figure 7-3 Warruwi ASR scheme, showing well head infrastructure (left), and one of two storage tanks (right) where recovered water is aerated by "splash-entry".

Recovery is via the same ASR well, into one of two storage tanks where aeration by "splash-entry", settling, and blending with water supply from the surficial aquifer attenuates potential sulphurous odours. The recovered water would be chlorinated before use as a drinking water supply (in keeping with the existing practice on the island).

The Warruwi ASR system components are shown schematically in Figure 7-4 and summarised in Table 7-1.

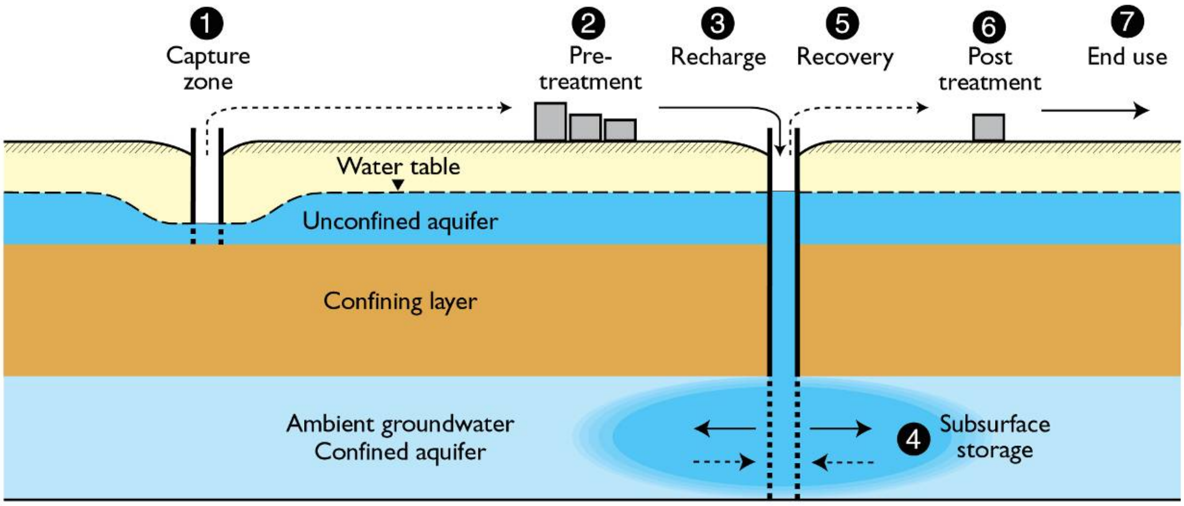

Figure 7-4 Warruwi ASR system schematic of water flow

Table 7-1 Warruwi ASR system components

Component	Warruwi ASR system
1. Capture zone	From 3 km well field in the shallow unconfined lateritic aquifer
2. Pre-treatment	Sediment trap
3. Recharge	ASR well (RN 32931), open interval 119.8 – 128.0 m bgs
4. Subsurface storage	Confined Cretaceous Marligur sandstone aquifer ~100 m bgs
5. Recovery	ASR well (RN 32931)
6. Post-treatment	Recovered water is returned into storage tanks where aeration by "splash-entry", settling, chlorination and blending with water supply from the surficial aquifer.
7. End use	Use as drinking water for Warruwi.

7.1.3 Aquifer description

The target aquifer is the Marligur aquifer situated within Marligur member, which is composed of medium to coarse grained, poorly consolidated quartzose sandstone, clayey sandstone and sandy claystone of Lower Cretaceous age (McLennan *et al*. 1990). At the Warruwi site, the sandstone layer exhibits transmissivity up to 70 m^2/d, porosity from 30 to 40% and storage coefficient of ~ 2×10^{-4}. The aquifer is 8 m thick and it is confined by low permeability Wangarlu mudstone member (Pavelic *et al*. 2001). Ambient groundwater in the Marligur aquifer is brackish (2,400-2,550 µS/cm) and anoxic.

7.1.4 Source water description

The source water is fresh (EC ~200 µS/cm); contains oxygen; and is acidic in pH due to a high dissolved carbon dioxide content. The source water meets the Australian guidelines for all health-related parameters but does not meet the aesthetic guideline values for pH, dissolved oxygen and occasionally iron.

7.2 Stage 1 Entry level risk assessment

The Stage 1 entry level assessment for the Warruwi ASR system is given in Table 7-2 and Table 7-3, as per section 4.3 of the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a). Table 7-3 also provides a summary of Stage 2 investigations required as identified in the Stage 1 assessment.

Table 7-2 Warruwi entry level assessment part 1 – Viability

	Attribute	Answer
1	**Intended water use**	
	• Is there an ongoing local demand or clearly defined environmental benefit for recovered water that is compatible with local water management plans?	✓ Recovered water intended for use as drinking water supplies during dry season to meet critical need.
2	**Source water availability and right of access**	
	• Is adequate source water available, and is harvesting this volume compatible with catchment water management plans?	✓ Potable groundwater from surficial aquifer, surplus to Warruwi's requirements in wet season, to be used as source water. Water table rises to surface and flows overland to sea. Harvested water is only a small proportion of this excess and unlikely to adversely affect ecosystem.
3	**Hydrogeological assessment**	
	• Is there at least one aquifer at the proposed managed aquifer recharge site capable of storing additional water?	✓ Deep Marligur sandstone aquifer with adequate storage capacity and reasonable well yields (Dames and Moore 1992b).
	• Is the project compatible with groundwater management plans?	✓ There was no use of groundwater from this deep aquifer. It is thought to be hydraulically isolated from the shallow aquifer, so no initial management plan except to evaluate its potential as an ASR target for storing water for drinking supplies.
4	**Space for water capture and treatment**	
	• Is there sufficient land available for capture and treatment of the water?	✓ Existing wells and water supply tank to be used to harvest water.
5	**Capability to design, construct and operate**	
	• Is there a capability to design, construct and operate a managed aquifer recharge project?	✓ Power and Water Corporation, NT Department of Planning and Infrastructure (DPI) and CSIRO combined expertise could design project. Operational strategy considered using the procedures adopted by Power and Water Corporation for operation of the Warruwi drinking water supply. →Continue to entry level assessment (Table 7-3)

Table 7-3 Warruwi ASR entry level assessment part 2 – degree of difficulty

Question	Warruwi ASR answers	Investigations required
1 Source water quality with respect to groundwater environmental values		
Does source water quality meet the requirements for the environmental values of ambient groundwater?	Yes – base environmental value on water quality in aquifer. Too saline to be used for irrigation. Confined system with low lateral gradient. ASR not expected to influence ecosystem.	None
2 Source water quality with respect to recovered water end use environmental values		
Does source water quality meet the requirements for the environmental values of intended end uses of water on recovery?	Yes – source water is currently used as a drinking water supply and meets all health related requirements for drinking water, but does not meet aesthetic guidelines for drinking water. Stage 2 investigations required.	Water quality and geochemical evaluation (Sections 7.3.1, 7.3.3)
3 Source water quality with respect to clogging		
Is source water of low quality, for example: total suspended solids, total organic carbon or total nitrogen >10 mg/L, And is soil or aquifer free of macropores?	No – source water is of good quality (TSS <1-2 mg/L; TOC <0.3 mg/L and TKN 0.07 mg/L), and should lead to a low rate of clogging in the target sandstone aquifer. However, requires Stage 2 investigations to assess the potential for geochemical clogging, e.g. iron precipitation.	Clogging evaluation (Section 7.3.4)
4 Groundwater quality with respect to recovered water end use environmental values		
Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery?	No – ambient groundwater salinity is above drinking water standards. Require Stage 2 investigations to assess recovery efficiency.	Recovery efficiency evaluation (Section 7.3.2)
5 Groundwater and drinking water quality		
Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?	No – target aquifer is too saline for use as drinking water supply; target aquifer does not support aquatic ecosystems with high conservation value.	None
6 Groundwater salinity and recovery efficiency		
Does the salinity of native groundwater exceed: (a) 10000 mg/L, or (b) the salinity criterion for uses of recovered water?	Yes to (b) only – ambient groundwater salinity above drinking water standards. Require Stage 2 investigations to assess recovery efficiency.	Recovery efficiency evaluation (Section 7.3.2)
7 Reactions between source water and aquifer		
Is redox status, pH, temperature, nutrient status and ionic strength of source water and groundwater similar?	No – redox status and ionic strength of source water are different to that of confined groundwater. Require Stage 2 investigations to assess potential geochemical reactions.	Geochemical evaluation (Section 7.3.3)
8 Proximity of nearest existing groundwater users, connected ecosystems and property boundaries		
Are there other groundwater users, groundwater–connected ecosystems or a property boundary near (within 100–1000 m) the MAR site?	No – there are no ecosystems connected to the target aquifer, and no other uses of the aquifer.	None
9 Aquifer capacity and groundwater levels		
Is the aquifer confined and not artesian? Or is it unconfined, with a watertable deeper than 4 m in rural areas or 8 m in urban areas?	Yes – target aquifer is confined and not artesian. However, injection may cause aquifer to become artesian. Require Stage 2 investigations to assess risk of upward leakage via well.	Extent of artesian zone to be identified (Section 7.3.4)

Question	Warruwi ASR answers	Investigations required
10 Protection of water quality in unconfined aquifers		
Is the aquifer unconfined, with an intended use of recovered water being drinking water supplies?	No – target aquifer is confined.	None
11 Fractured rock, karstic or reactive aquifers		
Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?	Yes – target aquifer contains pyrite and carbonate. Require Stage 2 investigations to assess potential for migration of recharge water, and matrix dissolution.	Geochemical evaluation (Section 7.3.3)
12 Similarity to successful projects		
Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?	No. Require Stage 2 investigations.	All (Section 7.3)
13 Management capability		
Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty, or with water treatment or water supply operations involving a structured approach to water quality risk management?	Yes – Power and Water Corporation have experience with water treatment and groundwater supply operations. However to identify and address all potential problems for drinking water supply arising from ASR operations local operator training will need to be undertaken.	Information for local operator training to be developed, and to identify and address potential new drinking water risks from ASR.
14 Planning and related requirements		
Does the project require development approval? And is it in a built up area; on public, flood-prone or steep land; close to a property boundary; contain open water storages or engineering structures; likely to cause public health, safety or nuisance issues, or adverse environmental impacts?	Yes – project site approval received from traditional landowners.	None

In summary of the Stage 1 assessment the following investigations were identified in proceeding to Stage 2 (Table 7-4).

Table 7-4 Summary of Stage 2 investigations required at Warruwi

Issue		Investigations required at stage two	Discussed in section
2	Source water quality with respect to recovered water end use environmental values	Water quality and geochemical evaluation	7.3.1, 7.3.3
3	Source water quality with respect to clogging	Clogging evaluation	7.3.4
4	Groundwater quality with respect to recovered water end use environmental values	Recovery efficiency evaluation	7.3.2
6	Groundwater salinity	Recovery efficiency evaluation	7.3.2
7	Reactions between source water and aquifer	Geochemical evaluation	7.3.3
9	Aquifer capacity and groundwater levels	Extent of artesian zone to be identified	
11	Fractured rock, karstic or reactive aquifers	Geochemical evaluation	7.3.3
12	Similarity to successful projects	None, first of its kind in the region	7.3
13	Management capability	Information for local operator training to be developed to identify and address potential new drinking water risks from ASR.	

7.3 Stage 2 Pre-commissioning investigations

A series of studies were performed to enable the Stage 2 pre-commissioning assessment, they are described below followed by the maximal and residual risk assessments.

7.3.1 Water quality evaluation

The injectant is low in nutrients, particulate material and bacterial activity; and also contains moderate levels of dissolved iron (up to 0.9 mg/L) (Table 7-5). The dissolved oxygen (DO) content of the source water may increase during surface storage. Examination of the DLPE water quality database reveals high variability in iron concentrations in the shallow groundwaters. Yin Foo (1986) suggests that samples collected by airlifting may contain significantly higher levels of particulate iron, presumably due to mobilisation of iron-bearing sediments from the aquifer, but this does not explain the high concentrations of soluble iron. However, it does illustrate the importance of determining total and soluble metal and metalloid concentrations to distinguish between mobilisation during MAR and any artefacts of the sampling procedure.

Ambient groundwater in the Marligur aquifer is brackish (Table 7-5; 2,400-2,550 µS/cm) and anoxic (Eh from -60 to -34 mV; Fe^{2+} <0.9 mg/L; ammonium <0.4 mgN/L; detectable H_2S). The XRD analysis of core samples from an observation well (32758) identified quartz as the most abundant mineral over most of the profile of Marligur Member, although the contribution of smectite in the upper part of the aquifer was significant. Minor mineral phases included kaolinite, muscovite, orthoclase, carbonates and pyrite. Organic carbon content was the highest in the clayey part of the profile (1-3%), whereas much lower in the Marligur sandstone (~0.1%) (Pavelic *et al*. 2001).

Table 7-5 Warruwi typical water quality data

		Source water (shallow aquifer) Production wells 1, 2, 5, 7, 9 & 11		Ambient GW 32931 & 32932		*Recovered water ASR well (RN 32931)*	
	DWG	**n**	**mean**	**n**	**mean**	**n**	**value**
Physical characteristics							
Temperature (°C)	-	5	31.9	2	34.8	1	*34*
pH (pH units)	6.5-8.5	5	**3.86**	2	6.8	**2**	***5.5***
Electrical Conductivity (µS/cm)	-	2	200	2	2455	1	*332*
Total Dissolved Solids (mg/L)	500	5	120	2	**1473**	1	*199*
Dissolved Oxygen (mg/L)	85%	5	1.14	2	**0.04**	1	*2.3*[#]
Eh (mV SHE)	-	5	398	2	-47		
Total CO_2 (mg/L)	-	5	591	2	83		
Total Suspended Solids (mg/L)	-	5	<1	2	1		
Turbidity (NTU)	5	5	0.23	2	3.4	**1**	***30***
Major ions (mg/L)							
Alkalinity as CaCO3	-	5	2	2	71	2	*6*
Calcium	-	5	1.3	2	169	2	*4.8*
Magnesium	-	5	4.8	2	44.6	2	*6.4*
Potassium	-	5	<1	2	13.9	2	*<1*
Sodium	180	5	23	2	**205**	2	*24*
Bicarbonate	-	5	<2	2	86	2	*16*
Chloride	250	5	51	2	**723**	2	*38*
Sulphate	250	5	6.3	2	1.7	2	*24*
Fluoride	1.5	5	0.12	2	0.76	1	*<0.1*
Nutrients (mg/L)							
Total Organic Carbon	-	5	<0.3	2	1.9	1	*0.8*
Dissolved Organic Carbon	-	5	<0.3	2	1.6		
Total Kjeldahl Nitrogen	-	5	0.07	2	0.50	1	*0.08*
Ammonia as N	0.5	5	<0.005	2	0.402		
Nitrate + Nitrite Nitrogen	11.3	5	0.014	2	<0.005	1	*0.009*
Total Phosphorus	-	5	<0.005	2	0.010	1	*0.018*
Filterable Phosphorus	-	5	<0.005	2	<0.005		
Metals and metalloids (mg/L)							
Aluminium - Total		5	0.115	2	0.130	1	*0.02*
Aluminium - Soluble	0.2	5	0.099	2	0.078	1	*<0.02*
Arsenic - Total	0.007	5	<0.001	2	0.002	1	*<0.0005*
Arsenic - Soluble		5	<0.001	2	0.002	1	*<0.0005*
Boron - Soluble	4	5	<0.04	2	0.167	1	*0.04*
Iron - Total	0.3	5	0.194	2	**0.632**	2	***2.61***
Iron - Soluble		5	0.189	2	**0.632**[‡]	1	*0.1*
Manganese - Total	0.1	5	0.007	2	**0.242**	2	*0.055*
Silica		5	9.9	2	15.1	1	*6*
Strontium - Total		5	0.033	2	3.01		
Titanium - Total		5	<0.001	2	0.004		
Zinc - Total	3	5	0.05	2	0.020	1	*<0.01*
Microbiological (cells/mL)							
Heterotrophic Iron Bacteria		5	<10	**2**	765		

[‡] Adjusted for analytical error (soluble reported > total); [#]within the range reported for the source water; **bold values** indicate exceedence of relevant guideline. *Values in italics* for the recovered water quality were obtained during the commissioning phase but are included here for ease of comparison.

7.3.2 Recovery efficiency evaluation

Solute transport modelling was undertaken to determine the extent of injected water plume and recovery efficiencies from Marligur aquifer (Pavelic *et al*. 2001; 2002a; 2002b). The aquifer was modelled as an axisymmetric 1D system under the standard assumptions involving ideal porous media without the influence of regional effects. Values for hydrogeological parameters were largely derived from the drilling program including geological logging, core analyses, and pumping tests in the ASR well (Knapton 2002) and water quality data. The salinity of the injectant was assumed to be 100 mg/L TDS and the salinity of the ambient groundwater was assumed to be 1,300 mg/L TDS.

The passage of the injected water front was predicted to move beyond the closest observation well at 12 m after 5 days of injection, but does not reach the next closest well at 100 m in this first modelled injection/recovery cycle. This does not account for aquifer heterogeneity which can distort the shape of the plume, with water migrating further in more permeable zones or fractures, or regional effects which have the potential to displace the plume, especially when residence times in the aquifer are extended.

If the maximum permissible TDS concentration in drinking water of 500 mg/L (NHMRC–NRMMC 2004) is used, recovery efficiencies range from 75 - 95% of the volume injected in the first cycle, according to the assumed magnitude of dispersivity, i.e. from 19 - 25 ML or 75 - 95 days supply at 3 L/s. In subsequent injection and recovery cycles the proportion of recoverable fresh water would be expected to increase due to remnant injectant diluting the ambient groundwater. This would need to be verified during commissioning.

7.3.3 Geochemical evaluation

A geochemical evaluation, comprising geochemical modelling using PHREEQC (Parkhurst and Appelo 1999) and evaluation of recovered water quality during an injection and recovery trial, was undertaken to assess the potential for geochemical reactions on injection of shallow groundwater into the Cretaceous Marligur Sandstone aquifer (Pavelic *et al*. 2001). This highlighted that redox-driven processes, pyrite oxidation or sulfate reduction, could result in increased concentrations of iron or hydrogen sulfide and were potential inorganic chemical risks within this ASR scheme. If these occurred, aeration and settling may be adequate treatment. However, the occurrence of such problems and the adequacy of treatment measures would need to be evaluated in a commissioning stage before any water was admitted to the drinking water supply.

7.3.4 Clogging evaluation

Characterisation of the source water-aquifer interactions during the pre-feasibility stage of the study had suggested a low potential for clogging primarily due to the low particulate concentrations, low nutrient status, and negligible clay dispersion from tests on core samples (Pavelic *et al*. 2001).

Bacteria in the deep and shallow aquifers have been isolated to assess their likely impact on the biogeochemistry of the Marligur system (Pavelic *et al*. 2001). The results indicate that biofilm production is unlikely to be of concern due to the low levels of organic matter in the source water (Table 7-5, DOC < 0.3 mg/L). If reducing conditions are maintained around the injection well there should be no negative effect associated with iron bacteria (Pavelic *et al.* 2006c). A lay-flat pipe was installed in the injection well to prevent cascading and the development of clogging. Monitoring and sampling during commissioning will reveal the extent of this problem and any steps required to manage it.

7.4 Stage 2 Pre-commissioning risk assessment

7.4.1 Maximal risk assessment

The risk assessment is presented in the order of the twelve key hazards outlined in the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a). A semi-quantitative risk assessment was performed for each of the hazards for human health and environmental endpoints, with green, orange and red indicating low (acceptable), uncertain and high (unacceptable) risks respectively (Table 7-6). The white boxes indicate that that hazard does not apply to that endpoint.

The maximal risk assessment for the human health end point was conducted by comparing the water quality data for the source water from the shallow laterite aquifer and the native groundwater in the Marligur sandstone for hazards 1 to 7 to the Australian Drinking Water Guidelines (NHMRC–NRMMC 2004). For the environmental endpoint, the aquifer's beneficial use was conservatively assumed to be for irrigation supplies (even though the salinity of the groundwater would not support irrigation), and for hazards 1 to 7 the quality of raw stormwater was compared to the irrigation guidelines (ANZECC–ARMCANZ 2000).

For hazards 8 to 12, the risks were assessed based on their potential impacts on the aquifer or biosphere as described in the MAR Guidelines.

Table 7-6 Maximal risk assessment summary for the Warruwi ASR system

	MAR Hazards	Human endpoint – drinking water	Environmental endpoint – aquifer
1.	Pathogens – ASR poses no greater risk than the current drinking water source.	**L**	**L**
2.	Inorganic chemicals – potential for mobilisation of metals and hydrogen sulphide.	**U**	**U**
3.	Salinity and sodicity – groundwater investigations and modelling suggest recovery efficiency will be high.	**L**	**L**
4.	Nutrients: nitrogen, phosphorous and organic carbon – these are all low in the source water and aquifer.	**L**	**L**
5.	Organic chemicals – ASR poses no greater risk than the current drinking water source.	**L**	**L**
6.	Turbidity and particulates – source water is low in particulates, but potential for particulate release in aquifer.	**U**	**L**
7.	Radionuclides – no mineralogy to suggest presence of radionuclides.	**L**	**L**
8.	Pressure, flow rates, volumes and groundwater levels – currently unknown.		**U**
9.	Contaminant migration in fractured rock and karstic aquifers – no known karstic features.		**L**
10.	Aquifer dissolution and stability of well and aquitard – currently unknown.		**U**
11.	Aquifer and groundwater-dependent ecosystems – low risk due to confined anoxic conditions of the target aquifer.		**L**
12.	Energy and greenhouse gas considerations – in comparison with seawater desalination this is much more efficient.		**L**

L low risk; **U** unknown risk; **H** high risk.

There is potential for geochemical reactions on injection of shallow groundwater into the Cretaceous Marligur Sandstone aquifer which, could result in increased concentrations of iron or hydrogen sulphide and potentially turbidity. This would need to be evaluated in a commissioning stage. The effects of the ASR operation on groundwater levels and well stability will need to be monitored. Energy considerations were not fully assessed and so remain uncertain.

7.4.2 Residual risk assessment

The Stage 2 semi-quantitative residual risk assessment for the Warruwi ASR system was performed by including a post-recovery storage tank with spray-entry to aerate recovered water and precipitate iron and remove hydrogen sulfide; all of the risks were considered

acceptable to proceed with a trial with recovered water not being returned to drinking water supplies until proven safe by analysis of monitoring samples.

7.5 Stage 3 Operational residual risk assessment

As part of the operational residual risk assessment two small recovery tests were conducted to assess changes in the quality of the injected water as a result of water-mineral interactions. During pumping, changes in the composition occurred beyond those expected through mixing. The principal reactions observed were:

- consumption of DO by oxidation of pyrite producing elevated Fe and SO_4
- consumption of hydrogen ions by reactions with carbonates producing Ca and HCO_3
- detection of sulfidic odours when DO levels drop below 0.2 mg/L and SO_4 reduction presumably takes place where there is sufficient organic carbon available (Pavelic *et al*. 2002c).

The sulfidic odours (hydrogen sulfide gas) were detected by smell. During the visit on 20 May 2002 a water sample was collected for sulfide analysis from a depth of 112 m at the 12 m observation well where groundwater is known to be composed almost entirely of injected water. This was intended to provide a crude indication of the levels of sulfide in the recovered water, and the likely effect of surface storage. On-site determination of total sulfide revealed an initial concentration of 0.46 mg/L, and with continued exposure to the atmosphere declined to ~0.31 mg/L within 10 minutes and a final pH of 6.4. This result suggests that although sulfide oxidation takes place following injection, this largely removes dissolved oxygen and storage of injected water under anoxic conditions leads to sulfate reduction within anoxic parts of the aquifer. Post-recovery treatment by aeration and surface storage would be an effective preventative measure in reducing the sulfurous smell to a level aesthetically acceptable to the community. Surface storage would also aid to precipitate excess iron (Pavelic *et al*. 2002c). Monitoring of hydrogen sulfide levels in recovered water and in the water treated by aeration should occur as part of an operational residual risk assessment. Further monitoring of pathogens is required to confirm the potability of recovered water.

Given that a major recovery phase has yet to occur, the groundwater from the 12 m observation well (where almost complete breakthrough of injectant was achieved after 13 ML of injection, and probably completely flushed by the injectant after 62 ML) gives the clearest indication of the likely quality of the recovered water (Table 7-5). The quality of the groundwater at the 12 m well meets the Australian Drinking Water Guidelines (NHMRC–NRMMC 2004) with the exception of salinity (sodium and chloride) and aesthetic guidelines for DO, iron, manganese and turbidity. Treatment for these parameters can be easily achieved by aeration and storage with the existing infrastructure (Pavelic *et al*. 2006c).

The feasibility study of the site revealed a decline in hydraulic conductivity and storage coefficient values when water was injected into the aquifer which is indicative of clogging development. Mineralogical analyses of backwash water clearly indicate the accumulation of iron oxyhydroxides around the ASR well due to reactions between oxygen in the source water and soluble iron in the groundwater. However, injection efficiency was restored after the installation of a dedicated pump to allow periodic flushing of the ASR well during injection (Pavelic *et al.* 2001).

7.6 Stage 4 Operation-refined risk management plan

For Stage 4 of project development a risk management plan is required for the Warruwi ASR system prior to recovered water being introduced into the town water supply. Key elements required in the plan are listed in Table 7-7.

Table 7-7 Key components required within the Warruwi risk management plan likely to arise from the Stage 3 operational residual risk assessment

Element and key components
Element 3: Preventative measures for recycled water management
• Determine CCP and QCP limits and trigger values (e.g. conductivity of recovered water) and link to operational procedures during the full recovery trial. • Chlorination of recovered water for human health protection
Element 4: Operational procedures and process control
• Define operational procedures for operation of the source water (avoiding aeration), back-washing of the injection well, and cessation of recovery upon reaching the salinity limit • Operational monitoring is required to ensure source water quality meets target values • Operational monitoring is required to ensure no well clogging occurs • Corrective actions required if operational performance measures are not met • Establish a program for regular inspection and maintenance of all equipment
Element 5: Verification of recycled water quality and environmental performance
• Monitor volumes injected and recovered • Monitor recovered water quality to ensure it meets drinking water quality guidelines, particularly for arsenic, iron, turbidity and pathogens.
Element 7: Operation, contractor and end user awareness and training
• Ensure that local operators, contractors and end users maintain the appropriate experience for ASR operation • Identify training needs and ensure resources are available to support training • Document training and maintain records of training

7.7 Conclusions

All indications suggest that the quality of the recovered water will be suitable for potable supplies. Dissolved oxygen, iron and turbidity levels will fall outside the aesthetic guidelines for drinking water but can be easily treated by aeration and settling with existing infrastructure. Sulfidic odour problems have not been detected in samples from the observation wells however this may be due to the absence of significant pumping.

The ability of the ASR system to recover useful volumes of good quality water has yet to be proven. Only 9% of the volume injected has been recovered at the time of writing. Monitoring of the salinity changes in the recovered water during earlier recovery events gave promising results. However, analysis of the breakthrough of injectant at the 12 m and 100 m observation wells suggests the bulk of the injectant has remained centred on the ASR well and gives promise for reasonable recovery efficiencies (Pavelic *et al*. 2006c).

The remoteness of the site and lack of adequately trained on-site personnel has restricted testing of ASR performance. Considerable data loss in 2003 and 2004 included some of the pressure transducer data (due to instrument failure) and most of the EC data (because the valve admitting water to the sensor had been inadvertently closed).

The ASR scheme cannot be considered fully operational but remains in the ‘commissioning phase’ until a major recovery event has taken place and the recovered water has been demonstrated to be of potable quality after simple post-treatment by aeration and settling.

7.8 References

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8 STORMWATER ASTR AT SALISBURY, SOUTH AUSTRALIA

The Aquifer Storage, Transfer and Recovery (ASTR) project was developed with the objective of gaining a sound scientific understanding of the processes affecting water quality; and to develop management strategies for reliable, sustainable production of water of potable quality sourced from stormwater. The Mawson Lakes subdivision, currently in development in the south-western part of the City of Salisbury council area, represent a potential user of water supplied by the ASTR project.

ASTR is similar to traditional aquifer storage and recovery (ASR), but the difference lies in the use of separate wells for injection to and recovery from a confined aquifer, rather than the same well for both. This type of MAR ensures a longer minimum residence time for recharged water than for ASR, to provide a more consistent treatment barrier in water recycling. This ASTR site is internationally unique because the aquifer was initially brackish and needed to be flushed with fresh stormwater.

Figure 8-1 The Salisbury ASTR project (clockwise from top left) – storage tanks and pump house; open hatch showing well head; and the Parafield stormwater harvesting system (covered by bird netting), with the cleansing reedbed on the left, mixing tanks in the centre, and in-stream basin on the far right.

8.1 Site description

The ASTR project is located on the Parafield Airport and Parafield Gardens Oval, on the Northern Adelaide Plains, South Australia (Figure 8-1). The scheme receives urban stormwater from the Parafield and Ayfield catchments which contain residential, retail business and mixed industrial areas (Figure 8-2). The Parafield catchment yields on average 1,100 ML of urban stormwater per year (Richard Clark & Associates 2001).

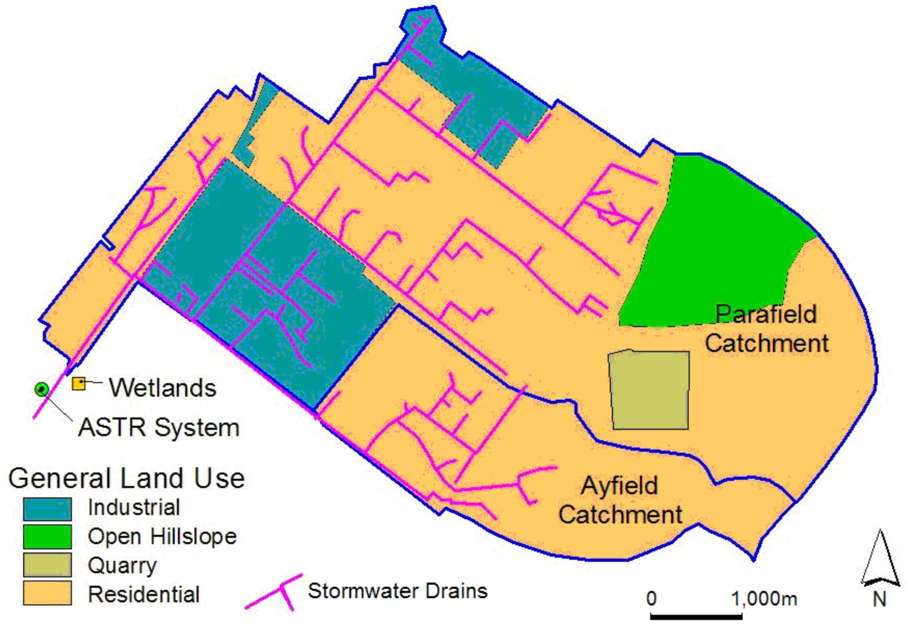

Figure 8-2 Parafield and Ayfield stormwater catchments showing main stormwater drains

A detailed description of the Parafield stormwater harvesting system is given by Marks *et al*. (2005). The ASTR system operates in conjunction with a two-well ASR system at Parafield Airport for storage of excess stormwater. When operating at capacity, the ASR system processes water at a maximum rate of 3.6 ML/day, which meets the needs of the Michell Australia wool processing plant and is also the maximum injection rate into the aquifer from the current wells.

8.1.1 Sequence of development

The ASTR project was designed to source water from the existing Parafield stormwater harvesting scheme that was commissioned in 2003.

The first ASTR injection and recovery wells were constructed in 2005 and associated pipe and pumping infrastructure was completed by 2008. This included horizontal boring under the railway line, a series of observation wells, geotechnical characterisation of the injection and recovery wells and a storage/mixing tank for recovery of water from the system. The development of the well system required several stages, as described by Pavelic *et al.* (2004). From September 2006 to June 2008 water from the Parafield wetlands was pumped into the two inner recovery wells in order to displace the saline groundwater with the fresh stormwater. Water was pumped into the aquifer until the aquifer storage zone occupied the area bounded by the outer injection wells. Injection into the aquifer through the four outer injection wells began in September 2008. The first recovery from the inner recovery wells occurred in February 2009.

The final water produced by the system will comprise at least 90% injected stormwater mixed with no more than 10% ambient ground water to sufficiently dilute the salts present in the natural groundwater and achieve potable water quality.

8.1.2 Site configuration

The ASTR site is located on the Northern Adelaide Plains, near the Parafield stormwater harvesting system (Figure 8-3). The site consists of three main components, the stormwater catchment, the Parafield stormwater harvesting system (pre-treatment) and the ASTR well field.

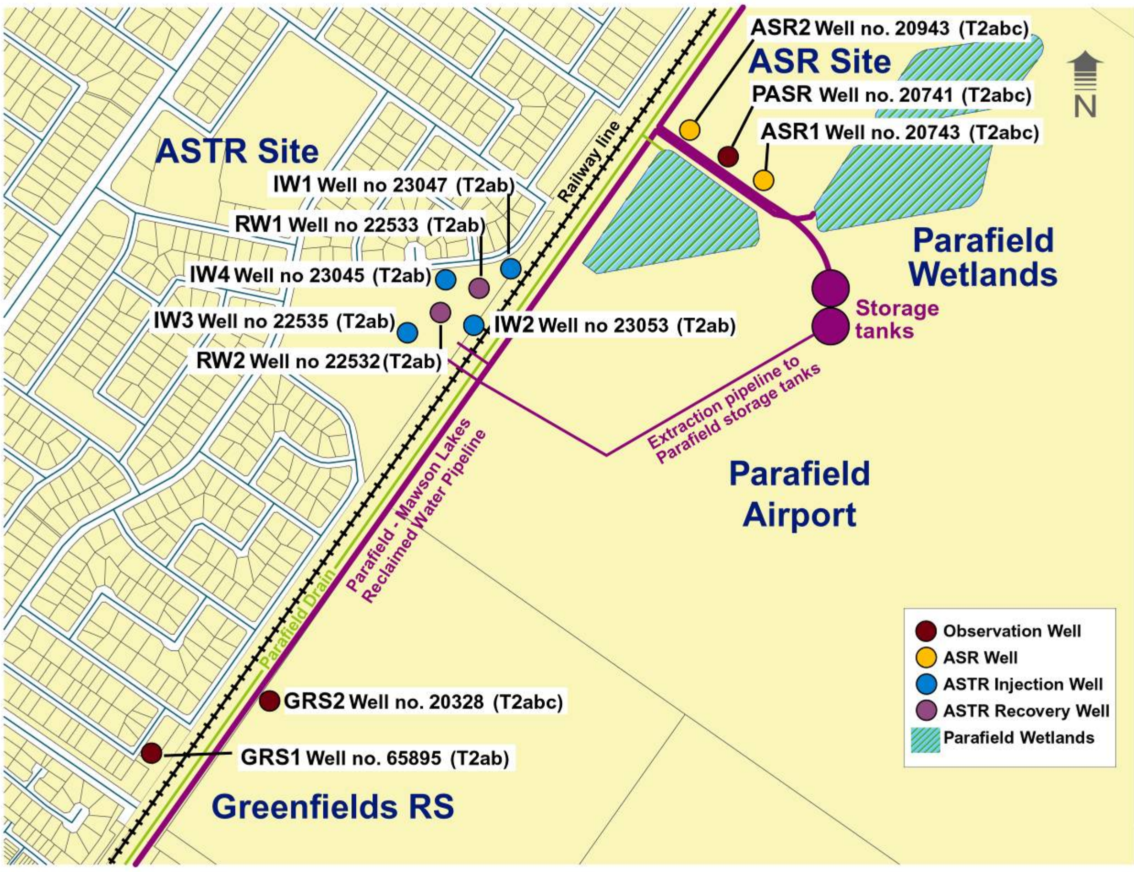

Figure 8-3 City of Salisbury water harvesting facilities in the Parafield area, identifying the location of wells at the ASTR, ASR and Greenfields Railway Station (RS) sites

The Parafield stormwater harvesting system consists of a weir which diverts water from the Parafield Drain into the 47 ML in-stream basin, the first of three stages of the system, and which serves as an initial settling basin for the stormwater. Excess stormwater flow overtops the diversion weir and continues to flow down the Parafield Drain during a storm event. Water flows into the in-stream basin and is pumped at 3 ML/hour to the 48 ML holding storage until capacity of the holding storage is reached or the in-stream basin is drained. Water in the holding storage then flows by gravity into the cleansing reedbed. The cleansing reedbed is vegetated with seven different species of reeds, planted in parallel rows that are perpendicular to flow through the wetland. The capacity of the reedbed is approximately 25 ML, and it has a surface area of 2 ha. The cleansing reedbed and holding storage are designed to achieve a minimum holding time of 7 days; however, the actual holding time varies with use. Water is pumped from the reedbed outlet to two storage tanks, and from there it is pumped to the ASTR well field.

Background information on the ASTR well system, including groundwater modelling for system design is given in Pavelic *et al.* (2004) and Kremer *et al*. (2009; 2010). The ASTR system comprises four injection wells (IW1 – IW4) surrounding two recovery wells (RW1 and RW2) and a series of three piezometers (P1 – P3) (Figure 8-4). The rhombic well configuration and 50 m inter-well spacing was designed to produce a mean residence time in the aquifer of 6 months.

Currently, water is recovered from the ASTR well field back into the two storage tanks, from where it enters the distribution pipeline and is pumped to end-users such as Mawson Lakes non-potable supply and municipal irrigation (SA Water 2009).

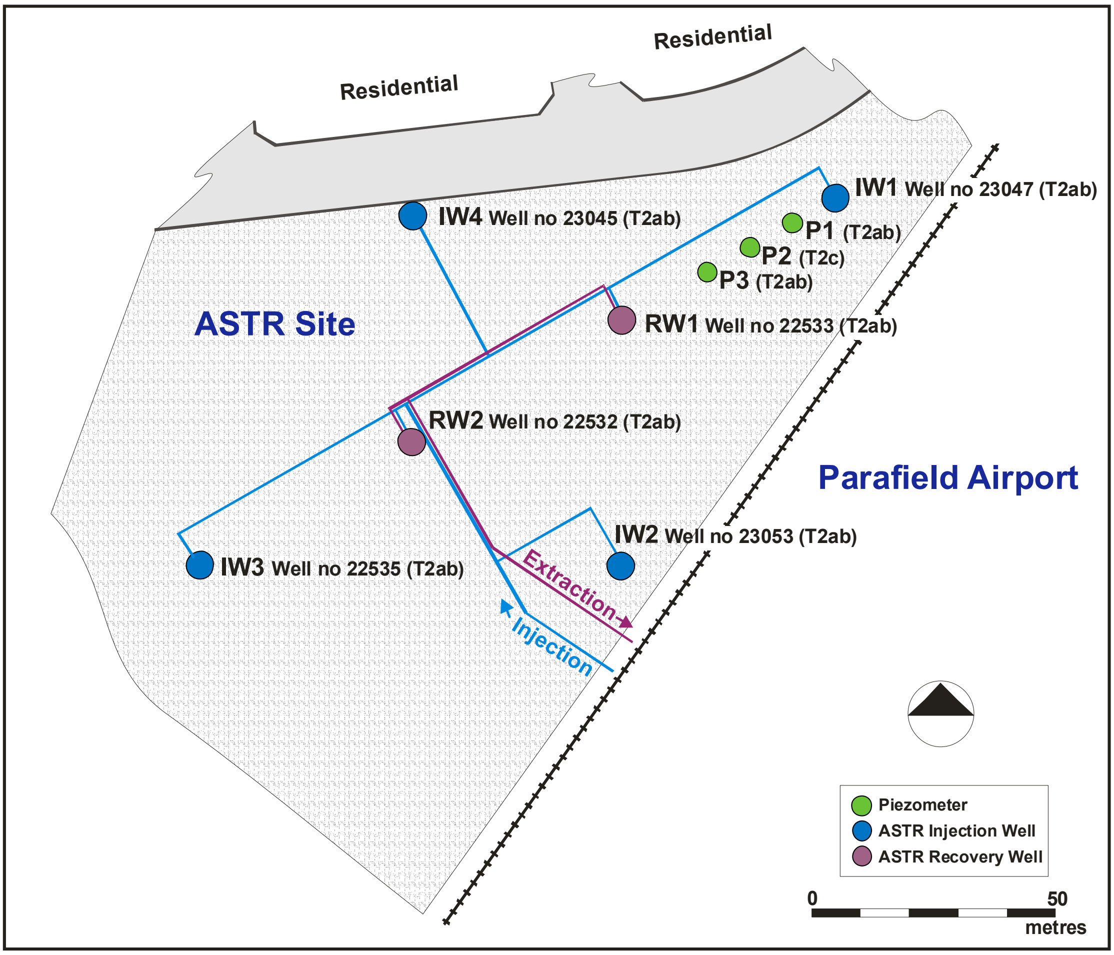

Figure 8-4 Map of the ASTR well-field showing four injection wells (IW1-IW4), two recovery wells (RW1-RW2) and three piezometers (P1-P3).

The ASTR system is conceptually summarised in Figure 8-5, and its components are listed in Table 8-1.

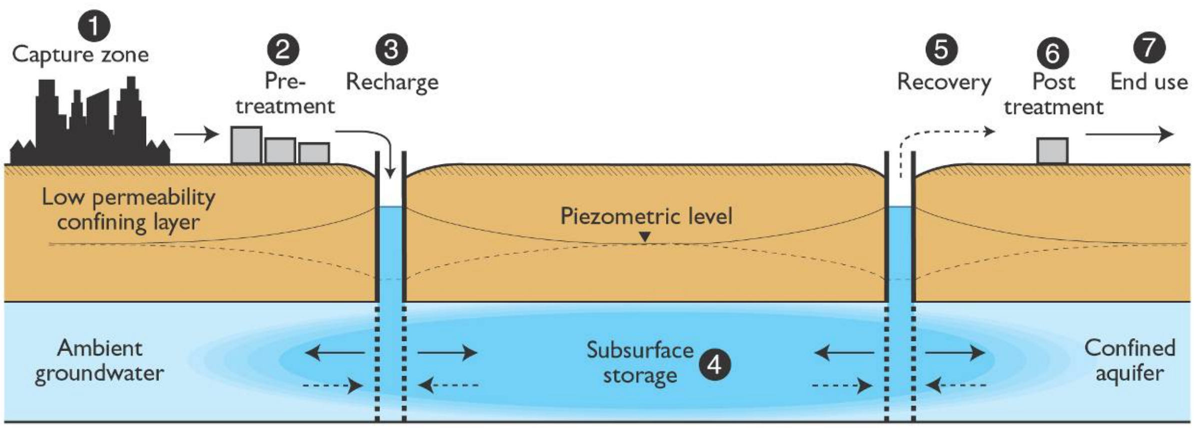

Figure 8-5 ASTR system schematic of water flow

Table 8-1 ASTR system components

Component	ASTR system
1. Capture zone	Parafield stormwater harvesting system (Parafield drain, 47 ML in-stream basin, 48 ML holding storage)
2. Pre-treatment	Settlement in the in-stream basin and holding storage and passive treatment in the reedbed only.
3. Recharge	Four injection wells (IW1, IW2, IW3, IW4)
4. Subsurface storage	T2 aquifer – confined limestone Tertiary aquifer
5. Recovery	Two recovery wells (RW1, RW2)
6. Post-treatment	Currently none – post-treatment measures discussed include aeration, UV and chlorine disinfection
7. End use	Currently discharged to storage tanks, then distributed to end-users such as Mawson Lakes non-potable supply and municipal irrigation. Potential future use in drinking water supply is being evaluated.

8.1.3 Aquifer description

The ASTR site is located within the Adelaide Embayment which is a section of the St Vincent Basin. The area is underlain by a thick sequence of sedimentary deposits of Quaternary and Tertiary age which in turn overlays the Precambrian basement.

The ASTR operations are aimed at the T2 (Lower Port Willunga) aquifer, which is the part of Tertiary formation (AGT 2007). This confined aquifer at a depth of 160-220 m consists of limestone series with sandy and silty components, 60 m thick. On the basis of lithological data (Gerges 2005) the T2 aquifer was subdivided into three units called T2a, T2b and T2c.

Local pump tests indicate an average transmissivity of 200 m^2/day for the T2 aquifer. The aquifer has a layered structure and is relatively homogeneous in the lateral direction (Gerges 2005; AGT 2007). The transmissivity of the 18 m open interval within T2a and T2b units is 50 m^2/day. A 2 m thick layer in the lower part of the profile (within T2c) contributes most of the aquifer's transmissivity.

The ambient regional groundwater flow is approximately from east to west in T2 at the ASTR site, with a natural hydraulic gradient of 0.0015 (Pavelic *et al*. 2004), however, ASR operations significantly affect the local gradients. The ambient groundwater in the T2 aquifer is brackish, with total dissolved solids (TDS) measured at ~2,000 mg/L (electrical conductivity (EC) ~3,600 µS/cm). Redox environment is anoxic with low concentrations of Fe^{2+} (0.75 mg/L) and the odour of H_2S is detectable.

8.1.4 Source water description

Water balance and stormwater flows for the Parafield and Ayfield catchments have been estimated by Richard Clark & Associates (2001) using the WaterCress Model. The results indicate that the Ayfield Catchment (373 ha) will yield an estimated 340 ML/year and the Parafield Catchment (1,248 ha) will yield an estimated 1,180 ML/year, for a combined average annual yield of 1,520 ML.

Stormwater derived from the Parafield and Ayfield catchments is expected to reflect impacts from a range of potential contaminant sources (Swierc *et al*. 2005). Both catchments have stormwater directed to the Parafield drain, which supplies water to the Parafield harvesting scheme and subsequently the ASTR system.

8.2 Stage 1 Entry level risk assessment

Table 8-2 and Table 8-3 show the completed entry-level risk assessment for the ASTR scheme, as per section 4.3 of the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a). Table 8-3 also provides a summary of Stage 2 investigations required as identified in the Stage 1 assessment.

Table 8-2 ASTR entry level assessment part 1 – Viability

	Attribute	Answer
1	Intended water use	
	• Is there an ongoing local demand or clearly defined environmental benefit for recovered water that is compatible with local water management plans?	✓ Recovered water intended for use as non-potable supplies including industrial and residential uses, and if proven suitable, for drinking water supplies.
2	Source water availability and right of access	
	• Is adequate source water available, and is harvesting this volume compatible with catchment water management plans?	✓ Adequate volume of stormwater available, harvesting is compatible with catchment management plans (i.e. reducing volume of stormwater discharged to sea) and maximising stormwater use.
3	Hydrogeological assessment	
	• Is there at least one aquifer at the proposed managed aquifer recharge site capable of storing additional water?	✓ T2 aquifer capable of storing additional water
	• Is the project compatible with groundwater management plans?	✓ Tradable replenishment credit granted to the City of Salisbury by the Department of Water, Land and Biodiversity Conservation* with support from the Adelaide and Mount Lofty Ranges Natural Resources Management Board and Environmental Protection Authority.
4	Space for water capture and treatment	
	• Is there sufficient land available for capture and treatment of the water?	✓ Stormwater capture and treatment reedbed already in existence at Parafield Airport
5	Capability to design, construct and operate	
	• Is there a capability to design, construct and operate a managed aquifer recharge project?	✓ Capability exists between City of Salisbury, SA Water, United Water and CSIRO to design, construct and operate project → Go to Table 8-3

* currently known as the Department for Water

Table 8-3 ASTR entry level assessment part 2 – degree of difficulty

Question	ASTR answers	Investigations required
1 Source water quality with respect to groundwater environmental values		
Does source water quality meet the requirements for the environmental values of ambient groundwater?	Yes – Ambient groundwater is too saline even for irrigation and is isolated from groundwater dependant ecosystems.	None
2 Source water quality with respect to recovered water end use environmental values		
Does source water quality meet the requirements for the environmental values of intended end uses of water on recovery?	No – stormwater does not meet drinking water standards. Require Stage 2 investigations to evaluate stormwater quality and hazard attenuation processes in aquifer.	Source water quality and hazard attenuation processes (Section 8.4.1)
3 Source water quality with respect to clogging		
Is source water of low quality, for example: either total suspended solids, total organic carbon or total nitrogen >10 mg/L, And is soil or aquifer free of macropores?	Yes – source water is of moderate quality, and should lead to a low to moderate rate of clogging in the target limestone aquifer. Require Stage 2 investigations to assess clogging potential.	Clogging evaluation (Section 8.3.3)
4 Groundwater quality with respect to recovered water end use environmental values		
Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery?	No – ambient groundwater salinity above drinking water standards. Require Stage 2 investigations to assess recovery efficiency.	Recovery efficiency evaluation (Section 8.3.1)
5 Groundwater and drinking water quality		
Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?	No – target aquifer is too saline for use as drinking water supply; target aquifer does not support aquatic ecosystems with high conservation value.	None
6 Groundwater salinity and recovery efficiency		
Does the salinity of native groundwater exceed: (a) 10000 mg/L, or (b) the salinity criterion for uses of recovered water?	Yes to (b) only – ambient groundwater salinity above drinking water standards. Require Stage 2 investigations to assess recovery efficiency.	Recovery efficiency evaluation (Section 8.3.1)
7 Reactions between source water and aquifer		
Is redox status, pH, temperature, nutrient status and ionic strength of source water and groundwater similar?	No – redox status, nutrient status, and ionic strength of source water is different to that of groundwater. Require Stage 2 investigations to evaluate geochemical reactions.	Geochemical evaluation (Section 8.3.2)
8 Proximity of nearest existing groundwater users, connected ecosystems and property boundaries		
Are there other groundwater users, groundwater–connected ecosystems or a property boundary near (within 100–1000 m) the MAR site?	Yes – property boundaries within 100 m of MAR site (but target aquifer unusable for irrigation or drinking). ASR site nearby. Require Stage 2 investigations to determine extent of attenuation and artesian zones.	Interactions with nearby ASR site warrant consideration (Section 8.3.4)
9 Aquifer capacity and groundwater levels		
Is the aquifer confined and not artesian? Or is it unconfined, with a watertable deeper than 4 m in rural areas or 8 m in urban areas?	Yes – target aquifer confined and not artesian. However, injection may cause aquifer to become artesian. Require Stage 2 investigations to assess artesian zone.	Extent of artesian zone to be identified (Section 8.3.4)
10 Protection of water quality in unconfined aquifers		

Question	ASTR answers	Investigations required
Is the aquifer unconfined, with an intended use of recovered water being drinking water supplies?	No – target aquifer is confined.	None
11 Fractured rock, karstic or reactive aquifers		
Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?	Yes – target aquifer contains reactive minerals, and dissolution of carbonate minerals is possible. Require Stage 2 investigations to assess risk of migration of recharge water and aquifer dissolution.	Geochemical evaluation of the dissolution of calcite (Section 8.3.2)
12 Similarity to successful projects		
Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?	Yes – Parafield ASR scheme has been operating successfully in the same aquifer for six years for non-potable uses.	None
13 Management capability		
Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty, or with water treatment or water supply operations involving a structured approach to water quality risk management?	Yes – proponents have experience with similar stormwater MAR operations in the same aquifer. However, they do not have experience with drinking water supplies from MAR. SA Water and United Water contribute water supply and water quality management to the project. Across the partnership this is achievable but will require significant innovation.	New ground to be broken in managing for potable use
14 Planning and related requirements		
Does the project require development approval? And is it in a built up area; on public, flood-prone or steep land; close to a property boundary; contain open water storages or engineering structures; likely to cause public health, safety or nuisance issues, or adverse environmental impacts?	Yes – project requires development approval. Water harvesting facility already exists. Horizontal drilling beneath railway line and well construction on council reserve require a permit, and ASTR requires entitlements to inject and recover.	As required by council and DWLBC* approval processes

* currently known as the Department for Water.

A summary of the degree of difficulty and required investigations for Stage 2 is given in Table 8-4.

Table 8-4 Summary of Stage 2 investigations required at ASTR

Issue		Investigations required at stage two	Discussed in section
2	Source water quality with respect to recovered water end use environmental value	Source water quality and hazard attenuation processes	8.4.1
3	Source water quality with respect to clogging.	Clogging evaluation	8.3.3
4	Groundwater quality with respect to recovered water end use environmental values	Recovery efficiency evaluation	8.3.1
6	Groundwater salinity	Recovery efficiency evaluation	8.3.1
7	Reactions between source water and aquifer	Geochemical evaluation	8.3.2
8	Proximity of nearest existing groundwater users, connected ecosystems and property boundaries	Interactions with nearby ASR site warrant consideration	8.3.4
9	Aquifer capacity and groundwater levels.	Extent of artesian zone to be identified	8.3.4
11	Fractured rock, karstic or reactive aquifers	Geochemical evaluation of the dissolution of calcite	8.3.2
13	Management capability	New ground to be broken in managing for potable use.	
14	Planning and related requirements	As required by council and DWLBC approval processes	

8.3 Stage 2 Pre-commissioning investigations

A series of studies were performed in support of the Stage 2 pre-commissioning assessment, they are described below followed by the maximal and residual risk assessments.

8.3.1 Recovery efficiency evaluation

Flow and solute transport modelling studies were performed to evaluate the likely recovery efficiency (RE) for the ASTR site (Pavelic *et al.* 2004; Kremer *et al.* 2009; Kremer *et al.* 2010). In the feasibility study, Pavelic *et al*. (2004) proposed an optimal design of the well field where both high recovery efficiencies and sufficiently long travel times of injected water in the aquifer are maintained. As a result of this work based on downhole electromagnetic flow metering of the well at nearby Greenfields Railway Station it was determined that RE and residence time constraints could not be met with the original 75 m spacing; to achieve these the high permeability layer T2c needed to be excluded and the optimal well spacing was then reduced to 50 m. This also allowed a shift in the location of the site to council-owned land adjacent to Parafield Gardens Oval. Further drilling was performed at this site.

On the basis of numerical modelling it was recommended to recover no more than 80% of injectant in order to enhance the buffer against the brackish water within the study area, and so ensure that the salinity of the recovered water can fulfil the potable requirements of 500 mg/L TDS reliably over the long term (Kremer *et al.* 2010).

8.3.2 Geochemical evaluation

The geochemical evaluation was undertaken by considering the reaction scenarios that could occur when the source stormwater is injected into the aquifer storage zone (Vanderzalm *et al*. 2006; 2007). It was based on evaluation of the end-members involved in reactions: the aquifer sediments, the ambient groundwater and the source water. Water recovered from the nearby ASR site was also considered in the geochemical evaluation as it is a possible source water for the ASTR scheme, with ASR representing an additional pre-treatment step. The available groundwater monitoring data was also used to understand the dominant reaction processes.

8.3.3 Clogging evaluation

In nearby stormwater ASR wells in the same aquifer clogging has been managed by frequent pumping at high rates to remove accumulated sediments and biofilm. Unclogging is facilitated by calcite dissolution as a result of buffering against carbon dioxide formed by oxidation of injected organic carbon. Hence clogging is expected to be easily managed by installing pumps (or possibly tubes to allow injection of compressed air), to purge injection wells as required.

8.3.4 Interactions with nearby ASR sites

Modelling simulations revealed that the interaction of the ASTR site with other well fields is apparent, Parafield ASR in particular. According to the numerical model, the artesian zone is apparent only during injection phase at the ASTR site when the piezometric pressure rises to 14.5 m and the maximal radius of the artesian zone increased up to ~2 km (Kremer *et al*. 2010). No wells aside from sealed observation wells and other council owned ASR wells intersect the T2 aquifer within a 2km radius of the ASTR site so artesian discharges are not expected to be induced.

8.4 Stage 2 Pre-commissioning risk assessment

8.4.1 Maximal risk assessment

The risk assessment is presented in the order of the twelve key hazards outlined in the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a). A semi-quantitative risk assessment was performed for each of the hazards for human health and environmental endpoints, with green, orange and red indicating low, unknown and high risks respectively (Table 8-5). The white boxes indicate that that hazard does not apply to that endpoint.

The maximal risk assessment for the human health end point was conducted by comparing the water quality data for raw stormwater and native groundwater for hazards 1 to 7 to the Australian Drinking Water Guidelines (NHMRC–NRMMC 2004) and/or the Augmentation of Drinking Water Supplies Guidelines (NRMMC–EPHC–NHMRC 2008). For the environmental endpoint, the aquifer's ambient environmental values do not include irrigation or ecosystem support due to the high salinity of the groundwater and the confined nature of the aquifer respectively. For each hazard where the mean of the relevant water quality parameter exceeded the water quality guideline the risk was deemed unacceptable (labelled red) and where it was below it was labelled green (see Table 8-6 below which includes the raw stormwater data used in this assessment).

For hazards 8 to 12, the risks were assessed based on their potential impacts on the aquifer or biosphere as described in the MAR Guidelines. For hazard 12, energy and greenhouse gas considerations a comparative risk assessment was performed. The energy consumption per ML of water produced by ASTR was compared to the current energy consumption per ML of water to supply drinking water to Adelaide (Page *et al*. 2009).

Table 8-5 Maximal risk assessment summary for ASTR, SA

	MAR Hazards	Human endpoint – drinking water	Environmental endpoint – aquifer
1.	Pathogens – requires an assessment of pathogen removal in the wetland and aquifer and a QMRA to be performed.	H	L
2.	Inorganic chemicals – release of arsenic and iron	H	H
3.	Salinity and sodicity – requires management of mixing or is likely to exceed drinking water guidelines	H	L
4.	Nutrients: nitrogen, phosphorous and organic carbon – stormwater is of low nutrient status	L	L
5.	Organic chemicals – potential herbicides present may exceed drinking water guidelines	H	L
6.	Turbidity and particulates – high in the injectant, and may also cause clogging (operational risk)	H	L
7.	Radionuclides – residential catchment and aquifer unlikely to have radioactive sources	L	L
8.	Pressure, flow rates, volumes and groundwater levels – modelling showed that the risk was unlikely but needs to be confirmed		U
9.	Contaminant migration in fractured rock and karstic aquifers – not present in this aquifer		L
10.	Aquifer dissolution and stability of well and aquitard – unlikely based on nearby ASR wells but needs to be confirmed		U
11.	Aquifer and groundwater-dependent ecosystems – none present within 2 km and aquifer is anoxic and saline		L
12.	Energy and greenhouse gas considerations – lower than comparable options of pumping additional water from the River Murray.		L

L low risk; **U** unknown risk; **H** high risk.

8.4.2 Residual risk assessment

The Stage 2 semi-quantitative residual risk assessment for the ASTR system was performed using the same approach as for the maximal risk assessment but with inclusion of all the barriers: source control; reedbed treatment; aquifer treatment; UV disinfection, chlorination and an aeration tank (for iron removal). Stormwater quality data for use in the risk assessments is given in the following table for untreated stormwater, the injectant into the aquifer (reedbed treated stormwater), ambient groundwater quality and recovered water quality (Table 8-6).

Table 8-6 ASTR water quality data summary 2006-2010

		WE1 – Raw Stormwater 2006-2010		WE2 – Reedbed treated stormwater 2006-2010		Ambient groundwater 2006		Groundwater 2007-2008 – flushing phase – IW wells		Groundwater 2008-2009 – injection phase – RW wells		Recovered water – RW wells 2009	
	DWG	**n**	**Mean**	**n**	**Mean**	**n**	**Mean**	**n**	**Mean**	**n**	**Mean**	**n**	**value**
Physical characteristics													
Temperature (°C)	-	9	13.5	15	13.6	3	25.5	21	22.8	3	13.3	11	17.7
pH	6.5-8.5	8	7.2	14	7.3	3	6.88	21	7.5	3	7.61	11	7.7
Conductivity (µS/cm)	-	9	217	15	335	3	3670	21	1840	3	454	12	528
Total Dissolved Solids (mg/L)	500	17	120	38	147	3	**2020**	21	1049	3	247	5	314
Dissolved oxygen (mg/L)	85%	8	7.0	14	5.1	1	0.03	21	0.0	3	1.01	11	1.9
Redox potential (mV SHE)	-	8	361	14	348	1	196	19	-18	3	-14	11	48
Suspended Solids (mg/L)	-	17	18	38	4	3	3	21	1.9	3	27	5	<1
Turbidity (NTU)	5	17	16	38	3.9	3	**25**	21	9.0	3	17	5	0.4
True Colour (HU)	15	7	104	24	42	3	**14**	6	<1			5	**24**
Major ions (mg/L)													
Alkalinity as $CaCO_3$	-	18	57	39	77	3	260			3	201	7	173
Bicarbonate	-	18	70	39	94	3	317	21	274	3	246	7	211
Bromide	-	12	<0.1	29	0.16	3	3.28	10	1.49	3	0.12	7	0.18
Sulfate	250	17	10.7	39	12	3	**275**	21	149	3	2.7	7	18.9
Chloride	250	18	28	39	35	3	**920**	21	407	3	22	7	65
Fluoride	1.5	18	0.16	39	0.18	3	0.43	21	0.56	3	0.17	7	0.24
Calcium	-	18	18.9	39	24	3	135	21	78.9	3	66.2	7	54.0
Magnesium	-	18	3.9	39	5.7	3	82.6	21	47.0	3	6.5	7	9.5
Potassium	-	18	4.0	39	3.9	3	13.3	21	8.5	3	5	7	4.5
Sodium	180	18	18.3	39	25	3	**501**	21	254	3	14.8	7	47
Microbiological													
Thermotolerant coliforms (cfu/100 mL)	0	17	309	39	52	3	0	20	0	3	0	6	0
E.coli (cfu/100 mL)	0	17	161	39	50	3	0	20	0	3	0	6	0
Enterococci (cfu/100 mL)	0	17	145	38	23	3	0	20	0	3	0	5	0
Faecal Streptococci (cfu/100 mL)	0	17	145	38	23	3	0	20	0	3	0	5	0
Clostridium spores (cfu/L)^	0			2	10			2	0			3	**1**
Campylobacter (cfu/L)^	0			3	10								
F-specific phage (MPN/L)^	-	13	>94 [2]	5	13 [2]								
Somatic phage (MPN/L)^	-	**13**	>94 [2]	**13**	>94 [2]								

		WE1 – Raw Stormwater 2006-2010		WE2 – Reedbed treated stormwater 2006-2010		Ambient groundwater 2006		Groundwater 2007-2008 – flushing phase – IW wells		Groundwater 2008-2009 – injection phase – RW wells		Recovered water – RW wells 2009	
Enteric virus (PDU/L)^	0	5	ND	5	ND							3	absent
Nutrients (mg/L)													
Nitrate + Nitrite as N	11.3	18	0.055	39	0.008	3		21	<0.005	3	0.069	6	<0.005
Ammonia as N	0.5	18	0.095	39	0.022	3	0.035	21	0.028	3	4.1	6	0.357
Total Kjeldahl Nitrogen	-	18	0.826	39	0.43	3	<0.05	21	0.123	3	4.8	5	0.556
Total Nitrogen	-	18	0.882	39	0.44	3	<0.05	21	0.124	3	4.8	6	0.522
Filterable Reactive Phosphorus	-	18	0.029	39	0.014	3	0.006	21	<0.005	3	0.12	6	0.020
Total Phosphorus	-	18	0.113	39	0.051	2	0.017	21	0.012	3	0.27	6	0.035
Biodegradable Dissolved Organic Carbon		3	1.8	6	2.4								
Dissolved Organic Carbon	-	18	8.6	39	6.0	3	1.4	21	1.6	3	9.8	6	4.5
Total Organic Carbon	-	18	10.6	39	6.9	3	1.4	21	1.6	3	13.2	6	4.8
Silica				3	3							3	5.3
UV_{254} (cm^{-1})	-	15	0.251	35	0.243	3	0.073	13	0.054	3	0.351	3	0.175
Metals and metalloids (mg/L)													
Aluminium (s)		4	0.281	8	0.028			12	<0.01	3	0.018	4	<0.01
Aluminium (t)	0.2	16	0.323	37	0.169	3	<0.020	15	<0.01	3	0.107	4	<0.01
Antimony (t)	0.003	5	0.0014	9	0.0021			4	0.0007	3	0.001	3	0.0006
Arsenic (s)	-	17	0.001	35	0.0012	3	0.01	19	0.005	2	0.003	7	0.002
Arsenic (t)	0.007	18	<0.001	39	0.0010	3	**0.011**	21	0.006	3	0.005	7	0.002
Barium (t)	0.7	11	0.01968	20	0.0174			17	0.0208	3	0.038	3	0.0178
Boron (s)	4	11	<0.040	20	0.046			17	0.163	3	<0.040	3	0.082
Cadmium (t)	0.002	16	<0.0005	37	<0.0005	3	<0.0005	21	<0.0005	3	<0.0005	3	<0.0005
Chromium (t)	0.05	16	<0.003	37	<0.003	3	<0.003	21	<0.003	3	<0.003	3	<0.003
Cobalt (t)	-	5	<0.0005	9	<0.0005			5	<0.0005	3	<0.0005	3	<0.0005
Copper (t)	1	11	0.0041	20	0.0027			17	<0.0010	3	<0.0010	3	<0.001
Iron (s)	-	17	0.267	35	0.170	3	1.53	20	0.247	3	7.8	7	0.428
Iron (t)	0.3	17	**0.506**	39	**0.531**	3	**1.54**	21	**0.646**	3	**8.4**	7	**0.414**
Lead (s)	-	10	0.0011	13	<0.0005			16	<0.0005	3	<0.0005		
Lead (t)	0.01	16	0.0022	37	0.0006	3	<0.0005	21	<0.0005	3	<0.0005	3	<0.005
Lithium (t)	-	11	0.0021	19	0.0024			17	0.0115	3	0.002	3	0.0034
Manganese (s)	-	12	0.0763	27	0.0264	3	0.007	9	0.0039	3	0.47	7	0.0619

		WE1 – Raw Stormwater 2006-2010		WE2 – Reedbed treated stormwater 2006-2010		Ambient groundwater 2006		Groundwater 2007-2008 – flushing phase – IW wells		Groundwater 2008-2009 – injection phase – RW wells		Recovered water – RW wells 2009	
Manganese (t)	0.1	18	0.0625	39	0.0502	3	0.007	21	0.0036	3	**0.52**	7	0.0632
Mercury (t)	0.001	11	<0.0003	19	<0.0003			16	<0.0003	3	<0.0003	3	<0.0003
Molybdenum (t)	0.05	11	0.0018	19	0.0012			17	0.0011	3	<0.0005	3	<0.0005
Nickel (t)	0.02	16	0.0009	37	0.0009	3	<0.0005	21	<0.0005	3	0.002	3	0.0007
Selenium (t)	0.01	5	0.004	9	0.003			5	<0.003	3	<0.003	3	<0.003
Silver (t)	0.1	5	0.0006	9	0.0003			5	<0.0002	3	<0.0002	3	<0.0002
Thallium (t)	-	5	<0.0005	9	<0.0005			4	<0.0005	3	<0.0005	3	<0.0005
Vanadium (t)	-	11	<0.003	19	<0.003			17	<0.003	3	0.008	3	<0.003
Zinc (t)	3	16	0.049	37	0.0198	3	<0.0005	15	0.011	3	0.014	3	0.002
Organic chemicals (µg/L unless otherwise specified)													
2,4-D		4	<0.01	4	<0.01			1	0.02			3	<0.01
2,6-Dichlorophenol		12	<1	12	<1			6	<0.1			2	<0.1
Atrazine		12	0.55	12	<0.1			7	<0.1			3	<0.01
Caffeine	0.35	4	0.28	4	0.07			1	<0.01			3	0.01
DEET	2500	4	0.06	4	0.12			1	0.06			3	0.07
Desisopropyl Atrazine		4	0.01	4	<0.01			1	<0.01			3	<0.01
Detergent as MBAS (mg/L)		10	0.09	11	0.05			6	<0.05			3	0.128
Dicamba	100	4	0.04	4	0.04			1	<0.01			3	<0.01
Dichloromethane	4	11	<1	12	<1			6	<1			3	<1
Diuron	30	4	0.15	4	0.12			1	0.1			3	0.17
Fluometuron		4	<0.1	4	<0.1			1	0.04			3	<0.01
MCPA	35	4	0.35	4	0.21			4	<0.01			3	0.018
Mecoprop	350	4	0.02	4	0.02			1	0.03			3	<0.01
Metolachlor	300	4	<0.01	4	0.01			1	<0.01			3	<0.01
Nitroso-piperidine (ng/L)		2	32	3	<20			1	<10			3	<20
Paracetamol	175	4	0.07	3	<0.01			1	<0.01			3	<0.01
Salicylic acid		4	<0.1	4	<0.1			1	<0.01			3	0.01
Simazine	5	12	0.26	12	0.21			1	<0.01			3	<0.01
Sulphamethoxazole		4	<0.01	4	<0.01			1	0.04			3	<0.01
Triclopyr	10	4	0.03	4	0.03			1	0.02			3	0.011

DWG = drinking water guideline, taken from Australian Drinking Water Guidelines, or Augmentation of Drinking Water Supplies guidelines; Bold values exceed DWG, ND = Not detected; [1] summary statistics not possible due to the use of MPN (most probable number) technique, analysis at CSIRO; [2] maximum value.

Overall the quality of the stormwater entering the holding basin/cleansing reedbed pre-treatment system was good and resulted in most risks being assessed as low without the need for additional post-recovery treatment. In addition to the traditional water quality monitoring, sediment analysis and passive samplers for assessment of micropollutants were trialled as tools for risk assessment where concentrations of hazards are below standard laboratory detection limits. Very few micropollutants or enteric pathogens were detected using the conventional water monitoring programs, however, the passive samplers detected trace quantities of micropollutants throughout the system of which diuron, simazine and chlorpyrifos appeared to be most significant but were all below drinking water guideline values.

The results of the monitoring program were also used to construct a water and chloride balance for the holding storage and cleansing reedbed components of the ASTR system as a step to quantitatively assess their treatment performance for physical, chemical and microbial hazards (Page *et al*. 2008b). The performance of the system over August-September 2006 was found to have removal efficiencies of 0.66, 0.77 and 0.64 for total nitrogen, phosphorous and organic carbon respectively. The water produced after the cleansing reedbed was of near-potable quality, with the exceptions of colour caused by elevated iron concentrations and small numbers of faecal indicator bacteria caused by indigenous fauna in the cleansing reedbed.

8.5 Stage 3 Operational residual risk assessment

The results of the Stage 3 operational residual risk assessment as reported by Page *et al*. (2009) for the ASTR system are summarised here.

Pathogen risks were assessed to be acceptable (< 1×10^{-6} DALYs) for all index pathogens (*Campylobacter*, *Cryptosporidium* and Rotavirus) using the default pathogen concentrations suggested in the Stormwater Harvesting and Reuse Guidelines (NRMMC–EPHC–NHMRC 2009b). The assessment of the risks involved Quantitative Microbial Risk Assessment (QMRA) simulations as described by Page *et al*. (2009). The QMRA model included the results of pathogen decay experiments in the wetland and aquifer as well as UV-disinfection and chlorination post-recovery treatments which have yet to be installed; as such the results of the QMRA will have to be revised when the system is operating and water is recovered on a continuous basis.

There is potential for release of both arsenic and iron via either pyrite oxidation or reductive iron oxide dissolution at the ASTR site when reedbed treated stormwater is introduced into the T2 aquifer, as revealed using the decision trees in Appendix 7 of the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a). The impact of aquifer dissolution on the stability of the overlying clay aquitard was considered by assuming that dissolution of a 2 m radius around the injection well would result in stability concerns. The calcium and magnesium excess observed in groundwater sampled from IW1 on 1/9/2008 indicate 0.2 to 0.5 mmol/L of dissolution, while equilibrium modelling with PHREEQC (Parkhurst and Appelo 1999) suggests 0.3 mmol/L dissolution. Dissolution amounts of 0.3 and 0.5 mmol/L were considered in this evaluation of the impacts of aquifer dissolution. The annual injection volume is dependent on the availability of the seasonally variable source water. Kremer *et al*. (2009) considers injection volumes of 104, 173 and 300 ML/year as estimates of injection volumes in dry, normal and wet years. A ‘normal’ year is suitable for examining the long-term impacts of aquifer dissolution over the lifetime of an injection well and equates to 43 ML/year in each of the four IW wells. The time required to dissolve the calcite in a 2 m radius around an injection well is estimated at 200 years based on 0.3 mmol/L of dissolution, and around 120 years based on 0.5 mmol/L of dissolution.

These calculations indicate aquifer dissolution is not a risk to the lifetime of the injection wells. However, the amount of aquifer dissolution needs to be determined in the proximity of

the injection well using the calcium changes between injection well (IW1) and piezometer (P1) during an injection phase. Hence, the residual risk assessment indicated that carbonate mineral dissolution and redox processes are expected to be the major influences on the recovered water quality. While dissolution of carbonate minerals increases the concentration of dissolved calcium, magnesium and bicarbonate it does not lead to water quality risks. Redox processes can lead to water quality improvements through removal of nutrients and organic chemicals, but can degrade water quality through increases in iron and arsenic concentrations.

The residual risk from iron was deemed to be acceptable for the ASTR scheme when the aeration tank was included in the treatment train. However, this will require validation as the groundwater quality to date indicates iron concentrations in recovery wells may remain above the 0.3 mg/L aesthetic water quality guideline value. The subsurface storage and transfer aspect of the ASTR scheme is not advanced enough to fully evaluate the residual risks from inorganic chemical hazards. In particular the risk due to arsenic mobilisation from the aquifer cannot be assessed although no elevated arsenic concentrations were recorded in the recovered water during commissioning (Table 8-6). The evaluation of hydrogeochemical processes was largely based on operation of the ASTR site in the flushing mode, with injection occurring via the central recovery wells. Injection through the outer injection wells commenced in September 2008 and as a result there is little data available to assess the subsurface processes and their impact on the quality of recovered water.

The residual risks from organic chemicals are currently assessed to be acceptable; however, there is some uncertainty in this assessment resulting from the sporadic nature of the detections and the multitude of potential chemicals which can be present in urban stormwater. However dispersive mixing within the aquifer will eliminate peak concentrations and unless there are chronic persistent sources the risks will be acceptable. Suggested organic chemicals to be monitored are based on detections over the previous four years (Page *et al*. 2009).

The evaluation of turbidity in Page *et al*. (2009) was largely based on operation of the ASTR site in the flushing mode, with injection occurring via the central recovery wells. Injection through the outer injection wells commenced in September 2008 and extraction from the inner recovery wells commenced in February 2009, and as a result there was little data available to assess the production of turbidity and impact on the quality of recovered water. The levels of turbidity in the initial water recovered in March 2009 were below the drinking water aesthetic guideline for turbidity (5 NTU), and subsequent sampling between April and July 2009 resulted in a mean turbidity of 0.4 NTU. However, the residual risk for turbidity cannot be fully defined without additional evaluation of the capacity of the aquifer as a treatment step for turbidity and particulates.

Treatment of turbidity can be achieved in a number of ways, for example by storing the recovered water in holding tanks to allow the particulates to settle out, or by coagulation followed by filtration through granular media. The effect of aeration / mixing tanks on the turbidity of recovered water is yet to be assessed and may represent an additional preventative measure if this is needed.

8.6 Stage 4 Operation-refined risk management plan

There is currently no risk management plan in place for operating the Salisbury ASTR site. This section contains a gap analysis of the requirements of a risk-based management plan consistent with the requirements for progression of the ASTR site to a Stage 4 operational assessment. The plan lists the 12 elements of the framework for management of recycled water quality and use, and shows how the ASTR scheme could potentially meet the various elements. This is intended as a starting point to initiate discussion on future actions (Table 8-7). Additional details on all of the elements required within a risk management plan are available in the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a).

Table 8-7 Key requirements within the Salisbury ASTR risk management plan for progression to a Stage 4 operational assessment

Element and key components
Element 1: Commitment to responsible use and management of recycled water quality
• Ensure responsibilities of each agency are clearly defined and communicated (multiple agencies involved, project is the first of its kind) • Form stakeholder reference group and expert health reference group • Develop public engagement program • Develop a recycled water policy to be implemented by CoS with endorsement at senior management level (CEO)
Element 2: Assessment of the recycled water system
• Consider inadvertent or unauthorised uses of recycled water • Revise assessment of the system as required; including system components, flow diagrams; catchment attributes, water quality data; and analysis of hazards and hazardous events • Develop assessment criteria for the SCADA data and implement
Element 3: Preventative measures for recycled water management
• Identify alternative or additional preventative measures, e.g. UV disinfection and aeration for iron removal. • Document preventative measures and strategies, removal efficiencies of wetland and aquifer • Validate barriers by monitoring of water quality • Assess CCP and QCP limits and trigger values and link to operational procedures
Element 4: Operational procedures and process control
• Document all operational procedures within the risk management plan • Document monitoring protocols, including the frequency for each parameter • Document the procedures for corrective actions when operational parameters are not met • Establish regime for equipment maintenance and performance assessment • Establish procedure for quality assurance of materials and chemicals
Element 5: Verification of recycled water quality and environmental performance
• Assess the water quality monitoring in relation to operational and reporting requirements • Document the location and frequency of sampling to ensure representative and reliable data • Establish and inquiry and response program for users (Mawson Lakes residents) • Develop reporting mechanisms and procedures for quarterly review of monitoring data • Document the procedure for corrective responses to non conformance or feedback from users
Element 6: Management of incidents and emergencies
• Define a communication protocol including a list of key contacts and stakeholder agencies • Develop a public and media communication strategy • Define potential incidents and document response plans
Element 7: Operation, contractor and end user awareness and training
• Develop mechanisms to increase awareness of the recycled water system • Document training required and undertaken
Element 8: Community involvement and awareness
• Assess requirements for effective involvement of users of recycled water and the community • Develop a comprehensive communication and education strategy
Element 9: Validation, research and development
• Validate SCADA system, CCPs and QCPs • Develop a research plan to address remaining knowledge gaps e.g. revised health risk assessment, infrastructure and aesthetics, public engagement and preliminary risk management plan for the catchment.
Element 10: Documentation and reporting
• Develop a records management system • Establish procedures for internal and external reporting
Element 11: Evaluation and audit
• Centralise all system information for ease of access • Develop procedures for annual and longer-term (3-5 years) performance review • Establish procedures for internal and external auditing including communication of results
Element 12: Review and continual improvement
• Review by senior managers • Develop a recycled water quality management improvement plan

8.7 Conclusions

The ASTR project is a research intensive project due to the level of innovation required to satisfactorily address the range of risks involved. In general, significant investment in data and evaluation will be needed to demonstrate that risks can be effectively managed in first-of-kind MAR projects.

The ASTR project has made significant progress in terms of the project stages progressed, but additional work is required in establishing and documenting the operation of the system and providing timely responses that are auditable. A risk management plan, the main components of which have been highlighted above (Table 8-7), is yet to be developed.

8.8 References

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9 TOWARDS STORMWATER ASTR AT MOUNT GAMBIER, SOUTH AUSTRALIA

The majority of Mount Gambier’s urban stormwater is discharged directly via drainage wells into the unconfined, karstic Gambier Limestone aquifer. This aquifer provides the majority of recharge to the Blue Lake from which Mount Gambier’s drinking water supply is sourced. Discharge of urban runoff to the aquifer commenced in the 1800s as a means of stormwater drainage, but is now recognised as contributing to the drinking water supply in Blue Lake. More recently, this example of stormwater to potable recycling via the aquifer that has been operating for over 100 years has been examined in a risk assessment framework (Wolf *et al.* 2006; Vanderzalm *et al.* 2009a,b). This serves as an example of the transition from historical unintentional potable reuse via drainage wells to managed aquifer recharge where risks are identified and preventative measures put in place to protect human health and the environment.

9.1 Site description

The regional city of Mount Gambier is in the southeast corner of South Australia, approximately 30 km inland (Figure 9-1). Stormwater recycling via the aquifer contributes to Mount Gambier’s drinking water supply sourced from the Blue Lake, a groundwater fed volcanic crater lake (Figure 9-2). Blue Lake is also of high environmental value to the region as a tourist attraction due to its annual colour change process and vibrant blue colour in summer.

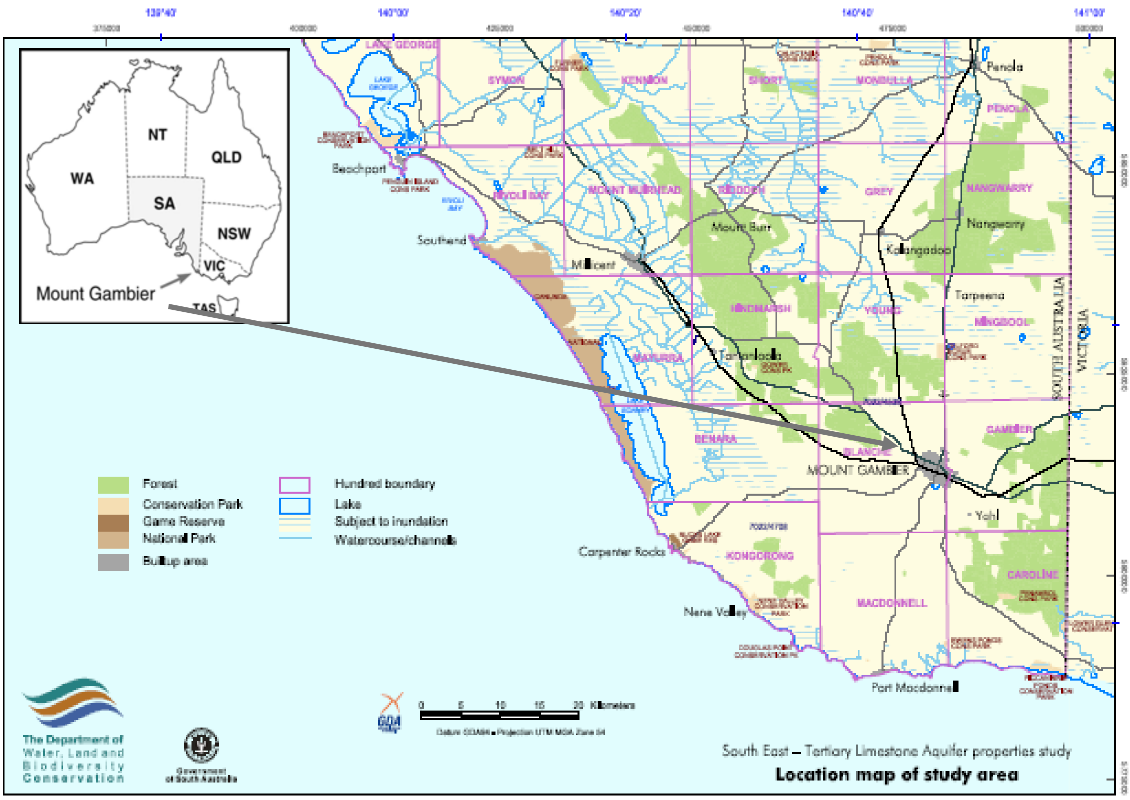

Figure 9-1 Location of the City of Mount Gambier, South Australia (after Mustafa and Lawson 2002)

Figure 9-2 The Blue Lake, a groundwater fed volcanic crater which is the source of drinking water supply for Mount Gambier

9.1.1 Sequence of development

Mount Gambier's stormwater drainage scheme was initiated to prevent flooding of the urban area and has through time become recognised to be a stormwater-to-potable recycling scheme, via the aquifer, by Aquifer Storage Transfer and Recovery (ASTR). A summary of the key development milestones is given in Table 9-1.

Table 9-1 Time series of key development milestones in Mount Gambier

Timeline	Key development milestones
1840	Settlement, farming, forestry and railway industries commence
1880s	Hand dug drainage wells
1884	Reticulated water supply commenced from Blue Lake
1940s	Commencement of drilled drainage wells
1973	First drainage wells fitted with silt traps (pre-treatment)
1976	*Water Resources Act* prevents discharge of waste into groundwater system
2001	Blue Lake Management Plan recognises the role of stormwater discharge in recharging Blue Lake and its groundwater system
2003-2009	Impact of stormwater recycling on water quality in Blue Lake assessed
2005	EPA Guideline for Stormwater Management (applicable to new residential developments)
2009	Australian Guidelines for Water Recycling: Managed Aquifer Recharge

The activities from 2001 onwards allow this case study to be examined within a risk assessment framework consistent with the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a). Following recognition of the significance of stormwater to the Blue Lake and its capture zone (BLMC 2001; 2006), the impact of stormwater recycling on the water quality within Blue Lake was assessed and forms the basis of the case study assessment. A new set of guidelines for stormwater management in new urban developments in Mount Gambier and the surrounding areas based on water sensitive urban design principles (SA EPA 2005) compliments the risk assessment of the existing measures for stormwater management and recycling.

9.1.2 Site configuration

The city of Mount Gambier provides the ~25 km^2 capture zone for stormwater harvesting, which comprises around 11 km^2 (40%) of impervious surfaces divided into over 400 stormwater drainage catchments (0.2–58 ha each). Residential land use dominates the impervious area of the city, followed by industrial and commercial land uses.

Stormwater recharge to the unconfined Gambier Limestone aquifer occurs predominantly through stormwater drainage wells. Most drainage catchments have at least one operational stormwater drainage well and there are currently ~640 operational in the city area (Figure 9-3). The City of Mount Gambier manages 350 of the drainage wells with the remaining wells being privately owned.

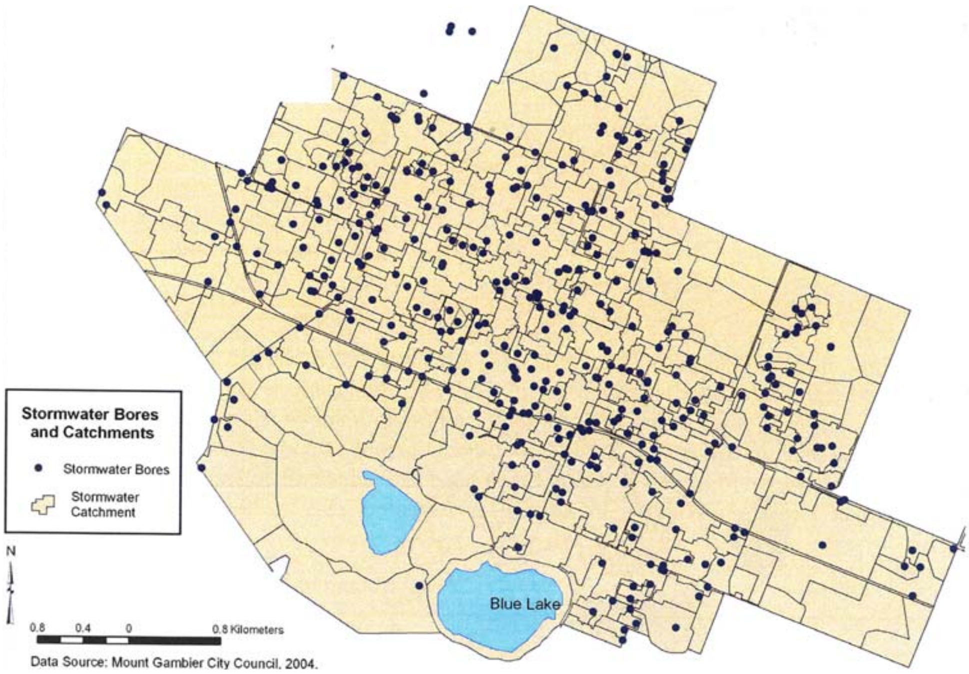

Figure 9-3 Stormwater drainage wells and catchments areas in the City of Mount Gambier (Wolf et *al*. 2006)

Annually ~3.6 GL of water is extracted from the Blue Lake for the reticulated water supply. The volume of stormwater discharged annually is estimated at 2.9-4.2 GL and contributes 35-55% of the water entering the lake (Wolf *et al.* 2006). The distance between individual drainage wells and the Blue Lake varies from only 200 m to approximately 5 km.

Pre-treatment consists of gross pollutant removal using three-chamber silt traps (Figure 9-4) prior to discharge via drainage wells, and continuous deflective separation (CDS) units prior to discharge via karst features. Post-treatment is chlorination prior to drinking water supply. In addition there are supporting programs to minimise stormwater pollution by improving community and industry awareness of the potential hazards to water quality in the catchment.

Figure 9-4 Three chamber silt trap in Mount Gambier

The major components of the stormwater recycling scheme in Mount Gambier are summarised in Figure 9-5 and Table 9-2.

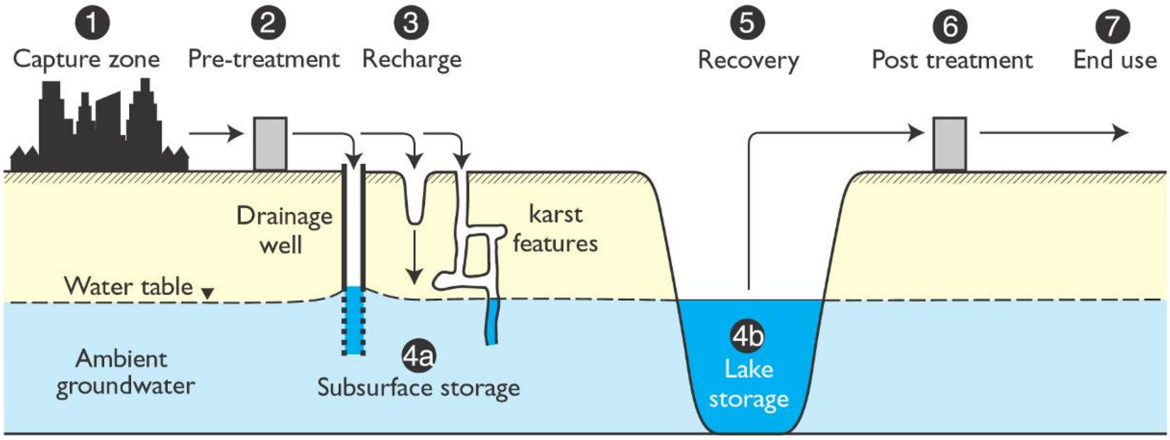

Figure 9-5 Mount Gambier stormwater recycling system schematic of water flow

Table 9-2 Mount Gambier stormwater recycling system components

Component	Mount Gambier system
1. Capture zone	Stormwater from the City of Mount Gambier
2. Pre-treatment	Triple chamber silt traps prior to some drainage wells; continuous deflective separation (CDS) units prior to some karst features
3. Recharge	Drainage wells; karst features e.g. sinkholes, caves; infiltration
4. Subsurface storage	a) Aquifer storage – Unconfined Gambier Limestone aquifer; minimum 2-20 years
	b) Lake storage – Blue Lake; 6-10 years (Herczeg *et al.* 2003)
5. Recovery	Extraction from Blue Lake (~3.6 Mm3/year)
6. Post-treatment	Disinfection via chlorination
7. End use	Reticulated drinking water supply

9.1.3 Aquifer description

MAR operations are aimed at a series of carbonate formations of Tertiary age. The aquifer consists of an interconnected series of limestone (Green Point Member), dolomite (Camelback Member) and marl (Greenways Member) that form the Gambier Limestone Aquifer. Up to seven alternating sub-units have recently been defined within this aquifer; Units 1 through 5 are alternating aquifers and aquitards within the Green Point member, overlying the Camelback and Greenways members (Figure 9-6) (Lawson and Hill, in press).

The Gambier Limestone is a dual porosity medium with karstic flow supplementing primary intergranular flow. While considerable variation in travel time is expected in the karstic aquifer, natural and applied tracers suggest a minimum transit time of 2-20 years (Vanderzalm *et al.* 2009).

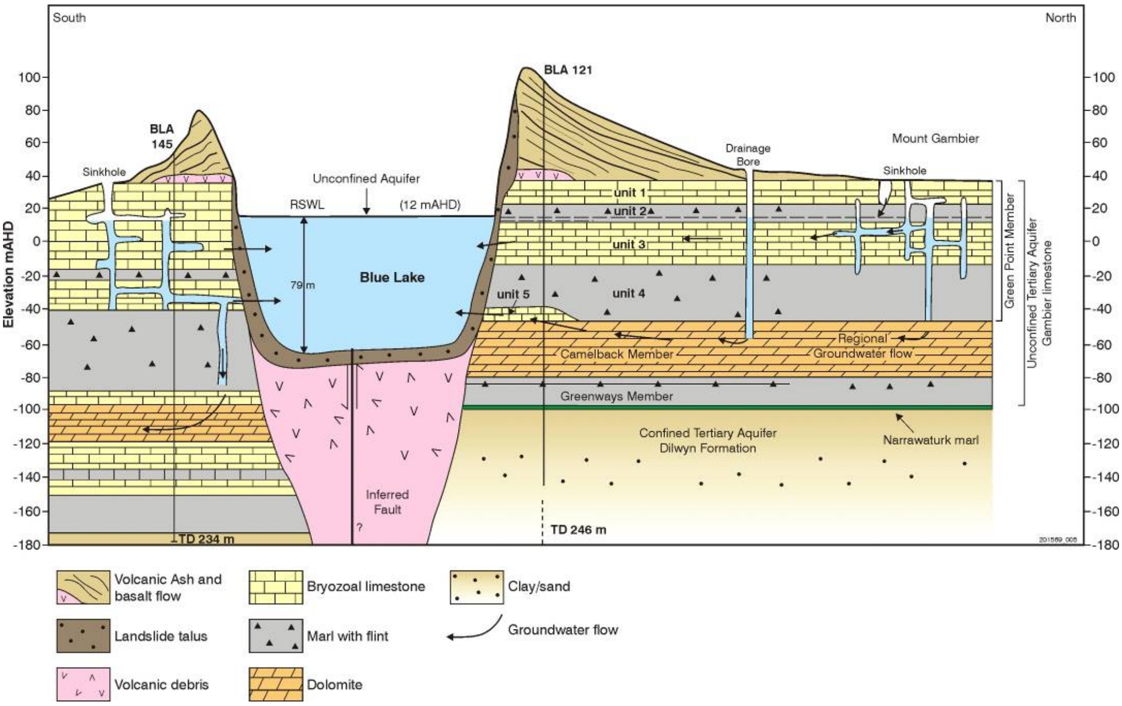

Figure 9-6 Conceptual diagram of interactions between groundwater and surface water in the vicinity of the Blue Lake (Lawson and Hill, in press).

The regional groundwater flow direction is towards the southwest with groundwater discharges via coastal and offshore springs. However, in the lake vicinity, the hydraulic gradient is low (0.0001) and local pumping in the karstic domain can reverse the flow direction. Due to the karstic nature of the aquifer, pumping-test derived transmissivities vary over two orders of magnitude from 200 m^2/day to greater than 10,000 m^2/day, with porosity estimates between 30% and 50% (Wolf et al. 2006).

Lake inflow is believed to be coincident with the dolomitic Camelback layer of the aquifer at ~50 m below the lake surface (~ -40 m AHD). However the contribution of individual stratigraphic units to lake inflow and the connection between these units is largely unknown and is currently under investigation (J. Lawson, DWLBC pers. comm.). To the south of Blue Lake, it is possible that Unit 1 provides flow into Blue Lake. While the Camelback member shows potential for outflow, outflow is not significant to the lake's water balance (Lamontagne 2002).

On the basis of differences in salinity of the aquifers, it has been estimated that less than 20% of the annual groundwater input to Blue Lake originates from the confined Dilwyn aquifer underlying the Gambier Limestone aquifer (Herczeg *et al*. 2003).

Ambient groundwater is fresh (470 mg/L TDS on average) and oxic. Reactive minerals include calcite and dolomite.

9.1.4 Source water description

The source water for recharge is urban stormwater from a mixed residential, industrial and commercial catchment. The volume of stormwater discharged is not gauged but the annual volume is estimated at 2.9-4.2 GL based on 11 km^2 of impervious surfaces, rainfall of 625-870 mm/year, evaporation of 1,270-1,300 mm/year and 184-207 rainfall days/year (Wolf *et al*. 2006). In general, the quality of urban stormwater available for recharge is oxygenated, fresh and a source of nutrients. Microbial indicator species and trace organic chemicals have also been detected in the stormwater.

9.2 Stage 1 Entry level risk assessment

Table 9-3 and Table 9-4 show the completed entry-level risk assessment for the Mount Gambier scheme, as per section 4.3 of the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a). Table 9-4 also provides a summary of Stage 2 investigations required as identified in the Stage 1 assessment.

Table 9-3 Mount Gambier entry level assessment part 1 – Viability

	Attribute	Answer
1	Intended water use	
	• Is there an ongoing local demand or clearly defined environmental benefit for recovered water that is compatible with local water management plans?	✓ Stormwater drainage enhances groundwater recharge and contributes to Blue Lake, which is a drinking water supply and has unique environmental value
2	Source water availability and right of access	
	• Is adequate source water available, and is harvesting this volume compatible with catchment water management plans?	✓ Adequate volume of stormwater available, harvesting meets stormwater management and flood protection goals
3	Hydrogeological assessment	
	• Is there at least one aquifer at the proposed managed aquifer recharge site capable of storing additional water?	✓ Unconfined karstic Gambier Limestone aquifer has storage capacity and is over-exploited
	• Is the project compatible with groundwater management plans?	✓ Improving quality and quantity of recharge is compatible with Blue Lake Management Plan
4	Space for water capture and treatment	
	• Is there sufficient land available for capture and treatment of the water?	✓ Stormwater drainage network is used for capture and harvesting. For many drainage wells there is little space available for installing new treatments.
5	Capability to design, construct and operate	
	• Is there a capability to design, construct and operate a managed aquifer recharge project?	✓ Capability exists between SA Water, City of Mount Gambier, South East Natural Resources Management Board, DWLBC*, CSIRO and SA EPA to operate this project →Go to Table 9-4

* currently known as the Department for Water.

Table 9-4 Mount Gambier entry level assessment part 2 – degree of difficulty

Question	Mount Gambier answers	Investigations required
1 Source water quality with respect to groundwater environmental values		
Does source water quality meet the requirements for the environmental values of ambient groundwater?	No – environmental values of the aquifer include drinking and pristine ecosystem support. The aquifer is the major source of water to Blue Lake. Require Stage 2 investigations to assess risks.	Stormwater quality evaluation for nutrients, pathogens, inorganic and organic chemicals (Section 9.3.1)
2 Source water quality with respect to recovered water end use environmental values		
Does source water quality meet the requirements for the environmental values of intended end uses of water on recovery?	No – stormwater does not meet drinking water standards or aquatic guideline values. Require Stage 2 investigations to evaluate hazard attenuation processes in aquifer and lake.	Water quality and hazard attenuation processes evaluation (Section 9.3.1)
3 Source water quality with respect to clogging		
Is source water of low quality, for example: total suspended solids, total organic carbon or total nitrogen >10 mg/L, And is soil or aquifer free of macropores?	No – source water is of moderate quality but karst aquifer is unlikely to be affected by clogging. Where drainage bores clog they are readily rehabilitated by reaming.	None
4 Groundwater quality with respect to recovered water end use environmental values		
Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery?	Generally yes but some groundwater in unconfined aquifer and is affected by anthropogenic sources and quality is variable. Require Stage 2 investigations to evaluate groundwater quality.	Groundwater quality evaluation against environmental guidelines (Section 9.3.1)
5 Groundwater and drinking water quality		
Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?	Yes – target aquifer is used for drinking water supply via Blue Lake and directly via private wells. Require Stage 2 investigations to assess the risk to groundwater quality.	Groundwater quality evaluation against drinking water guidelines (Section 9.3.1)
6 Groundwater salinity and recovery efficiency		
Does the salinity of native groundwater exceed: (a) 10000 mg/L, or (b) the salinity criterion for uses of recovered water?	No – mean salinity of the Gambier Limestone aquifer < 500 mg/L.	None
7 Reactions between source water and aquifer		
Is redox status, pH, temperature, nutrient status and ionic strength of source water and groundwater similar?	Yes – similar water quality thus limiting the potential for adverse reactions. However, some dissolution of calcite likely.	Assessment of drainage well stabilities
8 Proximity of nearest existing groundwater users, connected ecosystems and property boundaries		
Are there other groundwater users, groundwater–connected ecosystems or a property boundary near (within 100–1000 m) the MAR site?	Yes – potential for other groundwater users nearby for non-potable purposes.	Identify other uses and ensure they are not potable
9 Aquifer capacity and groundwater levels		
Is the aquifer confined and not artesian? Or is it unconfined, with a watertable deeper than 4 m in rural areas or 8 m in urban areas?	Yes – the unconfined aquifer has a deep water table, and good drainage through the karst features.	None

Question	Mount Gambier answers	Investigations required
10 Protection of water quality in unconfined aquifers		
Is the aquifer unconfined, with an intended use of recovered water being drinking water supplies?	Yes – unconfined aquifer with recovered water used for drinking water supplies. Require Stage 2 investigations to assess the protection of groundwater quality.	Urban land use and risk assessment for hazards present in the catchment draining to Blue Lake (Section 9.3.2)
11 Fractured rock, karstic or reactive aquifers		
Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?	Yes – karstic limestone aquifer. Require Stage 2 investigations to assess the potential consequences of migration of recharge water.	Tracer test to evaluate travel time in karstic aquifer (Section 9.3.3)
12 Similarity to successful projects		
Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?	Yes – stormwater drainage has been operating >100 years.	None
13 Management capability		
Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty, or with water treatment or water supply operations involving a structured approach to water quality risk management?	Yes – proponents have history of operating stormwater drainage wells and drinking water supplies. Structured approach to risk management is understood by city council and SA Water and is being implemented through the Blue Lake management plan.	None
14 Planning and related requirements		
Does the project require development approval? And is it in a built up area; on public, flood-prone or steep land; close to a property boundary; contain open water storages or engineering structures; likely to cause public health, safety or nuisance issues, or adverse environmental impacts?	No – already in operation.	None

In summary of the Stage 1 assessment the following investigations were identified in proceeding to Stage 2 (Table 9-5).

Table 9-5 Summary of Stage 2 investigations required at Mount Gambier

Issue		Investigations required at stage two	Discussed in section
1	Source water with respect to groundwater environmental values	Stormwater quality evaluation for nutrients, pathogens, inorganic and organic chemicals.	9.3.1
2	Source water quality with respect to recovered water and environmental values	Water quality and hazard attenuation processes evaluation	9.3.1
4	Groundwater quality with respect to recovered water and environmental values	Groundwater quality evaluation against environmental guidelines	9.3.1
5	Groundwater and drinking water quality	Groundwater quality evaluation against drinking water guidelines	9.3.1
7	Reactions between source water and aquifer	Assessment of drainage well stabilities	
8	Proximity of groundwater users	Identify other uses and ensure they are not potable.	
10	Protection of water quality in unconfined aquifers	Urban land use and risk assessment for hazards present in the catchment draining to Blue Lake	9.3.2
11	Fractured rock, karstic or reactive aquifers	Tracer test to evaluate travel time in karstic aquifer	9.3.3

9.3 Stage 2 Investigations

A series of studies were performed in support of the Stage 2 assessment as identified in Table 9-4, they are described below followed by the maximal and residual risk assessments.

Note that in this case study operational data are available unlike the preceding case studies where Stage 2 studies are required to determine whether to proceed to commissioning and what data and monitoring would be necessary to constrain risks. Hence the Stage 2 is somewhat redundant but is useful to identify hazards to be addressed in the operational risk assessment.

9.3.1 Water quality assessment

The water quality evaluation involved examining data for Mount Gambier's stormwater, the groundwater within the unconfined Gambier Limestone aquifer and Blue Lake itself (Table 9-6). Stormwater quality data were assessed using monitoring commissioned by the City of Mount Gambier (URS 2000; 2003) and supplemented with targeted studies to improve the characterisation of trace organic chemicals within stormwater (Wolf *et al.* 2006). The water quality data (SA EPA, unpublished data) for the unconfined aquifer was compiled for monitoring bores within the Blue Lake Protection and Capture Zone (BLPCZ) between 1981 and 2005. The historical water quality data for the Blue Lake between 1968 and 2005 was obtained from the SA Water and EPA database, a compilation of analytical results from the Australian Water Quality Centre (AWQC) (electronic format, unpublished data). Water quality data preceding 1968 may be available, but have not been included in this analysis as the reliability of historical analytical and sampling methodologies is uncertain. As Blue Lake is important as a drinking water supply and as a tourist attraction due to its vibrant colour over summer (Figure 9-2), water quality was compared to drinking water guidelines (NHMRC–NRMMC 2004) and target values for aquatic ecosystem protection (ANZECC–ARMCANZ 2000; SA EPA 2003).

Mount Gambier's urban stormwater, the source water for recharge, is oxygenated, fresh (EC ~ 77 µS/cm) and of neutral pH, but exhibits considerable variability in the concentration of nutrients, metals and metalloids. Turbidity and iron exceed the drinking water guidelines (NHMRC–NRMMC 2004), while mean concentrations of phosphorus, aluminium, copper, lead and zinc all exceed the target value for aquatic ecosystem protection (ANZECC–ARMCANZ 2000; SA EPA 2003). There is some evidence for the presence of atrazine in Mount Gambier's stormwater in excess of the drinking water guideline value, but detection limits were not sensitive enough to confidently assess this risk. Targeted sampling for analysis with sensitive analytical capabilities (2005-2006) reported 7 ng/L atrazine in Blue Lake, and 0.3-26 ng/L in the unconfined aquifer, far below the drinking water quality guideline value of 100 ng/L.

Phosphorus mobility in the carbonate aquifer and thus the concentrations in both the groundwater and the Blue Lake meet the target value and there is no indication of increasing concentrations with time. Similarly the metal concentrations within Blue Lake meet the aquatic ecosystem targets and have remained constant with time. As the unconfined aquifer is susceptible to contamination from the overlying land use, it is understandable that copper, lead and zinc exhibit variable concentrations within the groundwater which can be higher than in the stormwater. The annual colour change in Blue Lake is coincident with an annual calcite precipitation cycle which provides a mechanism to remove inorganic species from the water column. As a result, some inorganic species exhibit lower concentrations in the Blue Lake than in the groundwater that replenishes the lake (Vanderzalm *et al*. 2009a).

Detection of microbial indicators in Blue Lake has been attributed to external sources (birds) and managed by chlorination prior to reticulation. While the carbonate aquifer is considered a low risk for release of radionuclides, a more detailed assessment should be undertaken as part of a future risk management plan to verify the risks are low.

Table 9-6 Mount Gambier water quality data summary for stormwater 1999-2004; Blue Lake prior to chlorination (1968-2005); and the groundwater from the unconfined Gambier Limestone aquifer (1981-2005)

	DWG	Aquatic guideline	Stormwater		Blue Lake		Gambier Limestone aquifer	
			n	mean	n	mean	n	mean
Physical characteristics								
Temperature (°C)			10	17	367	17		
pH (pH units)	6.5-8.5		10	7.9	919	8.2	75	7.5
Conductivity (µS/cm)			10	77				
Total Dissolved Solids (mg/L)	500		10	49	821	370	47	470
Dissolved Oxygen (mg/L)	85%		10	5.1				
Redox Potential (mV)			10	229				
Suspended Solids (mg/L)			86	200	27	<1		
Turbidity (NTU)	5		10	79	163	0.29		
True Colour (HU)					163	1.1		
Major ions (mg/L)								
Bicarbonate			10	47	754	220	50	280
Bromide					37	0.31		
Sulfate	250	5	10	8.6	748	19	67	13
Chloride	250		40	6.2	772	87	209	84
Fluoride	1.5				823	0.19	62	0.24
Calcium			10	14	755	46	50	74
Magnesium			10	1.2	757	21	50	22
Potassium			10	1.3	770	3.1	82	4.6
Sodium	180		10	8.8	759	60	73	57
Nutrients (mg/L unless otherwise specified)								

	DWG	Aquatic guideline	Stormwater		Blue Lake		Gambier Limestone aquifer	
			n	mean	n	mean	n	mean
Nitrate as N	11.3		77	0.44	1500	3.4	179	9.8
Ammonia as N	0.5	0.5	2	0.01	764	0.017	16	0.012
Total Kjeldahl Nitrogen			85	0.98	699	0.24	249	0.3
Total Nitrogen		5	85	1.4				
Total Phosphorus		0.5	86	0.59	891	0.02	241	0.2
Dissolved Organic Carbon		15 [1]	11	10	296	1.1	213	1.3
Chlorophyll *a* (µg/L)		5 [2]			301	1.2		
Metals and metalloids (mg/L)								
Aluminium - Soluble	0.2	0.1	7	0.19	110	0.025	185	0.046
Aluminium - Total			11	0.9	99	0.032	191	1
Antimony - Total	0.003	0.03			38	0.001		
Arsenic - Total	0.007	0.05	34	0.002	139	<0.001	205	0.002
Barium - Total	0.7				21	0.005		
Beryllium - Total		0.004			11	<0.0005		
Boron - Soluble	4		10	0.07	110	0.05	22	0.04
Cadmium - Soluble			2	<0.0005				
Cadmium - Total	0.002	0.002	10	<0.0005	56	<0.001		
Chromium - Soluble			32	0.001				
Chromium - Total	0.05 as Cr (VI)		86	0.01	149	0.008	209	0.02
Copper - Soluble			32	0.003				
Copper - Total	1	0.01	85	0.019	150	0.009	209	0.04
Iron - Soluble			2	<0.03				
Iron - Total	0.3	1	10	**0.84**	698	0.047	221	**4.2**
Lead - Soluble			32	0.001				
Lead - Total	0.01	0.005	85	**0.02**	43	0.001	208	0.008
Manganese - Total	0.1				32	<0.005		
Mercury - Total	0.001				48	<0.0005		
Molybdenum - Total	0.05				30	<0.002		
Nickel - Soluble			32	0.0006				
Nickel - Total	0.02	0.15	85	0.005	30	0.019		
Selenium - Total	0.01	0.005			30	<0.003		
Tin - Total					10	0.0005		
Zinc - Soluble			32	0.05				
Zinc - Total	3	0.05	86	**0.15**	229	0.023	204	**0.07**
Microbiological (cfu/100 mL)								
Coliforms					455	16		
E.coli	0				244	**1**		
Thermotolerant coliforms	0				226	**1**		
Pesticides (µg/L)								
Atrazine	0.1		72	<0.5				
Simazine	0.5		73	<0.5				

DWG = drinking water guideline, taken from Australian Drinking Water Guidelines, or Augmentation of Drinking Water Supplies guidelines; Aquatic guideline taken from SA EPA (2003); [1] Guideline is for Total Organic Carbon; [2] ANZECC–ARMCANZ (2000) 95% level of protection

9.3.2 Urban land use and hazard identification

Given the variable nature of stormwater quality and the lack of data for organic chemical hazards, hazard identification was also undertaken by identifying high risk land use activities within the urban area. The current urban land use activities deemed as hazardous to the stormwater water quality were fuel depots, service stations, timber treatment plants, road works depots, roads with high density traffic and dry cleaners. The associated hazards were identified as benzene, ethylbenzene, toluene and xylene (BTEX), polycyclic aromatic

hydrocarbons (PAHs), copper chrome arsenic (CCA) and tetrachloroethene (PCE; also known as perchloroethylene and tetrachloroethylene).

The number and nature of the chemical hazards contained within each stormwater catchment was used to prioritise a small number (16) of high priority catchments where additional measures, such as additional pre-treatment steps or improved source control, could be implemented. Based on the existing data, the stormwater quality could be improved with pre-treatment capable of removing fine particulate matter (which would also serve to removal particle-bound organics such as PAHs).

Two risk assessment scenarios were considered in a quantitative risk assessment (QRA) to examine the potential for the aquifer to provide protection against the organic chemical hazards (Vanderzalm *et al*. 2009b). The first scenario used a range of input concentrations from a review of available urban stormwater in the United States over a 25 year period (Makepeace *et al.* 1995) and the second scenario simulated a 'worst case scenario', where the source water concentration could be several orders of magnitude greater than the guideline value with a uniform concentration distribution between zero and the maximum defined as the water solubility limit for the relevant parameter. BTEX compounds were rapidly degraded under aerobic conditions; with half-life estimates ranging between 3 and 28 days (NRMMC–EPHC–NHMRC 2009a). Despite the longer-half life estimates for the PAHs (32-3,800 days) and PCE (180-360 days), the simulated concentrations were also below the guideline values due to the long residence time within the system. Testing the treatment system for a suite of organic chemicals with two scenarios for source water concentration, both exceeding those observed for Mount Gambier's stormwater, gives confidence in the natural treatment in the system which adequately protects the quality of the drinking water supply. Assessment of the risks posed by emerging chemical hazards may require additional site specific studies to be undertaken.

9.3.3 Tracer test to evaluate travel time in a karstic aquifer

Aquifer travel time estimates were based predominantly on a sulfur hexafluoride (SF_6) tracer test, where SF_6 was injected into 24 bores situated 1-3 km from the northern to north-western side of Blue Lake. While some injection sites were located up gradient of the very gentle groundwater gradient (north to south), the majority of injection sites were within a zone further to the west, to account for the observed orientation of preferential flow paths in the NW to SE direction (J. Lawson, DWLBC, unpublished data); this was intended to maximise the opportunity to detect early breakthrough of SF_6 to the lake. The injection bores consisted of 22 stormwater drainage bores and 2 groundwater observation bores, and were predominantly completed in the Camelback member.

The SF_6 tracer test indicated that it is possible for stormwater recharged directly into the unconfined aquifer via stormwater drainage wells to reach Blue Lake in ~2 years. This value was used to refine the estimate of minimum travel time in the aquifer to 2-20 years (Vanderzalm *et al.* 2009a). Re-sampling the injection bores and groundwater monitoring provided varying SF_6 concentrations indicating that the SF_6 tracer had not been evenly dispersed through the aquifer due to the variable nature of groundwater movement in a karstic aquifer.

The potential for trace organic chemical signatures within Blue Lake to serve as time markers was investigated but was not successful due to the lack of analytical detections.

9.4 Stage 2 Pre-commissioning risk assessment

9.4.1 Maximal risk assessment

The risk assessment is presented in the order of the twelve key hazards outlined in the MAR Guidelines (NRMMC–EPHC–NHMRC 2009a). A semi-quantitative risk assessment was

performed for each of the hazards for human health and environmental endpoints, with green, orange and red indicating low, uncertain and high risks respectively (Table 9-7). The white boxes indicate that that hazard does not apply to that endpoint.

The maximal risk assessment for the human health end point was conducted by comparing the water quality data for raw stormwater and native groundwater for hazards 1 to 7 to the Australian Drinking Water Guidelines (NHMRC–NRMMC 2004). For the environmental endpoint, the aquifer's beneficial use was the maintenance of groundwater dependent ecosystems (i.e. Blue Lake), therefore the quality of raw stormwater was compared to the South Australian Environment Protection (Water Quality) Policy (SA EPA 2003) water quality criteria or the Guidelines for Fresh and Marine Water Quality (ANZECC–ARMCANZ 2000).

For hazards 8 to 12, the risks were assessed based on their potential impacts on the aquifer or biosphere as described in the MAR Guidelines. A pilot study of biodiversity of stygofauna in stormwater recharge wells in Mount Gambier is reported in Appendix 3 of Dillon *et al*. (2009).

Table 9-7 Maximal risk assessment summary for Mount Gambier, SA

	MAR Hazards	Human endpoint – drinking water	Environmental endpoint – aquifer and lake
1.	Pathogens – enteric pathogens in stormwater	U	L
2.	Inorganic chemicals – presence of arsenic and iron	H	H
3.	Salinity and sodicity – both stormwater and groundwater are fresh	L	L
4.	Nutrients: nitrogen, phosphorous and organic carbon – potential for eutrophication of the Blue Lake	L	H
5.	Organic chemicals – presence of pesticides and other organic chemicals in stormwater	H	H
6.	Turbidity and particulates – untreated stormwater is relatively turbid	H	L
7.	Radionuclides – low potential for release from aquifer sediments or presence in the source stormwater	L	L
8.	Pressure, flow rates, volumes and groundwater levels – gravity drainage in an unconfined aquifer		L
9.	Contaminant migration in fractured rock and karstic aquifers – many karstic features in aquifer identified		H
10.	Aquifer dissolution and stability of well and aquitard – drainage wells observed to be stable after 100 years		U
11.	Aquifer and groundwater-dependent ecosystems – potential for stormwater impacts		H
12.	Energy and greenhouse gas considerations – lower than other options for drinking water supply to Mount Gambier.		L

L low risk; **U** unknown risk; **H** high risk.

For hazard 1, it was assumed pathogens could be present in the source water despite a lack of monitoring data for pathogens in Mount Gambier's stormwater and was hence labelled unknown. For hazard 12, energy and greenhouse gas considerations a comparable risk assessment was performed. The energy consumption per unit volume of water recharged is negligible in comparison with any alternative supply of water to Mount Gambier.

9.4.2 Residual risk assessment

The Stage 2 residual risk assessment for the Mount Gambier system was performed using the same approach as for the maximal risk assessment but with inclusion of aquifer and lake treatment and chlorination and regulated extraction from the Blue Lake. The results indicated that the risks were considered acceptable but the uncertainty of the assessment was high for organic chemicals.

9.5 Stage 3 Operational residual risk assessment

Water quality data for Blue Lake (1968-2005) illustrates compliance with guidelines for protection of human health and environmental end points. The operational residual risk assessment for this case study is identical to the pre-commissioning residual risk assessment. Specific water quality monitoring targets for Blue Lake have been defined to allow management responses to be implemented in response to any detrimental change in water quality (Vanderzalm *et al*. 2009a) and these can be implemented as part of the risk management plan.

9.6 Stage 4 Operation-refined risk management plan

Currently, there are a number of programs in place to protect the water quality within Blue Lake and its groundwater system, but these remain to be incorporated within a risk management plan, the essential elements of which are given in Table 9-8.

Table 9-8 Draft framework for managing the recycled stormwater component in recharge to Blue Lake, Mount Gambier's drinking water supply (Vanderzalm *et al*. 2009a).

Framework element and components	Activity
Element 1: Commitment to responsible use and management of recycled water	
Responsible use of recycled water *Recycled water policy* *Regulatory and formal requirements* *Engaging stakeholders*	• Stormwater discharge to the groundwater recognised as a major component of the recharge to Blue Lake Commitment from State and Local government to protect Blue Lake and its aquifer system - Blue Lake Management Plan • SA EPA guideline for the management of stormwater in Mount Gambier in new developments • Water Quality Environmental Protection Policy • SA EPA Licence arrangements
Element 2: Assessment of the recycled water system	
Identify intended used and source of recycled water *Recycled water system and analysis* *Assessment of water quality data*	• Environmental values of Blue Lake include drinking water supply, maintaining the annual colour change and clarity, prevention of algal blooms • Stormwater discharge to the groundwater is a major component of the recharge to Blue Lake • Stormwater quality indicates potential to breach water quality guidelines for inorganic chemicals, nutrients, trace organic chemicals • No evidence of degradation in Blue Lake water quality from long-term stormwater discharge • Nitrate levels in Blue Lake are increasing but not due to stormwater discharge
Hazard identification and risk assessment	• Hazard identification based on the current urban land use identified risks from BTEX, PAHs, PCE, CCA in stormwater discharge • Knowledge gap identified regarding P cycle in Blue Lake, could impact on algal blooms
Element 3: Preventative measures for recycled water management	
Preventative measures and multiple barriers *Critical control points*	• Chlorination of Blue Lake (human health) • Stormwater pre-treatment includes gross pollutant removal through street sweeping and three-chambered settling pits • Industry best-practice • Community awareness (e.g. drain stencilling) • Potential modifications include improved pre-treatment (fine material, organic contaminants) in high risk stormwater

Framework element and components	Activity
	catchments • Aquifer and lake storage
Element 4: Operational procedures and process control	
Components: *Operational procedures* *Operational monitoring* *Corrective action* *Equipment capability and maintenance* *Materials and chemicals*	• Prevent gross contamination stormwater – spill response actions, council maintenance of stormwater pre-treatment • Monitoring recommendations based on groundwater and Blue Lake quality • Disinfection, post-treatment measures if necessary (human health) • Stormwater pre-treatment measures – maintenance schedule, suggest upgrade in high risk catchments • Material used for stormwater treatment and drainage well construction suitable for function
Element 5: Verification of recycled water quality	
Recycled water quality monitoring *Application and discharge site monitoring* *Satisfaction of users of recycled water* *Short-term evaluation of results* *Corrective action*	• Stormwater quality monitoring undertaken • Groundwater quality monitoring undertaken annually • Blue Lake water quality monitoring undertaken at various frequencies, based on parameter/s of interest • Recommendations for monitoring program and evaluation of results • Corrective action depends on the exceedance
Element 6: Management of incidents and emergencies	
Communication *Incident and emergency response protocols*	• Protocol for managing spills that could impact on stormwater quality
Element 7: Operation, contractor and end user awareness and training	
Operator, contractor and end use awareness and involvement *Operator, contractor and end user training*	• Drillers – appropriate drainage well construction (material and depth) • WaterCare program - Industry education regarding stormwater quality and impacts on reuse • Industry best practice
Element 8: Community involvement and awareness	
Community consultation commendation and education	• WaterCare program - Community education regarding stormwater quality and impacts on reuse
Element 9: Validation, research and development	
Validation of processes *Design of equipment* *Investigative studies and research monitoring*	• Water quality monitoring within Blue Lake • Stormwater treatment device – design and test new device or retrofit of existing infrastructure • P cycling, aquifer residence time, contaminant attenuation, hydrostratigraphy
Element 10: Documentation and reporting	
Management of documentation and records *Reporting*	• All monitoring results, new preventative measures, new drainage wells, incidents and research to be recorded and stored • Results and actions reported on an annual basis to EPA/NRMB (via Blue Lake Management Committee)
Element 11: Evaluation and audit	
Long-term evaluation of results *Audit of recycled water management*	• Reporting • Blue Lake Management Committee
Element 12: Review and continual improvement	
Review by senior managers	• Blue Lake Management Plan review

9.7 Conclusions

The scheme for stormwater recycling via the unconfined Gambier Limestone aquifer and the Blue Lake at Mount Gambier, SA has progressed from a stormwater management activity to a recognised stormwater to indirect potable recycling activity with over 100 years of operation. Recently this scheme has been assessed in the risk framework of the MAR Guidelines, which has developed the understanding of natural treatment processes in this stormwater ASTR system. The next step is to encompass the risk assessment and current management activities within a risk management plan that is accepted and implemented by the relevant stakeholders.

9.8 References

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