Australian Water Recycling
Centre of Excellence

Economics and experiences of managed aquifer recharge (MAR) with recycled water in Australia

A report of the Managed Aquifer Recharge and Recycling Options (MARRO) project funded by the Australian Water Recycling Centre of Excellence

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Managed Aquifer Recharge and Recycling Options (MARRO)

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About the Australian Water Recycling Centre of Excellence

The mission of the Australian Water Recycling Centre of Excellence is to enhance management and use of water recycling through industry partnerships, build capacity and capability within the recycled water industry, and promote water recycling as a socially, environmentally and economically sustainable option for future water security.

The Australian Government has provided $20 million to the Centre through its National Urban Water and Desalination Plan to support applied research and development projects which meet water recycling challenges for Australia's irrigation, urban development, food processing, heavy industry and water utility sectors. This funding has levered an additional $40 million investment from more than 80 private and public organisations, in Australia and overseas.

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Cover Photograph

Description: Soil Aquifer Treatment Basin (Basin A) filling in 2014.
Photographer: Karen Barry, CSIRO

Contents

Figures

Tables

Glossary

aquifer	A geological formation or group of formations capable of receiving, storing and transmitting significant quantities of water. Aquifer types include confined, unconfined and artesian.
ASR	Aquifer Storage and Recovery, a MAR technique
ASTR	Aquifer Storage Transfer and Recovery, a MAR technique
BCR	Benefit cost ratio
BGL	Below ground level
capex	Capital expenditure
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CBA	cost benefit analysis
discounting	The standard approach to discounting reduces a time stream of costs and income to an equivalent amount of today’s dollars. That single amount is known as the present value of the future stream of costs and income. Present Value is calculated using the method of compound interest. The rate at which the present value is computed is known as the discount rate.
disinfection	The process designed to kill most microorganisms, including essentially all pathogenic bacteria. There are several ways to disinfect; chlorine is most frequently used in water treatment.
GWR	Groundwater replenishment; Water Corporation approach to replenish an aquifer with advanced treated wastewater for later use as a drinking source.
GWRT	Groundwater replenishment trial; Water Corporation Aquifer Transfer Storage and Recovery trial at Beenyup
irrigation	Provision of sufficient water for the growth of crops, lawns, parks and gardens; can be by flood, furrow, drip, sprinkler or subsurface water application to soil. cost and benefits per kilolitre of recycled water supplied
levelised cost	Levelised cost (or benefits) allows options of different capacity to be compared on a like-for-like basis. It is calculated as the present value cost (or benefits) of the option divided by the present value of water supplied
managed aquifer recharge (MAR)	The intentional recharge of water to aquifers for subsequent recovery or environmental benefit.
monitoring	Systematically keeping track of something, including sampling or collecting and documenting information.
net present value	The standard approach to discounting reduces a time stream of costs and income to an equivalent amount of today’s dollars. That single amount is known as the present value of the future stream of costs and income. Present Value is calculated using the method of compound interest. The rate at which the present value is computed is known as the discount rate.
opex	Operating expenditure; includes operating and maintenance costs
pathogen	A disease-causing organism (e.g. bacteria, viruses, protozoa).
pre-treatment	Any treatment (e.g. detention, filtration) that improves the quality of water before injection.

quality	The totality of characteristics of an entity that bear on its ability to satisfy stated and implied needs; the term ‘quality’ should not be used to express a degree of excellence.
RWQI	Recycled water quality indicator
RWQP	Recycled water quality parameter
reuse	Using water that would otherwise be discharged to wastewater or stormwater systems, for domestic, commercial, agricultural or industrial purposes.
salinity	The presence of soluble salts in soil or water. Electrical conductivity and total dissolved salts are measures of salinity.
SAT	Soil aquifer treatment, a MAR technique
schmutzdecke	Over a slow sand filter, the reddish-brown sticky coating formed on top of the sand, consisting of micro-organisms, partly decomposed organic matter, iron, manganese, aluminium and silica.
sewage or wastewater	Material collected from internal household and other building drains; includes faecal waste and urine from toilets, shower and bath water, laundry water and kitchen water.
source water	The water pumped or fed by gravity into a managed aquifer recharge scheme.
TSS	Total suspended solids
TWW	Treated wastewater
WWTP	wastewater treatment plant

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Executive summary

Despite the numerous benefits that Managed Aquifer Recharge (MAR) offers for water recycling, the uptake of this water resource management tool has been slower than expected due to uncertainty regarding the impact of clogging, water quality impacts and the overall economic feasibility. This report aims to address these knowledge gaps by presenting a national compilation of MAR experiences, including lessons learnt and economic assessment. Seven case studies of MAR for water recycling are presented, three of which use infiltration techniques for recharge while the remaining four employ well injection methods for recharge.

A companion report (Bekele *et al.* 2015) details the investigations relating to the impact of clogging and the fate of nutrients in two water recycling MAR schemes employing novel infiltration techniques. This research was undertaken within a three year Australian Water Recycling Centre of Excellence research project on ‘Raising the national value of water recycling by overcoming impediments to managed aquifer recharge’.

Table 1 summaries the economic assessment of six managed aquifer recharge case studies. The seventh case study (Werribee Aquifer Storage and Recovery) is under development and therefore cost information was not available at the time of writing. The economic case studies vary in nature from hypothetical assessments through to operational schemes. Infiltration basins, Western Australia, is a hypothetical case study based on experience with operational wastewater infiltration schemes. The evaluation of infiltration galleries at Floreat is based on outcomes from technical feasibility assessments and concept design recommendations, but is not currently in operation. Soil Aquifer Treatment is in operation at Alice Springs and the economic assessment is based on data for the scheme’s feasibility assessment (investigations, monitoring), construction and operation. Aquifer Storage and Recovery at Bolivar considers two options for irrigation supply (9 GL/yr wastewater ASR and 6 GL/yr year blended stormwater and wastewater ASR) using economic values from a field scale wastewater ASR trial and capital and operating costs for operational stormwater ASR schemes. Aquifer transfer storage and recovery at Anglesea is a hypothetical case of recycling water via an aquifer for eventual inclusion in the drinking water supply, an option not supported by current Victorian Government policy. The economic assessment of groundwater replenishment at Beenyup relates to an operational scheme currently under construction and was calculated on the basis of publically available data, drawing heavily on the information provided by the Beenyup groundwater replenishment trial.

Costs varied from $0.88-$3.56 per kilolitre for the six case studies with target recharge volumes ranging from 28 to 14,000 ML per year (a total of 42 GL/yr at a volume weighted mean cost of approximately $2.00/kL). However, it is difficult to make a direct comparison between the levelised cost or benefit of individual schemes due to the differences in case specific costs or benefits assessed. Notably the lowest cost for the Bolivar ASR scheme does not include any capital expenditure for water treatment as the ASR scheme was designed to was designed to use seasonally surplus excess capacity of an existing water recycling plant and pipeline.

The benefit to cost ratio can be compared to discuss the feasibility of using MAR to recycle water for a range of case studies. Five of the six economic assessments reported favourable benefit to cost ratios (benefit>cost) due to avoided costs associated with above ground storage, wastewater treatment, potable water or desalination. The infiltration gallery case study provides an example where MAR is only favourable when potable water costs are avoided. In this example, alternative sources such as groundwater are potentially available to supplement groundwater dependent ecosystems at considerably lower cost, but may not be sustainable.

The Soil Aquifer Treatment scheme at Alice Springs reported an unfavourable benefit to cost ratio. However in this case study the prime benefit of the scheme was to protect the health of the local community (from encephalitis, a mosquito-borne disease). This was not possible to quantify within the assessment and the avoided costs of an alternative were not considered to provide adequate health protection to the broader community. That is the benefits are understated in this analysis. In most instances the wastewater treatment plant upgrade to produce a suitable quality of recycled water or benign discharge to the environment precedes the decision to add storage and treatment via MAR. Therefore wastewater treatment plant capital expenditure is commonly a sunk cost.

Benefits were quantified at $0.20-$8.50 per kilolitre, with each end of the range representing the avoided cost of groundwater and surface storage respectively. Avoided costs of wastewater treatment and potable water supply including desalination were reported at $2.00-$4.10 per kilolitre. Additional benefits such as the value of aquifer replenishment, social and ecological benefits of maintaining groundwater dependent ecosystems or marine environments, long-term augmentation of drinking water supply, public health protection and willingness to pay for water security were not able to be quantified. It is apparent through this range of case studies that the potential benefits associated with water recycling via the aquifer are understated where these are currently not well understood and therefore not adequately quantified in cost benefit analysis. Even without a thorough assessment of potential benefits, MAR was found to be economic in the majority of case studies.

Table 1 Summary of economic assessment of six recycled water managed aquifer recharge case studies.

Case study		Target ML/yr	Cost (C)/ kL ($)	Benefit(B)/ kL ($)	BCR [‡]	Case specific costs assessed [#]	Benefits assessed	Potential benefits not quantified
1	Infiltration basins, WA	28.5	2.68	8.50	3.2	Loss to the environment Land costs equal, not considered equal	Avoided cost of above ground storage, aquifer treatment	Aquifer replenishment
2	Infiltration galleries, Perry Lakes and Floreat, WA	1,800	1.07	0.20 (avoided groundwater)	0.2	Loss to the environment	Avoided cost of maintaining wetland with groundwater or potable water	Ecological benefits due to reduced discharge of treated wastewater to marine environment
		1,800	1.07	2.00 (avoided potable water)	1.9			
3	Soil Aquifer Treatment, Alice Springs, NT	1,200[≠]	2.09	0.39(high value crops)	0.2	Wastewater treatment plant, agricultural productivity, employment, carbon emissions	Avoided wastewater cost	Health protection (against encephalitis), avoided potable water cost, long-term augmentation of drinking water supply
			2.09	0.26 (low value crops)	0.1			
			2.09	0.21 (no agriculture)	0.1			
4	Aquifer storage and recovery, Bolivar, SA	9,000[†]	0.88[*]	2.51	2.9	40 wells, purge water management	Reduced discharge of treated wastewater to marine environment	Increase in crop value, urban stormwater management, willingness to pay for fresher water
		6,000[†]	1.55[*]	2.04	1.3			
5	Aquifer storage transfer and recovery, Anglesea, Vic	6,400-8,900	3.56	4.10	1.2	14 wells, 21 monitoring wells, carbon emissions	Avoided costs for wastewater, potable water, greenhouse gas emissions	Willingness to pay for water security
6	Groundwater Replenishment, Beenyup, WA	14,000	2.24	3.14	1.4	Groundwater pumping and treatment	Avoided cost of desalinated water	Social and ecological benefits of maintaining groundwater dependent ecosystems, wastewater pumping station costs

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[‡] BCR- Benefit cost ratio; [≠]estimated capacity, current approval for 600 ML/yr; [#] site specific costs in addition to capex and opex; [†] recycled water (9 GL) and stormwater/recycled water blend (6 GL) considered; [*] utilising seasonal spare capacity of existing recycled water treatment plant

Recharge rate and source water quality

MAR investigations allow proponents to gain an understanding of their system and the management strategies necessary to operate the scheme effectively. Soil and aquifer properties influence the recharge rate, which is evident when comparing infiltraton rates below 1 m/d in loamy sand to sandy clay loam at Alice Springs to considerably higher rates, around 4 m/d, in Perth's Spearwood Sand. Particularly in sites with less permeable sediments care must be taken to avoid clogging, which can be caused by physical processes such as soil compaction or development of a clogging layer.

MAR operators state that it is essential that a good understanding of local hydrogeology is obtained to minimise risks and costs and ensure successful scheme delivery. This highlights the importance of site selection for pilot investigations which should be chosen to represent the conditions at the intended scheme location. This highlights the importance of site selection for pilot investigations which should be chosen to represent the conditions at the intended scheme location. However aquifer characteristics have a very important impact on costs of MAR operations, so groundwater investigations should give sufficient confidence in scheme location and aquifer characteristics before conducting pilot recharge studies.

Clogging is a prevalent issue that reduces infiltration rate. An operational strategy is necessary to ensure recharge rates are maintained at an acceptable rate as the strategy chosen will impact on the cost of the MAR scheme. For example, this may involve advanced treatment of the source water to minimise clogging processes (e.g. Groundwater replenishment, Perth), drying periods to allow the clogging layer to dry out or dessicate (e.g. Soil Aquifer Treatment bains, Alice Springs), basin scraping or well backflushing to physically dislodge the clogging layer (e.g. Aquifer Storage and Recovery, Adelaide or infiltation basins, Perth), use of geofabric to prevent root ingress (e.g. infiltration galleries) or application of herbicide ensuring residuals do not negatively impact on the quality of the receiving groundwater (infiltration basins).

Documentation of case studies allows experience to be shared and confidence to be gained through accumulation of knowledge, with advice such as control over source water quality is essential. Clogging due to algae growth in a temporary suface storage used for a wastewater injection trial illustrates how a pilot trial can be hindered by an artefact of the trial design. Again, it is essential to ensure the pilot investigations adequately represent the intended opertational scheme.

It is necessary to have some control over the quality of source water used in a MAR scheme. For example, Water Corportation's experience with infiltration basins for wastewater disposal has shown that filamentous growth in the wastewater treatment plant binds the infiltration pond floor and impedes infiltration. A source water quality target of < 5 mg/L total suspended solids (TSS) was established to prevent physical clogging in infiltration galleries.

Value of investment in innovation

A number of the case studies presented here represent a novel or innovative approach to MAR. For example, the Bolivar Aquifer Storage and Recovery (ASR) trial was internationally regarded as the first application of a nutrient rich source water (DOC > 10 mg/L) in ASR. At the time of writing this report, 20 years after conception, the Bolivar ASR concept has not proceeded to an operational scheme. However it is currently being actively considered as a means of water supply to increase agricultural productivity, while concurrently reducing nitrogen loads discharged to the marine environment. The scientific understanding made through investigations associated with the Bolivar ASR research project was integral in development of the NWQMS *Managed Aquifer Recharge Guidelines* and was a precursor to the initiation of schemes at Anglesea and Aldinga (SA, case study not reported) and indirectly led to the Beenyup groundwater replenishment trial.

Water Corporation's groundwater replenishment in Perth is Australia's first augmentation of a drinking water supply with recycled water via the aquifer. This application was also considered by Barwon Water at Anglesea, Victoria but did not proceed past an injection trial. Infiltration galleries represent an innovative approach to infiltration of wastewater adopted to suit the urban environment where land may not be available for open infiltration basins. Alice Springs' Soil Aquifer Treatment basins is the first intentional application of SAT in Australia although some infiltration basins in WA have been operated intermittently for operational reasons.

Investment in MAR investigations allows proponents to gain an understanding of their system and regulators to build the detailed scientific knowledge to enable efficient regulation of projects. Documentation of case studies allows experience to be shared and confidence to be gained through previous experience. Table 2 illustrates the timeframe from conception to preliminary investigations, trial and operation for Bolivar ASR, Perth Groundwater Replenishment and Alice Springs Soil Aquifer Treatment schemes. Preliminary investigations and trials may span several years, particulary when the scheme is breaking new ground or addressing new challenges. Hence, for MAR to be adopted requires gestation periods aligned with long-term water planning. In the absence of planning, MAR is unlikely to be possible as a spontaneous response to unanticipated water supply issues.

A funding program for MAR investigations should take into account reducing the commercial risk of utilities seeking to undertake innovative projects that also have environmental, social and reduce costs of water and wastewater services. In some states. review of policies that inhibit the evaluation of options that may reduce the costs of safe water supplies is warranted.

Table 2 Timeline from conception to operation for Bolivar ASR, Perth Groundwater Replenishment and Alice Springs SAT schemes.

	Conceived	**Preliminary investigations (laboratory and field)**	**Field-scale trial**	**Full scheme construction**	**Operation**
Bolivar ASR	1995	1997-1999	1999-2010	-	-
Alice Springs SAT	2000	2003-2008	2005-2008	2008	2008
Perth Groundwater Replenishment	2002	2009-2010	2010-2012	2014-2016	2016

Introduction

Increasing demand on water resources due to population growth and climate variability leads to growing interest in opportunities for water recycling. Managed Aquifer Recharge (MAR) with recycled water has the potential to significantly increase the portion of water recycled in Australia. In 2012-13, forty three non-major urban utilities (each servicing < 50,000 people) collected a total of 283 GL per year of sewage and recycled 22% of it. In the same period, 24 major water utilities (each servicing > 50,000 people) collected 1,314 GL per year of wastewater and recycled only 12% (NWC 2014). Rural areas have advanced faster than major cities in water reuse because of less access to alternative water supplies and the closer proximity of sewage treatment plants to municipal and agricultural demands for irrigation water.

There is great potential for increasing the proportion of water that is recycled in water-stressed areas using MAR. MAR provides storage to:

- increase the resilience of supplies;
- provide water in seasons and years of high demand;
- replenish over-exploited aquifers;
- prevent saline intrusion;
- reduce evaporative losses;
- avoid the need for new dams;
- further treat the water;
- to allow time for ‘naturalisation’ of water from a public perspective, and
- help meet the needs of groundwater dependent ecosystems (Dillon *et al.* 2009).

Infiltration techniques for water recycling can be particularly attractive as they generally have lower costs than well injection techniques, especially in rural areas with lower cost of land, and they take advantage of the potential for natural treatment during infiltration through the unsaturated zone.

Despite the numerous benefits that MAR offers for water recycling, the uptake of this water resource management tool has been lower than expected (Parsons *et al.* 2012). Uncertainty regarding the impact of clogging processes on infiltration or injection rate, water quality in the receiving groundwater and economic feasibility of the scheme can influence decisions to construct and commission MAR schemes. To date, such uncertainty has impeded the uptake of water recycling. Therefore, this report aims to address these knowledge gaps by presenting a national compilation of MAR experience, including lessons learnt and economic assessment (where applicable). Seven case studies of MAR for water recycling are presented (Table 3; Figure 1), three of which use infiltration techniques for recharge (1-3) and four employ well injection methods for recharge (4-7). A companion report details the investigations relating to the impact of clogging and the fate of nutrients in two water recycling MAR schemes employing novel infiltration techniques (Bekele *et al.* 2015). This research was undertaken within a three year Australian Water Recycling Centre of Excellence research project on ‘Raising the national value of water recycling by overcoming impediments to managed aquifer recharge’.

Case study overview

Table 3 Overview of seven recycled water managed aquifer recharge case studies.

Case study		MAR technique	Aquifer	Source water treatment	End use
1	Infiltration basins, WA	Infiltration basin	Unconfined alluvial	Disposal schemes infiltrate wastewater treated by oxidation ditches/ponds and clarifiers; or activated sludge and oxidation ditch; or oxidation ponds; or reactor basin and settling basins.	Non-potable – irrigation public open space, playing fields, suburban parks
2	Infiltration galleries, Perry Lakes and Floreat, WA	Infiltration gallery	Unconsolidated dune sands and coastal limestone	Activated sludge with biological nutrient removal.	Groundwater replenishment - sustain groundwater dependent ecosystem
3	Soil Aquifer Treatment, Alice Springs, NT	Soil aquifer treatment	Unconfined alluvial	Facultative and maturation lagoons followed by dissolved air flotation (DAF) (until Sep 2013) or dissolved air flotation and filtration (DAFF) and ultraviolet disinfection (from Sep 2013).	Irrigation horticulture
4	Aquifer storage and recovery, Bolivar, SA	Aquifer storage and recovery	Confined limestone	Activated sludge or trickling filters (activated sludge replaced trickling filters in Jan 2001), stabilisation lagoons, dissolved air flotation and filtration (DAFF) and chlorination.	Irrigation horticulture
5	Aquifer storage transfer and recovery, Anglesea, Vic	Aquifer storage transfer and recovery	Confined/ unconfined, interbedded sand, gravel, clay and coal	Blend of 75% ultrafiltration, reverse osmosis and ultraviolet and chlorine disinfection and 25% ultrafiltration.	Drinking water supply
6	Groundwater Replenishment, Beenyup, WA	Aquifer storage transfer and recovery	Interbedded sandstone, siltstone, confined at recharge location	Ultrafiltration, reverse osmosis and ultraviolet disinfection.	Drinking water supply
7	Aquifer storage and recovery, West Werribee, Vic	Aquifer storage and recovery	Confined sand	Blend of 60% reverse osmosis treated Class A water and 40% Class A recycled water that is chlorinated.	Third pipe supply

Figure 1 Location of seven recycled water managed aquifer recharge case studies.

The types of managed aquifer recharge used within the case studies are outline below and in Figure 2 (NRMMC-EPHC-NHMRC, 2009).

Aquifer storage and recovery (ASR)

ASR involves injection of water into a well for storage, and recovery from the same well. The aquifer may be confined or unconfined.

Aquifer storage, transfer and recovery (ASTR)

ASTR involves injection of water into a well for storage, and recovery from a different well, generally to provide additional water treatment.

Infiltration ponds

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

Infiltration galleries

Infiltration galleries are geotechnically-stabilised buried trenches, or slotted pipes in permeable media. They allow infiltration through the unsaturated zone to an unconfined aquifer.

Soil aquifer treatment

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

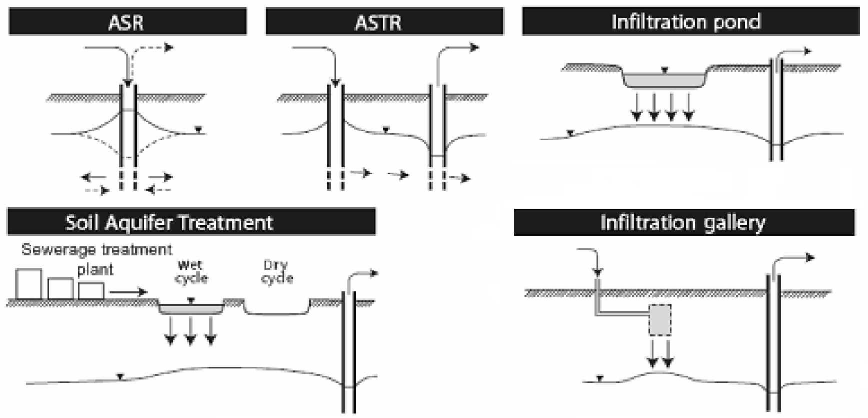

Figure 2 Schematic of types of managed aquifer recharge represented by the case studies. ASR = Aquifer storage and recovery; ASTR = Aquifer storage transfer and recovery (after NRMMC-EPHC-NHMRC, 2009).

Methodology

Interviews were held with operators or owners of each of the MAR case study sites identified in Table 2. Site descriptions were developed, an economic assessment was undertaken at all sites where data allowed and the key learnings documented.

Economic assessment

The economic assessment of the MAR case studies follows the principles and approach established in Marsden Jacob (2013) *Economic viability of recycled water schemes.* The assessment utilises a cost benefit analysis (CBA) framework, which is the most robust and comprehensive of the economic appraisal techniques and is the preferred method of analysis for most State and Commonwealth agencies responsible for economic management.

The CBA identifies the economic benefits and costs of each option to stakeholders, including water businesses, governments, the private sector and the community. The CBA is based on an assessment of market and non-market economic benefits and costs. All CBA options are compared against a 'without project' option.

COST-BENEFIT ANALYSIS MODEL

The economic analysis was conducted with the Recycled Water Economic Assessment Tool developed for the Australian Water Recycling Centre of Excellence (AWRCoE 2015a) by Marsden Jacob to support the application of the principles contained in Marsden Jacob (2013).

The Recycled Water Economic Assessment Tool accounts for factors including:

- water volumes supplied / recovered each year (including recovery efficiency);
- capital and operating expenditure of the scheme, including the timing of future augmentations;
- avoided water and sewerage costs; and
- broader, quantifiable social and environmental costs and benefits.

The Tool sets out the timing and magnitude of the costs and benefits and, utilising the principles of discounting, reduces the costs to a single present value for each option. The option with the highest net present value (NPV) would generally be considered the preferred option, all other things being equal. The Tool also provides results on a levelised cost basis, i.e. cost and benefits per kilolitre of recycled water supplied. Levelised cost (or benefits) allows options of different capacity to be compared on a like-for-like basis. Levelised cost (or benefit) per kilolitre is calculated as the present value cost (or benefit) of the option divided by the present value of the annual volume of water to be supplied.

In addition to the core economic model, the sensitivity of the results was tested for a range of factors including:

- demand volumes;
- discount rate;
- capital and operating expenditure; and
- benefits associated with the schemes.

The Recycled Water Economic Assessment Tool can be used for water recycling with or without MAR, but also for all MAR projects with various types of source water. Information is required for input on only the elements relevant to the specific project being assessed. The tool takes into account the recovery efficiency of MAR by scaling up the operating and maintenance costs of treatment and recharge, so that the recovered volume meets the specified demand. This is necessary for cases where the volume of water that can be recovered is less than the volume that is recharged due to mixing of fresh water in brackish aquifers, or to account for any imposed entitlement conditions specific to the project.

COMMON ASSUMPTIONS

For the purposes of the modelling, the following assumptions were applied to all case studies unless otherwise stated:

- 50 year evaluation period was adopted for the cost benefit analysis.
- Construction of all infrastructure is completed within the first year, with operations therefore assumed to commence in the second year, following construction.
- A discount rate of 7% (real) has been applied to future costs and benefits, with sensitivity testing undertaken at 4% and 10%. A 7% discount rate is widely used in evaluations and recommended by both the NSW (NSW Treasury 2000) and VIC (Department of Treasury and Finance, Victoria, 2013) Treasuries for projects of this nature.
- No residual value of the infrastructure was included at the end of the evaluation period.
- Since the repeal of the Commonwealth Government's Carbon Pricing Mechanism (the Carbon Tax), carbon emissions are no longer included in the price of electricity. Therefore a cost of carbon estimate of $40 per tonne was applied and held constant in real terms over the analysis period. The cost reflects the highest marginal cost of the Coalition government's Direct Action Plan (The Coalition's Direction Action Plan), which represents the externality that would be incurred for every new tonne of carbon emitted.
- Commercial value of crops, industry production and incomes generated through use of the recycled water were excluded as there are many inputs that contribute to these (land, fertiliser and labour). However, willingness to pay by water users was considered as a surrogate for direct benefit of water use. In the absence of a local market the price in the nearest representative market for equivalent water was used to estimate the benefit to users.
- Where implementation of a MAR project avoids otherwise essential additional wastewater treatment costs or water supply costs the present value of the most cost effective equivalent scheme is considered to be the avoided cost. This is recorded as a benefit of the project. If there is no mandated requirement to improve quality of receiving waters or providing new water supplies, these are benefits of the scheme but are not included in calculations within the Recycled Water Economic Assessment Tool.

APPLICATION OF THE MODEL TO CASE STUDIES

The case studies presented were analysed using the Recycled Water Economic Assessment Tool developed by Marsden Jacob. Economic analysis was undertaken by Marsden Jacob (N. Arold/P. Pickering) or CSIRO (S. Tapsuwan/ P. Dillon) as follows:

- Infiltration basins, WA (CSIRO)
- Infiltration galleries, Perry Lake and Floreat, WA (CSIRO)
- Soil Aquifer Treatment (SAT), Alice Springs, NT (Marsden Jacob/CSIRO)
- Aquifer Storage and Recovery (ASR), Bolivar, SA (Marsden Jacob/CSIRO)
- Aquifer Storage and Recovery (ASR), Anglesea, Vic (Marsden Jacob)
- Groundwater Replenishment, Beenyup, WA (CSIRO)

West Werribee ASR was not evaluated with the Recycled Water Economic Assessment Tool as the project is still in implementation stage and costs have not yet been finalised.

Infiltration Basins, WA

The economic assessment of infiltration basins presented here is a hypothetical case study as it was not based on a current operational scheme. However, the cost estimates were informed by Water Corporation's experience with wastewater infiltration, in particular the schemes of Caddadup and Gordon Road, WA and the understanding of the benefits of managed aquifer recharge.

The Water Corporation uses infiltration for disposal at many Wastewater Treatment Plants (WWTPs) across Western Australia. At several of these WWTPs, the infiltrated treated wastewater is abstracted and recycled for beneficial non-potable uses. The majority of these schemes were instigated prior to the Western Australian Department of Water policy on managed aquifer recharge (Department of Water 2011) and are not managed through the process described in this policy. Hence these wastewater infiltration schemes are not recognised by the Department of Water or Water Corporation as managed aquifer recharge. However the experience gained through long-term operation of these wastewater infiltration schemes is relevant to proponents of managed aquifer recharge schemes using infiltration basins.

A suite of five WWTPs (Caddadup, Gordon Road, Halls Head, Narngulu and Esperance No. 1) that use infiltration for wastewater disposal are presented here as a low-technology case study of water recycling via the aquifer, or managed aquifer recharge.

Infiltration schemes

CADDADUP WWTP

The Caddadup WWTP, established in 1994, is located in the suburb of Dawesville within the City of Mandurah, approximately 80 kilometres south of the Perth CBD. The WWTP is situated on the Swan Coastal Plain in a soil system consisting of gently undulating plains (deflation basins) enclosed by discrete parabolic dunes in moderately deep to very deep calcareous sands overlying limestone. The infiltration basins are approximately 600 to 700 m inland from the bordering Indian Ocean. The depth to groundwater in the Superficial Aquifer is generally 2.0-15.6 m below ground level. The Superficial Aquifer overlies the Leederville confined aquifer.

The Caddadup WWTP treats wastewater to a tertiary standard. In 2008 treatment technology was upgraded from a pond system to an activated sludge process utilising a single oxidation ditch. Approximately 1.3 MLD of treated wastewater is discharged to infiltration ponds onsite. Pond use is rotated every two to four weeks, followed by at least four weeks for pond maintenance; the period of use is influenced by water quality and season. Maintenance practices include drying, weed management, scraping and backfill with clean sand (described below in 'Lessons from experience'). To date, the infiltrated water remains in storage within the aquifer. Extraction under a managed aquifer recharge scheme for water recycling by the City of Mandurah is planned for the future.

GORDON ROAD WWTP (ALSO REFERRED TO AS MANDURAH NO. 1 WWTP)

The Gordon Road WWTP, established around 1991, is located in the suburb of Parklands within the City of Mandurah, approximately 60 kilometres southwest of the Perth CBD. The WWTP is located in the Swan coastal dune system approximately 2 kilometres from the Indian Ocean. Spearwood Sand beneath the site can be described as shallow to moderately deep siliceous yellow-brown sands. This soil system consists of dune ridges with slopes up to 15% and limestone outcrops. The depth to groundwater in the Superficial Aquifer is generally less than 3 m below ground level in swales.

The Gordon Road WWTP treats wastewater to a tertiary standard and consists of three oxidation ditches and four clarifiers. Approximately 9.5 MLD of treated wastewater is disposed of through a series of infiltration ponds onsite. The ponds are swapped every eight weeks, followed by a minimum of 16 weeks for maintenance. A portion of infiltrated wastewater is recovered by the City of Mandurah and used for irrigation of nearby playing fields.

HALLS HEAD WWTP (ALSO REFERRED TO AS MANDURAH NO. 2 WWTP)

The Halls Head WWTP, commissioned in 1985, is located in the suburb of Halls Head within the City of Mandurah approximately 70 kilometres southwest of the Perth CBD. The WWTP situated on coastal deposits that consist of a thin veneer of Spearwood Sand overlying Tamala Limestone. The infiltration basins are approximately 300 to 400 m inland from the Indian Ocean. The soil system consists of a flat stony plain with poorly drained shallow siliceous sands and large areas of bare limestone pavement. The depth to groundwater in the Superficial Aquifer is generally 2.0-4.0 m below ground level.

The Halls Head WWTP is designed to treat wastewater to a tertiary standard and consists of two oxidation ditches and four clarifiers. Approximately 2.5 MLD of treated wastewater is discharged via infiltration basins onsite. The infiltration basins are each typically wetted for two weeks, followed by at least six weeks of drying during which additional maintenance can be carried out. A portion of infiltrated wastewater is recovered by the City of Mandurah and used to irrigate public open space in the Seascapes urban development.

NARNGULU WWTP

The Narngulu WWTP, established in 2008, is located on the outskirts of Geraldton. The facility was constructed to have sufficient capacity to receive sewage from the Geraldton central area and replace septic tanks by connecting unsewered residential and commercial properties to the new Narngulu reticulated sewerage system.

Narngulu WWTP lies on the western edge of an alluvial plain that is underlain by generally clayey sediments with some sand, gravel and minor calcarenite. The south western part of the site is underlain by permeable sand and calcarenite of the Tamala Limestone. The water table is approximately 15 m deep below ground level in the vicinity of the WWTP.

Narngulu WWTP is a High Performance Aerated Lagoon (HPAL) System, comprising a reactor basin and three settling basins. Approximately 1.5 MLD of treated wastewater is currently discharged to infiltration ponds onsite. In the future, it is intended that the treated wastewater can be recycled for irrigation of adjacent recreational or horticultural areas or for industrial reuse directly (without aquifer storage) or via the aquifer.

Currently the ponds are rotated on a weekly basis, the ponds do not fill and are dry by the day following use (P. Hepburn and M. Graham, pers. comm.). As this system is new, operating below design capacity and the infiltrating water is of high quality, the ponds have not yet been cleaned out ?.

ESPERANCE NO 1 WWTP

The Esperance WWTP, established in 1991 or earlier, is located approximately 1.5 km north west of the Esperance town centre. The level of ground water in the vicinity of the treatment plant ranges from 8.0 to 9.5 m below ground level.

The Esperance WWTP is separated into two locations: Esperance No. 1 WWTP located at Jetty Road, and Esperance No. 2 WWTP located at Wylie Bay Road. Treated wastewater is re-used by the Shire of Esperance with excess to their requirements discharged to infiltration ponds. Esperance No. 1 treats up to 1.7 MLD per day and consists of two oxidation ponds, one with aeration, prior to discharging to infiltration ponds on site. There are two additional ponds supplied by a five kilometre pipeline to Wylie Bay Road site. Extraction of infiltrated water at No. 1 WWTP under a managed aquifer recharge scheme for water recycling is planned for the future.

Benefits of managed aquifer recharge

The Water Corporation values managed aquifer recharge for the following reasons:

1. ***Infiltration provides effective pathogen removal.***

If appropriate recycled water quality is achieved by a managed aquifer recharge scheme, the WA Department of Health does not require the installation of an additional pathogen barrier in the form of disinfection. This can mean that the treatment provided by infiltration effectively replaces the filtration and chlorination/UV required for direct recycling schemes.

In addition, the pathogen removal provided by MAR can be sufficiently high that the recycled water quality is suitable for some higher risk end uses.

The majority of recycling schemes supplied by the Corporation are low exposure risk end use schemes. To achieve low exposure end use, irrigation of public open spaces must have:

- buffer zones between the irrigated area and public areas
- barriers to access (between public area and irrigated area)
- warning signage, and
- irrigation at night with sufficient drying time.

If parks and public open spaces are in suburban areas and close to houses, it may not be possible to achieve the above conditions, and the recycling scheme can become a medium exposure risk scheme, with commensurately higher water quality requirements. Depending on the performance of the scheme, managed aquifer recharge schemes may be able to provide recycled water of sufficiently high quality to meet the requirements for these irrigation medium exposure risk end uses.

MAR has been highly advantageous for the Mandurah schemes. The Halls Head scheme irrigates a series of small parks embedded in residential areas, and has been deemed medium exposure risk by the Department of Health. The scheme can achieve the water quality required because it is an infiltration scheme; no additional capital or operational costs have been incurred to meet the medium exposure end use requirements. It is anticipated that this will also prove an advantage for the Caddadup scheme, and allow greater flexibility in the City of Mandurah's use of the recycled water.

2. ***Infiltration provides storage and retrieval mechanisms which avoid the issues of above-ground storage, including; cost of storage installation, evaporation from storage leading to water losses and concentration of the dissolved solids in TWW creating recycled water with unacceptably high salinity.***

In order to use recycled water in irrigation schemes, there must be sufficient storage to store it during the wetter months of the year and then discharge it over the irrigation period. The cost of TWW storage is significant and can act as a barrier to the development of new recycling schemes.

In some new recycling schemes, storage dams have held treated wastewater for several years before the recycling scheme is commissioned. These have had high dissolved solids and required discharge of the high TDS water and replenishment with fresh TWW before use in the recycling scheme.

3. ***Infiltration may have a lower capital cost than direct filtration and chlorination.***

This understanding is yet to be tested, as the installation of a managed aquifer recharge scheme in accordance with the Department of Water managed aquifer recharge policy has not been compared to the installation of a direct recycling scheme in a planning or project delivery process within the Water Corporation. However, based on preliminary feasibility studies, it would appear that the installation of infiltration ponds and abstraction bores may be cost-competitive with the installation of filtration and chlorination, under suitable conditions (e.g. volume of water which may be feasibly abstracted is a significant percentage of volume of infiltrated water). This is explored in the Economic analysis section, using a hypothetical case study.

4. ***Infiltration has reduced operational complexity compared to direct filtration and chlorination.***

Infiltration ponds require regular monitoring and maintenance to operate effectively. However, the monitoring and maintenance is relatively simple, consisting of observational monitoring and scraping and replacement of the pond floors. The monitoring and maintenance of filtration and chlorination systems for direct recycling is more complex. Chlorine storage and dosing systems include mechanical and electrical equipment, instrumentation, alarms and remote communications equipment. There are also significant occupation health and safety considerations with the storage and dosing of chlorine gas or hypochlorite. The use of infiltration ponds simplifies the operation and maintenance of recycling schemes by removing these considerations.

When providing advice to external proponents (third parties) who have approached the Water Corporation for access to treated wastewater from WWTPs, the Corporation recommends that proponents consider accessing the treated wastewater directly from the WWTP or by installing a production bore nearby (i.e. that the proponents consider managed aquifer recharge as an option for treatment, storage and reuse of the water). Dependent on technical considerations, the local environment and regulatory requirements, MAR may provide the opportunity to simplify operations, reduce costs and improve the pathogen removal of the scheme.

Lessons from experience

Soil clogging leading to a reduction in infiltration rate is the most significant technical impediment for the infiltration basins. The infiltration ponds are run on duty/standby mode. One pond is filled (active) while the other pond/s remain idle. When the active pond's infiltration capacity has reduced, it is rested and the next pond is brought online.

This following sequence of activities outlines pond operation and maintenance in the Perth Mandurah area (encompassing the Caddadup, Halls Head and Gordon Rd WWTPs):

- One infiltration pond is operated at a time.
- The infiltration rates vary between summer and winter, so the changeover between ponds is not based on a time period or duration, but rather observation of the ponds.
- The water is run into the pond by a single distributor/pipe. The water sinks into the pond as it enters the pond.
- Once there is a pooling effect in the pond (i.e. the water is not sinking in immediately but forming pools on the surface of the pond) and the ponds have unacceptable weed growth (the triggers for weed growth and pooling occur concurrently – when weeds are at unacceptable levels, the pond starts to pool), the next infiltration pond is used and the first pond is rested.
- The rested pond is dried and weed growth and deposited solids are scraped off the pond's sand lining and disposed off-site to waste.
- After scraping, the pond is backfilled with clean sand to replace any lining which has been removed with the scraping (i.e. the pond is returned to base level).

The quality of the effluent has by far the most significant effect on duration of use for any infiltration pond. If there is an operating issue within the WWTP and filamentous algal growth occurs, the filamentous growth can bind the infiltration pond floor and impedes infiltration. When this occurs, the WWTP is settled and the filamentous growth brought under control, and then the infiltration ponds are swapped over and the resting pond is cleaned of the filamentous growth.

Economic analysis

ASSUMPTIONS

For this particular economic assessment case study, the costs of recycling via the aquifer (MAR) and recycling with surface storage (direct recycling) are compared. This is a hypothetical case study and is not based on any scheme currently in operation in WA. While the scale of this recycling scheme is small, it is similar to various small treatment plants operated by Water Corporation. The cost estimates are informed by experience with coastal wastewater infiltration schemes such as Caddadup and Gordon Road, WA.

The following assumptions are made:

Supply / Demand

An operator is establishing a new wastewater treatment plant (WWTP) or expanding an existing plant. There is a need to dispose of 28,500 kL per year of treated wastewater (annual average daily flow = 78 kL/d (0.078 MLD), peak week = 145 kL/d). There are two feasible management options which will also allow recycling; managed aquifer recharge or direct recycling with surface storage component. The envelope for study is from the discharge of the last WWTP pond to the discharge of the abstraction bore or recycling process (Figure 3).

There is an irrigation demand of 28,500 kL per year (peak demand in irrigation period = 200 kL/d). The operator's only water source for oval irrigation aside from recycled water is potable water. The WWTP is an oxidation ditch or similar technology with performance comparable to the coastal wastewater infiltration schemes examined earlier (i.e. Caddadup, Gordon Road). The recycling infrastructure will be proximate to the WWTP and within the WWTP compound.

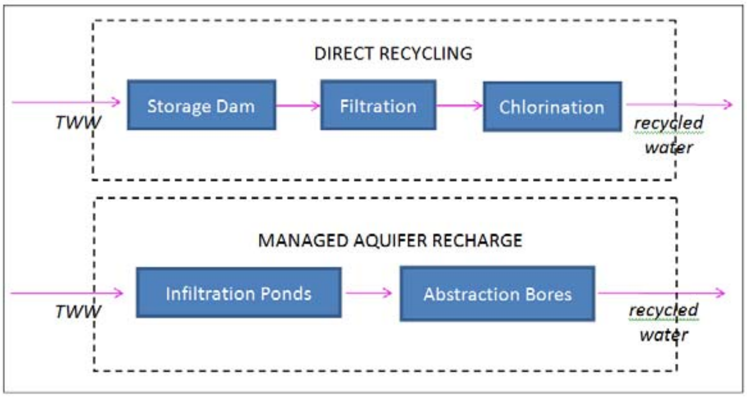

Figure 3 Case study envelope for comparison of wastewater infiltration basins (MAR) and direct recycling with surface storage (TWW = treated wastewater). Source: Water Corporation (2014).

Costs

- Land is already available for the WWTP and recycling infrastructure and therefore land acquisition and opportunity costs are neglected as they are considered equal for both options.
- Storage capacity to provide annual irrigation demand, assume 30 ML storage tank for the surface storage option.
- Capital works cost for the filtration and chlorination plant includes the cost of pumps, filtration and chlorination.
- Capital works costs for infiltration pond establishment is \$360/m^2, including allowances for transport of soil away from site and additional provisional sums for potential issues in construction arising from geotechnical issues.
- Recovery (groundwater abstraction): infiltration ratio of 1:1 for CAPEX, but variable ratio provided for OPEX.
- Two abstraction wells, both operate at 100 kL/d.
- Loss to the environment is assessed as 20% due to mixing with presumably brackish groundwater for the MAR option (i.e. 80% recovery efficiency) and 15% due to evaporation

from surface storage for the direct recycling option. The loss is made up with potable water and priced (costed) at the long run marginal cost (LRMC) of $2.00/kL. Note that in the case of loss to the aquifer, there would not be a need to supplement with potable water supply if the ambient groundwater is fresh and suitable for irrigation.

- Infiltration rate of 0.4 m/d when ponds are wet and each pond is wet 50% of the time.
- Infiltration basin OPEX includes basin desludging, maintenance of bore pumps, sampling and operator time.
- Direct recycling OPEX includes electricity, chemicals, maintenance of equipment in treatment train, sampling and operator time.
- Equipment and installation costs are considered typical for the metropolitan area.
- Analysis life of the scheme is 50 years.

The economic analysis assumes that all capital costs were incurred during financial year 2015, with the scheme being fully operational in financial year 2016. Table 4 and Table 5 present the capital expenditure (CAPEX), operation and maintenance costs for MAR and direct recycling, respectively.

Table 4 Capital expenditure (capex), operation and maintenance cost – infiltration basins.

Item	Capex $	Operating Cost $/a	Maintenance Cost $/a
Infiltration basins (2 basins @ 360 m^2 each)	280,000	2,500	22,500
Abstraction wells (2 wells @ 100 kL/d)	270,000		
Loss to environment (20%)		11,400	
Total	**550,000**	**13,900**	**22,500**

Source: Water Corporation 2015

Table 5 Capital expenditure (capex), operation and maintenance cost – recycling with surface storage.

Item	Capex $	Operating Cost $/a	Maintenance Cost $/a
Above ground storage (size 30 ML)	2,250,000	2,150	19,350
Filtration and chlorination plant (size 200 kL/d,20 kL/hr)	670,000		
Loss to environment (15% evaporation)		8,550	
Total	**2,920,000**	**10,700**	**19,350**

Source: Water Corporation 2015

Benefits – avoided potable water costs

Both schemes offer almost the same amount of water for irrigation, which is approximately 28,500 kL per year. Loss to the environment of 15% for above ground storage and 20% for MAR result in a cost difference of $2,850 per year between the two scheme (assuming loss to the environment is supplemented by potable water and is priced at the long run marginal cost of $2.00/kL). As noted above, loss to the aquifer would only need to be supplemented with potable water supply if the ambient groundwater salinity is unsuitable for irrigation.

Benefits – aquifer replenishment

It is likely that recycling via the aquifer (MAR) will lead to other environment benefits associated with aquifer replenishment such as recharge and enhancement of groundwater dependent ecosystems and prevention of salt water intrusion. The benefits associated with aquifer replenishment will not be quantified as an environmental impact assessment is not possible for a hypothetical case study.

RESULTS

Table 6 presents a cost comparison between infiltration basins (MAR) and recycling with an above ground storage component. It shows that the cost per kilolitre of water supply from recycling is over three times the cost of that supplied by MAR, for the same size scheme of 28,500 kL per year (benefit cost ratio = 3.2). The most significant saving associated with MAR is the cost of storage (Figure 4) as the capital cost of establishing a MAR scheme is a fraction of the surface storage cost. In addition, natural treatment during infiltration is recognised as treatment barrier for pathogen removal, which reduces treatment costs prior to use in irrigation. The analysis also shows that the cost of water supplied by MAR ($2.68/kL) is within the range of the long run marginal cost of potable water, which is between $1.37 and $2.86 per kilolitre (MJA, 2013), making recycling via the aquifer a cost effective source of alternative water supply.

Table 6 Results of the economic analysis of the water recycling case study using infiltration basins and recycling with above ground storage.

Item	Infiltration basins PV ($)	Recycling with above ground storage PV ($)
Present Value of Costs		
Capital works for infiltration basins	280,000	-
Capital works for abstraction wells	270,000	-
Capital works for above ground storage dam	-	2,250,000
Capital works tertiary treatment	-	670,000
Operating and maintenance	344,170	295,986
Loss to environment (environmental cost in Figure 4)	156,942	117,706
Total Net Present Cost	**1,051,111**	**3,333,692**
Cost per kilolitre	$2.68 per kL	$8.50 per kL

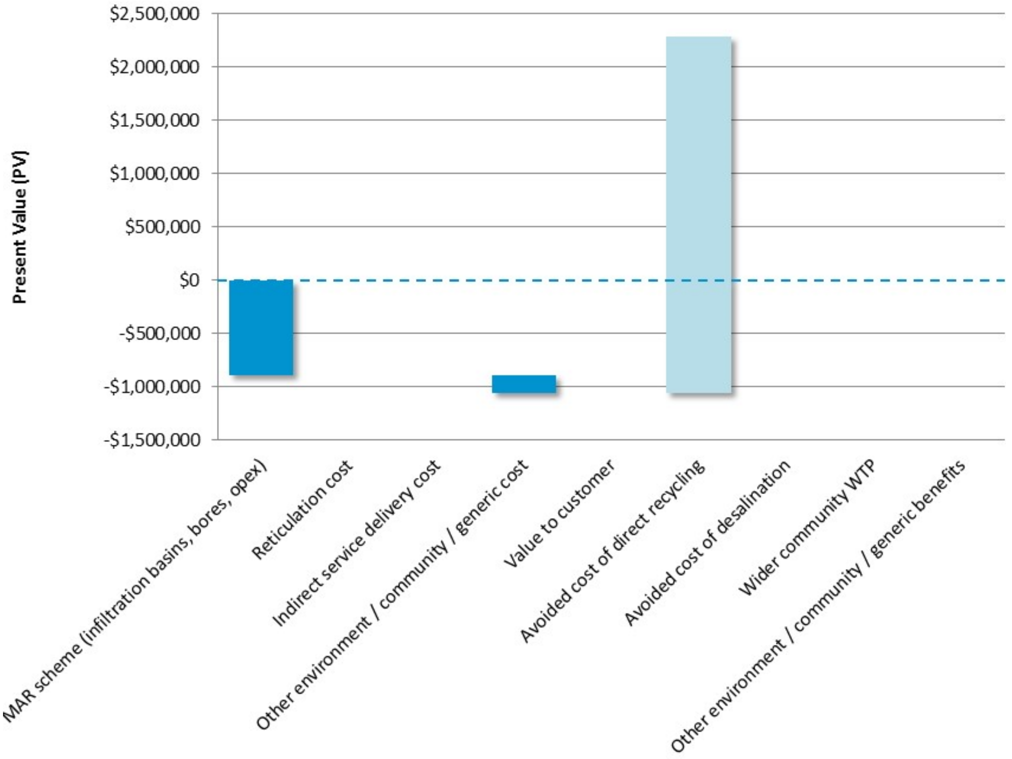

Figure 4 Results of the economic analysis of wastewater recycling using infiltration basins (MAR) versus recycling (direct recycling) with a surface storage component.

Sensitivity Analysis

Sensitivity analysis was undertaken on the following parameters:

Increased scheme capacity: Four scheme capacity sizes (28,500 kL, 48,000 kL, 76,000 kL and 100,000 kL per year) were analysed and compared.

Decreased infiltration rate: Four levels of infiltration rate and corresponding pond size were analysed for a scheme size of 28,500 kL per year.

Infiltration rate	Basin requirement
- 0.4m/d	2 basins @ 360 m^2 each
- 0.2m/d	2 basins @ 720 m^2 each
- 0.1m/d	2 basins @ 1,450 m^2 each
- 0.04m/d	2 basins @ 3,600 m^2 each

Increased loss to the aquifer: Although 28,500 kL per year of water is infiltrated, not all can be abstracted for later use due to loss to the aquifer. Three levels of loss to the aquifer were considered – 20%, 30% and 40%.

Discount rates of 4% and 10% (compared to 7% base case).

Sensitivity analysis results are presented in Table 7. The results show that:

- An increase in scheme size leads to an increase in the cost of each scheme. However, the cost increase of recycling with surface storage is significantly higher than for infiltration basins. As such, for scheme sizes larger than 28,500 kL/yr, MAR is the preferred water recycling option.
- Lower infiltration rates lead to higher cost of MAR, due to the increase in basin size required to achieve the recharge target volume (28,500 kL/yr). With a 90% reduction in infiltration rate (i.e. an infiltration rate of 0.04 m/d rather than 0.4 m/d), the cost of MAR increases by 183%. In any case, the cost of MAR is still lower than direct recycling. Further investigation is required at lower infiltration rates, such as 0.01 m/d, to determine whether MAR becomes more expensive than direct recycling or not. Based on the experience with operating wastewater infiltration schemes at Caddadup and Gordon Road infiltration rates of at least 0.4 m/d are expected. Infiltration basins are operated in sequence to allow basin maintenance when infiltration rates decline.
- An increase in the loss to the aquifer has very little impact on the total cost of MAR. At a loss to the aquifer of 40%, the total cost of the MAR scheme is only 15% higher than the cost of the scheme when the loss to the aquifer is at 20%.
- MAR remains cost effective with changes to the discount rate.

Table 7 Results sensitivity analysis of the water recycling case study using infiltration basins (MAR) and recycling with a surface storage component.

Item	MAR (in $)	Change (in %)	Direct recycling (in $)	Change (in %)
Base Case	1,051,111	0%	3,333,692	0%
Scheme size 48,000 kL/yr	1,387,098	32%	5,344,630	60%
Scheme size 76,000 kL/yr	1,840,052	75%	8,093,669	143%
Scheme size 100,000 kL/yr	2,259,728	115%	10,507,131	215%
Infiltration rate 0.2 m/d	1,291,111	23%	3,333,692	0%
Infiltration rate 0.1 m/d	1,751,111	67%	3,333,692	0%
Infiltration rate 0.04 m/d	2,971,111	183%	3,333,692	0%
Loss to aquifer of 30%	1,129,582	7%	3,333,692	0%
Loss to aquifer of 40%	1,208,053	15%	3,333,692	0%
Discount Rate of 4%	1,326,830	26%	3,561,311	7%
Discount Rate of 10%	910,589	-13%	3,217,684	-3%

Infiltration Galleries, Floreat (WA)

This case study assesses the use of infiltration galleries to recycle treated wastewater and is based on outcomes from technical feasibility assessments (Bekele *et al.* 2009, 2011, 2013, 2015) and concept design recommendations (GHD 2011) rather than data from an operational scheme. The feasibility of using buried infiltration galleries to infiltrate recycled water and replenish groundwater resources was evaluated and reported by Bekele *et al.* (2009, 2011, 2013, 2015). Buried infiltration galleries are a novel technique for MAR via infiltration as they are suited to urban areas, where available land may be limited, due to their small footprint.

Groundwater levels in the Swan Coastal Plain (WA) have declined due to declining rainfall. In the Perry Lakes area, this decline in groundwater level has impacted groundwater-dependent wetlands, East and West Lake. Infiltration galleries were considered as a means to raise groundwater levels in the vicinity of East and West Lake (GHD 2011) and computer modelling indicated that infiltration rates of 3 to 5 m/d were required to raise groundwater levels in the vicinity of these wetlands. Infiltration galleries were first trialled at the CSIRO Floreat site (WA) at a low wastewater application rate of 1 m/d (Bekele *et al.* 2009, 2011, 2013). Recently a second trial was undertaken at the Floreat site, with an average infiltration rate of 4 m/d (Bekele *et al.* 2015). The second trial was undertaken to confirm that infiltration galleries could be operated at the target infiltration rate of 4 m/d and to develop the understanding of technical impediments and solutions.

GHD (2011) used knowledge gained from the first Floreat infiltration gallery trial to develop a concept design for buried horizontal galleries to replenish groundwater in the Perry Lakes area and restore water levels the East and West Lakes. The Floreat trial location is within 1 km of East Lake. Estimated capital, operating and maintenance costs of this concept design operated at a scale of 5 ML/d forms the basis of the economic evaluation.

MAR scheme

The recycled water for use in the infiltration gallery was treated wastewater from the Subiaco wastewater treatment plant (WWTP). The treatment plant is designed to treat up to 61.4 ML per day and services a population of 350,000 (Water Corporation 2009). The treatment train involves screening of large materials at the inlet to the plant; primary sedimentation treatment which removes 90% of the remaining solids; advanced secondary treatment processes incorporate a conventional activated sludge process with biological nutrient removal (Water Corporation 2009). The majority of the final effluent is currently pumped to the Swanbourne Ocean Outlet 1 km offshore. A small quantity of secondary effluent undergoes further treatment (filtration and chlorination) and is diverted for reuse for irrigation on the McGillivray/University of Western Australia sporting ovals.

Galleries were constructed in Spearwood Sand and recharge targeted the Superficial Aquifer comprised of Spearwood Sand and Tamala Limestone. Infiltration galleries were constructed using Atlantis Flo-Tank® modules (Figure 5), each with dimensions of 685 mm x 450 mm x 408 mm (Lx H x W) and internal partitions approximately every 340 mm (Bekele *et al.* 2009, 2011, 2013). Geofabric was used to reduce root ingress into the modules. The base of the gallery was approximately 1 metre below ground level.

Figure 5 Construction of infiltration galleries using Atlantis Flo-Tank® modules at Floreat in 2008 (Toze and Bekele 2009).

Lessons from experience

Soil clogging is a key technical challenge for buried infiltration galleries, as remediation is more challenging than for open basins where the basin surface can be accessed for removal of the clogging layer. Physical clogging can occur due to suspended solids that are present in the wastewater treated at Subiaco. GHD (2011) reported annual average total suspended solids (TSS) of 12 to 20 mg/L from 2007-2009. Concentrations were variable with maximum values up to 135 mg/L. As a result of laboratory experiments reported in Bekele *et al*. (2015) source water pre-treatment to maintain total suspended solids (TSS) < 5 mg/L was recommended to prevent physical clogging of the soil matrix. Trial 1 used multi-media filtration anthracite (1.1 mm grading), sand (0.5-1.3 mm grading) and gravel (1.5-3 mm grading) as source water pre-treatment.

Clogging due to plant roots can also occur and can be influenced by gallery construction. Bekele *et al*. (2009) reported that clogging due to root ingress was more severe in an infiltration gallery filled with gravel than one with Atlantis® tanks. Furthermore, geofabric covering the top and sides of the gallery was applied to reduce the impact of root ingress (Bekele *et al.* 2015). GHD (2011) allowed for periodic removal of the clogged sand layer from the base of the galleries in their economic assessment.

While algal growth is inhibited by excluding sunlight from the gallery, the recycled water is still relatively nutrient-rich and bacterial biofilm growth occurs with attendant exocellular polymers (slime). These can also be a cause of chronic clogging on the interface between the infiltration gallery and the sand. Frequency and type of maintenance procedures were not assessed within the infiltration gallery trials.

Recharge with treated wastewater can impact on the quality of the receiving groundwater. In this case study, removal of phosphate was attributed to adsorption during infiltration. However, it should be noted that removal by adsorption may not be a sustained indefinitely. Adsorption can be reversed and may also be constrained by a capacity limitation. There was no evidence of nitrogen removal as aerobic conditions in the unsaturated zone and aerobic source water were not conducive to denitrification. In the second trial, the concentrations of total dissolved nitrogen sampled from a down-gradient monitoring bore were comparable to those in the source water applied to the gallery, at approximately 8 mg N/L (Bekele *et al.* 2015).

Economic analysis

ASSUMPTIONS

Supply / Demand

The system is designed to infiltrate 1.8 GL per year into the aquifer (i.e. infiltration rate of 5 ML/day) to raise groundwater levels in the vicinity of East and West Lakes.

Costs

The costs estimates are based on the concept design of infiltration galleries for the Perry Lakes MAR project, estimated by (GHD, 2011), for the Town of Cambridge, Western Australia. The cost estimates are not based on previous experience in constructing and operating infiltration galleries. A wet:dry ratio of 2:1 was assumed, which acknowledges the need for drying to maintain infiltration rates. However the effectiveness of the ratio assumed has not been tested. For comparison, infiltration basins typically have a wet:dry ratio of between 1:2 and 1:4. The concept design is for 15 galleries, 50 m in length by 5 m wide, with 10 active at any one time. Gallery rejuvenation involves removing covers, excavating and disposing of 100 mm sand from the gallery, adding 100 mm of clean sand to the floor and replacing covers. It was assumed that treated wastewater supplied to the galleries would have a total suspended solids concentration of less than 5 mg/L, thus water treatment costs are not included (GHD 2011). Loss to the environment is assessed as 20%, due to mixing with groundwater and the loss is made up with potable water and priced (costed) at the long run marginal cost (LRMC) of $2.00/kL. The assumed frequency of rejuvenation is once every 10 years, but this is yet to be tested in an operational scheme.

The cost estimates were adjusted to current ($2014/15) using consumer price index from the Australian Bureau of Statistics (ABS 2014). Table 8 presents the capital expenditure and assumed operation and maintenance costs. The economic analysis assumes that all capital costs were incurred during financial year 2015, with the scheme being fully operational in financial year 2016.

Table 8 Capital expenditure (capex), operation and maintenance cost ($2014) – Perry Lakes infiltration galleries, WA.

Item	Capex $	Operating Cost $/a	Maintenance Cost $/a
Preliminaries and pre-instatement (clear vegetation, reinstate road crossings etc.)	90,060	-	-
Distribution system	260,361	-	-
Earthworks	101,921	-	-
Capital works for infiltration galleries (15)	308,597	-	-
Capital works for monitoring wells (20; 10 shallow and 10 multi-level)	52,535	-	-
Contractor overhead (30% of capex)	244,043	-	-
Professional fees (preliminary investigation, documentation to support approvals, project management etc.)	525,887	-	-
Contingency	276,904	-	-
Personnel/Consultant costs (operating gallery and distribution system)	-	591,581	-
Environmental monitoring program	-	1,254,600	-
Contingency	-	240,588	-
Maintenance *	-	-	147,600
Gallery rejuvenation (10-yearly)	-	-	55,128 †
Total	**1,860,308**	**2,086,769**	**202,728**

*Source: GHD (2011). * Provisional estimates only. † Rejuvenation may be required more frequently.*

Other costs – Cost of buying treated wastewater

Water Corporation negotiates with proponents the price of treated wastewater. The analysis assumes a volumetric charge of up to $0.50 per kilolitre for the Town of Cambridge to buy treated wastewater from the Subiaco Wastewater Treatment Plant. This cost is based on the market price of groundwater (the cheapest alternative to treated wastewater), which is being traded at $0.50 per kilolitre in Western Australia (Department of Water 2013).

Benefits – Avoided cost of maintaining wetlands

In this case study MAR would replenish the aquifer and in turn the groundwater dependent wetlands, Perry Lakes. Without MAR, the Town of Cambridge would need to pump approximately 1.8 GL per year of water into the Perry Lakes to maintain them. Two possible sources of water for replenishing the wetlands are groundwater and potable water The cost of groundwater is estimated to be around $0.20 per kilolitre (MJA 2013). This is the cost of running the bore (e.g. electricity) only, and the cost of water itself is assumed to be nil. However, this represents an unsustainable solution as it is likely that the declining groundwater table will prevent the Town of Cambridge from pumping groundwater in the future. Therefore, an alternative source of water for replenishing the wetlands, which does not require any significant investment in infrastructure, is potable water (around $2.00/kL).

RESULTS

The net present value (NPV) benefit and cost estimates indicate that the Town of Cambridge is better off replenishing wetlands with groundwater, rather than investing in infiltration galleries (see Table 9 Scenario 1). However, this represents an unsustainable solution as it is likely that the declining groundwater table will prevent the Town of Cambridge from pumping groundwater in the future. Therefore, an alternative source of water for replenishing the wetlands, which does not require any significant investment in infrastructure, will have to be potable water. At this point, the Town of Cambridge is better off investing in infiltration galleries to avoid buying potable water to replenish wetlands (see Table 9 Scenario 2; Figure 6). Direct discharge of treated effluent into Perry Lakes was not considered in this analysis, as treatment requirements and costs have not been established.

Table 9 Results of the economic analysis of the infiltration galleries, Perry Lakes

Item	**Scenario 1:** Groundwater to sustain lakes **(PV in $)**	**Scenario 2:** Potable water to sustain lakes **(PV in $)**
Present Value of Costs		
Infiltration gallery scheme cost	14,685,401	14,685,401
Reticulation cost	-	-
Indirect service delivery cost	-	-
Other environment / community cost (loss to aquifer 20%)	10,049,763	10,049,763
Other costs	2,026,603	2,026,603
Total Net Present Cost	**26,761,768**	**26,761,768**
Present Value Benefits (avoided cost)		
Value to customer	-	-
Avoided cost of maintaining wetland	5,024,881	50,248,851
Avoided potable water cost	-	-
Wider community willingness to pay	-	-
Other environment / community benefits	-	-
Total Net Present Benefits	**5,024,881**	**50,248,815**
Net Present Value	**-21,736,887**	**23,487,047**
Cost per kilolitre	$1.07 per kL	$1.07 per kL
Benefit per kilolitre	$0.20 per kL	$2.00 per kL
Benefit cost ratio	0.2	1.9

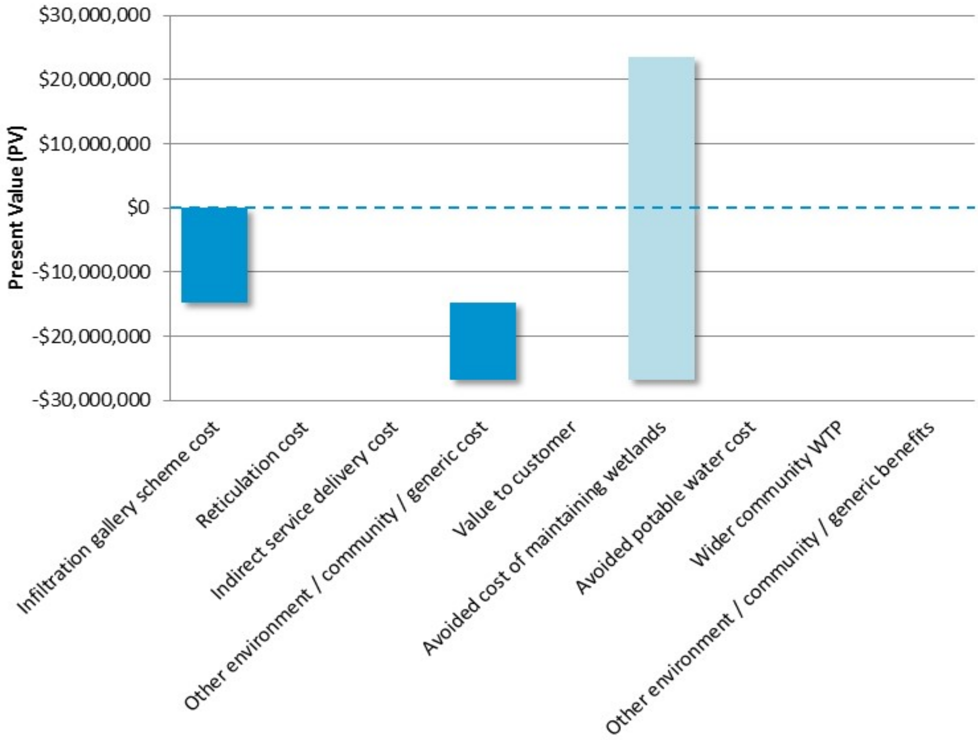

Figure 6 Results of the economic analysis of the Perry Lakes infiltration galleries in comparison to maintaining wetlands with potable water (Scenario 2).

Sensitivity Analysis

Sensitivity analysis was undertaken on the following parameters:

- **Decrease in price of treated wastewater:** The Perry Lakes MAR project can buy treated wastewater from the Kwinana WWTP at $0.25/kL or $0.50/kL (base case).
- **Increased loss to the aquifer:** Three levels of loss to the aquifer were considered – 20% (base case), 30% and 40%.
- Discount rates of 4% and 10% (7% for base case).

Sensitivity analysis (Table 10) indicate:

- The Perry Lakes infiltration gallery scheme would have a positive NPV under any of the sensitivity analysis scenarios in comparison to use of potable water to replenish and maintain wetlands. Hence, these results are relatively robust to variations in underlying assumptions.

Table 10 Results of the sensitivity analysis of infiltration galleries – Perry Lakes, WA.

Item	Scenario 1 (in $)	Change (in %)	Scenario 2 (in $)	Change (in %)
Base Case	-21,736,889	0%	23,487,045	0%
Treated wastewater price $0.25/kL	-15,455,787	-29%	29,768,146	27%
Loss to aquifer of 30%	-26,761,770	23%	18,462,163	-21%
Loss to aquifer of 40%	-31,786,651	46%	13,437,282	-43%
Capex +10%	-21,922,919	0.9%	23,301,014	-0.8%
Capex -10%	-21,550,858	-0.9%	23,673,075	0.8%
Opex +10%	-24,227,035	11%	20,996,898	-11%
Opex -10%	-19,246,742	-11%	25,977,191	11%
Discount Rate of 4%	-32,664,236	50%	37,442,499	59%
Discount Rate of 10%	-16,167,441	-26%	16,374,741	-30%

Soil Aquifer Treatment, Alice Springs (NT)

Soil aquifer treatment (SAT) is the process of intermittently infiltrating treated sewage effluent to provide further treatment and store the water in aquifers for reuse. The Alice Springs SAT is Australia's first purposefully constructed SAT scheme. It commenced in June 2008 to reduce health and environmental impacts associated with overflows from the wastewater stabilisation ponds to the adjacent Ilparpa Swamp. Instead, the wastewater is treated and stored in an underground aquifer. The economic assessment is based on data for the SAT scheme's feasibility assessment (investigations, monitoring), construction and operation provided by NT Power and Water Corporation (NT PWC).

There is potential to recover the water for irrigation supplies for new agricultural production (e.g. horticulture). To date no recovery has occurred. However, the ambient groundwater has moderate salinity levels that makes it marginally suitable for irrigating crops. Recharging the aquifer has reduced salinity on site and at 200 metres down gradient of the SAT operation to approximately 2,000 to 2,500 µS/cm. Salinity levels remained relatively constant from 2013 to 2015 (see also Figure 7). The high salinity of native groundwater means that it is unlikely that salinity will drop below current levels at the irrigation extraction points and therefore only salt-tolerant crops would be viable in the short to medium term.

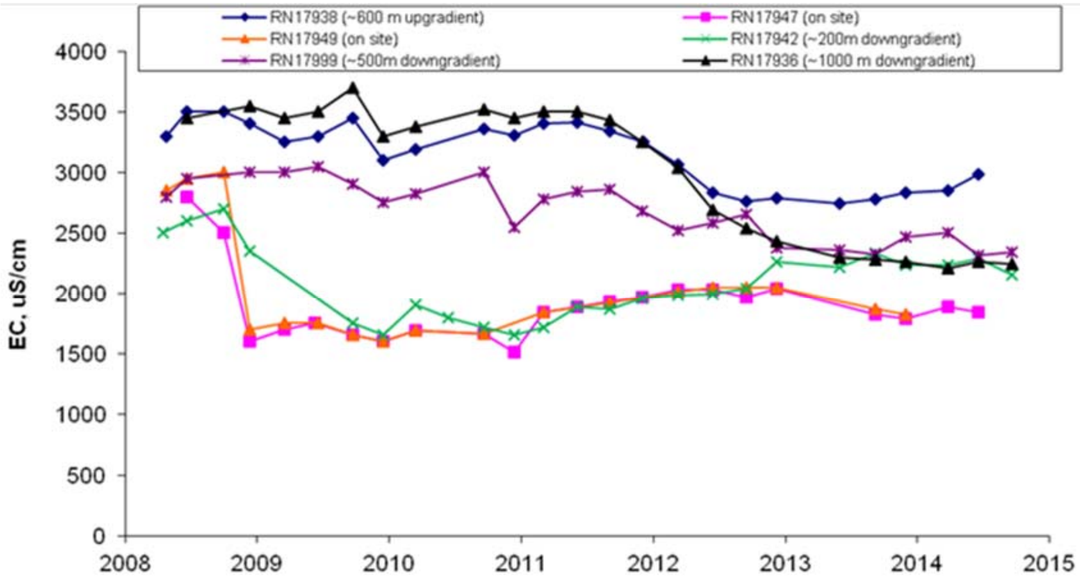

Figure 7 Electrical conductivity (EC) in groundwater adjacent to the Alice Springs SAT scheme (on site), 600 m upgradient and 200 m, 500 m and 1000 m and downgradient (Bekele *et al.* 2015).

Irrigated agriculture has yet to be established in the area and support for the development of an irrigation district has yet to be confirmed. It is envisaged that development of an irrigation district may also lead to development of food processing industries (requiring new infrastructure).

Three different scenarios were examined in the economic analysis:

- Scenario 1 (best economic case): Salinity decreases to 1,800 µS/cm by 2020; water is reused for irrigation of low value crops from 2017 to 2019 and high value crops (such as table grapes or vegetables) from 2020 onwards;
- Scenario 2: Salinity remains at current levels (2,500 µS/cm) and water is reused for irrigation of low value crops (e.g. Sorghum) from 2017 onwards;
- Scenario 3 (worst economic case): the water is not reused for irrigation. It is noted that unrecovered recharge would ultimately augment the Mereenie sandstone aquifer from which Alice Springs draws its water supply. This aquifer is currently over-exploited as evidenced by declining groundwater levels. However the time before benefits would be experienced exceeds the 50 year time frame of the current economic analysis.

MAR scheme

The Alice Springs Soil Aquifer Treatment (SAT) scheme is located at the Arid Zone Research Institute (AZRI) situated approximately 7 km south of Alice Springs towards the airport (Figure 8). The Water Reclamation Plant (WRP), where recharge water is produced, is situated next to Ilparpa Swamp adjacent Blatherskite Park. The area under investigation is characterised by desert climate, with very high evaporation rates and an annual average rainfall 284 mm.

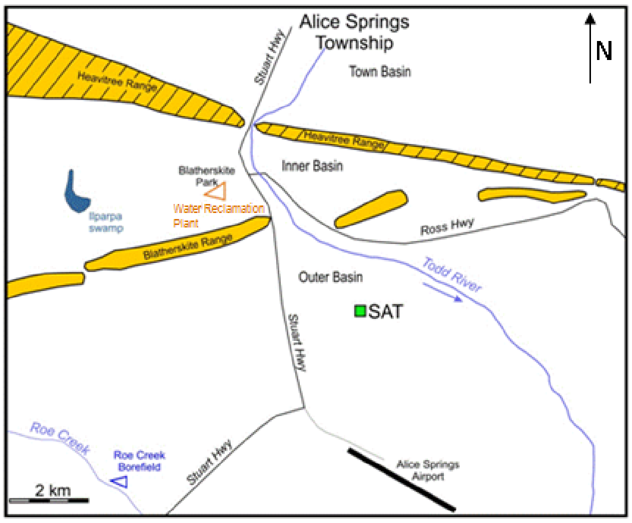

Figure 8 Location of the Alice Springs SAT scheme (Bekele *et al.* 2015).

The current configuration of the Soil Aquifer Treatment basins consists of five recharge basins providing a total recharge area of 38,473 m^2. Details are described in Bekele *et al.* (2015). The scheme has approval to infiltrate 600 ML per year into the aquifer to avoid dry weather discharges to the Ilparpa Swamp.

The source water for recharge is supplied from the Alice Springs Water Reclamation Plant (WRP). Treatment is provided by a series of lagoons, consisting of an initial facultative lagoon and a series of maturation ponds, followed by dissolved air flotation (DAF) (until the end of August 2013). The DAF treatment step was upgraded to dissolved air flotation and filtration (DAFF) and UV disinfection from 16 September 2013, to provide Class A recycled water and increase the potential for direct recycling for irrigation of sports fields and public open space. Recharge targets a paleochannel of the Todd River, a Quaternary alluvial aquifer consisting of coarse grained sediments overlain by finer grained clayey silts, clays and sands (Knapton *et al.* 2004).

Lessons from experience

The primary technical issue for the Alice Springs SAT scheme is hydraulic performance, which is influenced by soil properties and clogging mechanisms. SAT basins in Alice Springs constructed in sediments of variable grain sizes showed that infiltration was higher (>300 mm/day) in more permeable loamy sands. In heterogeneous soils, described as loamy sand to sandy clay loam, clay dominated lenses influenced infiltration rates. Detailed site characterisation assisted in selecting the most appropriate scheme location.

At this site, the duration of standing water in the basins is restricted to seven days in order to prevent mosquito breeding. This constrains the hydraulic loading rate in each basin and therefore larger basin areas were needed than otherwise would be required. This may also have inhibited nitrogen removal in the basin floor as anoxic conditions are generally achieved only in micro niches during ponding. The depth of water in the basins is not constrained by the mosquito breeding requirements, as an optimum depth of 0.3 m water was adopted to allow sufficiently rapid drying of basins.

Another factor influencing infiltration was soil compaction. Use of heavy machinery to level the floor of recharge basins can compact soils, reducing infiltration rates and should be avoided. For one basin, where infiltration rates were reduced to less than 50 mm/d by levelling, infiltration rate was restored to greater than 100 mm/d by deep ripping of the basin floor to a depth of 700 mm.

A protocol for basin operation and maintenance is required. It is essential to ensure drying times are adequate to allow desiccation of the clogging layer under the range of climatic conditions and vegetation growth experienced. While vegetation can enhance infiltration through soil structure improvement, in the Alice Springs SAT basins vegetation was observed to act as a mulch which prevented adequate drying of the basin surface.

Moreover, development of the surface clogging layer (or 'schmutzdecke') is influenced by source water quality. In this case study, additional pre-treatment by filtration as a result of the upgrade from DAF to DAFF treatment reduced concentrations of coagulant, algae and nutrients in the recharge water. This markedly increased infiltration rates. However, variability in hydraulic performance within basins remained dependent on the soil profile and the soil compaction history.

At the Alice Springs SAT site, groundwater freshening resulted from recharge with recycled water, but there were increases in nitrate concentrations due to nitrogen in the recharge water being virtually unabated. Basin operation and length of wetting and drying cycles can be manipulated to optimise water quality treatment processes. Using the maximum length of the filling period without breaching the seven day limit for standing water may assist in obtaining anoxic conditions needed for nitrogen reduction while also maximising the annual hydraulic loading of the recharge basins. Future use of groundwater down-gradient from the SAT scheme will depend on water quality targets for a range of potential beneficial uses of this groundwater.

The project site is in an intake area that ultimately replenishes the Mereenie Sandstone aquifer which is the primary source of water supply for Alice Springs. Any substitution of recycled water for non-potable uses of drinking water in Alice Springs will benefit the longevity of this aquifer where groundwater levels have been in decline at about 1 m/yr for the last 40 years. Similarly any water recharged through SAT that is not recovered for irrigation will mix with natural waters and migrate through at least 6 km of porous media over decades to centuries and augment recharge of the Mereenie Sandstone Aquifer system via the Todd River system. Water quality changes will be unmeasurable at the water supply wells due to dilution and further extensive attenuation of constituents of recycled water within the groundwater system.

EXPLORING THE POTENTIAL CAPACITY OF THE ALICE SPRINGS SAT SCHEME

Currently the SAT scheme is achieving the licenced infiltration volume of 600 ML per year. However, it is feasible that the available infiltration area of 38,473 m^2 could be used to increase the annual recharge volume. Applying the average infiltration rate with DAFF treated source water for each basin (Table 11), a wetting time of 3 or 4 days all year round and a drying time of 10 days in summer and 20 days in winter average infiltration rate indicates the SAT system could recharge 1,400-1,700 ML per year (3.8-4.7 MLD). Assuming a 10% decline in performance each year and an maintenance interval of 6 months every 3 years per basin reduces the average annual recharge volume to approximately 1,000-1,300 ML per year (2.7-3.6 MLD). Nonetheless this is around twice the volume currently recharged and comparable to the volume of water treated by the Alice Springs WRP.

Table 11 Summary of infiltration rate, drying time and wetting time (average±standard deviation) for Alice Springs SAT basins based on source water treatment (DAF or DAFF) (Bekele *et. al.* 2015).

Basin	DAF treated source water				DAFF treated source water			
	n	Infiltration rate (mm/d)	Drying time (d)	Wetting time (d)	n	Infiltration rate (mm/d)	Drying time (d)	Wetting time (d)
A	57	170±100	7±3	4±1	17	250±100	10±2	3±2
B		Impacted by soil compaction			16	200±30	10±8	2±1
C	46	140±50	8±5	4±1	14	250±100	10±6	3±1
D	30	500±200	12±8	2±1	15	1000±400	10±5	3±1
E	16	550±460	12±8	2±1	19	760±520	11±6	3±1

Economic analysis

ASSUMPTIONS

Supply / Demand

An annual recharge volume of 1,200 ML per year was assessed in the economic analysis, based on the potential capacity of the current scheme (estimated above). This is greater than the scheme's current approval to infiltrate 600 ML per year into the aquifer to avoid dry weather discharges to the Ilparpa Swamp.

Costs

NT Power and Water Corporation (NT PWC) provided cost estimates for the Alice Springs SAT scheme. Table 12 presents the capital expenditure, and operation and maintenance costs.

The economic analysis assumes that all capital costs were incurred during financial year 2008, with the scheme being fully operational in financial year 2009. The water treatment operating cost is for all the wastewater that is treated, whereas only a portion (~50%) is directed to the SAT scheme.

Table 12 Capital expenditure (capex), operation and maintenance cost ($2014) – Alice Springs SAT.

<table>
<tr><th>Item</th><th>Capex
$</th><th>Operating Cost
$/a</th><th>Maintenance Cost
$/a</th></tr>
<tr><td>Water Treatment</td><td>7,201,920</td><td colspan="2">823,553</td></tr>
<tr><td>Distribution System (pipeline to SAT site, pumping station, manifolds, valves, instrumentation)</td><td>5,227,200</td><td></td><td></td></tr>
<tr><td>SAT scheme (basin construction, land cost, SCADA, power supply, access road, environmental approvals and clearances)</td><td>1,742,400</td><td colspan="2">131,803</td></tr>
<tr><td>Water Quality Monitoring & Reporting</td><td></td><td>507,260</td><td></td></tr>
<tr><td>Total</td><td>14,171,520</td><td>1,462,616</td><td>131,803</td></tr>
</table>

Source: NT PWC, 2014; Note: Capital costs were adjusted for inflation

Other costs – Carbon emissions

The Greenhouse Gas (GHG) emissions associated with the Alice Springs SAT scheme were estimated at 482 tonnes CO_2 per year. This is based on an annual electricity consumption of 709,065 kWh per year for treatment and infiltration and an emissions factor of 0.68 (Department of Environment 2014).

As noted earlier, a constant (in real terms) carbon price of $40 per tonnes CO_2 was applied.

Benefits

Avoided waste water cost

In the absence of the SAT scheme NT PWC would have to construct additional evaporation ponds to avoid dry weather discharge to the Ilparpa swamp. A study undertaken in 2000 found that it is feasible to construct an additional four evaporation ponds with 150 ML storage capacity each. The costs for a 150 ML evaporation pond were estimated at $600,000 (in $2000) (SKM 2012), or $875,700 (in $2014) after adjusting for inflation. Hence, the avoided waste water capital costs total $3.5M.

Further avoided costs for supporting infrastructure, e.g. pipelines, may be incurred in construction additional evaporation ponds. Estimates for supporting infrastructure have not been quantified and these avoided costs were excluded from the assessment.

Avoided potable water cost

The SAT scheme may augment drinking water supplies over time. Drinking water supply in the area is from the Mereenie Sandstone aquifer via the Roe Creek borefield. Recharge to the alluvial aquifer via the SAT scheme may be considered to augment the water resource within the Mereenie Sandstone aquifer over longer time scales. Notably the salinity of the recharge is typically greater than that of the ambient groundwater in the sandstone aquifer.

Total potable water supply from the Amadeus Basin system is approximately 8.5 GL per year, of which 7 GL per year is from the Mereenie Sandstone aquifer. An additional 1.5 GL per year is supplied from the Pacoota and Goyder aquifers. Assuming 1,200 ML per year is recharged to the aquifer (and subsequently recovered for potable water supplies), the benefit of deferring cost of capital and operating costs for future supply augmentations, e.g. at Rocky Hill, could be attributed to the project. Due to the uncertainties associated with the recharge over long time scales and the salinity levels, this benefit was not quantified in the assessment.

Agriculture production

As noted above, recycled water could potentially be reused for irrigated agriculture. However, this opportunity has not yet been taken up by growers, with high salinity levels likely a limiting factor. As such, three different salinity and uptake scenarios were analysed, as described earlier.

In the scenarios in which the water is reused (scenarios 1 and 2), the annual benefits from agricultural production were estimated using an analysis of agricultural gross margins and salinity thresholds. EC of irrigation water is assumed to be 1,800 µS/cm (scenario 1) or 2,500 µS/cm (scenario 2).

Gross margins estimates for high value (e.g. grapes, citrus, melons, mangos) and low value (e.g. sorghum hay, sugar) crops are based on information for the Ord River Irrigation Area, and have been adjusted for inflation:

- Gross margin high value crops: $3,800 per ha; and
- Gross margin low value crops: $300 per ha.

It was assumed that an area of approximately 100 ha could be irrigated with the 1,200 ML per year that has currently been approved for injection into the aquifer (B. Sawyer, pers. comm.).

Yield thresholds describe the relationship between salinity and yield. The thresholds were used to interpolate linear yield functions for relevant crops (see Table 13) and to establish the yield loss due to saline water for scenarios 1 and 2.

Table 13 Yield thresholds – tolerance of crops to irrigation with saline water.

Irrigated enterprise	**EC (µS/cm) at various % yield loss**		
	0 percent	**10 percent**	**25 percent**
Sorghum (low value crop)	4,500	5,000	5,600
Grapes (high value crop)	1,000	1,700	2,700
Vegetables (high value crop)	1,000	1,600	2,500
Citrus (high value crop)	1,100	1,600	2,200

Source: WA Department of Agriculture and Food (2004)

Gross margins per hectare were adjusted accordingly to reflect the respective yield loss and multiplied by the total hectares under production. It was assumed that the hectares under production will remain constant over the evaluation period.

The annual values of agricultural production (assuming 100 hectares of productive area) based on the gross margin and yield threshold analysis are:

- High value crops: $339,568 per year; and
- Low value crops: $30,000 per year.

It should be noted that the benefits identified above are likely to be significantly overstated as the estimates do not take into account any capital expenditure required to set up irrigation infrastructure and to access the water. However, as the infrastructure requirements will not be known until development occurs, the capital costs have been excluding from the assessment.

However this economic assessment, in accordance with principles outlined earlier, does not include the value of agricultural produce, but does include willingness to pay for recycled water. As there are currently no agricultural users, the price of recycled water for direct consumption should be substituted, or the cost of purchase of a groundwater entitlement (of equivalent quality groundwater, if available) whichever is lower. Currently recycled water is supplied to sports fields and parks in Alice Springs at no cost in an effort to reduce mains water consumption. Hence in Table 15, the value to customer is assumed to be zero. Ultimately the price of recycled water is likely to increase to some proportion of mains water price.

Benefits – indigenous employment

Based on information from NT Department of Primary Industry and Fisheries (DPIF) it was assumed that 200 ha production area could employ 12 workers, albeit not full time (B. Sawyer, pers. comm.). This information was extrapolated for a 100 ha production area and assumed that it could support 3 unskilled FTEs at an annual wage of $33,000. The annual wage is based on the minimum weekly wage ($640.90) that applies to farming and livestock workers with limited experience.

Therefore an employment benefit of $99,000 per year was attributed to the Alice Springs SAT scheme under scenarios 1 and 2.

Increased indigenous employment is a social benefit. However, the cost benefit analysis recognises that the opportunity cost for labour drawn from the Indigenous population is effectively zero due to the very high unemployment rate and reliance on government income sources. That is other gainful employment opportunities are not foregone due to this new opportunity. This workforce is considered highly immobile and therefore is unable to take advantage of opportunities in other regions.

RESULTS

Table 14 and Figure 9 present the results of the economic analysis. As the Alice Springs SAT scheme is operational since June 2008, this is an ex post economic analysis.

It shows that the scheme is not economically viable under any of the three scenarios: 1) irrigation of low value crops in the short term and high value crops in the long term; 2) irrigation of low value crops; or 3) the water is not reused. The high capital and operation and maintenance costs associated with the recycled water treatment and SAT scheme – $32 million – cannot be offset with the benefits attributed to the scheme (avoided cost of evaporation ponds, willingness to pay for new agricultural production and indigenous employment benefits).

However it must be noted that the initial driver for this scheme, that of preventing sewage treatment plant overflows to Ilparpa Swamp to prevent encephalitis in a nearby indigenous community has not been fully accounted for in this analysis. The distance to which recycled water would need to be pumped for infiltration to avoid the requirement for multiple basins each with surface residence times of less than 7 days, has not been defined. Furthermore the analysis is based on a supply of 600ML/yr although the system that has been built is capable of twice this volume and this amount of water is produced by the plant, but the balance is supplied directly to large users. Hence costs of SAT are inflated by a factor of approximately two. The willingness to pay, if it were raised in future to $0.20 to $0.50 /KL would yield a present value of benefit to users of $1.6 to $4 million ($3.2 to $8M at 1200 ML/yr). Finally, the benefit of groundwater replenishment of an over-exploited aquifer has been ignored. Deferment of costs of alternative water supplies may be of considerable value, but due to current uncertainties it is unclear whether this would occur within the 50 year time frame of this economic assessment. None of these considerations were made in the economic assessment, nor tested under the sensitivity analysis.

Table 14 Results of the economic analysis of the Alice Springs SAT scheme.

Item	Scenario 1 (high value crops) (PV in $M)	Scenario 2 (low value crops) (PV in $M)	Scenario 3 (no agriculture) (PV in $M)
Present Value of Costs			
Recycled water	30.75	30.75	30.75
SAT scheme direct cost	3.56	3.56	3.56
Reticulation cost	-	-	-
Indirect service delivery cost	-	-	-
Other environment / community cost	0.26	0.26	0.26
Other costs	-	-	-
Total Net Present Cost	**34.57**	**34.57**	**34.57**
Present Value Benefits (avoided cost)			
Value to customer	-	-	-
Avoided wastewater cost	3.50	3.50	3.50
Avoided potable water cost	-	-	-
Wider community willingness to pay	-	-	-
Other environment / community benefits	2.96	0.83	--
Other benefits	-	-	-
Total Net Present Benefits	**6.46**	**4.33**	**3.50**
Net Present Value	**-28.1**	**-30.2**	**-31.1**
Cost per kilolitre*	$2.09 per kL	$2.09 per kL	$2.09 per kL
Benefit per kilolitre*	$0.39 per kL	$0.26 per kL	$0.21 per kL
Benefit cost ratio (BCR)	0.2	0.1	0.10

*Source: Marsden Jacob analysis; *based on potential operating capacity of 1,200 ML/yr (current approval is for 600 ML/yr)*

Sensitivity Analysis

Sensitivity analysis was undertaken on the following parameters:

- **Increased agricultural production area:** An increased production area implies an increase in demand for recycled water. It also results in higher benefits associated with agricultural production and indigenous employment. The sensitivity analysis examined the impacts of an increase from 100 ha to 200 ha.
- **Capital expenditure:** Both a 10% increase and decrease in capital expenditure
- **Operation and maintenance cost:** Both a 10% increase and decrease in operation and maintenance cost.
- Discount rates of 4% and 10%.

Sensitivity analysis results are presented in Table 15. The results show that:

- The Alice Springs SAT scheme has a negative NPV under any of the sensitivity analyses completed. The results are relatively robust to variations in the underlying assumptions tested.
- An increased agricultural production area results in an improvement in the NPV (although it remains negative), because both the value of agricultural production and associated indigenous employment benefits increase under both scenarios 1 and 2. Doubling the potential production from 100 ha area to 200ha results in a minor improvement in the NPV of 10% and 3% under scenarios 1 and 2, respectively.
- Threshold analysis shows that, under current assumptions, an increase in production area to over 1000 ha would help to close the gap between costs and benefits and achieve a positive NPV. However, that this also require a considerable increase in water supplies, which may require infrastructure upgrades and lead to additional costs.

- Increasing capital expenditure or operating and maintenance costs reduces the NPV further under all scenarios. The impact is greater for increases in operation and maintenance costs, due to high treatment and monitoring and reporting costs.
- The results are sensitive to changes in the discount rate. A lower discount rate of 4% leads to a further deterioration of the NPV of 30 to 36 percent due to the higher weight given to future benefits or cash flows. The result also highlights that the assumed ongoing costs of operating the scheme outweigh the ongoing benefits assessed. Conversely, a higher discount rate of 10% results in an improvement in the NPVs.

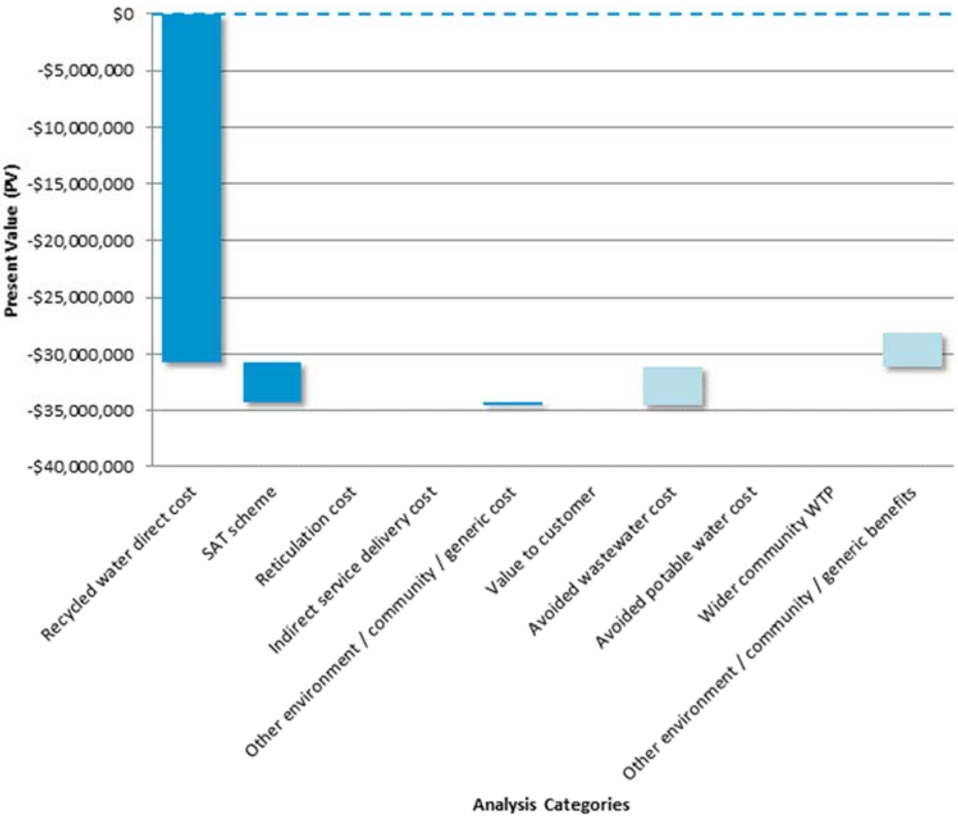

Figure 9 Results of the economic analysis of the Alice Springs SAT scheme (Scenario 1).

Source: Marsden Jacob analysis

Table 15 Results of the sensitivity analysis of the Alice Springs SAT scheme.

Item	Scenario 1 (in $)	Change (in %)	Scenario 2 (in $)	Change (in %)	Scenario 3 (in $)	Change (in %)
Base Case	-28,110,424	0%	-30,238,878	0%	-31,069,774	0%
Increased ag. production area (200 ha)	-25,151,073	11%	-29,407,982	3%	-31,069,774	0%
Capex +10%	-29,527,576	-5%	-31,656,030	-5%	-32,486,926	-5%
Capex -10%	-26,693,272	5%	-28,821,726	5%	-29,652,622	5%
Opex +10%	-30,464,871	-8%	-32,593,326	-8%	-33,424,222	-8%
Opex -10%	-25,755,977	8%	-27,884,430	8%	-29,715,326	8%
Discount Rate of 4%	-36,496,765	-30%	-40,768,868	-35%	-42,294,702	-36%
Discount Rate of 10%	-23,693,611	16%	-24,851,957	18%	-25,348,885	18%

Source: Marsden Jacob analysis

Aquifer Storage and Recovery, Bolivar (SA)

The Bolivar Aquifer Storage and Recovery (ASR) site is located 25 km north of the centre of Adelaide on farmland within the northern boundary of the Bolivar Waste Water Treatment Plant (WWTP). The ASR field trial was undertaken from 1997 to 2010 to determine if nutrient rich Class A recycled water could be recycled via ASR in a confined limestone aquifer to expand the water resources available for irrigation in the nearby Virginia horticultural region on the Northern Adelaide Plains. The Virginia Pipeline Scheme has the capacity to meet annual demand of 32 GL, but peak daily supply capacity will be reached before the seasonal capacity is exceeded (Martin and Dillon 2005). ASR provides the capacity to store surplus recycled water produced in winter for use in high demand summer months, which provides a means to meet the current peak daily demands and growth in demand.

Between 1997 and 2010, a consortium comprising CSIRO, the Government of South Australia (SA Water Corporation, SA Department of Water, Land and Biodiversity Conservation, SA Department of Administration and Information Services) and United Water were involved in an evaluation of the technical feasibility, economic viability and environmental sustainability of recycled water ASR within the Bolivar ASR research project. Four full-scale ASR cycles were undertaken between 1999 and 2010, injecting 704 ML and recovering 501 ML in total (Dillon *et al*. 1999; Barry *et al*. 2010). This trial was the first application internationally where a water with high nutrient content (total organic carbon concentration >10 mg/L) was used in ASR. It proved the feasibility of the scheme and enabled the collection and interpretation of a significant amount of data that subsequently in 2009 provided one of the foundations of the Australian Guidelines for MAR.

The Bolivar ASR scheme is not currently in operation. However, the trial has informed and supported the implementation of other ASR schemes, such as the Aldinga Wastewater Storage and Recovery Scheme, which increases the use of recycled water, thereby replacing potable supplies from the River Murray and reducing discharge to the Gulf St Vincent. It allowed design of a 9GL per year ASR system using 40 wells to inject water into Tertiary aquifers on the perimeter of the Virginia horticultural triangle, as documented in Martin and Dillon (2005). Together with the results of a project (MAR and Stormwater Use Options) evaluating safety, economics, public acceptance and reliability of stormwater harvesting for a range of uses, including blending with recycled water for non-potable use (Dillon *et al.* 2014), it allows consideration of a conceptual design for a 6GL/yr ASR scheme with notionally 3GL per year stormwater blended with 3GL per year recycled water. The blend has a lower salinity than the groundwater in use for irrigation on the northern Adelaide Plains allowing higher valued uses for which there is evidence of higher willingness to pay. It also could potentially allow blended water to be stored in the aquifer within the existing cone of depression of the potentiometric surface. Although not yet evaluated, it is considered that there would be sufficient recycled water and stormwater, and pipeline capacity in winter to implement both projects. That is they are not mutually exclusive and both augment the current direct use of recycled water. In the evaluations below these are considered separately.

This case study is a hypothetical examination of the economics associated with a 9 GL per year wastewater ASR scheme and a 6 GL per year blended water ASR scheme for stormwater and wastewater. The economic values have been extrapolated from published information from the field scale trial undertaken from 1999-2001 (Martin and Dillon 2005). Capital and operating costs for stormwater ASR systems were calculated using current data from Aqueon (unpublished data 2015).

MAR scheme

The Bolivar ASR trial site is within the grounds of the Bolivar wastewater treatment plant, approximately 25 km north of the centre of Adelaide, South Australia (Figure 10).

The Bolivar WWTP treats water to a tertiary standard using sedimentation, activated sludge or trickling filters (activated sludge replaced trickling filters in January 2001), stabilisation lagoons, dissolved air flotation and filtration and chlorination. The recycled water is approved for unrestricted irrigation use. There is no treatment of water recovered from the aquifer prior to use for irrigation.

The ASR well at the trial site is open hole from 103-160 m BGL and intersects the lower of two Tertiary limestone aquifers, the Lower Port Willunga or ‘T2’ aquifer. The lithology ranges from fossiliferous and marly limestone to siliceous calcarenite (Pavelic *et al*. 2006). Transmissivity is approximately 180 m^2/d and the average porosity is 0.45 (Pavelic *et al*. 2006). Karstic features are not identified in the vicinity of the trial site. An extensive monitoring network surrounds the ASR well consisting of observation wells and piezometers 4 m, 50 m, 75 m, 120 m and 300 m from the ASR well and one observation well in the overlying T1 aquifer (Figure 11). The ASR well is equipped with a turbine pump. In operational schemes it is expected there would be one observation well in the vicinity of each injection well to allow precise evaluation and management of clogging, maximise hydraulic efficiency of operations and minimise energy use, and provide warning of increased salinity during periods of sustained recovery. The costs of the array of wells used to understand aquifer processes at the trial site are therefore not included in the full-scale scheme.

The ambient groundwater in the T2 aquifer is brackish, with average salinity of 2200 mg/L at the trial site, which makes it unsuitable for domestic or agricultural use. In the centre of the horticultural irrigation area the T2 aquifer has a salinity of about 800mg/L. The mineralogy of the aquifer is dominated by calcite (74±12%) and quartz (18±11%), with minor amounts of ankerite, hematite, microcline and albite (Vanderzalm *et al.* 2006).

Figure 10 Location of Bolivar ASR trial site situated on the grounds of the Bolivar wastewater treatment Plant and adjacent to the Northern Adelaide Plains (Virginia Triangle) horticultural region (Dillon *et al.* 1999, 2003; Page *et al.* 2010)

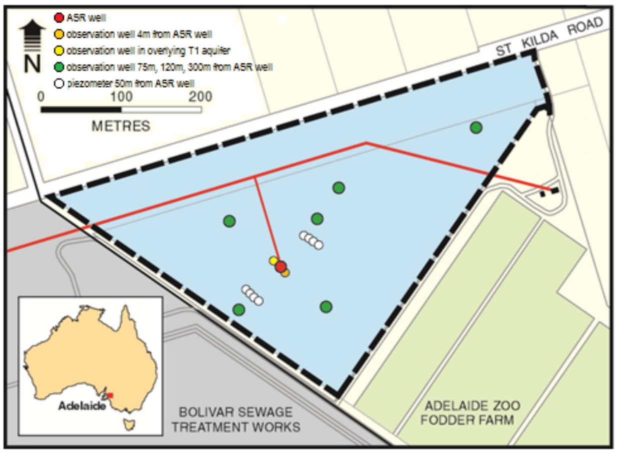

Figure 11 Location of wells and piezometers at the Bolivar ASR trial site. The red line represents the recycled water supply line (after Page *et al*. 2010).

Lessons from experience

A comprehensive research program was undertaken to determine whether recycled water with relatively high nutrient and dissolved organic carbon concentrations (N and DOC >10 mg/L) could be stored in an aquifer and recovered later for irrigation supply.

Laboratory and field investigations and modelling addressed the potential hazards and their management, including:

- Aquifer clogging.
- Water quality changes.
- Salinity and recovery efficiency.
- Impacts on other groundwater users.
- Pressure effects.
- Well and aquitard stability.

Community consultation for the initial trial commencing in 1999, was undertaken by the Bolivar ASR research project team to inform the community about what was planned, to seek their input on any issues not identified by the researchers or considered inadequately addressed. Plans were modified to address several issues raised by the community, and to provide the monitoring and reporting required to give them confidence that the project was protecting the aquifer and aquitard and not adversely impacting on their irrigation and drinking water supplies. This involved a series of community meetings and production of a portable, interactive display to illustrate the concept of ASR which included dialogue in a choice of English, Khmer or Vietnamese, to represent the largest ethnic groups operating market gardens in the Virginia Horticultural region. The community forums allowed an opportunity to address any concerns, present the benefits and to provide confidence that a trial could be managed without adverse impacts on current activities. Brochures and a video were also produced to disseminate information to the community (Martin and Dillon 2005).

Groundwater modelling was undertaken to determine the volumes of water that could be recharged and recovered each year while keeping hydraulic heads in the aquifer within acceptable limits. It was shown that when injecting only outside the perimeter of the 1000 mg/L TDS zone approximately 9 GL per year could be achieved (Martin and Dillon 2005).

Economic analysis: 9 GL/yr recycled water ASR scheme and 6 GL/yr recycled water and stormwater blended ASR scheme

The configuration of this scheme relied on small spur lines from the existing recycled water pipeline, particularly in the outer extremities of the system. These would be used to recharge water in winter when pipeline demand was low, and in summer recover back to the pipeline when demand exceeded the capability of the water recycling plant to supply the pipeline or when the instantaneous flow rate could not be delivered through the main trunk line of the pipe system.

ASSUMPTIONS

Benefits applicable to both schemes

The primary benefit is the reduction in nitrogen discharged to the marine environment.

Water Reticulation Systems Virginia (WRSV) system (without ASR) consists of the recycling plant located after the lagoons at the end of the Bolivar Sewage Treatment Plant, pumping station, pipeline and farmers dams. This was established on the basis of:

a) Contributing to a reduction to 600T N (from the Adelaide Coastal Waters Study) by reducing volume of effluent discharged to sea by 15 GL/yr (15GL * 20mg/L = 450T N/ yr)

b) Curbing unsustainable use of groundwater on the Northern Adelaide Plains by replacing approx. 6 GL/yr of groundwater irrigation with recycled water to bring the Tertiary aquifers into hydrologic equilibrium. Saving to growers of 6 GL/yr * 4c/kL = $240,000/yr in operating costs.

c) Allowing increase in irrigation with secure water supplies, to increase economic output of the Virginia horticultural region on the Northern Adelaide Plains, for which irrigators would pay part of water costs and state and commonwealth contributions would result in increased taxable income. Farmers were willing to take or pay 15 GL/yr at 9.5c/kL (2005) with CPI increases annually giving 12c/kL (2015) amounting to $1.8M/yr (indexed). It is assumed that the benefit is composed only of the price paid by users for the water, as there are a number of other inputs to the production values of various crops, including; land, labour, machinery, fertilisers and irrigation systems.

d) In the case of the blended water scheme, it is anticipated that higher valued crops can be grown with fresher water, but again the benefit is determined by the assumed willingness of irrigators to pay for access to fresher water.

Subsequently, the treatment plant at Bolivar was improved to activated sludge treatment at an estimated cost of say $750M (part of the $1.5B referred to as expenditure by SA Water in reducing N discharges from 1200 T to less than 600 T/yr to Adelaide Coastal Waters). This also reduced the excessive N in recycled water used for irrigation (i.e. 50 GL/yr – 15 GL/yr =35 GL/yr * (20 mg/L - 10 mg/L) = 350 T N/yr). Therefore the capital cost of reducing annual N load is $750M/350 T N/yr = $2.1M/ T N/yr. Assuming annual operating and maintenance costs are 10% of capital costs for the activated sludge plant, i.e. $210,000/ T N/yr. EPA (2008) noted that although SA Water had already reduced N discharges by more than 1000 T/yr between 1998 and 2003 substantial further reductions were needed to achieve coastal water quality targets. EPA recommended reduction of Bolivar discharges from 477 T N/yr (achieved in 2004) to 100 T N/yr (EPA 2008).

The nitrogen reduction to date was regarded as the simplest and most cost effective and therefore the cost of further reducing annual N discharges to sea from 477 T/yr to 100 T/yr would likely have a higher cost per Tonne of Nitrogen reduced from coastal discharges. Therefore applying the same unit costs of the combined impact of the activated sludge plant and the water recycling system is likely to under-estimate the avoided cost of marine discharge for new projects. Hence $2.1M/ T N capital and $0.21M/ T N/yr operating are likely conservative estimates for the avoided costs of additional treatments required to achieve mandated discharge targets.

The avoided cost of wastewater treatment to reduce N loading to sea was calculated on the basis of publically available data and was not provided by the relevant water utility on the basis that they regarded their information as commercial-in-confidence. It will be shown later that a lower shadow cost for avoided treatment costs may be possible.

Benefits applicable to 9 GL/yr recycled water ASR scheme

The benefits of this proposal are:

a) Further reduction in N discharge to sea based on recycling and recharging continuing through winter, to meet summer peak demand when the pipeline flow capacity was reached (so 9 GL/yr * 10 mg/L = 90 T N/y) *$2.1M/ T N= $190M capital plus $19M/yr operating (see also (c) below for alternative avoided cost calculation).

b) Allowing greater summer use of recycled water when crop needs were highest (the willingness to pay figure is taken as the current supply charge (9GL * 12c/kL = $1.08M/yr).

An alternative to subsurface storage is to build a surface storage to generate the same savings in discharge of nitrogen to sea and to produce the same water sales. This can be compared with the cost of additional treatment alone prior to discharge. The avoided costs of wastewater treatment may therefore be a large storage dam at the northern end of the pipeline (A 9 GL dam is half the size of Little Para Reservoir but on flat land).

Operating and maintenance costs are expected to be 3% capital works i.e. $5M/yr (smaller mechanical component than treatment alone). The avoided cost is $164M capital and $5M/yr (for dam option), which is cheaper than the treat and discharge to sea option of $190M capital and $19M/yr. The lower of these two costs is the avoided cost used in the economic evaluation. They both have the same effect on N discharge to sea but the dam option also allows summer irrigation use of recycled water produced during winter. A comparative analysis is provided in the results.

An approximate cost estimate for a 9 GL storage dam is $164M, calculated as follows:

Land area:	Assume average height of water is 4.5 m, then land area required = 2 million m^2 =200 ha. PV of production from land ~$30,000/ha/yr, so say $300,000 /ha capital cost of land.	$60M
Earthworks:	say 4 km long*5.5 m high*(4+15) m*0.5(ave width)*$20/$m^3$	$4.2M
Liner:	costs say $10/$m^2$ * 200 ha. Any leakage could raise shallow saline groundwater causing nearby land salinisation.	$20M
Cover:	To prevent algal growth and evaporation to make equivalent to subsurface storage say $30/$m^2$ *200 ha. Note that this quality of water would require a cover for surface storage as otherwise evaporative losses would increase salinity of water making it less fit for irrigation. Any brackish water retained in the basin when it exceeded acceptance limits for irrigation would need to be drained, and would reduce the saving in N discharge to sea. Furthermore DAFF filtration would need to be repeated, but water could not be returned to the original plant because that plant and the connecting pipeline would be operating at full capacity in summer. Hence, without a surface storage cover a new DAFF plant would be required, resulting in capital and operating costs, including sludge management, and possible nutrient discharges to sea from plant wastewater.	$60M
Other costs:	Recovery pumps, electricity to site, filtration and monitoring.	$20M

Benefits applicable to 6 GL/yr recycled water and stormwater blended ASR scheme

A recent National Water Commission-Goyder Institute for Water Research study (Managed Aquifer Recharge and Stormwater Use Options (MARSUO), Dillon *et al.* 2014) has shown that one of the most economic uses of harvested stormwater is to blend it with recycled water for use in irrigation use. Harvested stormwater could potentially be stored in the aquifer jointly with the recycled water diluting the water so that recharge within the groundwater drawdown cone at Virginia would be possible. This would allow a further 3 GL recycled water and 3 GL stormwater to be recharged together in winter.

This would have the benefit of:

(a) Further reduction of discharge of nitrogen to the gulf (3 GL*10 mg/L + 3 GL*1 mg/L (Vanderzalm *et al.* 2013) = 33T N/yr * $2.1M /T N = $69M capex plus $6.9M/yr opex.

(b) As with dam option above, scaling the costs volumetrically 6 GL/ 9 GL 3 * $164M = M$110M plus annual costs of $4M/yr. As the treatment option (a) is the cheaper of the two alternatives (a and b) for reducing N discharge to sea this becomes the avoided cost to meet environmental discharge requirements.

(c) Immediate improvement in hydraulic heads and reduction of pumping costs for irrigators where irrigation is most intense in summer months. (6 GL* 1c/kL = $60,000/yr saving for irrigators in pumping costs. This is a real economic saving retained as a benefit by irrigators. It is not transferred to the operator unless taken into account in willingness to pay and price of scheme water). Improvement in quality of recovered water to allow a wider range of higher valued crops, and watering of salt sensitive crops when they rely of having low salinity water. Presumably this could be part of negotiations with irrigators on water pricing and increased willingness to pay for all water. There would not be two reticulation schemes. It is expected that water use would decline by 10% due to smaller leaching fractions being required. That is 10% more land could be irrigated with the same water volume. A conservative estimate of beneficial impacts is 10% of current water price (12c/kL) i.e. 1.2c/kL, or 6 GL*1.2c/kL =$72,000/yr.

(d) If consideration of changes in crop type are taken into account, then benefits could be substantial. For vine irrigation in Willunga Basin where recycled water from Christies Beach plant is fresher, customers pay a once-only access fee of $7,260 per ML and a delivery charge of $0.95 or $1.25 per kL, depending on their location, with water security to 2038 (Institute for Sustainable Futures, 2013). (If growers were willing to cover a price increase from 12c/kL to 95c/kL for 6 GL of fresher water (TDS<1000 mg/L), this would give additional sales of $5M/yr and an initial income of $43M). A sensitivity analysis takes account of only realising a proportion of this income due to other factors, such as more resistant willingness to pay or differences in soil and micro-climate or changes in grape prices that may affect the value of production.

(e) Reduction in groundwater salinity in the drawdown cone would also be a consequence of this project, and while this real benefit would be experienced by growers, there is no assurance that this would be permanent and therefore result in a change of crops and hence a realisable benefit. This freshening would be regarded as a windfall gain for the broader community.

Costs applicable to 9 GL/yr recycled water ASR scheme

It is assumed that the costs of the sewerage system and sewage treatment need not be included in the analysis of costs of either of the water recycling schemes via the aquifer, which are superimposed on the existing water recycling system.

Furthermore it is assumed that the capital costs of the water recycling plant, pumping station, pipeline system and irrigator farm dams are also a sunk cost for any project to augment the existing 15 GL per year supply to irrigators on the northern Adelaide Plains. This was part of the previous environmental obligations for nitrogen discharge to sea, and operating costs were met at least in part by nominal recycled water charges to users. Hence neither the costs nor benefits of the use of the 15 GL per year directly from the WRSV system are used in the analysis of either of the supplemental MAR projects.

As reliable information of capital and operating costs for the recycling plant were not available at the time of publication, it is assumed that the operating cost for the recycled water plant is $0.20 per kilolitre and for pumping it is $0.04 per kilolitre. No account is taken of costs to irrigators for pumping water from their farm dam, as they would otherwise have had to cover the costs of pumping from groundwater, for which it was intended that recycled water would substitute.

Capital costs of components of the 9 GL per year recycled water ASR project were initially determined using costings developed by Martin and Dillon (2005) and inflated to 2015 costs by CPI. Unit costs were compared with current unit costs of components determined independently. Costs of most components had increased substantially faster than CPI, notably for drilling, pumps, pipelines and SCADA systems. In the latter case, costs now include SCADA via satellite communications with an existing central control system for water management. Capital costs associated with power supply for each ASR site have also been included.

Although the expected average injection capacity of each ASR well is 250 ML/yr, based on the Bolivar ASR trial results, a contingency of 10% was allowed by costing for 40 ASR wells of this capacity. This would also provide some redundancy and flexibility in system operation. Furthermore allowance was made for one monitoring well near each ASR well to assist in managing the system, particularly to identify the near-well clogging component of decline in specific capacity of the wells and thereby determine the timing of backflushing of each well, based on its own behaviour. This is expected to increase the efficiency of operation, minimise backflushing requirements and provide feedback on water quality variations with respect to operational efficiency of ASR.

In the analysis a conservative recovery efficiency of 80% was assigned to be constant. Recovery efficiency is the proportion of the volume of injected water that can be recovered at a water quality fit for its intended use. Because water is being stored in an initially brackish aquifer (typically 2,200mg/L total dissolved solids), mixing with native groundwater occurs and towards the end of recovery salinity will increase and could reach the threshold acceptable for irrigation. Recovery efficiency is expected to increase over successive years of ASR operation, as the unrecovered fresher water helps buffer against the more saline native groundwater. This means that for 9 GL/yr water stored in the aquifer, the analysis assumes that only 7.2 GL/yr is recovered for irrigation supplies. Operating costs for recycled water treatment and for pumping into injection wells are assigned to the full 9 GL/yr, however operating costs for recovery and the returns from irrigators (benefits of use) are assigned only to the 7.2 GL/yr recovered.

Each ASR well was assumed to have a capacity of 20-30 L/s and depth of 200 m. Capital and operating costs are itemised in Table 16 and Table 17, respectively. Each well was estimated to have a connection to the recycled water pipeline with an average length of 1 km of buried 200 mm high pressure pipe at an average capital cost per well of $200,000. Also not all wells would have an existing suitable power supply for recovery pump operation and an average allowance was made of $160,000 per well for provision of power including a transformer. Hence total capital works per ASR site were estimated to be $857,900.

Table 16 Estimated capital costs for each ASR well site (with a capacity for 250ML/yr injection over 4 months) in a 9 GL/yr Bolivar recycled water ASR Project.

Item	**$ (in 2015)**	**Lifetime (yr)**
ASR well drilling, logging, casing	168,000	30
Observation well	80,000	30
Well development	16,000	30
Pump, rising main and valves	102,000	15
SCADA and monitoring equipment	100,000	10
Headworks	12,800	30
Land /caveat	10,000	50
Purge water management/soakage pit	9,100	30
Pipeline (for recharge and recovery)	200,000	80
Power supply	160,000	80
Total per recycled water well	857,900	
Total for 40 wells	**34,300,000**	

Table 17 Estimated operating costs for a 9 GL/yr Bolivar recycled water ASR Project.

Item	**$/kL (in 2015)**
DAFF water treatment (9 GL/yr)	0.20
Pumping including injection (9 GL/yr)	0.04
Pumping - recovery (7.2 GL/yr)	0.04
Injection well maintenance (9 GL/yr)	0.04
ASR monitoring & reporting (9 GL/yr)	0.04
Maintenance – reticulation (9 GL/yr)	0.02
Total	0.37
Annual operating cost for 40 wells	**3,348,000**

Costs applicable to 6 GL/yr recycled water and stormwater blended ASR scheme

The ASR costs are composed of those for 3 GL/yr recycled water ASR and 3 GL/yr stormwater ASR, with 28 wells in total and 14 of each type. The recycled water costs are derived by scaling from the costs of the 9 GL/yr recycled water project. Capital and operating costs for stormwater ASR systems were calculated using current data from Aqueon (unpublished data 2015) and are shown in Table 17 and Table 18, respectively.

Excluding wastewater treatment costs, stormwater harvesting costs are in general higher than for recycled water due to the infrastructure required (i.e. wetland) to harvest the stormwater. Normally stormwater ASR assets experience lower rates of utilisation than recycled due to the seasonal and intermittent availability of stormwater, but in this instance it is assumed that the recycled water is only available for storage for the same duration as stormwater when the trunk pipeline is under-utilised. The average connection length of each ASR well from the pipeline is 1 km, as for the 9 GL/yr scheme except that wells would be located within the drawdown cone of the irrigation area, instead of outside the perimeter of the fresher groundwater.

Table 18 Estimated capital costs for each ASR well site (with a capacity for 250ML/yr injection over 4 months) in a proposed Bolivar 6 GL/yr blended ASR Project.

Item	$ (in 2015)	Lifetime (yr)
ASR well drilling, logging, casing	168,000	30
Observation well	80,000	30
Well development	16,000	30
Pump, rising main and valves	102,000	15
SCADA and monitoring equipment	100,000	10
Headworks	12,800	30
Land /caveat	10,000	50
Purge water management/soakage pit	9,100	30
Wetland (250 ML/yr/well)[#]	3,000,000	50
Pipeline (for recharge and recovery)	200,000	80
Pipeline (for wetland connection)	200,000	80
Power supply	160,000	80
Total per stormwater well	4,057,900	
Total for 14 stormwater ASR wells	56,810,600	
Total for 14 recycled water ASR wells	12,010,600	
Total for 28 wells	**68,821,000**	

[#] neglecting flood mitigation benefits of the wetland

Table 19 Estimated operating costs for a proposed Bolivar 6 GL/yr blended ASR Project.

Item	$/kL (in 2015)
DAFF water treatment (3 GL/yr)	0.20
Pumping including injection (6 GL/yr)	0.04
Pumping - recovery (4.8 GL/yr)	0.04
Injection well maintenance (6 GL/yr)	0.04
ASR monitoring & reporting (6 GL/yr)	0.04
Wetland maintenance (3 GL/yr)	0.04
Maintenance – reticulation (6 GL/yr)	0.02
Total	**0.29**
Annual operating cost for 40 wells	**1,752,000**

It is also assumed that stormwater harvested in wetlands could be conveyed to the pipeline with a total connection length of 14 km (i.e. averaging 1 km of connector per 250 ML/yr stormwater source), and using the existing Virginia pipeline to avoid duplication of pipelines.

Note that this is a worst case scenario where the full cost of the wetland for stormwater harvesting is attributed to water supply and reducing nitrogen discharge to sea, and no account is taken of flood mitigation benefits of wetlands. In some existing cases the full cost of wetlands has been attributed to the requirement for flood mitigation as the water supply was only considered after the wetland had been established and was then regarded as a sunk cost. A sensitivity analysis on the impacts of flood mitigation benefits on ASR water supply economics is performed later (Table 21).

Analyses of levelised costs of recovered water for eight stormwater harvesting, aquifer storage and recovery projects at a scale of 75 ML per year to 2 GL per year by Dillon *et al* (2009) gave a total levelised cost of $1.12 per kilolitre composed of $0.84 per kilolitre for capital and operating $0.28 per kilolitre. Adjusted by CPI from March Quarter 2008 to March Quarter 2015 gives a total levelised cost of $1.32 per kilolitre (excluding wetland) in 2015 dollars. In comparison, Dandy *et al.* (2014) have given levelised costs for, among other uses, non-potable supplies from an 880 ML scheme at Parafield of $1.57 per kilolitre and $0.42 per kilolitre including and excluding the costs of existing infrastructure (Tables 4.5 and 4.4 respectively in Dandy *et al* 2014). Using CPI adjustment from December Quarter 2013 to March Quarter 2015 gave these levelised costs in 2015 dollars as $1.60 per kilolitre and $0.43 per kilolitre respectively.

RESULTS

9 GL/yr recycled water ASR scheme

Applying the Recycled Water Economic Assessment Tool with the inputs described above, and allowing the full scheme to be constructed over four years commencing in 2015 with 10 new wells operational for recharge and recovery each year, gives the present value cost of $79.5M and a levelised cost of $0.88 per kL. A summary of costs and benefits is given in Table 20 and Figure 12.

Comparing the ASR scheme with the estimated costs of a surface water storage that would reduce the coastal discharge of N by the same amount (90 T N/yr) and yields up to 20% higher volume for irrigation gives a benefit to cost ratio of around 2.8 (option 1 in Table 20). Comparing the ASR scheme with a conservative cost estimate of a treatment process that would reduce the coastal discharge of N by the same amount gives a considerably higher benefit to cost ratio of 4.2 (option 2 in Table 20). That is the present value cost of the ASR system is approximately 35% of that of the cheapest alternative project, that of storing the water above ground before use, and would produce a saving of $144M ($2015).

6 GL/yr recycled water and stormwater blended ASR scheme

Applying the Recycled Water Economic Assessment Tool with the inputs described above, and allowing the full scheme to be constructed over four years commencing in 2015 with 7 new wells operational for recharge and recovery each year, gives the present value cost of $93.3M and a levelised cost of $1.55 per kL.

Comparing the 6 GL/yr blended water ASR scheme with a conservative cost estimate of a treatment process that would reduce the coastal discharge of N by the same amount (33 T/yr) gives a benefit/cost ratio of 1.3 (option 2 in Table 20). Also comparing the ASR scheme with the estimated costs of a surface water storage (option 1) that would allow the same reduction in N discharge to sea, and is assumed to yield 20% higher volume for irrigation gives a benefit cost ratio of 1.7. The present value cost of the ASR system is about 77% of that of the cheapest alternative project and would produce a saving of $28M ($2015) (Figure 13).

The analysis above does not account for increased willingness to pay for fresher water that this blended water system produces and can sustain higher valued production. Recycled water with total dissolved solids below 1,000 mg/L is used in the Willunga Basin south of Adelaide at a cost of $0.95/kL (30% of current mains water price $3.23/kL). If cost estimates assume the higher annual revenue for fresher water (i.e. $0.95/kL *c.f.* current recycled water price of $0.13/kL), the present value of the revenue from 4.8 GL/yr fresher water would amount to $56.7M (*c.f.* $7.9M) an increase in benefit of $48.8M.

A sensitivity analysis was undertaken for both projects (Table 21). This revealed that for both projects the net benefits were positive for all cases considered and were more sensitive to costs of the relevant alternative surface water storage projects, than to capital or operating present values of the ASR projects. The requirement to reduce nitrogen discharge to coastal waters was the most important driver for recycled water ASR, but the treatment costs were so large that there were cheaper alternative projects involving surface storage, that dictated the avoided costs. For both projects these avoided costs significantly exceeded the benefits of revenue from sale of recovered water. The base case blended water ASR project (that did not account for significant changes had a lower benefit cost ratio and higher contribution of operating costs to the direct costs and so was more dependent on discount rate, than the more capital intensive stormwater harvesting projects. For the blended water project net benefits increased by 59% when the cost of wetlands, that provided half the recharged water, were written off as a flood mitigation benefit. This resulted in almost identical net benefits per GL of water supplied between recycled water and blended water projects. If sale price increased to the same levels as Willunga Basin recycled water, which has a similar salinity to the blended water, the net benefits would increase by almost 74%. If both flood mitigation benefits and sale prices increased then the present value of net benefits per GL of the blended water project would be $31.8M/GL, compared with the baseline case of using only recycled water of $20.1M/GL.

Table 20 Results of the economic analysis of the Bolivar ASR scheme.

Item	**9 GL/yr recycled water**		**6 GL/yr recycled water/stormwater blend**	
	(PV in $)	**(PV in $)**	**(PV in $)**	**(PV in $)**
Present Value of Costs				
Recycled water	22,365,126	22,365,126	7,455,042	7,455,042
ASR scheme direct cost	56,516,357	56,516,357	85,239,483	85,239,483
Reticulation cost	-	-		
Indirect service delivery cost	-	-		
Other environment / community cost	637,926	637,926	637,926	637,926
Other costs	-	-		
Total Net Present Cost	**79,519,409**	**79,519,409**	**93,332,451**	**93,332,451**
Present Value Benefits (avoided cost)	**Storage (option 1)**	**Marine discharge (option 2)**	**Storage (option 1)**	**Marine discharge (option 2)**
Value to customer	-	-	-	-
Avoided wastewater cost	226,922,542	321,575,709	160,635,251	113,799,121
Avoided potable water cost	-	-	-	-
Wider community willingness to pay	-	-	-	
Other environment / community benefits	-	-	-	-
Revenue return from sales of water	-2,683,815*	10,735,261	-1,968,131*	7,753,244
Other benefits	-	-	-	-
Total Net Present Benefits	**224,238,727**	**332,310,969**	**158,667,120**	**121,552,365**
Net Present Value	**144,719,318**	**252,791,560**	**65,334,669**	**28,219,914**
Cost per kilolitre	$0.88 per kL	$0.88 per kL	$1.55 per kL	$1.55 per kL
Benefit per kilolitre	$2.51 per kL	$3.71 per kL	$2.66 per kL	$2.04 per kL
Benefit cost ratio (BCR)	2.9	4.2	1.7	1.3

* This additional revenue for covered storage negates some of its avoided cost in considering the benefits of the ASR scheme (due to loss to the aquifer).

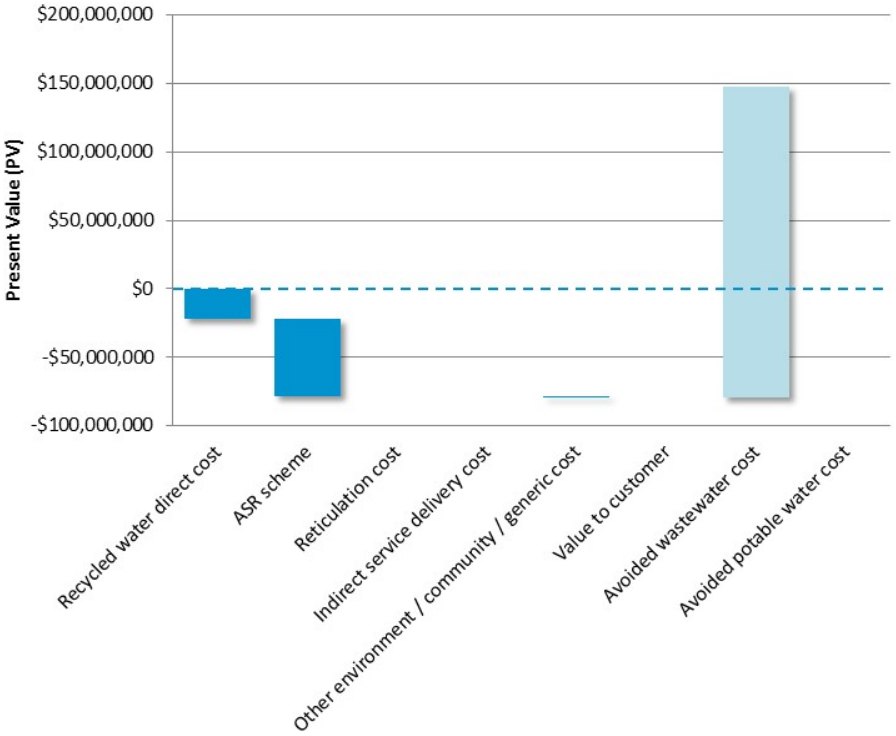

Figure 12 Results of the economic analysis of the 9 GL/yr recycled water Bolivar ASR scheme (with respect to option 1, storage). ' (Note that value to customer is negative with respect to option 1, due to reduced quantity of water supplied.)

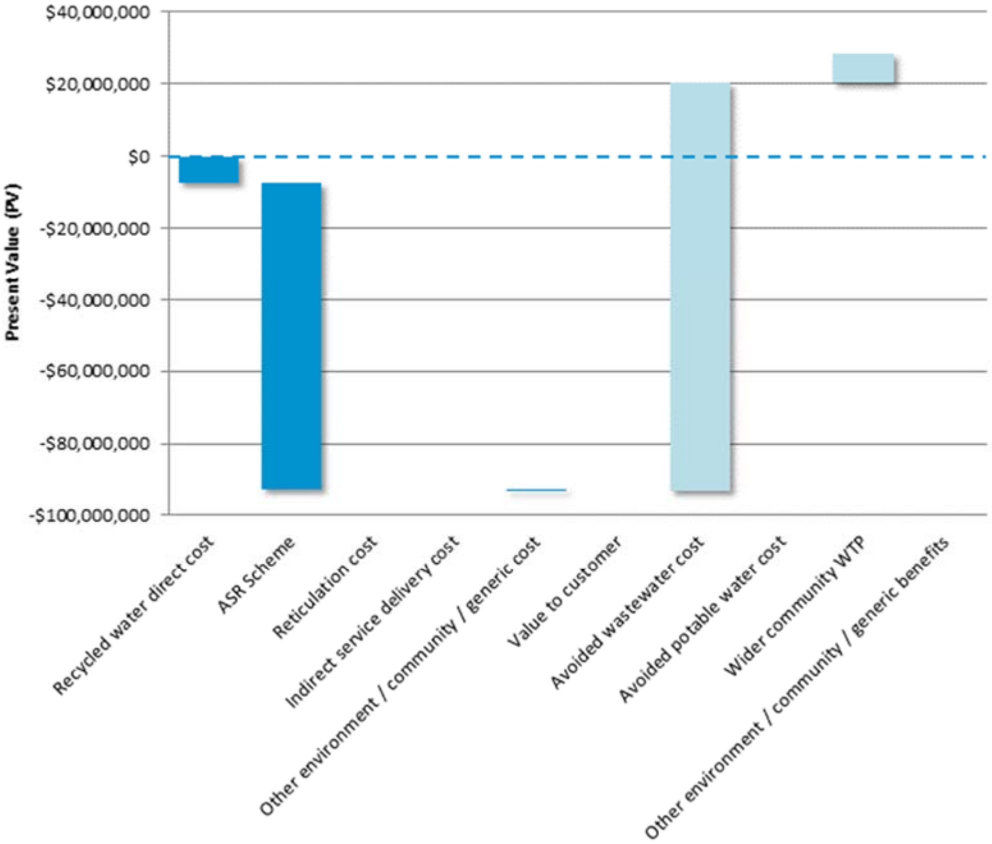

Figure 13 Results of the economic analysis of the 6 GL/yr recycled water and stormwater blended Bolivar ASR scheme (option 2, marine discharge).

Table 21 Results of the sensitivity analysis of Bolivar ASR schemes.

Item	NPV (in $M)	Change (in %)
9GL/yr recycled water ASR system		
Base Case	**144.4**	0%
Capex +10%	140.6	-2.6%
Opex +10%	140.3	-2.8%
Nitrogen discharge reduction benefit +10%*	144.4	0%
Capex of surface water storage alternative +10%	160.8	+11.4%
Sale price of recovered water +10%	145.5	+0.7%
Discount Rate of 4%	175.6	21.6%
Discount Rate of 10%	132.5	-8.2%
6GL/yr blended recycled water and stormwater ASR system		
Base Case	**65.3**	0%
Capex +10%	58.7	-10.0%
Opex +10%	62.6	-4.1%
Nitrogen discharge reduction benefit +10%*	65.3	0%
Capex of surface water storage alternative + 10%	76.3	+16.8%
Sale price of recovered water +10%	66.2	1.3%
Sale price of recovered water increased to 95c/kL	114.1	73.7%
Wetlands cost equated to flood mitigation benefit	104.1	59.4%
Sale price 95c/kL and wetland cost as flood mitigation	152.9	134.1%
Discount Rate of 4%	86.7	32.8%
Discount Rate of 10%	57.3	-12.2%

* compared with least cost project to give same N discharge benefit.

Aquifer Storage Transfer and Recovery, Anglesea (Vic)

Barwon Water is the retail water business that supplies drinking water, recycled water and sewerage services to the Greater Geelong region of Victoria. Water supply in the Greater Geelong region is sourced from surface water catchments on the upper Barwon and Moorabool Rivers. In times of drought, supply is supplemented with groundwater from the Barwon Downs and the Anglesea borefields (although this case study focuses on the latter).

Groundwater extraction from the Anglesea borefield via the Lower Eastern View Formation is limited to a maximum of 35 GL in five years (with an average of seven GL per year) with a maximum of 10 GL in any year. Groundwater extraction from the Lower Tertiary Aquifer via the Barwon Downs Borefield is limited to 20 GL in any one year, a maximum of 80 GL in any 10 year period and a maximum of 400 GL in any 100 year period. Additional supply can be sourced from the existing Melbourne Geelong pipeline, which has capacity to deliver 16 GL per year. In addition to a wide suite of other options, Barwon Water has also investigated the potential for supplementing potable water supplies through MAR.

The MAR option examined in this case study would treat and store Class A recycled water in an aquifer for eventual inclusion in the drinking water supply. This option is not supported by current Victorian Government policy and is therefore being examined as a hypothetical case study for consideration in future water supply decisions.

Under this option, recycled water from the Black Rock Recycled Water Plant would be injected and subsequently recovered from an Aquifer Storage Transfer and Recovery (ASTR) scheme north of Anglesea in the Upper Eastern View Formation aquifer. The Black Rock Recycled Water Plant comprises ultrafiltration, reverse osmosis, ultraviolet and chlorine disinfection. The recovered water would then be treated to potable standards at the Wurdee Boluc treatment plant. The current groundwater supply from the Lower Eastern View Formation, extracted at the Anglesea borefield, is also treated at the Wurdee Boluc treatment plant prior to distribution.

As noted earlier, CBA options are compared against a ‘without project’ option. In this case, the ASTR option was assessed against the next best alternative for augmenting local water supplies: the duplication of the existing Melbourne Geelong pipeline (MGP) along a new alignment, which would source up to an additional 8 GL per year from the Melbourne water system. The water would then be transferred to the Geelong region via the duplicated MGP.

MAR scheme

An aquifer storage and recovery (ASR) trial was undertaken in the Upper Eastern View Formation (EVF) in 2011 and included three cycles of injection storage and recovery of increasing duration (Table 22). The Upper EVF aquifer consists of interbedded sand, gravel, clay and coal (SKM 2010a; Geoscience Australia 2011). The ASR trial targeted sand/gravel layers intersected between 95-112 m BGL and 117-127 m BGL and transmissivity estimates of these layers were 200-400 m^2/d (SKM 2010a). The trial was primarily a hydrogeological investigation and the source water for injection was treated groundwater from the Anglesea borefield. Figure 14 illustrates samples of aquifer sediment collected during drilling, which were used to characterise the properties of the storage zone.

The managed aquifer recharge options assessed for drinking water supply by SKM (SKM 2012) were based on ASTR, or the use of separate wells for injection and recovery providing a minimum of one year residence time in the aquifer. SKM (2012) proposed an operational scheme layout capable of supplying 30 ML/d, comprising seven injection wells and seven extraction wells with a minimum well spacing of 800 m to provide a one year residence time in the aquifer. The source water proposed for injection was 75% RO treated wastewater and 25% ultrafiltered wastewater, with a combined salinity of approximately 500 mg/L TDS. Twenty one monitoring wells were included in the MAR scheme design.

Table 22 Details of the aquifer storage and recovery trial undertaken at Anglesea.

Cycle	Dates	Phase	Duration (hours)	Average pumping rate (L/s)	Total volume injected or recovered (ML)
1	5/5/2011-9/5/2011	Injection	23	43	3.5
		Storage	22	0	0
		recovery	54	25	4.8
2	11/5/2011-19/5/2011	Injection	48	30	5.4
		Storage	72	0	0
		Recovery	74	19	5.1
3	31/5/2011-1/7/2011	Injection	246	21	18.6
		Storage	98	0	0
		Recovery	401	9	11

Figure 14 Dr Ririn Erinawati inspecting aquifer samples collecting during drilling (Photo: Gwynn Hatton, Barwon Water).

Lessons from experience (injection trial)

Initially the efficiency of the ASR bore was considered low with a maximum yield of 15 L/s. Further development of the bore using conventional airlifting, jetting and back-washing resulted in a yield in excess of 30 L/s (SKM 2011). Injection and extraction rates were successively lowered in each of the three ASR cycles, indicating that well clogging had occurred which decreased bore efficiency. Bore clogging was attributed to physical and chemical clogging. While the source water (groundwater) was low in suspended solids (typically < 3 mg/L TSS and < 4 NTU), algae which were not visible to the eye developed in the holding pond and caused clogging. A 10 μm filter installed in the injection line, before the ASR bore, assisted with the removal of algae but did not completely resolve the issue as some algae species present were smaller than 10 μm. Clogging due to algae in the source water can be prevented by minimising the opportunity for algae to form during storage in open lagoons. Furthermore, this issue was not expected to impact on a future MAR scheme as the source water would not be stored in an open lagoon.

Chemical clogging was observed, resulting from oxidation of iron which forms insoluble precipitates due to injection of oxygen rich water into an anoxic groundwater with high dissolved iron levels. Backflushing contributed to management through removal of accumulated iron. However, SKM (2012) recommended redox control (pH/Eh) at the point of injection in a future MAR scheme to minimise precipitation at the well face.

SKM (2012) reported key lessons from their experience with regulatory consultation as follows:

- Three month timeframe for approval of the licence for the injection trial was reasonable.
- Regulatory process was fairly clear and consistent.
- Approval process was efficient as Southern Rural Water (SRW) acted as a 'one stop shop' for the licence. SRW had discussions with relevant agencies (Victorian Department of Sustainability and Environment (DSE) and EPA) but did not formally refer the licence request to them.
- SRW expected the risk assessment and management plan to cover the operational MAR scheme, rather than the injection trial only. This was not anticipated.
- Engaging with the local EPA regarding discharge of the recovered water was difficult.

Prior to the current economic analysis and the Anglesea injection trial, SKM (2012) assessed seven options for MAR using a Multi Criteria Assessment (MCA). The source water for these were recycled water and recycled water blended with stormwater and the end-uses considered were indirect potable reuse via Wurdee Boluc treatment plant and dual pipe non-potable supply. Of these, indirect potable reuse end-uses were ranked highest due to the higher volumes of water that could be recycled. However, the trial investigation revealed a lack of community support for recycled water MAR which mean that it did not proceed to an operational scheme.

Economic analysis

All CBA options must be compared against a 'without project' option. In this case, the ASTR option was assessed against the next best alternative for augmenting local water supplies: the duplication of the existing Melbourne Geelong pipeline (MGP) along a new alignment, which would source water from the Melbourne water system.

ASSUMPTIONS

Demand

For this analysis it was assumed that the scheme would supply 6.4 GL of water per year for the first 15 years, increasing to 8.9 GL per year thereafter. The demand for the ASTR option was adjusted (downward) to achieve the same total supply over the analysis period as the alternative supply option. That is, it is assumed that both options deliver the same amount of water. This ensures the options are compared on a like-for-like basis.

This demand scenario is similar to the "full supply from day 1" scenario assessed by SKM in their planning study for the Anglesea ASTR scheme (SKM 2012). It was assumed that the next best alternative option – duplication of the Melbourne Geelong Pipeline – would supply the same volumes each year over the analysis period.

Costs

Recycled water direct cost

Recycled water direct costs include distribution pipelines, pump station (injection and recovery pumps), balancing tanks, recycled water treatment plant upgrades, land purchase for easements and the ASR scheme. The cost estimates for the Anglesea ASTR option were provided by Barwon Water (SKM 2012). Table 23 presents the capital expenditure, and operation and maintenance costs.

The capital cost estimates include contingencies and allowances, including:

- Design survey and approvals: 10%
- Project management: 10%
- Contractor preliminaries: 10%
- Contingency: 30%

Table 23 Capital expenditure (capex), operation and maintenance cost – Anglesea ASTR option.

Item	Capex	Capex incl. contingency / overheads	Operating Cost	Maintenance Cost
	$'000	$'000	$'000/a	$'000/a
Recycled Water Treatment Plant	75,675	124,864	3,644	-
Pipelines	12,535	20,683	-	159
Storage tanks	3,949	6,157	-	53
Pumping stations (source water supply, ASTR injection and recovery pumping stations)	23,103	38,120	2,127	318
ASTR scheme (14 ASTR wells, 21 monitoring wells)	13,327	21,989	-	267
Land (easements)	214	352	-	-
Water Quality Monitoring	-	-	534	-
Total	**128,803**	**212,525**	**6,305**	**797**

Source: SKM, 2012; Note: Costs were adjusted for inflation to $2014

Other costs – Carbon emissions

For its *Water Supply Demand Strategy*, Barwon Water estimated the Greenhouse Gas (GHG) emissions associated with the ASTR scheme at 29,539 tonnes CO_2 per year (Barwon Water 2012). These emission are generated by pumping and treatment of waste water.

As noted earlier, a constant (in real terms) carbon price of $40 per tonne CO_2 was applied.

Benefits

Avoided potable water costs

The primary potable water cost savings resulting from the Anglesea ASTR scheme are the avoided cost of obtaining water from the Melbourne water grid. From a 'whole of community' perspective, the savings will be the actual reduction in cost rather than the price paid by Barwon Water for bulk water (which is a transfer, i.e. cost to Barwon Water and a revenue to Melbourne Water).

The bulk water cost savings should therefore be calculated using a long run marginal cost (LRMC) approach. The LRMC is the levelised cost associated with an increase in demand and, in turn, the need to bring forward the timing of supply augmentations to maintain the supply demand balance.

As LRMC estimates are not readily available for the Melbourne water grid, the variable bulk water charge was used as a proxy. Variable bulk water charges amount to $1,546 per ML ($1.55/kL), comprising:

- headworks charges of $1,346 per ML; and
- transfer charges of $200 per ML.

In addition to sourcing water from Melbourne Water, Barwon Water would also need to duplicate the existing Melbourne Geelong Pipeline (MGP) to transfer the bulk water from the Melbourne water grid via Cowies Hill to Lovely Banks Basins. The avoided capital, operation and maintenance costs for the MGP duplication are shown in Table 24. Capital cost estimates include the same percentages of contingencies and allowances as the Anglesea ASTR option.

Table 24 Capital expenditure, operation and maintenance cost – Melbourne Geelong Pipeline duplication.

Item	Capital Expenditure	Capital Expenditure incl. contingency and overheads	Operating Cost	Maintenance Cost
	$'000	$'000	$'000/a	$'000/a
Pipelines	87,761	144,805	-	348
Storage tanks	14,081	23,233	-	-
Pumping stations	18,447	32,088	1,732	267
Total	**121,288**	**200,126**	**1,732**	**615**

Source: SKM, 2012; Note: Costs were adjusted for inflation

Avoided sewerage costs

In addition to the avoided potable water costs, SKM identified avoided costs of $8.7 million associated with a pumping station at the Black Rock Recycled Water Plant (SKM 2012).

Other benefits

The avoided Greenhouse Gas (GHG) emissions associated with duplicating the Melbourne Geelong Pipeline are estimated at 14,848 tonnes CO_2 per year (Barwon Water 2012). These emissions savings are largely due to the avoided pumping from the Melbourne water grid.

The Marsden Jacob (2013) *Economic value of recycled water* paper notes that direct use value and the community's preference for the use of recycled water may also be considered benefits of a recycled water scheme. However, these benefits are not relevant to the Anglesea ASR scheme because:

- Recycled water is used for indirect potable reuse and is therefore a perfect substitute for potable water. The use of recycled water therefore represents neither a net cost nor a benefit to the community in this case.
- Surveys (Barwon Water 2012) have demonstrated that the wider community does not support indirect potable reuse projects as strongly as non-potable reuse projects due to perceptions about the potential impact on human health. Thus it was assumed the community would not be willing to pay more than the cost of potable water for this or any other potable water reuse scheme supply.

RESULTS

Table 25 and Figure 15 show the results of the economic analysis. The results demonstrate that based on the 'most likely' estimates of costs and benefits, the Anglesea ASTR scheme would provide a net benefit of $54 million over the analysis period of 50 years.

The net benefit of the scheme is largely due to the high (avoided) cost associated with bulk water supplied from the Melbourne Water grid ($154 million in present value terms) and the duplication of the Melbourne Geelong Pipeline ($237 million in present value terms).

Table 25 Results of the economic analysis of the Anglesea ASTR option.

Item	Present Value (in $)
Present Value of Costs	
Recycled water direct cost	312,660,519
ASTR scheme cost	25,826,809
Reticulation cost	-
Indirect service delivery cost	-
Other environment / community cost (carbon emissions)	16,266,298
Other costs	-
Total Net Present Cost	**354,753,626**
Present Value Benefits (avoided cost)	
Value to customer	-
Avoided wastewater cost	9,856,104
Avoided potable water cost	390,866,612
Wider community willingness to pay	-
Other environment / community benefits (avoided carbon emissions)	8,176,377
Other benefits	-
Total Net Present Benefits	**408,899,093**
Net Present Value	**54,145,466**
Cost per kilolitre	$3.56 per kL
Benefit per kilolitre	$4.10 per kL
Benefit cost ratio	1.2

Source: Marsden Jacob analysis

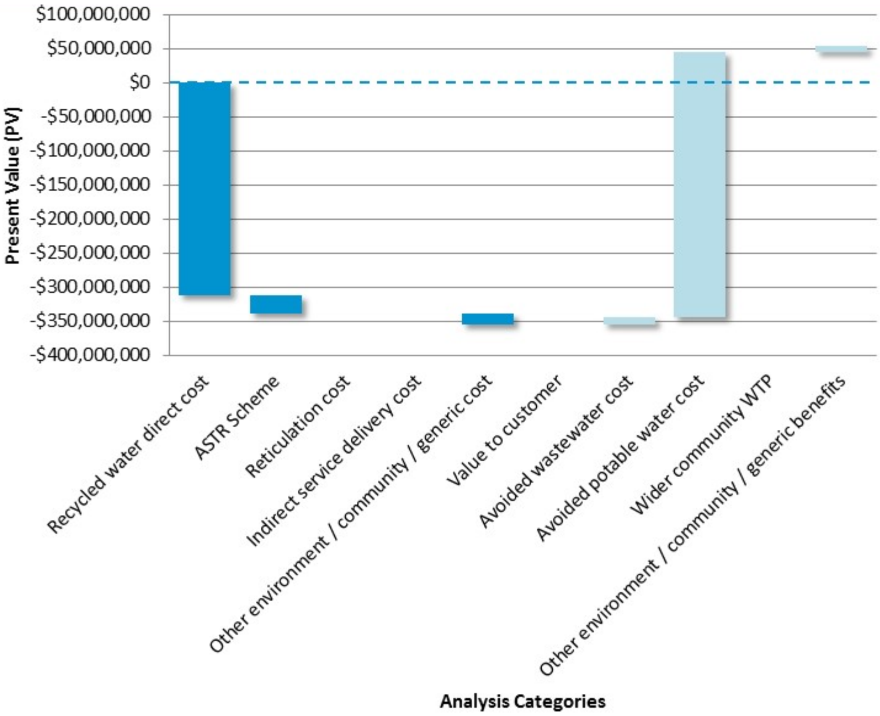

Figure 15 Results of the economic analysis of Anglesea ASTR option.

Source: Marsden Jacob analysis

Sensitivity Analysis

Sensitivity analysis of the results was undertaken based on potential changes in the following assumptions:

- **Water supplied:** In line with the 'staged implementation' scenario examined by SKM, this assessment examined a lower supply scenario of 1.5 GL during the first 8 years, increasing to 2.8 GL the following 8 years and then 4.3 GL for 5 years, before reaching full supply of 8.9 GL in the 22nd year of operation. The lower volume over the first 21 years of scheme operation means that capital expenditure for the recycled water treatment plant and a number of pump stations can be deferred by 21 years. Under the lower supply option, the lower volume reduces the cost of bulk water purchases from the Melbourne supply system.
- **Capital expenditure:** Both a 10% increase and decrease in capital expenditure.
- **Operation and maintenance cost:** Both a 10% increase and decrease in operation and maintenance cost.
- **Melbourne Water bulk supply charges:** 20% lower bulk supply charges for water from the Melbourne system.
- Discount rates of 4% and 10%.
- Sensitivity analysis results are presented in Table 26. The results show that:
- The Anglesea ASTR scheme has a positive NPV under any of the sensitivity analyses completed. The result is relatively robust to variations in underlying assumptions.
- Lower demands significantly increase the NPV, because some of the capital expenditure of the Anglesea ASTR scheme can be deferred. This deferral of expenditure is not possible if the same amount of water is supplied via the MGP duplication.
- Increasing capital expenditure or operating and maintenance costs result in a greater NPV for the Anglesea ASTR. This is due to the high avoided cost of the alternative MGP duplication option. A 10% increase in capital costs or operation and maintenance cost results in a larger increase in benefits (avoided costs) than in direct capital and operation and maintenance cost associated with the Anglesea ASTR scheme.
- Changes to the cost of Melbourne bulk water supplies have a considerable impact on the NPV because it as a major cost item associated with the "without project" option. Reducing the bulk supply cost by 20% reduced the NPV by over 50%.
- The results are sensitive to changes in the discount rate. A lower discount rate of 4% leads to a 60% increase in the NPV due to the higher weight given to future benefits or cash flows. Conversely, a higher discount rate of 10% results in a decrease of NPVs (-28%).

Table 26 Results of the sensitivity analysis of Anglesea ASTR option.

Item	NPV (in $)	Change (in %)
Base Case	54,145,466	0%
Lower demand	132,918,295	+145%
Capex +10%	51,495,105	-5%
Capex -10%	56,795,827	+5%
Opex +10%	47,597,433	-12%
Opex -10%	60,693,500	+12%
Melbourne bulk water +20%	84,989,333	+57%
Melbourne bulk water -20%	23,301,600	-57%
Discount Rate of 4%	86,591,173	+60%
Discount Rate of 10%	38,827,197	-28%

Source: Marsden Jacob analysis

Groundwater Replenishment/Aquifer Storage Transfer and Recovery, Beenyup (WA)

Groundwater replenishment is an integral component of Water Corporation's 50 year plan *Water Forever: Towards Climate Resilience* (Water Corporation 2008). Groundwater replenishment involves recharging an aquifer with recycled water for later use as a drinking water supply. Perth's groundwater replenishment scheme (GWR) has received approval from the WA State Government to inject 14 GL of treated wastewater into the Leederville and Yarragadee aquifers each year, starting from late 2016 (Water Corporation 2014). The scheme will be scaled up to 28 GL per year by 2022 (Huynh *et al.* 2013). It has been estimated that groundwater replenishment could meet up to 20 per cent of Perth's drinking water by 2060; utilising a source of water that would otherwise be discharged to sea (Water Corporation 2013c).

Extensive investigations were undertaken within the Beenyup groundwater replenishment trial (GWRT) to establish the feasibility of replenishing the Leederville aquifer with treated wastewater (Water Corporation 2013c). The trial was undertaken from 2010 to 2012 with three objectives (Water Corporation 2013c):

- To provide a context for States' regulatory agencies to develop health and environmental regulation and water allocation policy for groundwater replenishment.
- To demonstrate the technical feasibility of the treatment process and aquifer response to reliably meet health and environmental water quality guidelines.
- To raise awareness and encourage community discussion about groundwater replenishment and its potential as a future water source.

The economic assessment of groundwater replenishment was calculated on the basis of publically available data, drawing heavily on the information provided by the Beenyup groundwater replenishment trial (GWRT). Capital costs were available for the 14 GL groundwater replenishment scheme, while operating and maintenance costs were estimated from GWRT data.

MAR scheme

The source water for MAR is secondary treated wastewater that undergoes advanced treatment at the Advanced Water Recycling Plant (AWRP) using ultrafiltration (UF), reverse osmosis (RO) and ultraviolet (UV) disinfection.

The target aquifer for the trial and the initial stage of the operational replenishment scheme is the confined Leederville aquifer at a depth of 120 to 220 m below ground surface. Injection is expected to extend to the underlying Yarragadee aquifer.

The trial injected 2,533 ML of recycled water to the Leederville aquifer between November 2010 and December 2012. Water quality was monitored extensively during the trial with a suite of 292 Recycled Water Quality Parameters (RQWP) and 18 Recycled Water Quality Indicators (RWQI). Monitoring was undertaken throughout the wastewater treatment process, including the Advanced Water Recycling Plant (AWRP) and using a network of 22 groundwater monitoring wells.

This intensive monitoring program was used to confirm that the smaller suite of RWQI was sufficient to adequately represent the RWQP in management of groundwater replenishment (Water Corporation 2013c).

Research was undertaken by CSIRO and WA universities to assess geochemical changes in the aquifer, management of clogging of injection wells, fate of disinfection by-products, and to model the movement of injectant and gain a sound understanding of the safety of the groundwater replenishment trial (e.g. Patterson *et al*. 2011; Water Corporation 2013c; Siebert *et al*. 2014).

Lessons from experience

An Inter-Agency Agreement between Water Corporation and the State's regulatory agencies; the Department of Water (DoW), Department of Health (DoH) and Department of Environment and Conservation (DEC), was executed to develop policy and regulation for groundwater replenishment, the Groundwater Replenishment Regulatory Framework.

A 'two-step' communication theory of informing leaders first and then continuing to inform the broader community was adopted to instil consumer confidence in drinking recycled water. Furthermore information was primarily given 'face to face' to build trust rather than using mass communication methods. Engagement strategies for uptake of recycled water for drinking water supply are currently being developed in the National demonstration, education and engagement program (NDEEP), supported by the Australian Water Recycling Centre of Excellence (AWRCoE 2015b). While these apply to use of recycled water for drinking water supplies, the strategies developed may also be relevant to non-potable uses.

Economic analysis

ASSUMPTIONS

Costs

Recycled water direct cost

The cost of the capital infrastructure of the groundwater replenishment scheme is reported to be $124.6 million (Government of Western Australia 2014). The economic analysis assumes that all capital costs were incurred during financial year 2015/16, with the scheme being fully operational in financial year 2016/17.

There is currently no published information on the expected operating and maintenance costs for the Beenyup groundwater replenishment (GWR) scheme. For this analysis, operating and maintenance (opex) costs per kilolitre of the Beenyup groundwater replenishment trial (GWRT) were used as a starting point. Over the trial period from November 2010 to December 2012, the operating and maintenance costs per kilolitre varied between $1.49 to $2.95 per kilolitre (see Water Corporation (2013c) for the GWRT average monthly recharge volume). Note that costs associated with the Beenyup GWRT are comparatively higher than the expected costs of the operational Beenyup GWR scheme because of additional monitoring costs associated with the trial, the short time frame of the trial project, efficiencies gained through improved knowledge, as well as scale efficiencies for some items. As such, for this analysis operating and maintenance costs were assumed to be at 80% of the lower bound of the trial cost, or approximately $1.20 per kilolitre (Table 27). This estimate for operating cost remains equates to approximately 13% of the capital cost. For comparison, an alternative approach is to assume opex is 10% of the capital cost ($0.89/kL) (e.g. Bolivar ASR case study). The volume produced by the groundwater replenishment (GWR) scheme is assumed to be at a constant rate of 14GL per year.

Table 27 Capital expenditure (capex), operating and maintenance cost (opex, estimated) – Beenyup GWR.

Item	Capex $	Opex $/a
Capital expenditure	124,600,000	
Operating and maintenance costs		16,860,000
Total	**124,600,000**	**16,800,000**

Cost of treating water for potable use

The purpose of the GWR is so that the Water Corporation could extract groundwater for potable use in the future. In this analysis, it was assumed that the Water Corporation will be extracting 14 GL of groundwater for potable use once the GWR is operational, which is in late 2016. The cost of extracting groundwater is estimated to be $0.08-$0.12 per kilolitre (Marsden Jacob Associates 2006), while the cost of treating groundwater to potable water quality is estimated to be $0.25 to $1.00 per kilolitre (Water Corporation 2008). These two cost items will be added to the cost of sourcing water from the Beenyup GWR.

Carbon emissions

The Greenhouse Gas (GHG) emissions associated with The Beenyup GWR scheme are estimated at 20,664 tonnes CO_2 per year, based on an emission factor for electricity of 0.82 tonnes CO_2-e/MWh (Government of Western Australia 2013). Note, that this is more than twice the magnitude of emissions estimated using the energy requirements for treatment of recycled water (0.8 to 1 kWh/ kL) reported by Water Corporation (2008) (the same source used to estimate avoided carbon emissions from desalination of seawater, below).

Benefits

Avoided cost of desalinated water

The most reliable and climate independent source of water supply in Perth is desalinated sea water. Without the Beenyup GWR, the Water Corporation will have to rely on desalinated sea water as the source of potable water. It is estimated that the cost of desalinated sea water is $2.00 to $3.00 per kilolitre (Water Corporation, 2008). For this assessment, an avoided cost of $3.00 per kilolitre was adopted (without cost escalation) for future desalinated sea water schemes (Water corporation 2008), recognising that future plants may be situated further away from the existing supply infrastructure and thus would be associated with additional capital and operating costs.

Carbon emissions

The avoided Greenhouse Gas (GHG) emissions associated with a new source of desalination water are estimated at 46,000 tonnes CO_2 per year, based on the average energy needed for reverse osmosis desalination of seawater (3 to 5 kWh/ kL, Water Corporation 2008) and an emission factor for electricity of 0.82 tonnes CO_2-e/MWh (Government of Western Australia 2013.

Avoided sewerage costs (not estimated)

Recycling may also result in avoided costs associated with sewage pumping stations for disposal, but this was not quantified for the Beenyup GWR scheme.

Social and ecological benefits (not estimated)

There are also ecological benefits stemming from groundwater replenishment through the maintenance and enhancement of groundwater dependent ecosystems, which lead to biological diversity and abundance and effectiveness of natural ecological processes (Huynh *et al.* 2013). Enhanced ecological values can lead to social benefits including the provision of cultural and spiritual values; and the provision of recreation and aesthetic values. The willingness to pay for additional ecological and social benefits has not been assessed.

RESULTS

Table 28 and Figure 16 present the results of the economic analysis. Despite the fact that the Beenyup GWR requires treating water twice – first, the water is treated before it could be injected into the aquifer, and second, after the water has been extracted for later potable use – the NPV benefits and costs estimation indicate that the Beenyup GWR is still more cost effective than desalination. The NPV of the benefits of the Beenyup GWR becomes even more attractive when the Greenhouse Gas (GHG) emissions associated with desalinating sea water are considered.

Table 28 Results of the economic analysis of the Beenyup GWR scheme, WA.

Item	Present value (in $)
Present Value of Costs	
Beenyup GWR capital expenditure costs	124,600,000
Beenyup GWRS operating and maintenance costs	231,282,215
Other costs (groundwater pumping cost)	15,418,814
Other costs (cost of treating water for potable use)	48,183,795
Other costs (carbon emissions)	11,379,085
Total Net Present Cost	**430,863,910**
Present Value Benefits (avoided cost)	
Avoided cost of desalination	578,205,538
Wider community willingness to pay	-
Other environment / community benefits (avoided carbon emissions)	27,170,906
Total Net Present Benefits	**605,376,448**
Net Present Value	**174,512,538**
Cost per kilolitre	$2.24 per kL
Benefit per kilolitre	$3.14 per kL
Benefit cost ratio (BCR)	1.4

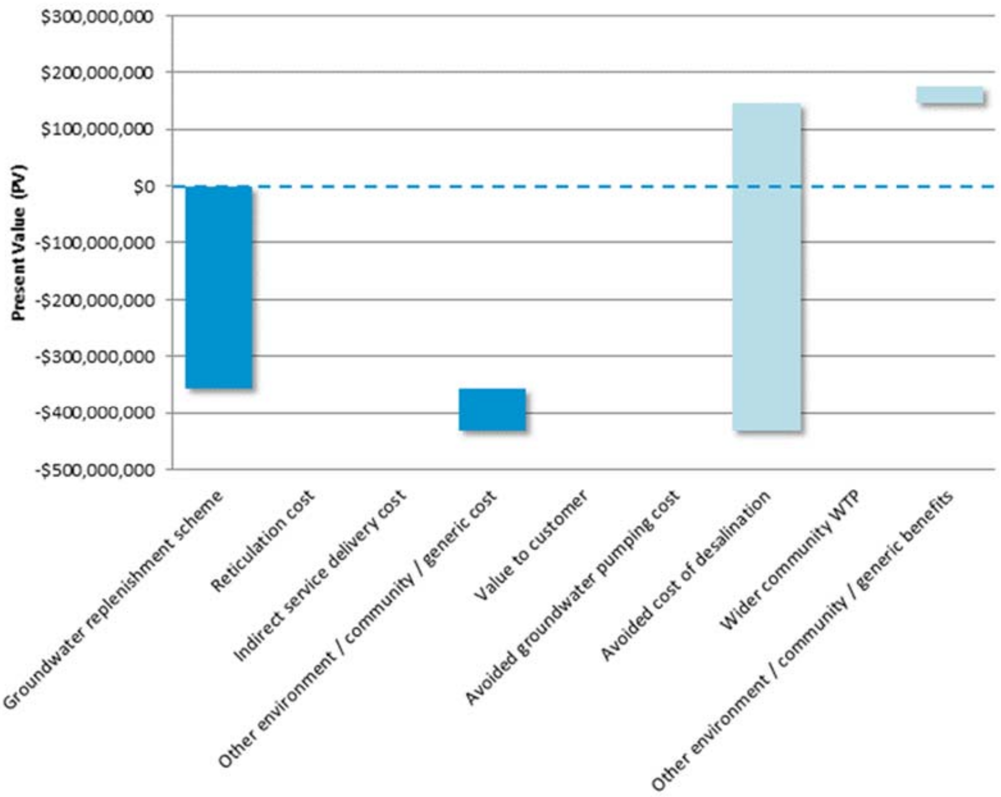

Figure 16 Results of the economic analysis of the Beenyup GWR scheme, WA.

Sensitivity Analysis

Sensitivity analysis was undertaken on the following parameters:

- **Change in price of desalinated sea water:** The cost of desalinated sea water was estimated to be $2.00-$3.00/kL (Water Corporation 2008). Allowing for a reduction in price and also potentially higher costs associated with inflation and new desalination plants located further away from existing infrastructure, the sensitivity analysis considered the price of desalinated sea water at $2.5/kL and $3.50/kL, instead of $3.00/kL (base case).
- **Increasing cost of treating groundwater for potable use:** The cost of treating groundwater is estimated to be $0.25-$1.00/kL (Water Corporation 2008). In the sensitivity analysis, it is assumed that the price of treating groundwater will go up from $0.25/kL to $1.00/kL.
- **Capital expenditure:** Both a 10% increase and decrease in capital expenditure
- **Operation and maintenance cost:** Both a 10% increase and decrease in operation and maintenance cost.
- Discount rates of 4% and 10%.

Sensitivity analysis results are presented in Table 29. The results show that:

- The benefit of the Beenyup GWR is sensitive to the price of desalinated sea water. If the price of desalinated sea water falls to $2.50/kL, it is more cost effective to continue with the GWR. However, if the costs associated with future supplies of desalinated sea water fall below $2.10/kL, desalination may be cost effective unless additional benefits of GWR are quantified.
- An increase in the cost of treating groundwater to potable water quality from $0.25/kL to $1.00/kL reduces the total NPV of the GWR, but it remains viable.

Table 29 Results of the sensitivity analysis of the Beenyup groundwater replenishment scheme, WA.

Item	NPV (in $)	Change (in %)
Base Case	174,512,538	0%
Cost of desalination $2.5/kL	78,144,948	-55%
Cost of desalination $3.5/kL	270,880,128	55%
Cost of treating groundwater $1/kL	29,961,154	-82%
Capex +10%	162,052,538	-7%
Capex -10%	186,972,538	7%
Opex +10%	151,384,317	-13%
Opex -10%	197,640,759	13%
Discount Rate of 4%	338,075,795	94%
Discount Rate of 10%	91,151,007	-48%

Aquifer Storage and Recovery, West Werribee (Vic)

In the future, City West Water will supply salt reduced recycled water via a dual supply network in the Werribee area. Aquifer Storage and Recovery (ASR) is proposed for storage of salt reduced recycled water (SKM 2013) during the winter months when the demand for domestic irrigation will be low. The Werribee ASR scheme proposes to inject a blend of approximately 40% Class A recycled water and 60% RO treated Class A water that is chlorinated. The ASR scheme is currently under construction and is scheduled for completion by the end of 2015. Recovered water will be reticulated for non-potable residential, municipal and industrial use via a third pipe system.

Uncertainty remains around the source water quality targets to prevent irreversible well clogging; in particular the potential for physical and biological clogging and the need to include dual media filtration or granular activated carbon (GAC) in the treatment train. CSIRO is assisting CWW with assessment of the potential for biological clogging and appropriate management in a separate study.

While an economic assessment cannot be undertaken at this stage of development, experience in scheme development and investigations will be documented.

MAR scheme

Source water for ASR will be a blend of approximately 40% Class A recycled water and 60% RO treated Class A water, that is chlorinated. Class A recycled water from Melbourne Water’s Western Treatment Plant is further treated by a Salt Reduction Plant located at the Werribee Treatment Plant which will include coagulation, ultrafiltration and reverse osmosis. Here it is intended that the RO treated Class A water and Class A water will be blended and chlorinated prior to use as source water for ASR. Dual media filtration and granular activated carbon may be required as additions to the treatment train if physical or biological clogging is expected to impact on the operation of the scheme.

ASR will target the confined Werribee Formation sand aquifer, at approximately 250 m below ground surface (SKM 2012). Well yield varies between 8 and 40 L/s, depending on the thickness of suitable sand available to be screened. The operational ASR scheme is intended to supply 1.0-1.5 GL per year. The initial stage of construction will comprise five wells, two of which will be equipped with extraction pumps. There is potential to increase storage and extraction capacity with the addition of another four wells over a longer timeframe (beyond 10 years).

Benefits of MAR

Water security and affordability are the key drivers for this ASR scheme, which will provide additional storage capacity for non-potable water. This will help to reduce the reliance on potable water use and reduce the stress on the traditional water supply catchment. Having sufficient water resources is considered to have a positive influence on urban amenity. Storing available water in the aquifer for subsequent use in periods of high demand is more cost effective than other options such as increasing the Salt Reduction Plant capacity. Discharge of treated wastewater to the sensitive marine environment of Port Phillip Bay is also reduced.

Lessons from experience

Aquifer storage is preferred due to land availability and the significant volume of storage required (SKM 2013). Scheme development has been undertaken in accordance with the Managed Aquifer Recharge Guidelines (NRMMC-EPHC-NHMRC 2009b).

Considerable time is required to establish a MAR scheme. City West Water has estimated that health department consents and approval for use of recovered water were obtained in approximately one month each and approval from Southern Rural Water required six months. One year was needed to obtain financial support, site selection took around six months and feasibility testing also required one year.

The construction phase revealed the importance of understanding aquifer heterogeneity. City West Water recommended constructing the scheme in close proximity to pilot wells that were used to inform scheme design, to reduce the risk of changing geology.

Furthermore it was essential to interpret the aquifer hydrogeological properties via preliminary investigations using *in situ* production and/or observation wells prior to full scheme construction.

Sonic coring of sediments has proved very useful in enabling accurate bore design and construction, and in obtaining aquifer samples for use in laboratory testing to evaluate the potential for aquifer clogging.

Costs of establishment

City West Water has advised that the cost of land is $4,000 per year and the capital cost of the ASR system, comprising five wells, is $11.4M. Capital costs and pre-commissioning investigations have been supported by Commonwealth Government funding. Operating and maintenance costs are the responsibility of City West Water.

Commonwealth funding was vital for City West Water to progress with the scheme. However this also led to some constraints on the way in which the scheme was developed. For example the nature of the Commonwealth agreement did not reflect a recognition of the level of uncertainty of some of the key parameters. The agreement fixed the scale of the scheme and the deadline for completion before the aquifer was well-characterised and hence before the explicit nature and costs of pre-treatment were identified for sustainable injection rates. Hence the Commonwealth's role increased rather than reduced the financial risks of innovation for the utility. A primary benefit that the Commonwealth could provide is to assist in reducing risks by contributing to better definition of unknowns in innovative projects with environmental and social benefits as well as technology demonstration benefits, such as this project exhibits. This would enable tenable commercial decisions by utilities on the scale and timing of their investments in managed aquifer recharge, as the risks would then be comparable with alternative systems which have a successful track record, but come at higher cost.

The Victorian Government at the time of approval of this scheme, had a policy that recycled water would not be used intentionally to augment drinking water supplies. This was a major consideration in the formation of the scheme being for a third pipe distribution system rather than treating to a higher standard and adding to the existing drinking water supply system. A study by Dandy *et al.* (2014) on MAR with urban stormwater has found that the costs of treatment and water management to augment drinking water supplies were substantially less than the cost of third pipe system for a case study in Salisbury. Given the likely high level of recycled water treatment required to manage clogging in ASR wells in the siliceous aquifer at Werribee, any supplemental treatment costs to reach requirements for potable use are likely to be small. In any such scheme the recovered water could initially be used for non-potable purposes only and well-monitored to give confidence to the utility, regulators and the public, that the water would be safe for use in augmenting potable supplies and compliant with the risk management in the relevant NWQMS Guideline (NRMMC-EPHC-NHMRC 2008) before transitioning. The currently configured scheme could potentially be used in this way depending on the future demand for non-potable water and the relative economics of constructing and maintaining separate non-potable and potable systems.

Conclusions

Economics of recycled water MAR

Economic assessment of six managed aquifer recharge case studies using recycled water reported costs from $0.88-$3.56 per kilolitre with target recharge volumes from 28 to 14,000 ML per year. These six case studies included infiltration basins (WA), infiltration galleries (Perry Lakes/Floreat, WA), Soil Aquifer Treatment (Alice Springs, NT), Aquifer Storage and Recovery (Bolivar, SA), Aquifer Storage Transfer and Recovery (Anglesea, Vic) and Groundwater Replenishment (Perth, WA). The seventh case study (Aquifer Storage and Recovery, Werribee Vic) is under development and therefore cost information was not available for an economic assessment.

Each case study involves case specific costs or benefits. For example, the Soil Aquifer Treatment scheme at Alice Springs includes the capital expenditure of a recycled water treatment plant that receives treated sewage whereas the Bolivar ASR scheme, which uses seasonal excess capacity of an existing plant, does not. In most instances the wastewater treatment plant upgrade to produce a suitable quality of recycled water or water fit for benign environmental discharge precedes the decision to add storage and treatment via MAR. Therefore wastewater treatment plant capital expenditure is commonly a sunk cost.

Aside from the Soil Aquifer Treatment scheme, where the principle driver, health protection, was not included in the economic assessment, the remaining five economic assessments reported favourable benefit to cost ratios (benefit>cost) due to avoided costs associated with above ground storage, wastewater treatment, potable water supply or desalination. The infiltration gallery case study provides an example where MAR is only favourable when potable water costs are avoided. In this example, alternative sources such as groundwater are potentially available at considerably lower costs but may not be sustainable in the long-term.

Benefits were quantified at $0.20-$8.50 per kilolitre, with each end of the range representing the avoided cost of groundwater and surface storage respectively. Avoided costs of wastewater treatment and potable water supply including desalination were reported at $2.00-$4.10 per kilolitre. Additional benefits such as the value of aquifer replenishment, social and ecological benefits of maintaining groundwater dependent ecosystems or marine environments, long-term reliable augmentation of drinking water supply, public health protection and willingness to pay for water security were not adequately addressed within all case studies. Therefore it is apparent that the potential benefits associated with water recycling via the aquifer are understated where these are currently not well understood and unable to be quantified adequately in cost benefit analysis.

Lessons from experience

A number of the case studies presented here represent a novel or innovative approach to MAR. In general, investment in MAR investigations allows proponents to gain an understanding of their system and the management strategies necessary to operate the scheme effectively. MAR operators state that it is essential that a good understanding of local hydrogeology is obtained to minimise risks and costs and ensure successful scheme delivery. This highlights the importance of site selection for pilot investigations which should be chosen to represent the conditions at the intended scheme location. However aquifer characteristics have a very important impact on costs of MAR operations, so groundwater investigations should give sufficient confidence in scheme location and aquifer characteristics before conducting pilot recharge studies.

Practical experience gained through the operation of wastewater infiltration basins for wastewater disposal provides guidance for management of MAR infiltration basins. Soil properties influence infiltration rate, which is evident when comparing infiltraton rates below 1 m/d in loamy sand to sandy clay loam at Alice Springs to rates around 4 m/d in Perth’s Spearwood Sand. In sites with less permeable sediments care must be taken to avoid clogging, which can be caused by physical processes such as soil compaction or development of a clogging layer.

Clogging is a prevalent issue that can be managed through operational strategies. For ASR wells this would involve a SCADA system to shut down injection if the water quality deteriorates beyond threshold values for a defined period, together with backflushing of wells periodically or when specific-capacity falls to a threshold value. For infiltration galleries, basins and SAT, strategies include; setting targets for source water quality, allowing time for the clogging layer to dry, crack and dessicate, physical removal of the clogging layer based on infiltration rate criteria, and application of herbicide to prevent excessive vegetation growth while ensuring residuals do not negatively impact on the quality of the receiving groundwater. Documentation of case studies allows experience to be shared and confidence to be gained through accumulation of knowledge, with advice such as control over source water quality is essential. Clogging due to algae growth in a temporary suface storage used for a wastewater injection trial illustrates how a pilot trial can be hindered by an artefact of the trial design. It is essential to ensure the pilot investigations adequately represent the intended operational scheme.

Documentation of experience and participation in in-house discussions on planning, monitoring and analysis of results, has occurred in some projects and also allows regulators to build the detailed scientific knowledge to enable efficient regulation of projects. Investigations associated with the Bolivar ASR research project were essential in providing the scientific foundations for development of the Australian Guidelines for MAR, a national framework for assessing and managing the risks associated with MAR schemes (NRMMC-EPHC-NHMRC 2009b). Monitoring of treated wastewater and experience with wastewater infiltration schemes has provided confidence in assessing log-removals of pathogens and given the evidence needed for low-exposure end use without additonal treatment.

Time is required to establish a MAR scheme. Effective communication with the regulator/s is necessary to ensure the expectations of the regulator are understood and met when seeking approvals to proceed. Finally, consideration must be given to strategies for community engagement. “Face to face” communication was reported as a more effective means for building trust than mass communication methods. Engagement strategies for uptake of recycled water for drinking water supply are currently being developed in the National demonstration, education and engagement program (NDEEP), supported by the Australian Water Recycling Centre of Excellence (AWRCoE 2015b). While these apply to use of recycled water for drinking water supplies, the strategies developed may also be relevant to non-potable uses.

There are significant potential savings in MAR with recycled water compared with alternative approaches to water recycling or disposal. In this report the net benefits are underestimated at some sites because costs were easy to quantify but some significant benefits remain unquantified. Hence, there are advantages in having programs to reduce the commercial risks to utilities of identifying opportunities for MAR to meet their objectives. This requires that utilities plan ahead to allow time for investigations to reveal the opportunity and economic viability of MAR options. It would also benefit from having Commonwealth and State government investment in investigations where there will be social and environmental benefits, and more effective use of water resources and aquifer capabilities, in addition to customer benefits from reduced costs of future water supply and sanitation. Care should be exercised in formulating funding agreements that the intention of reducing commercial risk of the proponent utility is also achieved. The issues of public acceptance have been well-addressed in the Perth Groundwater Replenishment Trial, which provides an exemplar for other utilities.

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