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Managed aquifer recharge:

An Introduction

Peter Dillon, Paul Pavelic, Declan Page, Helen Beringen and John Ward

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Waterlines

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Waterlines

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Abbreviations and Acronyms

ASR aquifer storage and recovery: the recharge on an aquifer via a well for subsequent recovery from the same well

DAFF dissolved air flotation and filtration: a water treatment process that uses coagulation to and fine air bubbles to strip organic and colloidal material from water, often a treated sewage effluent

GAC granular activated carbon: adsorptive carbon granules with a capacity to remove adsorbable solutes from water

GL Gigalitre, a measure of volume, equals 10^9 litres = 1 million kL = 10^6 kL = 10^6 m^3 = 1000 Megalitres

kL kilolitre, a measure of volume, equals 1000 litres = $1m^3$

MAR Managed aquifer recharge: a term applied to all forms of intentional recharge enhancement for the purpose of recovery for use or for environmental benefit

MF Microfiltration: a water treatment process that uses a membrane to remove colloidal material down to 0.2 microns

ML Megalitre, a measure of volume, equals 10^6 litres = 1000 kL = 10^3 kL = 10^3 m^3

RO Reverse osmosis, pressurising saline water to permeate through a semi-permeable membrane against the solute diffusion gradient to produce fresh water and a residual brine stream

Executive Summary

Objectives of this document

Climate change and a growing population, and increasing urbanisation, add to the stresses on Australia's water resources. To meet Australia's urban water requirements we need to both continue to conserve water and to diversify our sources of supply. Desalination of seawater, water recycling, increased use of groundwater, and stormwater and rainwater harvesting are being used in different Australian urban centres to augment water supply.

However to date managed aquifer recharge (MAR) has not been considered on an equal footing or as part of these more established alternatives for diversifying water sources for urban areas.

This document aims to provide information about the use of MAR primarily for cities but also in regional communities and rural areas. The document is intended to enable decision makers, water utilities and the broader community to consider MAR projects, where appropriate, as part of the water supply portfolio, taking account of costs, security, quality of supply and environmental and social benefits and constraints.

This document also provides an introduction for regulators or potential proponents of MAR projects to the new national guidelines for managing health and environmental risks associated with MAR projects.

Recent Australian MAR experience has highlighted a number of gaps and problems with existing policies and frameworks for water management. These appear to have the potential to unnecessarily constrain investment in urban or peri-urban MAR projects. These issues are discussed briefly and some suggestions are made for dealing with them.

Current status and potential for MAR

In Australia in 2008, MAR contributed 45GL/yr to irrigation supplies and 7GL/yr to urban water supplies across Qld, SA, WA and NT. These include 3ML/yr of stormwater recharge recovered for drinking supplies, and up to 700 ML/yr of reclaimed water recharge to augment horticultural irrigation supplies.

Where urban aquifers have been mapped in Perth, Adelaide and Melbourne, there are known prospects for managing the storage of 200 GL/yr urban supplies. Recharged water may be sourced from rainwater, stormwater, reclaimed water, mains water or other aquifers. Opportunities in other cities and in regional areas await assessment.

Substantial opportunities for MAR are expected, but not yet assessed, in rural catchments where water has not been over-allocated, particularly in coastal catchments with unconfined aquifers.

Costs

The average levelised cost of eight urban stormwater aquifer storage and recovery projects of between 75 and 2000 ML/yr was found to be $1.12/kL. This is less than current prices of mains water in capital cities. Approximately $0.84/kL of the above cost was attributed to project costs subsequent to the capture of stormwater. Projects between 15 and 75 ML/yr do not benefit as much from economies of scale with the levelised cost of the smallest project being $3.00/kL.

For agricultural recharge projects where infiltration basins can recharge unconfined aquifers at high rates the levelised cost of recharge and recovery is more than an order of magnitude less, *eg.* in the Burdekin Delta, Queensland, the cost is $0.07/kL. This project has proven to be economic for irrigation of sugar cane and has been operated continuously for 30 years.

Comparisons with alternative urban supplies show levelised costs of stormwater aquifer storage and recovery (ASR) are 30 to 46 per cent of the costs of seawater desalination and ASR consumes three per cent of the energy.

Comparative unit costs for urban water storages show that aquifer storage costs are one to four per cent of tank storages and they occupy less than 0.5 per cent of the land surface area. Injection well systems have a similar cost to lined earthen dam impoundments but occupy less than 0.2 per cent of the land surface area.

Public acceptance

In Australia, as in the United States over 40 years, there is evidence that public acceptance of water recycling via aquifer recharge for drinking water supplies is strong, in marked contrast with water recycling without natural storage and treatment.

Diverse objectives of MAR projects

MAR projects, particularly in urban areas, can have objectives additional to water supply. These objectives vary from site to site. MAR schemes can provide multiple economic, social and environmental benefits and often it is the combination of these benefits which provides the basis for investing in MAR. For example stormwater MAR in Salisbury commenced only because of the need for flood mitigation, coastal water quality improvement and due to the amenity value of public water features and green space reflected in real estate prices.

In rural and urban areas MAR has been used successfully to reduce salinity of groundwater and protect crops where irrigation water was salinising, and it can be used to protect coastal aquifers from saline intrusion.

Urban opportunities - water security

If 200GL of the Water Services Association of Australia projected 800GL shortfall in water in Australian cities by 2030 were met from stormwater ASR the cost savings in comparison with seawater desalination would be $400million per year in addition to significant environmental benefits.

Seawater desalination, water treatment and water recycling plants are most efficient when operated at a constant rate. Aquifer storage may be used effectively in combination with these sources to reduce costs of meeting seasonal peak demands.

Less than three per cent of urban stormwater runoff is currently harvested for use in Australian cities. In capital cities with annual rainfall in excess of 800mm, the volume of urban runoff exceeds the amount of water delivered by water mains. Water storage is the main impediment and MAR provides a solution to this where suitable aquifers are present.

Currently all urban MAR is for immediate economic benefit, including by local government. No government or water utility has yet undertaken MAR to develop strategic reserves for drought and emergency supplies, even though this may be the cheapest form of augmenting urban water supplies.

Recharging aquifers from mains water at times when reservoirs are approaching spill, subject to environmental flow considerations, is among the cheapest ways to build high quality drought and emergency supplies.

The highest valued use of aquifer storage and recovery (ASR) or aquifer storage, transfer and recovery (ASTR) would be to expand drinking water supplies by recovering stored water at drinking water quality and putting it into water mains. This would make use of the mains to transfer water entitlements from water rechargers to water users and thereby effectively expand the headworks reservoir capacity by water that has been banked in aquifers.

MAR potentially could provide opportunities to develop competition in otherwise monopoly water markets and could therefore benefit communities overlying aquifers.

The number, diversity and scale of MAR projects is growing in Australia and many other countries, particularly in urban areas, due to water shortages, fewer available dam sites, low costs compared with alternatives where conditions are favourable, and associated benefits of MAR.

Urban opportunities - water quality

New Australian guidelines address the risks to human health and the environment, and will bring national uniformity and reduce uncertainties in approval processes for new MAR water supply projects using all sources of water (including recycled water).

Water quality improvements during aquifer storage of recycled waters are being documented at demonstration sites and operational projects in Australia and overseas. The growing body of knowledge allows more confident reliance on aquifer treatment processes allowed for within the Australian Guidelines for MAR.

Urban stormwater stored in an aquifer for a year has been proven to meet all drinking water quality requirements and has been bottled as drinking water. Further research is needed to build confidence in the robustness and resilience of preventive measures to ensure that drinking water quality can be met reliably on an ongoing basis.

Recycled water, if stored in an aquifer for a period before recovery as drinking water, provides an additional level of public health protection beyond direct reuse.

In urban areas confined aquifers provide better protection for waters recharged via wells to supplement drinking water supplies. However, unconfined aquifers may generally be used for non-potable uses to substitute for mains water supplies and, in some cases, provide adequate protection for recovery as drinking water.

Governance

MAR is at the cutting edge of integrated water management, presenting opportunities for conjunctive management of surface water and groundwater resources and producing fit-for-purpose water supplies.

MAR can help to sustain groundwater supplies and dependent ecosystems in heavily used aquifers or as an adaptation to climate change if environmental flows and downstream entitlements can be assured.

However, where groundwater levels have been in decline, MAR alone may be insufficient to restore groundwater equilibrium. Appropriate resource management, to prevent excessive use of groundwater may also be needed, and this applies to rural and urban areas. In urban areas new governance methods may be required involving collective management, for example through groundwater users associations, due to large numbers of well owners. Costs imposed by restricting groundwater use may be compared with costs of MAR to determine optimal strategies in relation to changes in climate, land use and the value of various uses of water.

MAR should be avoided in over-allocated surface water catchments as its use would otherwise further deplete environmental flows and availability of water to meet downstream water entitlements. A possible exception is where it could be clearly demonstrated that MAR would increase environmental flows by reducing diversions and evaporation losses from off-stream surface storages.

Issues and solutions

Several actions are identified that could facilitate effective use of MAR.

Awareness

There is a need for awareness of the diverse range of potential uses of MAR. This document helps address that by describing the diversity of MAR, and its costs and effectiveness as a supply option.

The current lack of localised knowledge of MAR opportunities is being addressed by the production by NWC of maps of the suitability of aquifers for MAR for several cities. State natural resources management agencies could consider preparing MAR opportunity maps for water-scarce areas where there is a source of water available for recharge.

Approval processes

The time taken for the entitlements and approvals process for new MAR projects could be substantially reduced from the current range (six to 22 months). New National Water Quality Management Strategy Guidelines for MAR are expected to assist. Benefits can also be expected where jurisdictions look to address fragmentation in various aspects of urban water management and devise simpler interfaces and approval processes for proponents.

Entitlements

For investment to occur in MAR projects a level of certainty is required. In 2008 most jurisdictions in Australia had no system of entitlements *for* urban stormwater, reclaimed water nor *for the* allocat*ion of* available aquifer storage capacity. Rights to recover stored water and rights to transfer entitlement to water are also immature. *Adoption of NWI consistent principles, regulatory and legal frameworks will facilitate investment in MAR.*

Integrated planning

MAR, because of its diverse benefits, is relatively disadvantaged by narrow sectoral evaluations with respect to alternative supplies. Recognition of the entire complex of costs and benefits in integrated urban water management is in any case a superior approach to water system planning and management. Mechanisms and institutions are needed to address coastal water quality, flood mitigation, urban amenity, land value, carbon offsets and water supply. Local demonstrations may assist States identify and value these associated costs and benefits in selecting city water supply projects, and aid in the development of appropriate planning and assessment processes. A water bank, an institution to optimise investment to meet projected future water allocations and associated criteria, could be part of the solution and assist in creating strategic reserves.

Urban green space is needed to allow stormwater harvesting and water treatment such as in wetlands. Provision of urban green space for MAR as part of water sensitive urban design allows a wider array of benefits than previously taken into account in urban planning. The symbiosis between land and water in urban areas through integrated planning processes will yield significant benefits for both sectors.

Investigations

The high cost of investigations and low level of knowledge of risk at the outset of MAR projects can be a deterrent especially to pioneering projects in new locations. As initially demonstrated in SA, some hydrogeological investigations supported by governments is warranted to assist with pioneering projects to facilitate private investment, considering the public good outcomes from such projects.

Inherent differences between sites mean that project-specific investigations will be required. However costs may be reduced if information gained in investigations and in monitoring at Australian and other MAR sites is recorded on publically accessible databases to facilitate knowledge exchange and synthesis.

To counter the high cost of monitoring, web-based real-time systems and well-designed reporting packages could be applied to meet different information requirements for operators, regulators and stakeholders.

Demonstrations

Increased familiarity with MAR within utilities and state agencies will lead to improved implementation and governance. This can be encouraged by establishing in each state at least one confined and one unconfined aquifer demonstration project and other pioneering projects, involving partnerships between state stakeholders. This would provide stakeholders experience with investigations, design, approvals, commissioning and operation, including testing water recovery for drinking water supplies. These sites also provide an excellent resource for research, training, evaluation, trialling of investigation methods, planning and governance arrangements and for raising awareness.

Pilot scale water treatment plants are also needed to allow inexpensive testing of treatment requirements for source-water, aquifer and end use combinations, particularly where drinking water is an end use.

Research

Increased diversity of MAR projects requires research and demonstration projects to help offset the risks for pioneering proponents where it is evident that project replication would have national value. Examples could include: use of aquifers for energy and water storage conjunctively, systems analysis of conjunctive management of surface and aquifer storages via MAR, and extending the types of aquifers used, water types and pre-treatment methods, recharge methods (eg. bank filtration), and applications (saline intrusion barriers, wetland protection, aquifer flushing).

The MAR Guidelines have little information on attenuation rates of some contaminants in aquifers needed for pre-commissioning risk assessments. Hence the NWC has initiated a project to produce first basic information and models, to be available on the web. Further information can be obtained from validation monitoring and research and be made publicly available in a useful form. Standardised methods are required for measuring in-situ attenuation rates in aquifers so that data are directly comparable.

Research is required to demonstrate sustainable achievement of drinking water quality for MAR sourced by urban stormwater and treated sewage effluent. Research is also warranted to establish bank filtration projects for towns whose run-of-river drinking supplies will be less reliable as a result of climate change. Effects of mixing of recovered water with other sources of water of drinking water quality and integrating infrastructure also warrant evaluation at demonstration sites.

Further research is needed to record and underpin improvements in MAR-related policies, management practices and institutional arrangements. Such research at the interface between integrated water management and urban planning would benefit from demonstration projects.

Further evaluation of community engagement processes and public support for establishment of MAR operations where water is recycled to produce drinking water supplies will be of great value. This will help ensure that local issues are addressed appropriately and thereby maintain or improve public confidence in the way this emerging technology is being implemented.

Training

With new technologies comes a need to develop new skills for effective utilisation. Establishing national short courses for MAR operators and regulators involving demonstration projects and current skilled operators would overcome the current lack of operator and regulator training. These would help to ensure risk management plans are designed and implemented effectively and entitlement issues are understood and addressed. A national accreditation program for operators would be a logical step in establishing ISO9000 quality management systems for drinking water supplies derived from MAR.

In-service training courses on hydrogeological investigation methods already address MAR, and MAR could also provide definitive applied case studies for use in university teaching of aquifer processes and measurement methods. Existing water quality management courses, particularly those involving augmentation of drinking water supplies with recycled water, could be expanded quite simply to address MAR.

Dissemination of information

Documentation of existing projects, such as a variety of demonstration projects, in a case study format, would simplify the task of project development and risk assessment for those encountering MAR for the first time. It is proposed that a national anthology of innovative projects be assembled and combined with reviews of projects at an international level.

Key information and data from investigations and monitoring, if recorded on nationally accessible databases, would facilitate knowledge exchange, synthesis and research. The Bureau of Meteorology water data system may be appropriate. Uses would depend on the level of information provided and could range from quantifying the annual water supply contribution of MAR to facilitating research. Public access to information from MAR sites would assist in reducing investigation costs at new sites and in ensuring all likely issues are addressed.

1. Introduction to Managed Aquifer Recharge

1.1. This document

This document summarises at an introductory level the relevant information needed to consider managed aquifer recharge (MAR), alongside other better-known alternatives, as a prospective new water supply for drinking or non-potable uses. It contains information on economics of MAR and some governance issues that has not previously been published. The document outlines the opportunities that MAR may provide, primarily for cities but also in rural and regional areas. It does not attempt to describe the many technical issues that are covered in the scientific literature accessible from the sources referenced here.

Chapter 1: explains MAR, shows the variety of its forms and describes the fundamental components of all MAR projects, gives a brief history of MAR in Australia. It also describes some examples and provides references to other sources of technical information and assistance.

Chapter 2: offers a description of the diverse drivers for MAR, accounting for multi-purpose urban applications, climatic, hydrogeological, land use and public perception drivers and constraints.

Chapter 3: presents new information on the economics of MAR in relation to alternative sources of supply, its niche in the economic scale of supplies, and presents results of analysis of costs of eight urban stormwater aquifer storage and recovery projects and a rural infiltration basin project, and identifies costs and benefits currently unaccounted for in urban water supply decisions.

Chapter 4: deals with how to establish a MAR project and provides information to assist consultants, water utilities, local government, sporting clubs, industries and commercial enterprises considering such projects.

Chapter 5: outlines considerations for government regulators on the new challenges for integration of water resources management and environment protection policies presented by MAR. This aims to help with transitions to MAR and offers some insight into the recently drafted MAR Guidelines.

Chapter 6: looks at opportunities presented in integrated urban water management that will be of interest to urban planners, local government and water utilities. It also contains observations on new institutions that could help state and territory governments address urban water supply more efficiently with respect to economic, social and environmental costs and benefits, based on a water bank model currently operating in Arizona, along with key remaining research required to realise these opportunities.

1.2 What is managed aquifer recharge?

Managed aquifer recharge (MAR) is the purposeful recharge of water to aquifers for subsequent recovery or environmental benefit. Aquifers, permeable geological strata that contain water, are replenished naturally through rain soaking through soil and rock to the aquifer below or by infiltration from streams. The human activities which enhance aquifer recharge can be put into three categories:

1. Unintentional - such as through clearing deep-rooted vegetation, by deep seepage under irrigation areas and by leaks from water pipes and sewers
2. Unmanaged - including stormwater drainage wells and sumps, and septic tank leach fields, usually for disposal of unwanted water without thought of reuse
3. Managed - through mechanisms such as injection wells, and infiltration basins and galleries for rainwater, stormwater, reclaimed water, mains water and water from other aquifers that is subsequently recovered for all types of uses.

This paper focuses only on this final category, but acknowledges the opportunities to convert from unmanaged recharge to managed recharge with the aim of protecting the environment and using the recovered water.

Enhancing natural rates of groundwater recharge via MAR provides an important potential source of water for urban and rural Australia. This paper addresses all forms of MAR, but the emphasis is on urban applications.

MAR can be used to store water from various sources, such as stormwater, reclaimed water, mains water, desalinated seawater, rainwater or even groundwater from other aquifers. With appropriate pre-treatment before recharge and sometimes post-treatment on recovery of the water, it may be used for drinking water supplies, industrial water, irrigation, toilet flushing, and sustaining ecosystems.

Common reasons for using MAR include:

- securing and enhancing water supplies
- improving groundwater quality,
- preventing salt water from intruding into coastal aquifers,
- reducing evaporation of stored water, or
- maintaining environmental flows and groundwater-dependent ecosystems, which improve local amenity, land value and biodiversity.

Consequential benefits may also include:

- improving coastal water quality by reducing urban discharges,
- mitigating floods and flood damage, or
- facilitating urban landscape improvements that increase land value.

MAR can play a role in increasing storage capacity to help city water supplies cope with the runoff variability in Australian catchments exacerbated by climate change. It can also assist in harvesting abundant water in urban areas that is currently unused.

1.3. Types of managed aquifer recharge

A wide range of methods are in use for recharging water to meet a variety of local conditions. For examples see Figures 1 and 2.

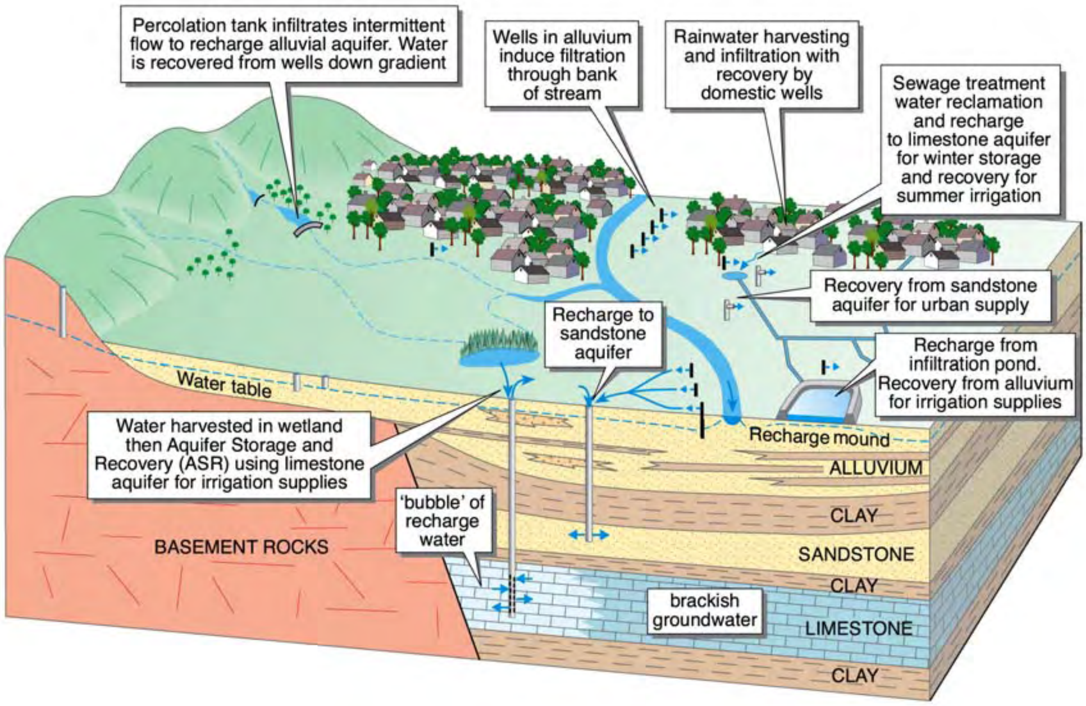


Figure 1: Managed aquifer recharge is adapted to the local situation, and is usually governed by the type of aquifer, topography, land use and intended uses of the recovered water. This diagram shows a variety of recharge methods and water sources making use of several different aquifers for storage and treatment with recovery for a variety of uses. An understanding of the hydrogeology of the locale is fundamental to determining options available and the technical feasibility of MAR projects. Recharge shown here occurs via wells, percolation tanks and infiltration basins. (*Adapted from Gale, 2005, with permission)*

There are a large number and growing variety of methods used for MAR internationally. Those currently in use in Australia are:

Aquifer storage and recovery (ASR): injection of water into a well for storage and recovery from the same well. This is useful in brackish aquifers, where storage is the primary goal and water treatment is a smaller consideration (for example Grange golf course, South Australia).

Aquifer storage, transfer and recovery (ASTR): involves injecting water into a well for storage, and recovery from a different well. This is used to achieve additional water treatment in the aquifer by extending residence time in the aquifer beyond that of a single well (for example Parafield Gardens, SA).

Infiltration ponds: involve diverting surface water into off-stream basins and channels that allow water to soak through an unsaturated zone to the underlying unconfined aquifer (for example Burdekin Delta, Qld).

Infiltration galleries: buried trenches (containing polythene cells or slotted pipes) in permeable soils that allow infiltration through the unsaturated zone to an unconfined aquifer (for example Floreat Park, WA).

Soil aquifer treatment (SAT): treated sewage effluent is intermittently infiltrated through infiltration ponds to facilitate nutrient and pathogen removal in passage through the unsaturated zone for recovery by wells after residence in the unconfined aquifer (for example Alice Springs, NT).

Percolation tanks or recharge weirs: dams built in ephemeral streams detain water which infiltrates through the bed to enhance storage in unconfined aquifers and is extracted down-valley (for example Callide Valley, Qld).

Rainwater harvesting for aquifer storage: roof runoff is diverted into a well, sump or caisson filled with sand or gravel and allowed to percolate to the water-table where it is collected by pumping from a well (for example metropolitan Perth, WA).

Recharge releases: dams on ephemeral streams are used to detain flood water and uses may include slow release of water into the streambed downstream to match the capacity for infiltration into underlying aquifers, thereby significantly enhancing recharge (for example Little Para River, SA).

Other forms of MAR that are not common in Australia in 2008 include:

Dry wells: typically shallow wells where water tables are very deep, allowing infiltration of very high quality water to the unconfined aquifer at depth (eg Phoenix, USA)

Bank filtration: extraction of groundwater from a well or caisson near or under a river or lake to induce infiltration from the surface water body thereby improving and making more consistent the quality of water recovered (eg Berlin, Germany).

Dune filtration: infiltration of water from ponds constructed in dunes and extraction from wells or ponds at lower elevation for water quality improvement and to balance supply and demand (eg Amsterdam, The Netherlands).

Underground dams: In ephemeral streams where basement highs constrict flows, a trench is constructed across the streambed, keyed to the basement and backfilled with low permeability material to help retain flood flows in saturated alluvium for stock and domestic use (eg in Kenya).

Sand dams: built in ephemeral stream beds in arid areas on low permeability lithology, these trap sediment when flow occurs, and following successive floods the sand dam is raised to create an “aquifer” which can be tapped by wells in dry seasons (eg in Namibia).

Selection of suitable sites for MAR and choice of method will depend on the hydrogeology, topography, hydrology and land use of the area. It is common to find similar types of MAR projects clustered in the same area due to shared physical attributes. In another area, the methods may be quite different.

MAR is in wide use in many countries to enhance water supplies, particularly those in semi-arid and arid areas, but also in humid areas, primarily for water quality improvement. The International Association of Hydrogeologists has a Commission on Managed Aquifer Recharge whose web site contains many case studies found in downloadable documents (*www.iah.org/recharge*).

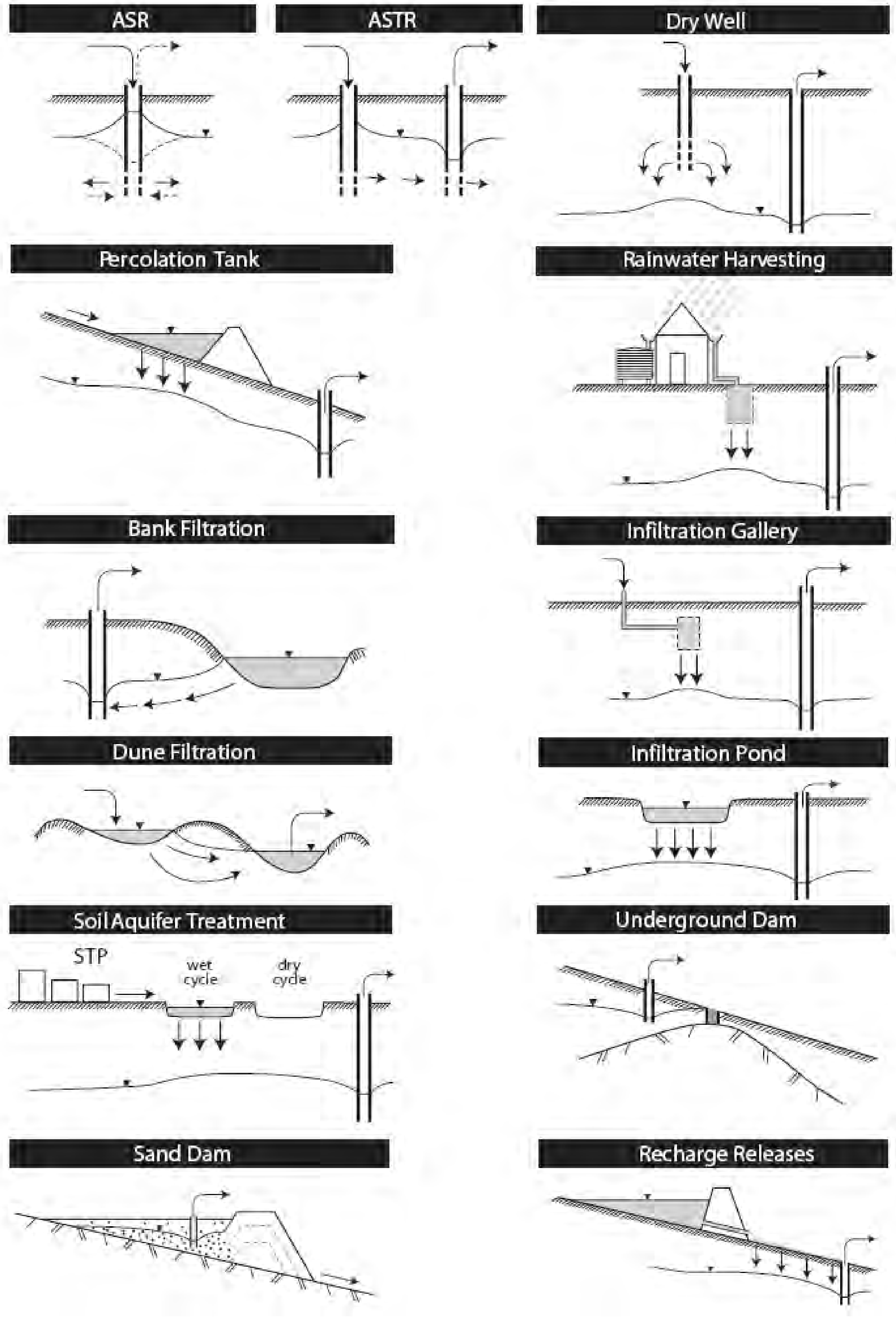
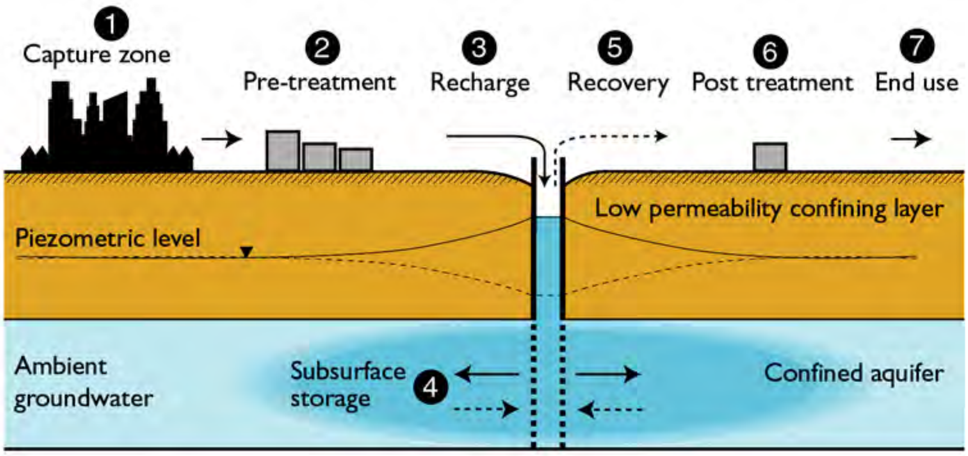


Figure 2. Schematic of types of Managed Aquifer Recharge. (*Source:* Dillon, 2005, extended in EPHC, 2008)

1.4. Components of a MAR project

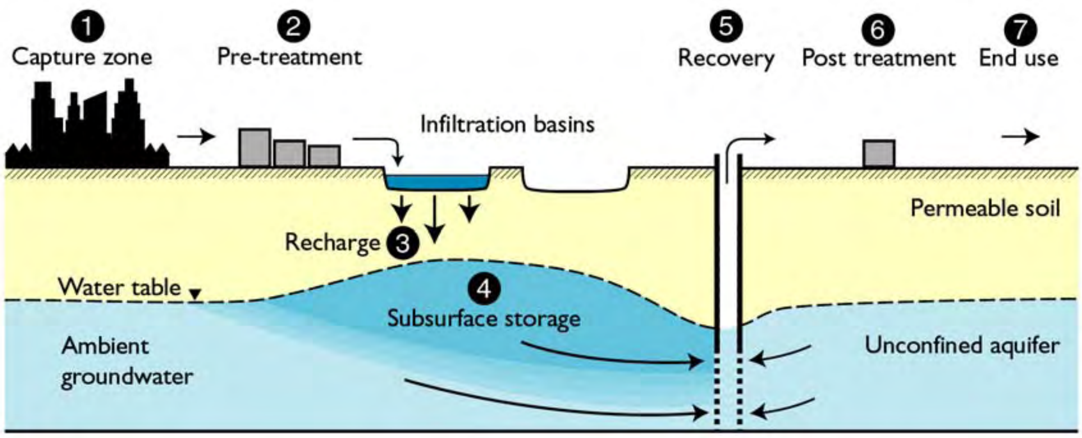
Figure 3 shows the seven elements common to all types of MAR projects. However MAR projects may appear quite different because of the type of aquifer available for storage. There are two main types of aquifers – those that are confined by a low permeability layer, which for MAR requires injecting water via a well (Figure 3a), and those that are unconfined and allow water to infiltrate through permeable soils, where recharge can be enhanced by basins and galleries (Figure 3b).

CONFINED AQUIFER



(a)

UNCONFINED AQUIFER



(b)

Figure 3. Two examples of managed aquifer recharge, (a) ASR and (b) SAT, showing the seven elements common to each system. Piezometric level is the level of water in a well if a well were constructed. For an unconfined aquifer this is the watertable. During recharge levels rise and near recovery wells levels fall. Numbers used in the figures correspond to those shown in Figure 4.

There are many combinations of water sources, water treatments and end uses (Figure 4). Generally poorer quality source waters will need a higher level of treatment before recharge in cases where:

- the aquifer already contains high quality water,
- the water is to be recovered for higher valued uses such as drinking, or
- the aquifer is fine-grained and there is a need a to avoid frequent or permanent clogging of the recharge basin, gallery or well.

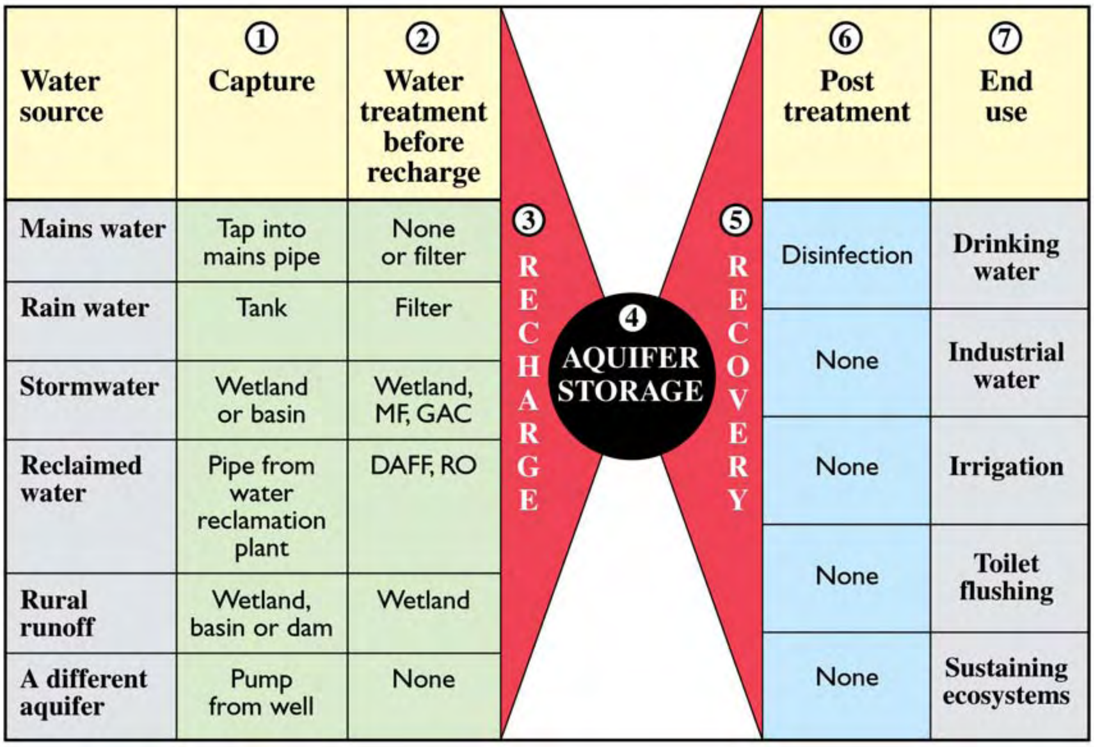


Figure 4 Typical sources of water, methods of capture and pre-treatment for MAR. All sources of water, in combination with the right treatment before recharge, can be recovered from the aquifer for any end use. (Circled numbers for elements correspond with those shown in Figure. 3. Recharge methods may be any of those shown in Figure 2.) (MF is microfiltration, GAC is granular activated carbon filtration, DAFF is dissolved air flotation and filtration, RO is reverse osmosis) Note pre-treatments and post-treatments may vary subject to preventive measures necessary to effectively manage risks.

Passive treatment such as in a wetland may be suitable when urban stormwater is being used to recharge a brackish limestone aquifer with recovery of water for irrigation without any requirement for post-treatment. It has been found that microfiltration (MF) and granular activated carbon (GAC) filtration were needed at an ASR site with a very fine-grained aquifer to prevent clogging of the well and that this requirement was more stringent than those to protect groundwater quality and for recovered water to be fit for use. No treatment may be necessary where river water of low turbidity is diverted to infiltration basins for enhancing irrigation supplies. Where reclaimed water is used for recharge to recover for potable supplies, the water will be highly treated prior to recharge. Residence time in the aquifer may also be needed to assure quality, with post-chlorination if recovering to mains without diluting the chlorine residual. The new risk-based MAR guidelines for protecting health and environment are briefly summarised in Chapter 4.

1.5. Some Australian examples of MAR

The diversity and geographic spread of MAR in Australia has increased in recent years and in 2008 five states and territories have operational MAR projects and two states have investigations underway. These are summarised in Figure 5. Following a brief history of MAR in Australia, three Australian examples of MAR are presented to illustrate the diversity of methods, source waters, hydrogeological settings, end-uses of recovered water and associated issues.

MAR began in rural areas of Australia before migrating to urban centres. It is expected that after water resources management restores environmental flows in currently over-allocated catchments, MAR will again grow in rural areas.

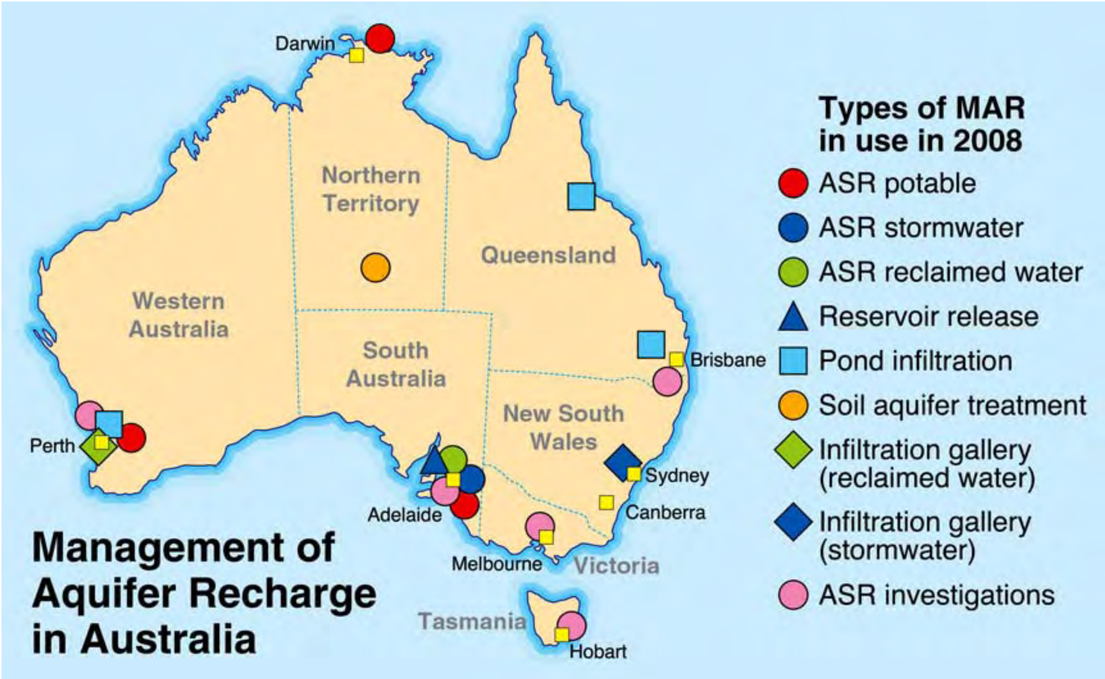


Figure 5. Locations and types of MAR in Australia in 2008

History of MAR in Australia

Infiltration basins established in the mid 1960s on the Burdekin Delta, Queensland, are the longest serving and currently the largest (up to 45GL/yr) managed aquifer recharge operations in Australia (Volker (ed) 1981, Charlesworth *et al,* 2002).

Recharge weirs were built on Callide and Lockyer Creeks in the 1970s, and recharge via wells commenced in 1970 in the Angas-Bremer irrigation area of SA and expanded to 30 wells recharging 2.4GL/yr in 1992 (Gerges *et al*, 2002). Recharge releases (1.5 GL/yr) commenced on the commissioning of the Little Para Dam, SA, in 1979 (Dillon, 1984) to substitute for the reduction in natural recharge of Northern Adelaide Plains aquifers from that stream.

In 1992, urban stormwater ASR was initiated at Andrews Farm SA in limestone and in 1994 at Regent Gardens in fractured rock (Gerges *et al* 2002). Reclaimed water ASR began at Bolivar SA in 1999, and via infiltration ponds at Halls Head WA in 2000 (Toze *et al,* 2002) and via infiltration galleries at Floreat Park WA in 2005 (Bekele *et al,* 2006). ASR with mains water began at Jandakot WA in 2000 (Martin *et al,* 2002) and with water from a shallower aquifer at Warruwi NT in 2001 (Pavelic *et al,* 2002). An infiltration gallery for stormwater recharge was established at Kensington NSW in 2007. Soil aquifer treatment of reclaimed water began in Alice Springs in 2008. Injection trials for stormwater ASR are underway at several sites in Melbourne in 2008.

Stormwater disposal wells in Mt Gambier, SA, that have operated since the 1880s, were proven in the 1990s to contribute to the city's water supply drawn from Blue Lake. Subsequently Wolf *et al* (2006) have established risk management plans that, on being adopted, turned unmanaged recharge to MAR. In Perth, recharge of roof runoff and stormwater into pits and basins makes a substantial contribution to the water recovered from wells for household irrigation and also to a few mains water supply wells. Blanket risk assessments are proposed to convert this formerly unmanaged recharge to managed aquifer recharge.

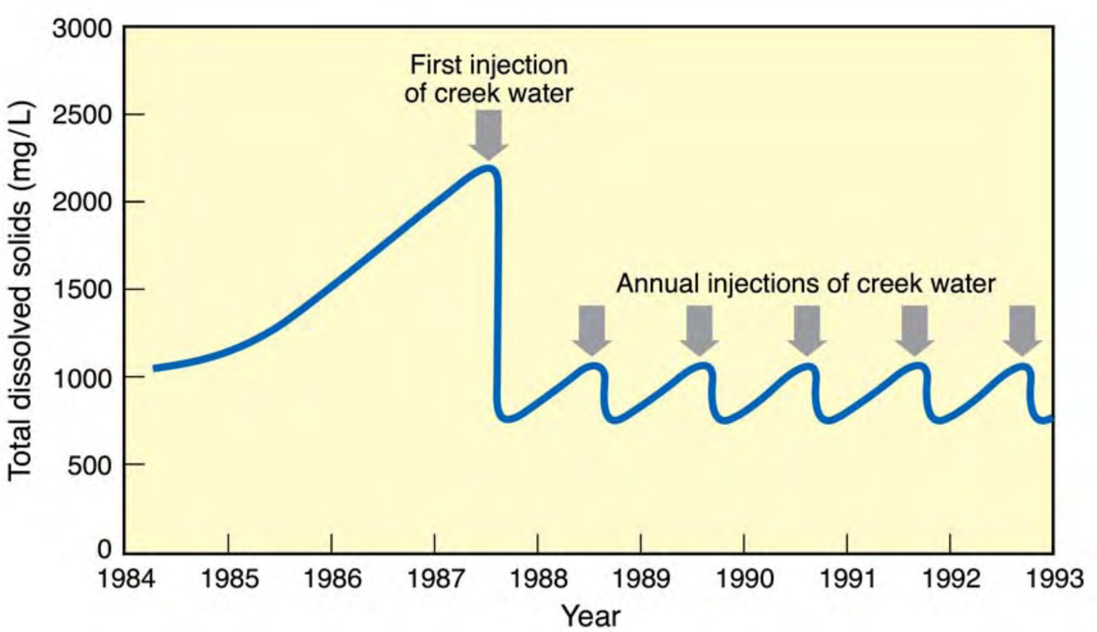


Figure 6. Groundwater salinity increases at Langhorne Creek, in the Angas-Bremer viticultural irrigation area were arrested in 1987 by recharging the aquifer by pumping water from the ephemeral creek into irrigation wells. This saved the vines and the process was subsequently repeated each winter in up to 30 irrigation wells with up to 2.4GL/yr recharged.

Infiltration basins at Burdekin Delta, Qld

Australia's planned recharge originated on the Burdekin River Delta near Townsville. About 38,000 ha of sugarcane and other crops rely on irrigation including from shallow groundwater which also serves as a drinking water supply. Since the 1960s MAR has been central to maintaining elevated watertables across the area and preventing coastal saline intrusion that would otherwise have occurred due to groundwater pumping (Charlesworth *et al,* 2002). Recharge of up to 45 GL/yr has been achieved over about 40 years using recharge pits situated over coarse sand deposits; by sand dams within the Burdekin River that slowly release water from upstream storages; and by diversions to constructed channels and natural waterways (Figure 7). These have been operated by the North and South Burdekin Water Boards. River water with the lowest turbidity levels is allowed to enter the recharge pits to maximise the time-span of operation between scraping and removal of the basin floor to remove deposited particles and renovate recharge rates. This is typically done at two year intervals. Some of the pits are reported have a recharge capacity of up to 20 ML/day (Marchant and Bristow, 2007).

(a) sand dams

(b) recharge pit

Figure 7 Burdekin Delta recharge operations (a) sand dams and (b) recharge pit *(photographs courtesy of Keith Bristow, CSIRO)*

Soil Aquifer Treatment for horticultural water reuse, Alice Springs, NT

Alice Springs relies on only slowly renewed groundwater reserves from deep aquifers for its water supply. To prevent winter overflows of sewage effluent to Ilparpa Swamp and to provide irrigation water supplies for a horticultural development, it was decided to build a soil aquifer treatment facility and intermittently recharge reclaimed water. A feasibility study was conducted (Knapton *et al* 2004), and a site was identified where 600 ML/yr reclaimed water could be stored in a palaeochannel aquifer, and then recovered for irrigation supplies.

A Dissolved Air Flotation (DAF) wastewater treatment plant, 3 ML storage tank, 6 km pipeline and five infiltration basins were constructed with associated civil works. Recharging of the basins began in May 2008 (Figure 8). The project is an initiative of NT Government and PowerWater Corporation.

Further information on the SAT project can be found at:
http://www.powerwater.com.au/powerwater/aboutus/water_reuse.htm
http://www.clw.csiro.au/research/urban/reuse/projects/soil_aquifer_alicesprings.html

Figure 8. First fill of a soil aquifer treatment basin near Alice Springs *(photo courtesy Power Water Corp, NT)*

Salisbury ASTR stormwater to potable water project

This Aquifer Storage Transfer Recovery (ASTR) demonstration project uses urban stormwater harvested from a residential and industrial catchment, which is treated in a reedbed wetland before injecting into wells in a limestone aquifer 160 to 180m below ground. After flushing out the formerly brackish storage zone by injecting stormwater into a number of wells, the system will be operated to produce water with sufficient residence time in transit between injection and recovery wells to meet drinking water quality requirements on recovery. However approximately 200 ML/yr of this water will be used for diluting the salinity of reclaimed water in a non-potable water supply for garden irrigation and toilet flushing at the nearby subdivision of Mawson Lakes. This will allow commercial use while evidence is gathered to assess whether the risks are being managed to conform with guidelines for augmentation of drinking water supplies. The ASTR well-field at the Parafield Gardens Oval consists of six production wells spaced 50m apart. The outer four wells are used to inject wetland-treated stormwater and the inner two inner wells are used to recover water from the aquifer (Figure 9).

As part of the proof of concept, water recovered after 12 months storage met drinking water requirements and 60 dozen bottles of 'recharge' drinking water were produced and some was consumed by the Prime Minister's Science Engineering and Innovation Council in June 2007 (Figure 10) and distributed widely.

Project partners are City of Salisbury, SA Government, Australian Government, United Water SA Water and CSIRO and the project is part of a European Union research project 'RECLAIM WATER' which is documenting the effectiveness of methods for recycling water via aquifers.

Figure 9 Salisbury ASTR stormwater to drinking water project. Shown are the drain, in-stream basin, holding storage and reedbed treatment (within Parafield airport). In lower left corner are the four outer injection wells and two inner recovery wells. In addition two ASR wells continue to operate on the northwestern side of the in-stream basin. *(photograph courtesy of United Water)*

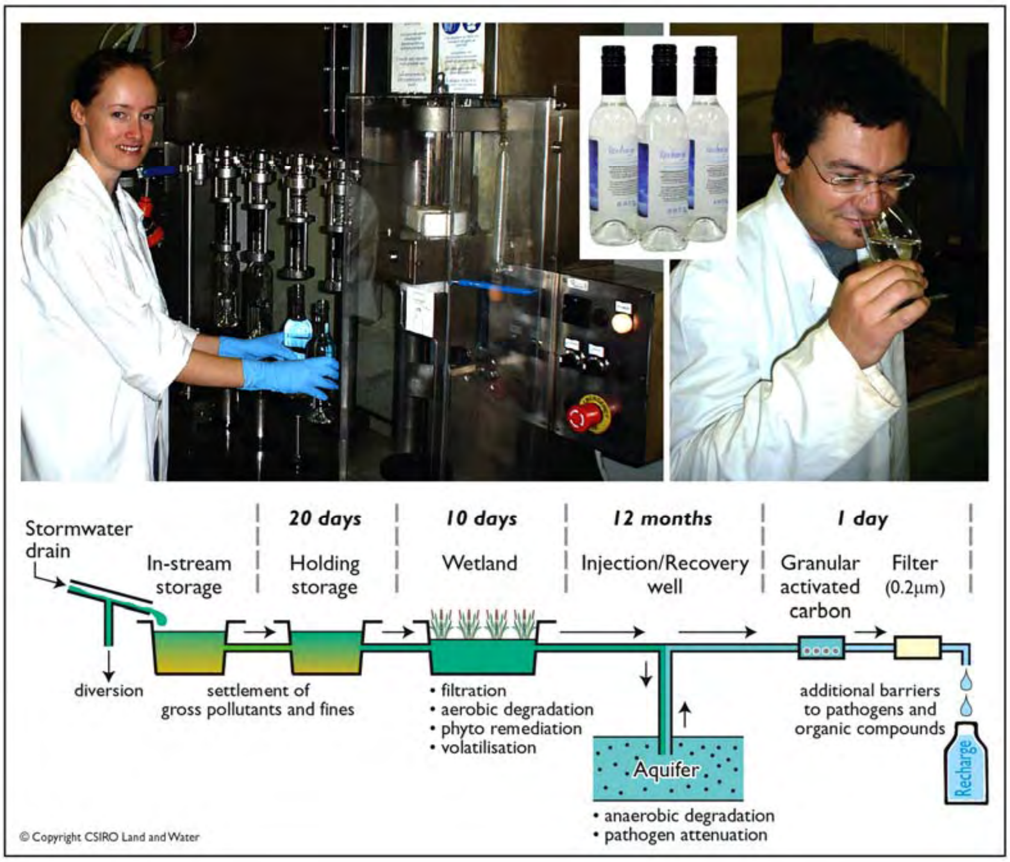


Figure 10. Drinking water was bottled from wetland-treated urban stormwater that had been stored in an aquifer and recovered. This met all drinking water quality requirements and additional barriers were used to prevent recontamination in transporting water to the bottling plant (Hickinbotham Wine Research Centre).

More information about the project can be found at:
http://www.clw.csiro.au/research/urban/reuse/
www.uwi.com.au/astr
http://www.reclaim-water.org

1.6. Other sources of information on MAR

There is wider assistance available on MAR from the International Association of Hydrogeologists Commission on Management of Aquifer Recharge http://www.iah.org/recharge/. This web site includes freely downloadable proceedings of its international symposia, together with brochures and reports, a grey literature web-searchable data base, and registration in a free email list for networking and information about new reports, workshops and symposia on MAR. The web site also contains links to numerous other relevant web pages.

The Centre for Groundwater Studies *www.groundwater.com* has run six Australian workshops on Aquifer Storage and Recovery since 1996 and continues to offer similar training.

MAR Guidelines can be found at *www.ephc.gov.au/ephc/water_recycling.html*. CSIRO's website also holds information about its current and recent research projects on MAR; *www.clw.csiro.au/research/urban/reuse/*.

The above sources cover the rapidly growing body of technical information including hydrogeological and water quality aspects. However they contain sparse information on economics or governance of MAR, and this Waterlines document largely addresses the important non-technical issues that are poorly addressed in the literature to date.

2. Drivers and Constraints

2.1. Purposes of managed aquifer recharge

In rural areas, managed aquifer recharge has been used primarily for increasing the security of groundwater irrigation supplies and improving the quality of irrigation water. In urban areas there can be many other drivers for managed aquifer recharge (Figure 11). For example, in Salisbury, ASR was really only considered after wetlands were established for flood mitigation, urban amenity and coastal water quality improvement. The additional costs of injecting and recovering the detained water provided a water supply competitive with mains water prices.

For new projects, there may be multiple reasons for introducing MAR at any one site. The combination of benefits as stated below, not just water supply, may determine whether a MAR project proceeds.

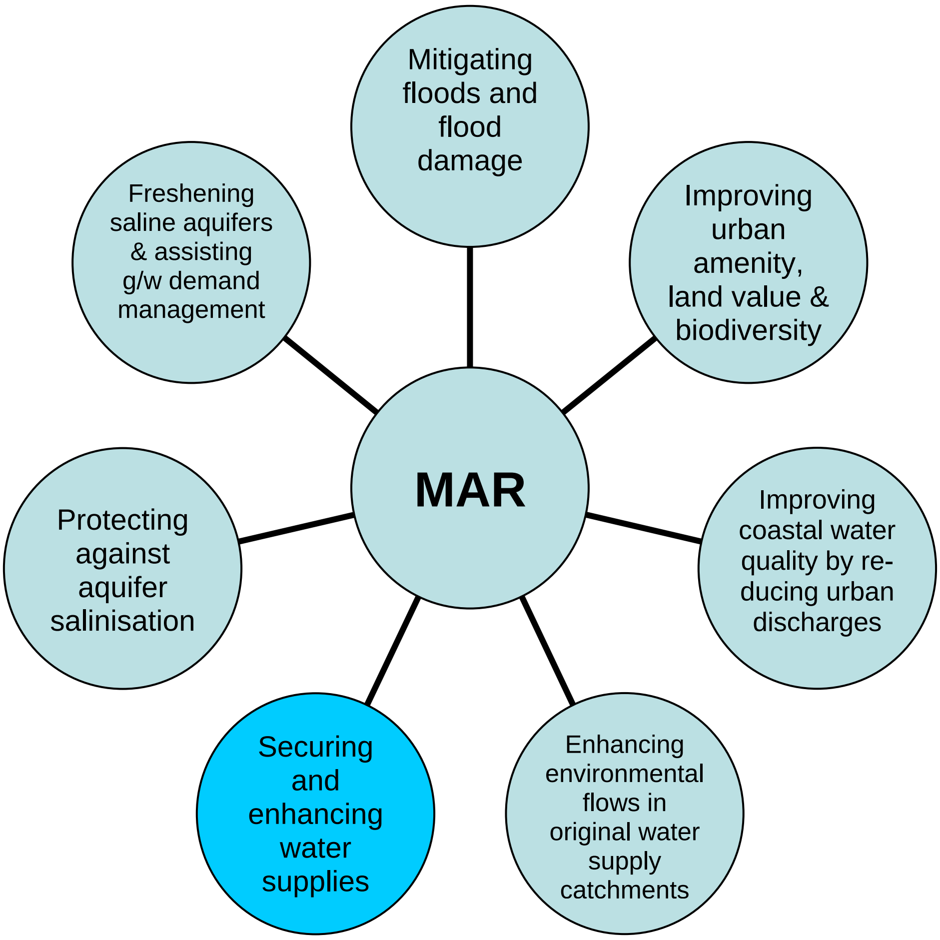


Figure 11. Managed aquifer recharge projects, particularly in urban areas, have many objectives in addition to water supply, and these vary from site to site. All of the economic, social and environmental benefits and costs of projects need to be taken into account in project selection.

In the specific case of securing and enhancing water supplies, pioneering Australian MAR projects were established to satisfy immediate non-potable needs on a commercial basis for agriculture, local government, sporting clubs and industry.

Application of MAR for establishing high-valued drought and emergency supplies could increase as governments and water utilities become more confident of MAR costs and reliability in relation to alternatives. Drought and emergency supplies have high social value but, unless procedures are established to support the development of strategic reserves to meet these demands, harvestable stormwater and aquifer storage capacity in urban areas will be consumed for more immediate needs. A hierarchical approach to allocate these resources could give priority to strategic reserves and substitutional supplies over supplies to meet new water demands. This would help increase the security of city water supplies, especially in light of climate change and population growth.

2.2. Climate variability as a driver for MAR

Australia has highly variable rainfall. In future, much of the continent will face decreasing mean annual rainfall, shifts in seasonal patterns, more frequent high intensity rainfall, higher temperatures and higher evaporation rates because of climate change. As a result, to retain the current level of urban water security may require more stable alternative supplies, larger water storages, and a range of demand management measures.

For example, a 25 per cent decline in rainfall has already resulted in more than 50 per cent reduction in stormwater runoff from rural water supply catchments near Perth. In urban catchments where most runoff is from impervious surfaces, annual runoff is expected to decline by the same proportion as rainfall, although peak storm intensity may increase. Hence the relative efficiency of urban catchments to rural catchments will increase as water supplies become more stressed, and MAR could play a role in averting the need to augment urban stormwater systems.

Climate change will also affect land use, soil cover, erosion and fire frequency, so water quality from traditional water supply catchments is likely to become increasingly variable. Water treatment may need enhancement to retain the current high level of health protection Australians enjoy. Therefore, the water quality advantages of traditional catchments over urban catchments may also partially erode over time.

Bank filtration could be adopted by towns currently using river water directly, as a measure to adapt to climate change. This MAR practice is common in Europe where drinking water supplies are drawn from wells in alluvium next to streams rather than the stream itself, as a means of smoothing out water quality variations and pre-filtering water.

Seasonal variations

The need for storage depends to a large extent on seasonal variations in water sources in addition to inter-annual variability. Cities with prolonged dry periods (in Figure 12, cities with low proportions of rainfall in the driest continuous 6 months of their annual rainfall, or with low ratio of mean annual rainfall to evaporation) (lower left hand side of Figure 12) have a greater need for water storage than wetter cities with more uniform rainfall (upper right hand side of Figure 12). However, for very dry cities (extreme left hand side of Figure 12) the opportunities for stormwater harvesting are infrequent and so MAR projects with stormwater in these areas are unlikely to be viable due to the low rate of utilisation of the invested capital. In these locations reclaimed water, which is a very stable flow, is likely to be the preferred source of water for MAR. Due to high evaporation rates, cities in this sector are more likely to prefer subsurface storage of water than dams.

In wetter cities there is more stormwater available, and therefore the unit costs of harvesting are reduced. So from a climate perspective Darwin, Brisbane, Sydney and Hobart, which look more promising for stormwater harvesting, surprisingly have been less active than

Adelaide, Perth and Melbourne in advancing MAR. Reasons for this in part may relate to the presumed aquifer properties beneath these cities, a topic which will be discussed later.

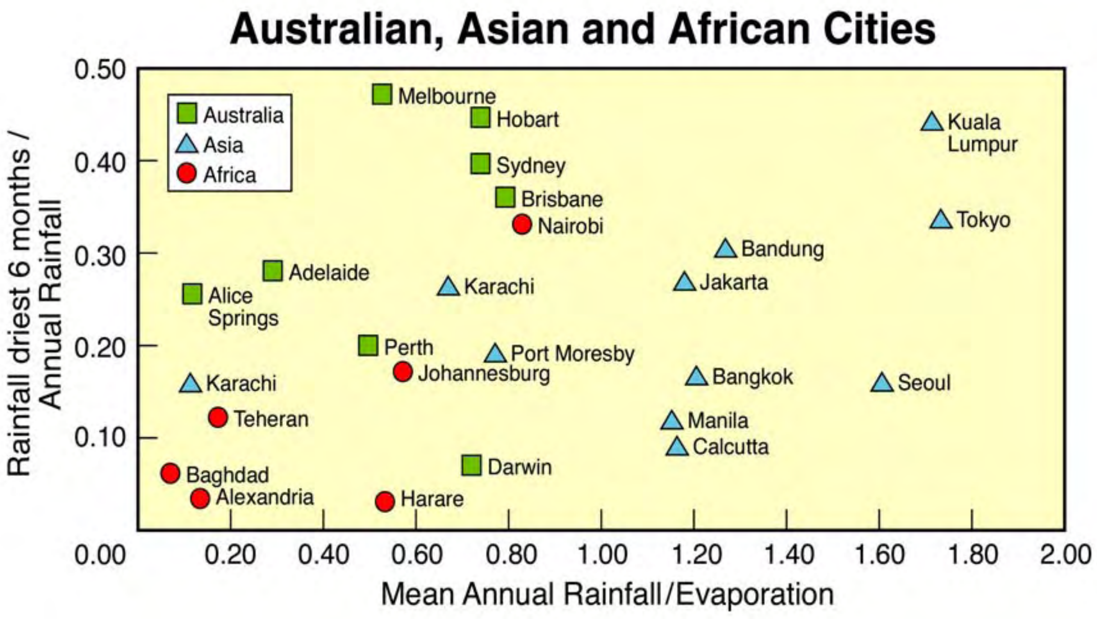


Figure 12. Seasonality of rainfall, shown (on the vertical axis) as the proportion of annual rainfall received in the driest continuous 6 months, and a 'wetness index', the ratio of rainfall to evaporation (on horizontal axis), are indicators respectively of the need for inter-season water storage and the likely availability of stormwater to meet water demand.

2.3. Water sources: urban stormwater and reclaimed water

Stormwater and reclaimed water are usually abundant resources in urban areas but require treatment and storage before reuse. Mean annual stormwater discharge is between 85 per cent and 145 per cent of mains water use and sewage effluent discharge is between 50 per cent and 80 per cent of mains water use across Australian cities (Figure 13).

The availability of stormwater or reclaimed water to make useful contributions to city water supplies is not a constraint. The primary limitation to stormwater harvesting and use is the ability to store the water from runoff events for subsequent use as drinking water supplies or as irrigation, industrial supplies or other non-drinking uses. MAR can provide an economic means of storing water in urban areas (see chapter 3).

Sewage effluent requires extensive treatment before placement in either dams or aquifers prior to reuse. Aquifers have advantages with respect to ongoing passive treatment of the water and allowing longer assured residence times before recovery for drinking.

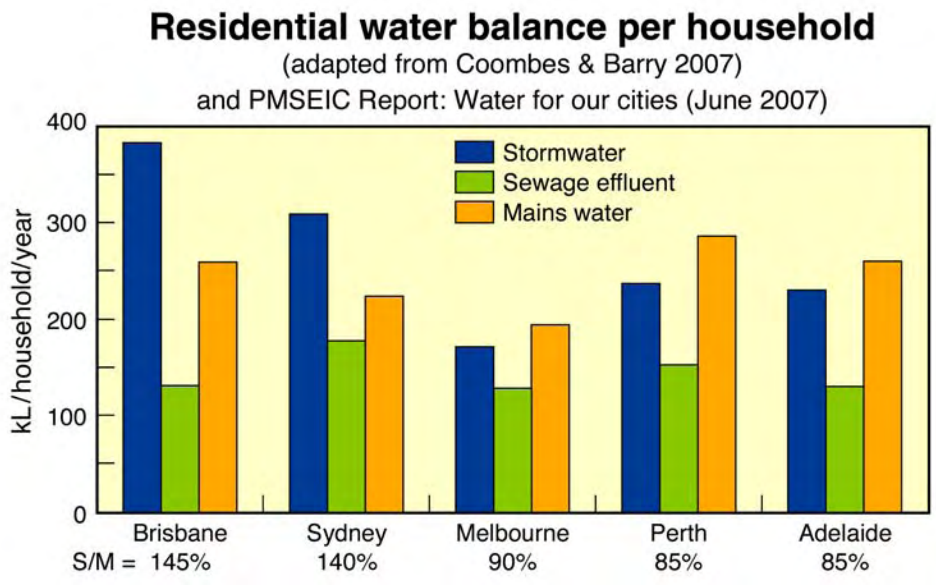


Figure 13. Mean annual stormwater, reclaimed water and mains water flows calculated on a residential household basis by modelling for Brisbane Sydney, Melbourne and Perth by Coombes and Barry (2007) with Adelaide figures scaled for consistency at 70% of gross mean city flows. S/M is the ratio of mean annual stormwater discharge to mains water use.

2.4. Water sources: rural catchments

In rural catchments streams and lakes as well as shallow aquifer systems may provide a source of supply for managed aquifer recharge projects. However, water in a number of major inland Australian catchments, for example the Murray-Darling Basin, is already over-allocated and access to water will be a major constraint to MAR. If irrigators were to store this water below ground in times of excess flows, this would have the same effect downstream as building new dams, except it would put the stored water under private management. Environmental flows essential to riverine health and water security of downstream users could be compromised by private MAR operations in catchments where water is over-allocated, or is likely to become so as a result of climate change.

Allowing substitution of MAR source water for irrigation supplies within surface water entitlements has potential to increase diversions. While this would increase local efficiency of water resource utilisation it would do so at the expense of environmental flows and water security of downstream users. The notion that MAR can be used in over-allocated catchments to reduce evaporation losses in dams downstream is a delusion, unless the sole purpose of MAR is to return the water to the river at times required to sustain flows. A possible exception is where MAR could be clearly demonstrated to increase environmental flows by reducing diversions and evaporation losses from off-stream surface storages.

2.5. Availability of aquifers for MAR in urban and rural areas

An essential prerequisite for MAR is the presence of a suitable aquifer in which to store water. The best aquifers are those that can store and convey large volumes of water, because increasing the storage volume reduces unit costs of recovered water. Aquifers that are thick and have uniform hydraulic properties are also preferred to maximize the ability to recover water. Having a very low regional flow rate through the aquifer also helps to make recovery of recharged water easier. Consolidated aquifers are preferred to unconsolidated ones for ASR due to simpler well construction and ease of maintenance.

There can be both positive and negative aspects of other aquifer attributes for MAR. For example, if aquifers are unconfined, infiltration methods may be used, and these are cheaper than well injection methods if sufficient land is available. However stored water needs to be protected from pollution from overlying land uses, especially where recovery is for drinking water supplies. Confined systems are by nature protected from pollution but wells are the only means of accessing these systems. For recharge wells the water quality requirements for turbidity and nutrients to avoid clogging are more stringent than for surface infiltration systems and depend on the pore sizes in the aquifer, its mineral composition and the form of construction of the well.

If the ambient groundwater is brackish the pre-treatment requirements for aquifer protection may be less than they would be for a fresh aquifer. However if groundwater is too saline the recovery efficiency may be low and the site non-viable. Reactive minerals in aquifers, such as carbonate, can assist in controlling clogging in ASR wells, but the same minerals can in some cases also contain metals that are released and impair the quality of recovered water. Finally the oxygen status of the aquifer can also affect water quality. Pathogens and some organics are most effectively removed under aerobic conditions but other organics are only removed under anoxic conditions. The ideal is to have different zones in the aquifer so that water is exposed to both conditions to get the best water quality improvement.

At any given location there may be several aquifers stacked on top of each other, interleaved with low permeability layers. This allows choice of one or more with the most favourable characteristics for water storage. Depending on their degree of inter-connection, it may be possible to store water of different qualities in different aquifers at the same location.

In other places there may be no aquifer, or none with suitable characteristics to allow sufficient storage while ensuring environmental protection. Such places could include:

- where the aquifer is unconfined and the water table is very shallow,
- where the aquifer is very thin or composed of fine grained unconsolidated material,
- where the site is adjacent a leaky fault or a semi-confining layer containing poor quality water, or
- where the aquifer contains poor quality water and is highly heterogeneous or has a high lateral flow rate.

At these locations MAR is not feasible. A site that is hydrogeologically complex requires more detailed investigations and more sophisticated management, which add to the costs, and even though technically feasible, becomes economically unviable. This is discussed further in Chapter 3.

Local hydrogeological knowledge is needed to identify the presence of aquifers and their suitability for MAR. State departments responsible for groundwater generally require drillers to lodge basic stratigraphic and hydrogeological information for each well drilled and this information is stored in departmental data bases which in some cases are publically accessible on the web. If they exist, hydrogeological reports from these departments and their predecessors (eg Geological Surveys, Minerals and Energy Departments, or Water Commissions) serve as valuable background information before drilling. Hydrogeological reports generally provide some indication of the level of knowledge of the local aquifers and their degree of uniformity. Aquifer properties vary spatially so it is not generally reliable to extrapolate from one site to predict viability or performance at a nearby site.

Maps showing potential for aquifer storage and recovery are available for Adelaide (Tertiary aquifers- Hodgkin, 2004; Upper Quaternary aquifer- Pavelic *et al,* 1992), Melbourne (Dudding *et al*, 2006) and Perth (Scatena and Williamson, 1999) and are being developed for Brisbane to Gold Coast, Hunter Valley (NWC) and Canberra (Evans, 2008). Examples of maps for Adelaide and Melbourne are shown later.

The maps are used as a guide to potential, and areas indicated as prospective have a higher chance of yielding a successful MAR site. However, until a site has been drilled and tested, the actual prospects will always be uncertain.

The results of mapping indicate potential storage capability for MAR of:

- 250GL in **Perth**, mostly in the superficial sands, with an unknown potential in deeper confined aquifers;
- 20 to 80GL in **Adelaide** mostly in confined limestone aquifers but in some places also in fractured quartzite bedrock aquifers, and
- 100GL in **Melbourne** largely in the Werribee Sandstone to the west and south east of the city with some potential for small projects in fractured rock and alluvial gravel aquifers to the north and east of the city.

Opportunities in **Sydney** are likely to be in the Botany Sands aquifer in the south east of the city, a shallow sandy aquifer on the northern beaches or the Hawkesbury Sandstone over the rest of the city. MAR in the Botany Sand is likely to be constrained by the shallowness of the watertable, proximity of the sea and localised pollution in the aquifer. The fractured Hawkesbury Sandstone is in some places sufficiently high yielding to provide a suitable MAR storage, but where it is incised by perennial streams, drawdown during recovery could dry out these streams with undesirable ecosystem effects. Exceptions will no doubt be found if Sydney is mapped for ASR potential.

Localised aquifers in **Brisbane** are providing useful drinking water supplies, suggesting there may be opportunities for MAR, although large parts of Brisbane and the Gold Coast have only low-yielding aquifers.

The **Hunter Valley** has the Tomago Sand Beds as a major drinking water supply and any recharge there would need to provide a high level of protection for groundwater quality.

Canberra is underlain by variable but relatively low yielding bedrock and in places coarse-grained alluvium may provide potential MAR storage targets.

In **Darwin** the climate is well suited to MAR, and where the local shallow lateritic aquifer does not fill in the wet season, for example due to groundwater extraction, there may be potential for MAR. Deeper aquifers, where they occur, such as used at Warruwi (Figure 14), may also provide suitable storage sites.

Figure 14. ASR well for the township of Warruwi on South Goulburn Island, Arnhem Land, NT. In spite of 2m annual rainfall, the water supply wells along the spine of the narrow island drawing from the shallow aquifer become saline by the end of the dry season. Storing groundwater extracted in the wet season in a brackish lateritic aquifer at a depth of 80m secures the fresh water supply.

For other urban and non-urban centres, reference material and knowledge exists within the state agencies responsible for groundwater, and guidance may be provided from groundwater consultants with experience in MAR design, establishment and operation.

Mapping for MAR potential could be extended to other urban and rural areas with water shortages. In river basins that are already over-allocated there would be little point in doing such mapping until the water balance regains equilibrium.

Examples of maps of ASR potential are shown for Adelaide (Figure 15) and Melbourne (Figure 16). The shading colour represents the strength of the prospects for ASR projects, based exclusively on the hydrogeology of the areas from existing hydrogeological reports and drilling records. The dominant factor is the potential rate of injection considered to be achievable by interpolation from existing wells. The maps also reflect constraints on groundwater salinity and piezometric level. The maps are accompanied by reports that contain a great deal of information required to interpret them and to understand the strength of the supporting data on which they are based. They are at a scale that indicates prospects, but site-specific investigations are required to assess actual aquifer properties at any proposed site.

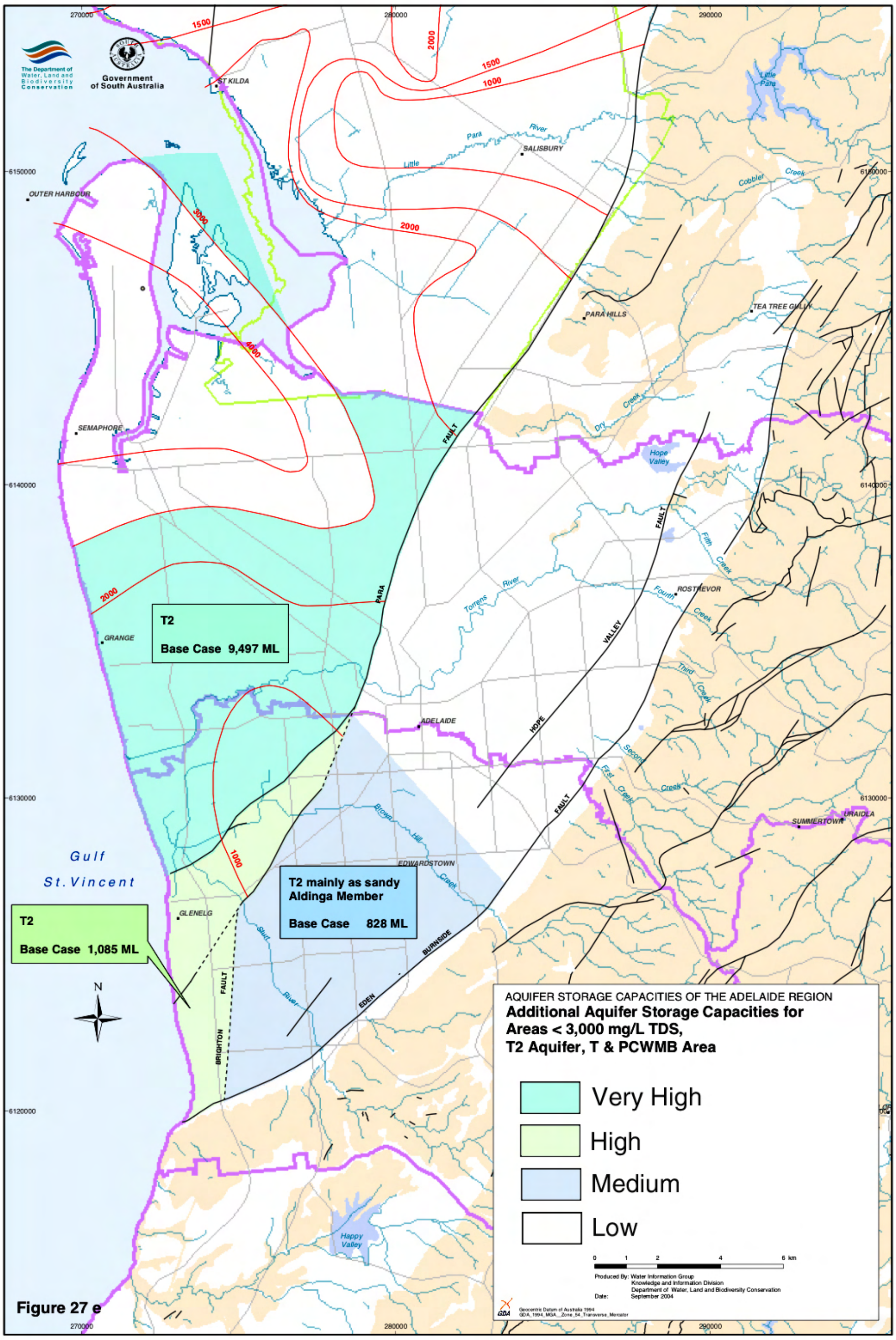


Figure 15. One example of maps showing ASR potential for the T2 aquifer (a Tertiary limestone and sand aquifer at a depth varying between 100 to 200m) in the central part of Adelaide (from Hodgkins, 2004)

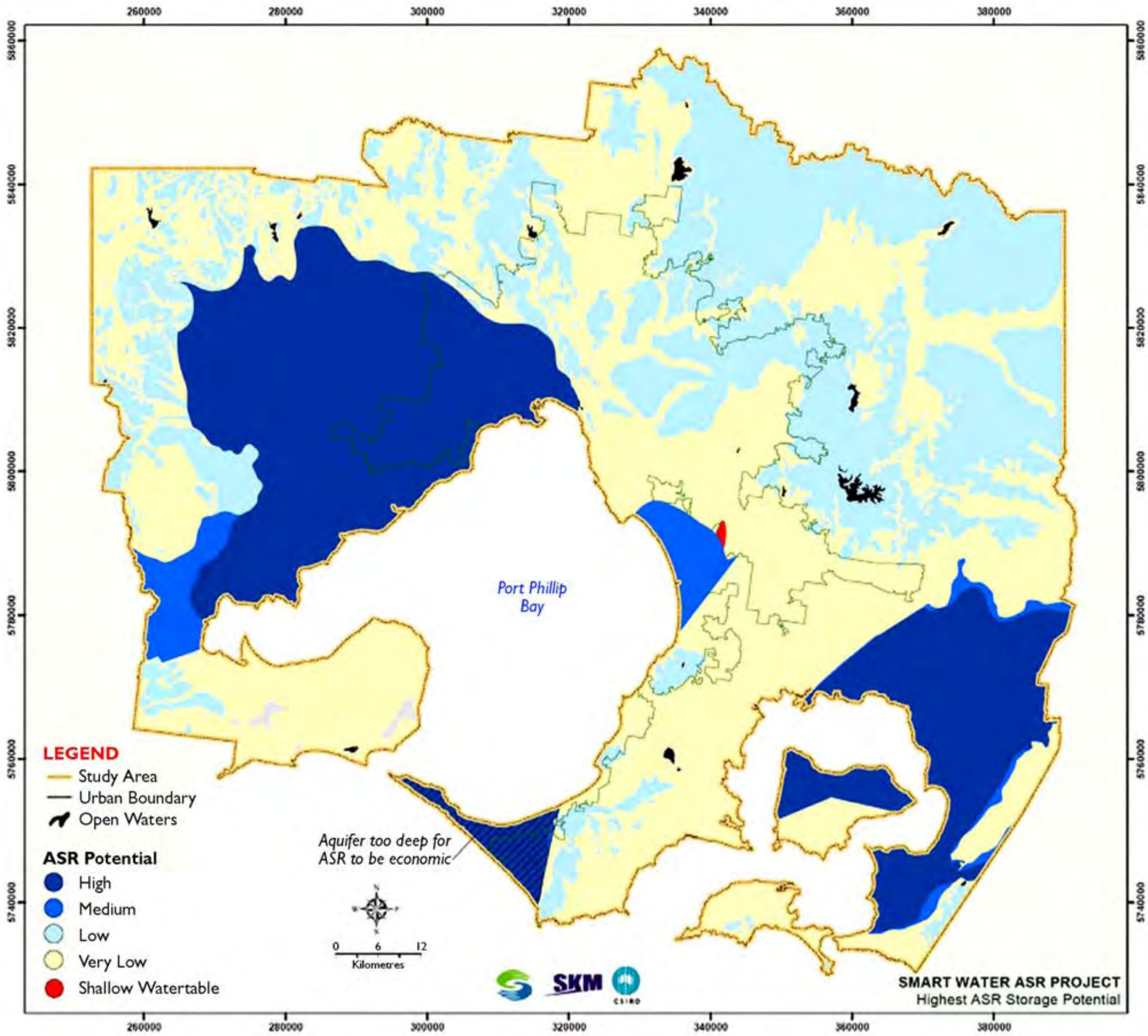


Figure 16. A regional-scale summary map of ASR opportunities in Melbourne for all aquifers. This map is based only on readily available hydrogeological data and should only be used in conjunction with the Broad Scale Mapping Report (Dudding *et al* 2006)

2.6. Storage advantages of MAR

Storing water below ground rather than above ground can have a number of benefits but also some disadvantages as noted in Table 1. A definite advantage is that the land above the storage zone may be used for urban and rural uses, particularly if the target aquifer is confined. Even brackish aquifers may be used to store fresh water for recovery for meeting high-valued uses. Although evaporation is eliminated, mixing in a brackish aquifer can result in loss of a similar volume of water to that which would have been lost through evaporation from a surface storage. The rate of recharge and recovery may restrict the volume of water that may be recharged and recovered and may require multiple recharge systems and recovery wells to move water quickly. Water treatment capabilities of aquifers are substantial, particularly for pathogen removal and are taken into account in the Draft MAR Guidelines (EPHC, 2008).

Table1. Comparison of attributes of storing water above ground in new dams and below ground via managed aquifer recharge

Attribute	New dams	Aquifer storage
Land area required	large	very small
Proximity to city	far	within
Capital costs	high	low
Investigations costs	high	low
Intake and supply rate	high	low
Evaporation losses	moderate	low
Algal problems	moderate	low
Mosquitoes	moderate	low
Mixing losses	none	none to high
Pathogen removal	some	substantial
Recontamination potential	moderate	none to moderate
Greenhouse gases- embodied energy	high	low
Greenhouse gases- operating energy	low to moderate	moderate
Requirement for viability – presence of:	suitable valley	suitable aquifer

Green colour coding shows the storage type which on average for a given attribute is more favourable or is less constrained.

Figure 17. This ASR well in the foreground stores and recovers treated drinking water using the underlying aquifer at a depth of 100 to 130 m. The volume stored below ground during the low demand period and recovered in the high demand period at Cocoa, Florida, USA is ten times the volume of the two tanks behind. The unit storage cost of ASR was less than 2 per cent of the alternative cost of constructing additional tanks.

2.7. Community preference for water recycling via aquifers

One driver for developing MAR with recycled water is its high level of public acceptance, especially for drinking water supplies, with respect to other forms of water recycling. Groundwater recharge with reclaimed water has been practised since the 1960s in USA for recovery for non-potable and drinking water supplies. Reclaimed water that has undergone natural treatment is well accepted by the public when recovered water is used for potable purposes. (Asano, 2005, p1249).

In Australia, while experience is limited, it appears that public acceptance of indirect potable reuse via aquifers as assessed at three locations in Australia is similar to that reported by Asano for the USA. In the South Australian city of Mount Gambier where 20,000 residents rely on the Blue Lake for drinking water supplies, urban stormwater has been disposed of via wells for 120 years into the aquifer adjacent the lake. Current annual recharge is 3GL/yr, the same volume as the town water supply. A study by Wolf *et al* (2007) included a hydrogeological study, a hazard analysis and risk assessment contributing to a recharge management plan to protect the quality of supplies, and reviewed attitudes in the community. The end result is that unmanaged recharge has successfully been turned into MAR with evidence of strong support of the local community.

A survey in 1996 of environment officers in 21 South Australian metropolitan councils on perceptions of MAR revealed a differentiation in attitudes towards recycling reclaimed water and stormwater via aquifers for irrigation supplies. When asked about their perception of the public acceptance of these waters for irrigation, 95 per cent believed that stormwater recycled via ASR would be acceptable in their community, compared to 67 per cent who believed treated effluent recycled via ASR would be acceptable (Figure 18).

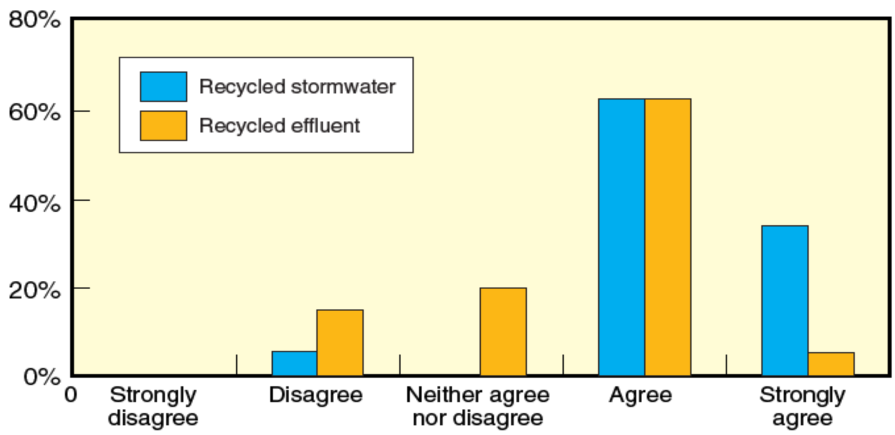


Figure 18. Adelaide local government environmental survey 1996 on perceptions on public acceptance of MAR with different sources of water for recovery for irrigation (n=21) (from Dillon 1996).

A 500-person survey in metropolitan Perth outlining a MAR scheme for recycling reclaimed water to drinking water in 2006 found that more than 78 per cent of people were unopposed (Leviston *et al* 2006). The researchers found the perceived risk to human health was the largest factor affecting opinions. This study compares very favourably with a broader Australian study surveying 2500 people in several cities where only 22 per cent said they were willing to drink recycled water although 63 per cent were willing to use it to irrigate their gardens (Marks *et al* 2006). It is anticipated that recently released Australian Guidelines for Water Recycling will do much to increase knowledge and give confidence in human health and environmental protection.

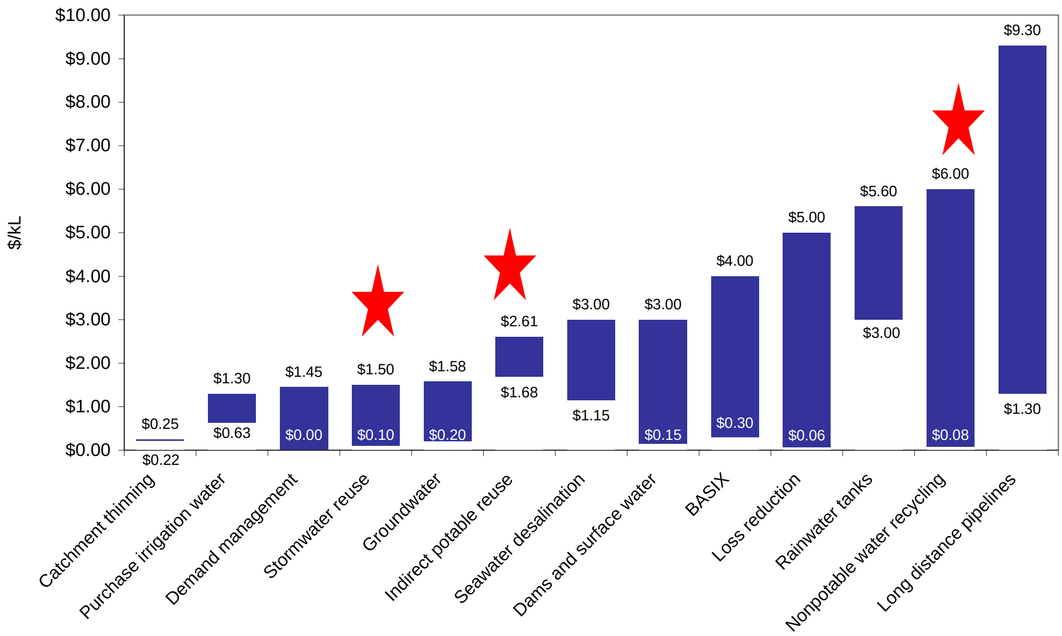
Perth respondents were asked '*if recycled water was left underground for a number of years would there come a time after which there was no difference between the groundwater and the recycled wastewater?*' Almost half of the respondents (45 per cent) said *yes*, 19 per cent said *no*, and the remaining 36 per cent were *unsure.* Most of those who were unsure said they did not have enough information. Of those who said *yes*, the most common reason given was that the aquifer acts as a filter and treats water. In spite of limited information being available the concept of aquifers as filters and natural attenuation was understood by almost half of respondents. This suggests that provision of factual information to the public on water treatment processes in aquifers would result in support by the majority and could address concerns of those who answered 'no'.

3. Economics of Managed Aquifer Recharge in Relation to Alternatives

3.1. Costs of MAR with respect to alternative water supplies

Managed Aquifer Recharge is commonly applied as part of water recycling for indirect potable or non-potable use of stormwater or reclaimed water to substitute for all or some uses of existing mains water supplies. In any city, town or rural area, the costs and benefits of MAR can be compared with a range of options including improved water conservation, tapping new surface water supplies or aquifers, rainwater tanks, and groundwater or sea water desalination. The local situation dictates the costs of each option and large variations occur between localities for costs of any option and therefore the relative cost effectiveness of different options.

Figure 19 demonstrates the range of unit costs evaluated on a consistent basis across four cities for a range of investment options. MAR may play a role in storage, additional passive treatment and distribution for three options shown: stormwater reuse, indirect potable reuse and non-potable recycling.



Source: Marsden Jacob Analysis based on water supply plans for Sydney, Adelaide, Perth, Newcastle. Lower bound of indirect potable reuse estimate based on Toowoomba.

Figure 19. A Comparison of direct costs of water supply enhancement and demand reduction options for four Australian cities. (Source: Marsden and Pickering, 2006) Blue bars represent the range in costs for each option. Stars represent options that may potentially include MAR among other approaches. Groundwater in this bar chart is for direct supply of groundwater only and does not include MAR.

Most cities will require diversified sources of water to enhance security of supply, taking account of the size, quality, reliability, proximity and cost of each new resource or water conservation measure. Before tapping new sources, investment is needed to assess the attributes of each resource and develop plans for an integrated portfolio of measures to secure future water supplies that account for climate change, population growth, changing demographics, existing infrastructure and its longevity, as well as environmental and social measures.

Figure 20 shows an example of the range of options available to a city, in this case Adelaide, taking account of potentially reduced security of supplies from established resources and demand growth. Wedges represent options that could potentially be developed to contribute to the portfolio of water supply capabilities. The extent to which each option will ultimately contribute depends on attributes listed above. These are shown qualitatively in Table 2. This also depends on the estimated size of each alternative resource and the financial costs of developing it. For example, seawater desalination is not capacity-constrained nor rainfall-dependent and can be built relatively quickly, but is the among the more expensive options for supply development. Hence expansion beyond immediate needs would depend on any remaining gap between cheaper sources of supply and demand.

Stormwater ASR/ASTR is a low cost option for potable supplies as well as irrigation and industrial supplies to replace the use of potable water for non-potable uses. Reclaimed water ASR will be needed to increase the amount of reclaimed water available for horticulture, viticulture and non-potable urban uses.

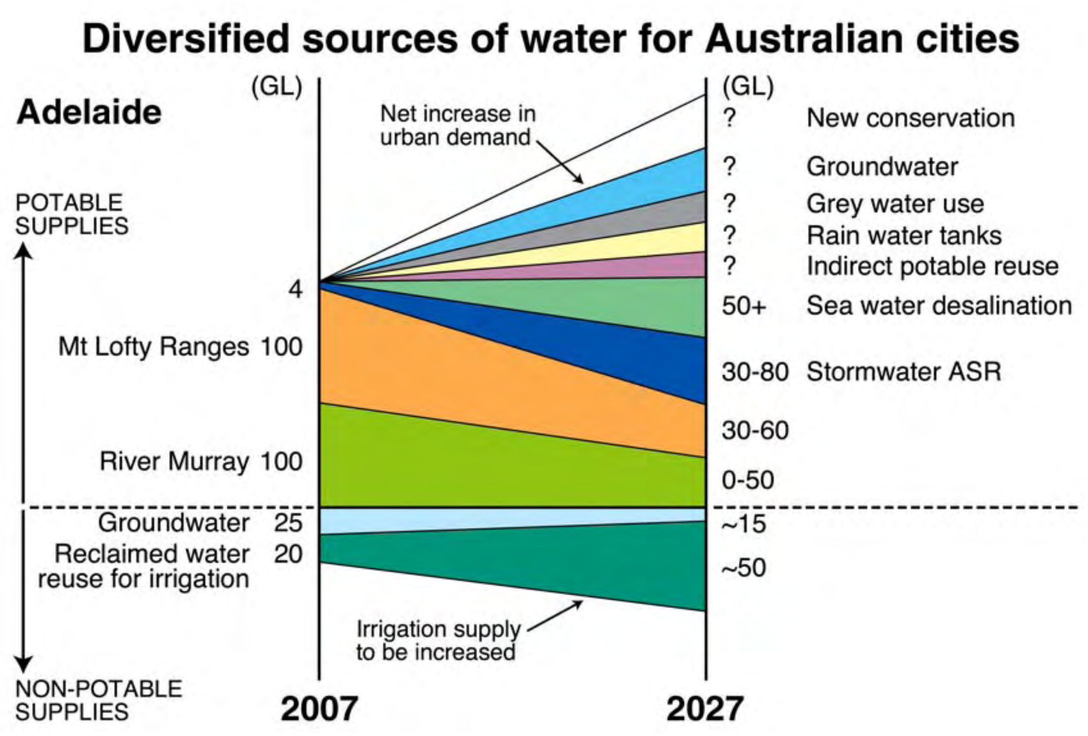


Figure 20. Diversified sources of water may include MAR as one of the elements of future city supplies that may complement other options such as desalination, and expand storage and robustness of supplies

The full range of costs and benefits (identified in section 2.1) and amplified in section 3.7) of different water source options should be evaluated when selecting projects for increasing water security. If water resource development is left to water utilities that are required to meet commercial objectives by their shareholder governments, unless directed, objectives of candidate projects where benefits and costs do not accrue to the utility may be under-represent or excluded from appraisal. As a conceptual example, in considering candidate alternative supplies in Figure 20, each of these contributes to different degrees to a range of objectives as estimated subjectively and qualitatively in Table 2. Market approaches to addressing costs and benefits associated with these other objectives (section 3.7) would provide quantitative analyses to allow assessment of the extent of achievement of multiple objectives through a diversified portfolio of projects. Most states vest management of mains water and sewage in separate organisations to those that are responsible for stormwater, urban groundwater, coastal water quality, greenhouse gas accounting and urban planning and will need to find constructive ways to address all objectives.

Table 2. Each option in a diversified portfolio of potential water supply projects contributes to a different degree to a range of social and environmental objectives. These are examples for Adelaide, with subjective and qualitative scoring as zero to three asterisks for the relative contribution of each potential source or saving toward each given objective, in the absence of quantitative assessments. For each source it is assumed that treatment is included to ensure that the water quality will be fit for its intended use. Note that the main point of this table is to illustrate that multiple objectives can and should be considered concurrently. The number of asterisks in any grid cell is subjective only.

Objective / **Source or saving**	Potential volume of supply or saving	Low unit cost of water sourced or saved	Improved security of supply – non-reliance on rainfall	Reduced demand on existing catchments	Improved coastal water quality	Reduced greenhouse gas emissions	Reduced urban flooding	Improved amenity and land value
Mains water conservation	*	***	***	***		***		
Urban groundwater	*	**	*	*		*		
Grey water use	*	*	***	***	*	*		
Rainwater tanks	*	*	**	***	*	*		*
Recycled water via a desal plant and storage (dam or aquifer) for potable uses	**	*	***	***	***			
Recycled water via a desal plant for non-potable uses	**	*	***	***	***			
Desalination of seawater	***	*	***	***				
Stormwater for non-potable uses via ASR	**	**	**	***	**	**	*	***
Stormwater for potable use via ASR/ASTR	**	**	**	***	**	**	*	***
Increased reservoir capacity and increased pumping from River Murray	**	*	*			*	*	

Table 2 illustrates that a broad range of objectives can be brought into consideration in an integrated way. As an example of the qualitative scoring in Table 2 achievement of coastal water quality objectives adopted by the Natural Resources Management Board in Adelaide involve reducing annual urban discharges of suspended solids by 50% and nitrogen by 75%. The potential for each supply option to contribute to these objectives is subjectively signified by the number of asterisks assigned in that column. In a quantitative assessment this could be scored by the tonnes of suspended solids and nitrogen prevented from discharging to sea. This could then be converted to a dollar figure by examining the wider range of measures by which such discharges can be prevented and costing each of these. Similarly approaches may be made to quantify other objectives. The extent to which each option will contribute to each objective will vary from city to city and from project to project for the same source category. (Almost all of Adelaide has clay-rich soils that prevent forms of MAR involving surface infiltration methods which have been excluded from Table 2 but offer significant opportunities in some other cities.)

3.2. Scale of MAR Projects

Individual MAR projects typically provide intermediate scale supplies. Taking account of the investigations to establish these projects they are generally cost effective at sizes above 50 to 100 ML/yr, depending on location. Projects bigger than two to 20 GL/yr will generally require multiple sites, depending on the local storage capacity of aquifers. Hence MAR occupies the gap between rainwater tanks or localised stormwater harvesting systems and new large dams or desalination plants (Figure 21). MAR may be a foundational supply for towns and regional cities but in major cities its primary use will be for supplementing supplies to meet incremental demand growth.

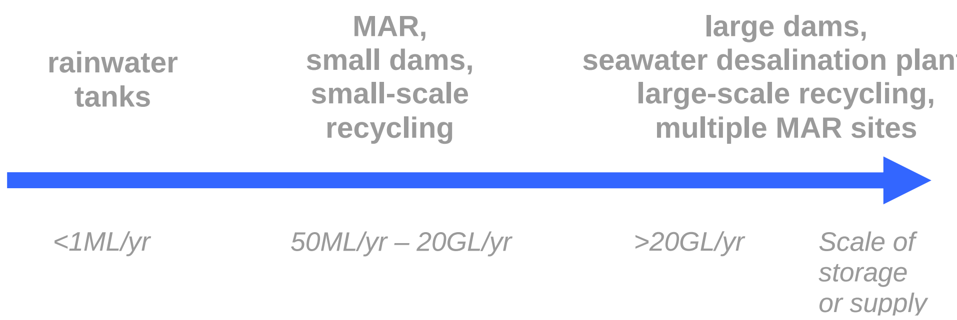


Figure 21. Role of MAR within the scale range of water supply augmentation projects

3.3 MAR costs compared with other storages, treatments, transfers and supplies

This section compares the costs of engineered alternative water storages, treatments and distribution systems with the costs of harnessing equivalent capabilities of aquifers through MAR projects. This is an attempt to value aquifers, where present, as latent elements of urban water infrastructure. The purpose is to demonstrate the potential benefits of investment in hydrogeological investigations to understand and wisely deploy urban aquifers. The last part of this section compares the costs of seawater desalination with stormwater ASR, as seawater desalination has been adopted by a number of coastal cities as a default emergency measure to address water shortages without serious evaluation of alternatives such as MAR.

Costs of storage alternatives

Capital costs per unit storage volume of infiltration projects that store water in unconfined aquifers are significantly lower than for any other form of water storage considered in Table 3. ASR and dams generally have similar unit capital costs if cost of land is neglected. Tanks and earthen impoundments have higher unit capital costs and land area requirements. Taking account of land area, especially where land value is high, such as in or near urban areas (~$1000/m^2 is common in capital cities), ASR has potential to have the least total capital costs per unit of water storage of alternatives in Table 3. It has long been known that the conjunctive use of surface and aquifer storages can reduce the costs of operating either system on its own (Johnston *et al,* 1973).

Table 3. Indicative costs (A$ in 2008) and land area requirements of managed aquifer recharge projects in relation to costs of alternative storages

Type of storage	Storage size range costed (ML)	Unit capital cost of storage† ($'000/ML)	Land surface area required (m^2 / ML)
Rainwater tank-polyethylene	0.002-0.010	200	500
Concrete tank - trafficable	1 - 4	1000	200
Pre-cast concrete panel tank	4 - 8	250	250
Lined earthen dam impoundment	4 - 8	12	600
Large dam – gravity or concrete	350 – 200,000	4 -10	100 - 200
Pond infiltration / Soil aquifer treatment #	200-600	1-2	20 – 60*
Aquifer storage and recovery #	75-2000	4 -10	1**

Source of tank and dam data is SKM and United Water. MAR costs from sections 3.4 and 3.5.
† excluding land cost
# storage size used here for MAR is the mean annual recharge volume. Actual storage volume of recoverable water may be many times this amount, however in brackish aquifers recoverable volume from earlier years will depreciate due to mixing.
* for hydraulic loading rates of 17 to 50 m/yr
** 1m^2/ML for ASR system, but if detention storage is required to capture stormwater, size may be 20 to 100 m^2/ML depending on runoff from catchment and capture efficiency.

Note that Table 3 only compares cost of storage, not cost of supply from such a storage. Generally the annual supply from a large dam will be less than its storage capacity, whereas for a rainwater tank the annual supply may be many times its capacity.

The least cost viable alternative should be used as the benchmark by which to value aquifer storage via ASR. If a dam is viable it would be the least cost alternative. Therefore, neglecting operating and maintenance costs of dams, and using a 7% discount rate over an asset life of 100 years, if 100% capacity was supplied in each year of dam operation the capital cost of the dam would be amortised by charging $0.28 to $0.70/kL. If, for example the average annual supply from the dam was 50% of its capacity, then a cost of $0.56 to $1.40/kL would recoup the capital cost. If the asset life was shorter or discount rate higher these values would increase. Therefore, if a new ASR project would allow construction of a dam to be avoided, the value of the aquifer storage could be attributed based on the costs calculated above.

In general such a cost is known as the **levelised cost**, which for a water supply project is the constant level of revenue necessary each year to recover all the capital, operating and maintenance expenses over the life of the project divided by the annual volume of supply. Levelised costs provide an effective means to compare the costs of water from alternative projects. This provides a basic framework with which to also compare the equivalent value of water storage, treatment and transmission in an aquifer.

If there were no suitable sites for a large dam, and for example precast panel tanks within the urban area were the least cost option, taking account of land value gives a capital cost of $500,000/ML which amortised over a 100 year life at 7% gives a levelised cost of storage of

$35/kL. Such a tank in existing city water systems is likely to supply many times its volume in a year but would be considered infeasible as an inter-seasonal storage. However if this was the cheapest alternative to ASR then the equivalent value of the urban aquifer for inter-seasonal or over-year storage is this value.

Costs of water treatment alternatives

The aquifer is considered to undertake several treatment functions on a sustainable basis, including filtration of colloidal material, disinfection (removal of viruses, protozoa and bacteria that are pathogenic to humans), and biodegradation of some trace organics (Dillon and Toze, 2005; EPHC 2008). Engineered processes that perform similar functions are slow sand filters or biofilters, chlorination or ultraviolet disinfection, and granular activated carbon filtration.

Table 4. Costs of treatments that cause similar improvements in water quality as occur during the residence of water in aquifers during managed aquifer recharge

	Biofiltration (SSF)*	Rapid sand filtration**	GAC	chlorination	Stormwater ASTR***
Flow (ML/d)	30	30	30	10	1
Yield (GL/yr)	10	10	10	3.6	0.1[†††]
CAPEX (A$/ML/d)	8.3	0.40	0.49	0.026	2.8
Levelised CAPEX (A$/KL) (15 yrs)	2.50	0.13	0.16	0.01	0.84
OPEX (A$/kL)	0.01	0.01	0.01	0.01	0.28
Levelised cost (A$/kL)	2.51	0.14		0.02	1.12

Source of water treatment data is SKM and United Water. MAR costs from section 3.4

* estimated based on scaling hydraulic loading rates against GAC (Slow Sand Filtration (SSF) is 50 times slower) and assuming a scale efficiency factor (3) – actual costs depend strongly on land value

** estimated based on same hydraulic loading rates as GAC and 20 per cent reduced capex & opex

*** costs for ASR derived from section 3.4

† CAPEX is capital expenditure

†† OPEX is operating expenditure

††† assumes 100 days recovery per year

Stormwater ASTR is at least as effective as biofiltration for contaminant removal, as the processes are identical (slow passage of water through granular media) but the residence time in the aquifer is generally 3 to 4 orders of magnitude longer than in the biofilter, the shortest travel distance 1 to 2 orders of magnitude further, and dispersion to buffer shock loadings is 3 to 4 orders of magnitude greater. Rapid sand filtration is much cheaper than biofiltration but not as effective for colloid, pathogen, nutrient or organics removal, unless coagulant doses are carefully managed on an ongoing basis. Granular activated carbon filtration is more effective at removal of trace organics than rapid sand filtration and is more representative of the quality of water likely to be recovered at an ASTR project, except that pathogens are better removed in the aquifer than during GAC filtration. Hence chlorination, among the cheapest forms of disinfection, combined with GAC filtration, gives the best analogue of the treatment provided by the aquifer during ASTR. That is, the levelised cost of engineered treatments equivalent to that provided by the aquifer is estimated at $0.19/kL. For soil aquifer treatment the level of treatment is similar or greater and therefore has a corresponding equivalent value.

Cost of water transmission alternative

Another function that aquifers fulfil is transmission of water. In fresh and transmissive aquifers where recovery does not depend on dilution of native groundwater by the recharged water, water may be extracted remotely from the recharged location In this case the aquifer acts as a distribution system that only requires access by a well to recover water at any location. In brackish or low permeability aquifers the transmission value is negligible.

The cost of a pipe system to transfer the same quantity of water as an aquifer from recharge to recovery wells may be used to value the transmission properties of an aquifer. Using a capital cost of $13/m for installed 100mm mains (source: SKM and United Water) and neglecting pumping costs, it would take 27km of pipe to amount to a levelised cost of $0.10/kL. In urban areas this cost can rise steeply because of the presence of other buried infrastructure to be avoided and the need for traffic diversion during construction. Hence the distribution capabilities of a fresh aquifer with typical (mid-range) values of transmissivity and hydraulic gradient and with recovery from several wells within 10km of the recharge location could be substituted by a pipe system for at least half the equivalent water treatment value of the aquifer.

Summary of aquifer value in relation to costs of equivalent water infrastructure

These very simple calculations indicate that from a substitution value perspective, aquifers have significant storage value, especially in urban areas where land value is high. In saline aquifers the long-term storage value may be diminished by a higher depreciation rate to reflect the mixing of fresh injectant with native groundwater restricting the proportion of injected water that can be recovered at an acceptable quality. Aquifers also have a tangible value for treatment, with the advantage that this treatment is passive, requiring no further input of energy or chemicals. Treatment values may vary between aquifers but design of ASR operations in accordance with MAR Guidelines should ensure that at least the values indicated above are achieved. If the aquifer is extensive and contains fresh groundwater, the transmission value is similar to the treatment value and, in already established urban areas, possibly of higher value. In brackish or localised aquifers the transmission value is negligible.

Overall this information reveals that knowledge of the existence and properties of aquifers has potentially huge value for urban areas in allowing more cost-efficient future water supply options via MAR, particularly for inter-seasonal storage. Investment in hydrogeological investigations may reveal latent water supply infrastructure that otherwise would be ignored, and in some cases may identify viable subsurface storage alternatives to unpalatable or expensive projects.

Costs in relation to one water supply alternative - seawater desalination

Recognising that there are many other attributes to consider, including reliability of supply, differences in scales, and differences between foundational and supplemental supplies, Table 5 compares stormwater ASR unit costs with seawater desalination costs. The two Australian reverse osmosis plants considered here are of different size and at different locations. Variations in capital costs reflect the presence or absence of supporting infrastructure. Beyond a size of 150 ML/d any economies of scale are small for seawater desalination.

Table 5. Comparison of economics of stormwater ASR with seawater desalination

	Seawater desalination plant A	Seawater desalination plant B	Stormwater ASR
Flow (ML/d)	150	300	1
Yield (GL/yr)	50	100	0.1
CAPEX (A$million/ML/d)	5	9	2.8
Levelised CAPEX (A$/kL) (15 yrs replacement; 7 per cent)	1.65	2.96	0.84
OPEX (A$/kL)	0.8	0.8	0.28
Levelised cost (A$/kL)	2.45	3.76	1.12
Unit energy cost (kWh/kL)	4.2	5.3	0.10

Source of desalination costs - SKM. MAR costs from section 3.4.

* cost information for seawater desalination was provided from actual Australian projects at 2007/08 prices. Scale efficiencies are negligible at this size, and the main difference in costs is due to differences in location and supporting infrastructure.

Using the mean results of the sample of ASR projects, the levelised unit costs were found to be between 30 per cent and 46 per cent of costs seawater desalination for capital, operating and total costs. Greenhouse gas emissions for ASR were found to be less than three per cent of those for seawater desalination per unit volume of water produced. An embodied energy analysis for capital works has not been undertaken but a similar figure is likely.

3.4 Breakdown of costs of urban ASR Projects

To provide an indication of the levelised costs of recovered water over the working life of ASR wells, wetland systems and distribution systems, an evaluation of costs was conducted at twelve ASR sites, nine in South Australia and three in Victoria.

Data were provided by consultants and project proponents. Eight of the South Australian ASR sites are operating and the other projects are in advanced stages of investigations that have allowed project construction and operation and maintenance costs to be calculated.
There was insufficient information from other types of MAR projects to give reliable indicative costs, with the exception of pond infiltration in rural areas as shown in section 3.5.

Information was provided in a form to allow levelised costs of recovered water to be determined using an assumed standardised working life of ASR wells, which is 15 years, wetland systems, with a standardised 25-year life, and distribution systems, with a 50-years life. A standard discount rate of seven per cent was applied for all data. For older projects the Reserve Bank of Australia consumer price index for goods and services was used to inflate capital costs to 2007/08 values prior to calculating cost recovery factors.

Information on aquifer type, source water type, well yield and designed annual recovery volume were recorded for these sites. Operational costs and issues identified during project establishment were also recorded. None of the sites had information on the land value consumed in providing a detention pond for stormwater capture. In each case the primary purposes of the wetland were to mitigate urban flooding and improve amenity value and hence land price of new subdivisions, with subsidiary benefits of improving the quality of stormwater prior to discharge to urban coastal waters. Producing a water supply via ASR was an additional benefit to which land value of the wetland was not ascribed as the land value increase of surrounding land more than compensated for the loss of saleable land (as described in section 6.2).

Twelve ASR sites were evaluated and had the characteristics shown in Table 6. The set of 'large stormwater sites' being in the range 75ML/yr to 2000ML/yr was used to give a breakdown of mean costs in order to reduce some of the scatter in data from reclaimed water sites. It also removed the cost distortion of expensive small scale stormwater projects which are more related to niche water supply markets and are likely to be only a small part of future urban bulk water supply MAR projects.

Table 6. Twelve ASR sites with a combined recharge capacity of 6330ML/yr were evaluated to identify establishment and operating costs and allow a consistent evaluation of levelised cost

Project size	mean	minimum	maximum	median
Annual recharge for all sites costed (ML/yr)	528	15	2740	210
Annual recharge for stormwater large sites* (ML/yr)	410	75	2000	210
Max injection rate per well for all sites costed (L/s)	13	3.5	40	10
Max injection rate per well for stormwater large sites* (L/s)	13	3.5	40	10

Aquifer type	limestone	fractured rock	alluvium
Number of sites	8	3	1
Number of stormwater large sites*	5	3	

Source water type	stormwater	reclaimed water
Number of sites	10	2
Number of stormwater large sites*	8	

* 8 sites using stormwater and sized between 75 and 2000 ML/yr reported in Table 7
Results of the evaluation which relate levelised costs to scale of project are shown in Figure 22. In general stormwater recharge projects larger than 75ML/year result in levelised costs of $1.12/kL. However in small scale projects, for example at 15ML/year, costs reach up to $3/kL.

The largest ASR project, supplying 2000 ML/yr of stormwater, had a levelised cost of $0.82/KL suggesting that increasing project size beyond 75ML/yr only marginally reduces unit cost. The expected inverse relationship between maximum recharge rate and cost was masked out by differences in relative availability of stormwater for recharge. The levelised costs for two reclaimed water ASR projects ranged from less than $0.45/kL to more than $3.00/kL. In the low-cost case, water treatment and distribution were already provided by an existing irrigation project, no additional detention storage was needed and water was continuously available for injection. The other case was for a proposed reclaimed water ASR project where the capital and operating costs of treatment and distribution were included and dominated project costs.

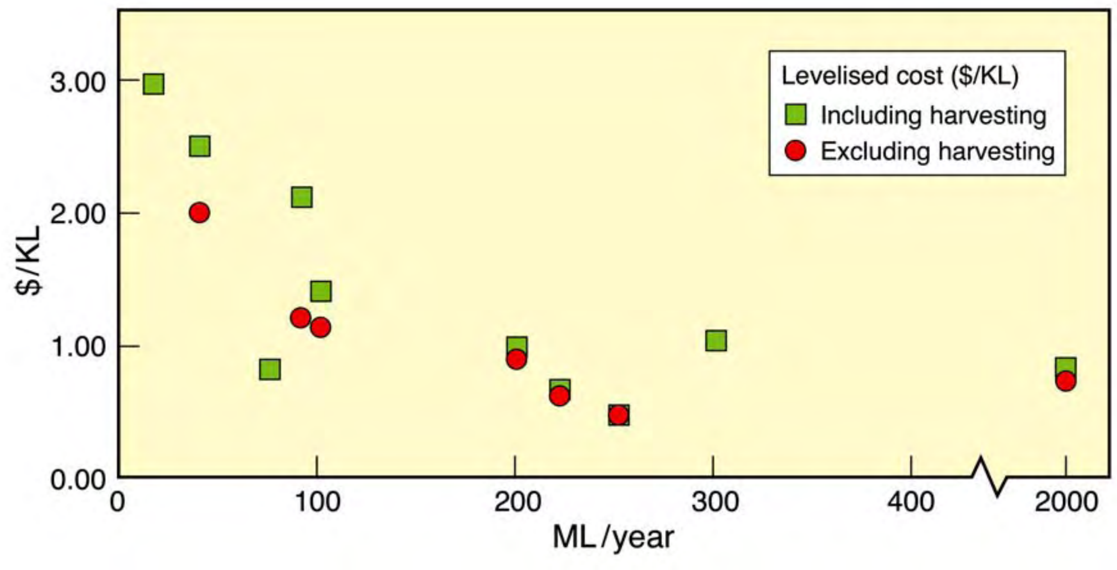


Figure 22. Levelised cost of water is shown in relation to the size of the stormwater ASR project. Economies of scale are observed between 15 and 75 ML/yr, and costs are relatively stable at larger volumes. Water harvesting costs (construction of wetlands and drain diversions) could not be separately identified at three sites. In all cases land cost is excluded. *(Sources of data were SKM, AGT and City of Salisbury)*

Cost breakdowns for urban stormwater ASR projects in the size range 75ML/yr to 2000ML/yr are summarised in Table 7. There were some variations in levelised cost between projects (as seen in Figure 22 above) and the distribution of costs among project components also varied significantly. For example, detention storage construction was the largest capital cost for some projects, but for others it was relatively small and across the projects averaged 25 per cent of the total levelised cost of water. Capital costs of stormwater ASR projects in the range 75-2000 ML/yr ranged from $4,100 to $10,000 per ML/yr, with the most expensive outlay being $8.2M for a 2000ML/yr project.

In all cases the proponent was the owner of the land on which detention storage was constructed and the land value had not been taken into account in water supply costs. However, wetland establishment can have large positive effects on adjacent real estate with consequences for local government income, as discussed in Chapter 6. In fact, land value increase can be one of the drivers for ASR projects.

Investigations costs averaged 11 per cent of water supply levelised costs and varied according to the complexity of the project.

Table 7. Mean levelised costs for components of urban stormwater ASR projects in the size range 75 to 2000 ML/yr.

Project component	Mean levelised cost (A$/kL)	Component cost as % of total cost	Number of sites with costs
Investigations	**0.12**	**11**	**7**
Capital costs of water harvesting	0.28	25	5
Capital costs of treatment, ASR, distribution	0.44	39	5
Total capital costs	**0.72**	**64**	**8**
Total initial costs (minus land)	**0.84**	**74**	**7**
Operation, maintenance and management	**0.28**	**26**	**8**
Total levelised cost minus water harvesting	**0.84**	**75**	**5**
Total levelised cost (minus land)	**1.12**	**100**	**8**

3.5. Costs of rural infiltration basins

For other forms of MAR, such as infiltration ponds and soil aquifer treatment, that are practised in rural settings it is expected that costs would be substantially lower than the ASR costs above. For example, in the Burdekin Delta, two infiltration basins that recharge a total of 5000ML/yr were constructed in the 1970s at current equivalent capital costs of $2.1M and current operation and maintenance costs of $85,000 per year. Levelised costs incurred by North Burdekin Water Board, using 7% discount rate and estimated asset lives, are 5c/kL recharged. Estimated costs to irrigators for pumping from high yielding pumps with low lifts is 2c/kL so that the whole recharge and recovery system cost is 7c/kL.

The unit cost of recharge depends strongly on the infiltration rate in the basins, and rates vary between basins and depend on permeability of the soil and the depth of the watertable. For example in a pit with half the infiltration rate the cost per kilolitre would be approximately double.

3.6. MAR costs in relation to prices of rural and urban water supplies

In relation to prices currently paid for agricultural irrigation water, costs of ASR, which average $1.12/kL, and pond filtration, as low as $0.07/kL, suggest that ASR is not likely to be a viable supply for irrigation supplies.

However, if aquifers are unconfined, water tables are low enough to allow storage, soils are permeable, land is available, and there is an entitlement to take water from the river catchment, then basin infiltration may be possible. With most urban water prices in the range $1.20-1.80/kL in 2008, both forms of recharge may be possible in urban areas but ASR would be preferred where land value is high and open space is at a premium.

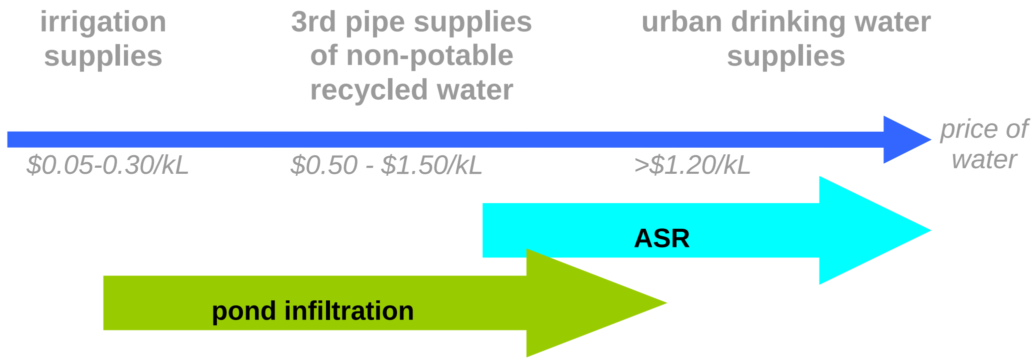


Figure 23. Cost scale of MAR in relation to typical costs of water supplies for irrigation, non-potable and drinking water supplies

3.7. Other costs and benefits of MAR

In Chapter 2 other benefits of MAR projects in urban areas were discussed. Calculating those benefits in dollar terms relies on the formation of markets or government intervention.

These may include:

- impact on coastal water quality - where there is a market for pollution abatement (eg Melbourne Water imposes a charge per kilogram of nitrogen in stormwater discharged to Port Phillip Bay, encouraging investment in stormwater pollution mitigation initiatives).
- impact on urban flooding - where insurance premiums could be reduced by investment in flood mitigation programs that may include water sensitive urban design and water detention features that feed MAR projects
- amenity value of having water features such as wetlands and irrigated parks in a subdivision - these directly affect real estate price in new subdivisions and land value in existing residential areas that influence council rates and in some areas water rates.
- protection against aquifer depletion and salinisation - may be recognised in the differences in the volume, quality and value of sustainable future groundwater extraction and use for situations with and without protection by a MAR operation. These scenarios may be forecast by groundwater modelling.
- greenhouse gas emissions - a national carbon trading market is currently being established.
- deferment of asset replacement or augmentation costs for stormwater and drinking water infrastructure as a result of MAR operations - based on asset management modelling with and without MAR.

4. How to establish a MAR project

Potential proponents need to know first whether they have the five essential elements of a MAR project outlined below before proceeding further. These lead first to questions on entitlements to water and then to entry level investigations concerning water quality. If the project looks potentially viable at this the first stage, the Draft MAR Guidelines (EPHC, 2008) lead proponents through the investigations (Stage 2) and commissioning trials (Stage 3) to an operational project (Stage 4). This section follows the sequence for a Stage 1 assessment to determine whether MAR is an option and its degree of difficulty. This precedes consideration of economic, social and environmental factors that would be considered in project selection decisions.

4.1. Five essential ingredients

The five critical elements for a successful MAR project are:

- a sufficient demand for recovered water
- an adequate source of water for recharge
- a suitable aquifer in which to store and recover the water
- sufficient land to harvest and treat water
- capability to effectively manage a project

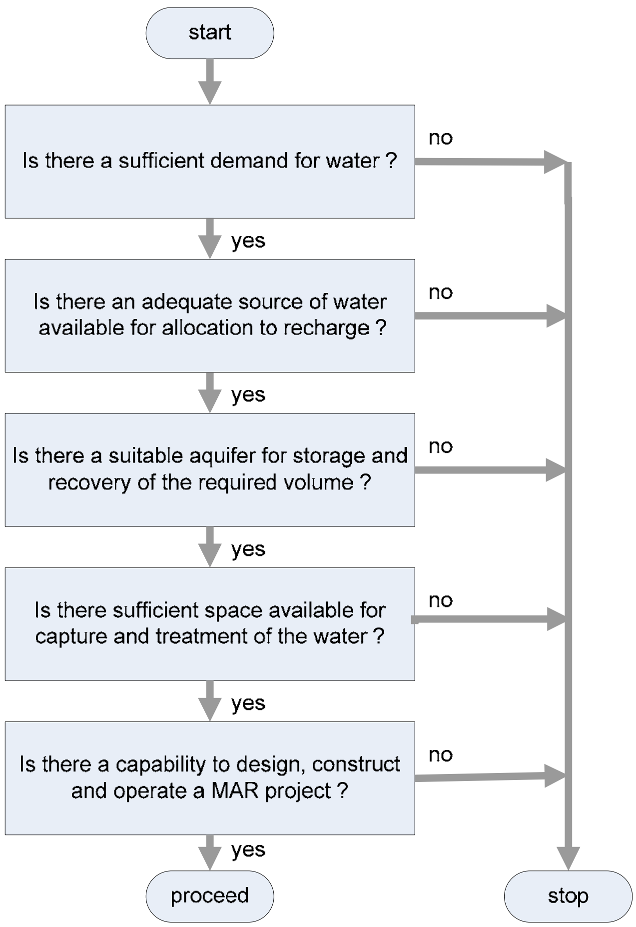


Figure 24. A checklist for considering whether to undertake a managed aquifer recharge project. Further details are given in the entry level assessment found in the Draft Guidelines for Managed Aquifer Recharge (Part of Stage 1, Figure 25).

Demand: The volumetric demand for recovered water (within an economic scale) or a clearly defined environmental benefit of recharge is essential for MAR. The purposes for which water will be recovered also need to be defined (Figure 4). Generally this will provide the revenue stream to pay for the water supply cost elements of the project. In urban areas demand for stormwater detention for mitigating floods, improving coastal or receiving water quality and enhancing urban amenity and land value may also contribute revenue streams for MAR projects. For reclaimed water projects the decline in discharge of treated effluent to sea may provide a motivation for investment in MAR.

Source: Entitlement to water to be used for recharge needs to be secured. Mean annual volume of recharge should exceed mean annual demand with sufficient excesses to build up a buffer storage to meet reliability and quality requirements. In an over-allocated catchment it is unlikely that an entitlement to surface water would be available.

Aquifer: A suitable aquifer is critical for MAR. It needs to have an adequate rate of recharge, sufficient storage capacity and be capable of retaining the water where it can be recovered. Low salinity and marginally brackish aquifers are preferred so that mixing with fresh recharge water should still allow recovered water to be fit for use. Maps of MAR opportunity will assist in determining likelihood of one or more suitable aquifers being present at the proposed site.

Detention Storage: There should be open space, or dams, wetlands, ponds or basins to detain sufficient water without causing flood damage to enable the target volume of recharge to be achieved. Similarly there needs to be space available for whatever treatment process, if any, is subsequently determined to be required. In established urban areas space for capture can be a major impediment to stormwater water harvesting and ASR wells are commonly used to avoid land requirements of infiltration systems. For recycled water from a sewage treatment plant generally no additional detention storage will be required at the recharge facility.

Management capability: Hydrogeological and geotechnical knowledge, as well as knowledge on water storage and treatment design, water quality management, water sensitive urban design, hydrology and modelling, monitoring and reporting are all required to meet governance requirements. Such expertise will be required from Stage 2 and a growing number of consultants are experienced in investigations and design of MAR projects.

4.2. Identify the degree of difficulty

The Draft MAR Guidelines (EPHC, 2008) give a further checklist to inform proponents of the degree of difficulty of their conceived project. This serves as a guide to the amount of effort required in project investigations and commissioning trials in order to manage human health and environmental risks in accordance with the National Water Quality Management Strategy.

Basic questions in this checklist address the water quality of the source water in relation to environmental values of the aquifer, of intended uses of recovered water, the potential for clogging and potential for mineral reactions. They ask about groundwater quality in relation to recovered water uses, and whether groundwater needs to be protected for drinking supplies or high conservation ecological values, or is highly saline. They also ask whether there are nearby groundwater users or ecosystems, if the aquifer is confined or artesian, fractured or cavernous, if there are similar projects with similar source water in the same aquifer and whether the project is likely to create attention under local planning or development regulations.

Costs of MAR investigations and trials are not trivial and, having completed this checklist, the proponent should know whether their proposed project has a low or high degree of difficulty and the types of information which will be of most value in the investigation stage. Because of the costs of these investigations it is normal to first seek assurance that at least the core approvals for MAR are likely to be obtained, before investing in such investigations, noting that some approvals will not be possible until after the investigation stage.

4.3. Approvals required

Currently there is no unified process for MAR project approvals in any Australian state or territory. Approvals that may be needed include:

- an entitlement to a share of the source water, such as stormwater, reclaimed water or other source, taking account of environmental flows and other users of the source water
- a permit to construct wells for investigations, ASR or recovery
- planning approval for a water impoundment, covering geotechnical safety, amenity, insect and pest nuisance and danger of drowning
- a declaration of environmental values of an aquifer, accounting for ambient groundwater quality and current uses
- approval to recharge water to an aquifer, to protect an aquifer's environmental values, prevent excessive changes in the hydraulic head, and to protect human health and the environment as a result of the recovery of stored water for intended uses.
- an entitlement to a share of the aquifer storage space, recognising that this is finite, and may be smaller than the harvestable volume of source water
- an entitlement to recover water from an aquifer, possibly as a proportion of the cumulative recharge that may depend on the degree to which the aquifer is over-exploited and will take account of other groundwater users and water bankers so as not to cause them adverse impacts
- transfer of water entitlement, endowing the recharger with an ability to transfer their entitlement to a third party, subject to hydrogeological constraints and not into locations where piezometric heads are already depressed
- a permit for the use of recovered water, to ensure that usage conforms with catchment management plans and that the water quality is fit for intended uses

Clearly each jurisdiction would benefit from having a coordinated approval process, and initiating demonstration projects would help to establish a flow chart for MAR approvals. Draft MAR Guidelines provide a common framework recommending that entitlement issues are addressed first before dealing with environmental and human health risk management.

Responsible agencies

Water resources management authorities at state and/or regional level are normally responsible for water quantity entitlements; environment protection agencies are normally responsible for water quality and approvals to recharge; local government is responsible for planning and development approvals; health commissions are responsible for permits for use; and water utilities will also be involved if reclaimed water is a source or their drinking water mains or non-potable supply mains are used to distribute recovered water.

In some jurisdictions there are also state planning departments, plumbing industry commissions, stormwater management authorities and collectives of local governments in a catchment that will also have a consultative role in decision making. A regulatory review of MAR in Australia and elsewhere summarised the relevant acts and regulations in each state in 2006 (Lumb, 2006).

Approval times of six months to 22 months for MAR projects have been reported to be a deterrent. Mostly this related to approval to recharge water to an aquifer. It is anticipated that the approval process could be accelerated following the release of the draft MAR Guidelines, and that each jurisdiction would find ways to harmonise the approval processes for each permit and entitlement required.

In South Australia, the Natural Resources Management Act 2004 empowers NRM Boards to produce regional Water Allocation Plans that are developed in consultation with the community and address water allocation criteria, transfer criteria, protected environmental values for aquifers, and water affecting activities, including MAR, use of imported water or effluent, and well construction. This offers the beginning of a model pathway for integrated approval processes to encourage aquifer recharge and water reuse:

- having consideration for current and future extraction patterns
- ensuring MAR activities do not impinge on each other
- enhancing long term sustainability of supplies, and
- protecting and improving the groundwater quality.

A proposed policy framework is identified later for regulators considering policy changes in sympathy with the National Water Initiative reform agenda.

4.4. Next steps

Assuming that the entry level assessment (stage 1) indicates that the project is potentially viable, the degree of difficulty does not deter the proponent, and regulators have not identified other impediments, the next stage is to undertake investigations on source water, pre-treatment methods and the aquifer to determine if the project will demonstrably protect human health and the environment, notably the aquifer.

Stage 1 was a rapid qualitative assessment but Stage 2 is quantitative, using existing information supplemented by site-specific investigations that were foreshadowed in Stage 1. Information to confirm that the project is operating as intended will not be available until commissioning of a pilot project, or the full-scale project after it is constructed. A staged approach to project development helps avoid wasting time and money, and can improve the design of the project by tailoring it to the aquifer. It also allows investment appropriate to the MAR project in relation to alternative or complementary projects.

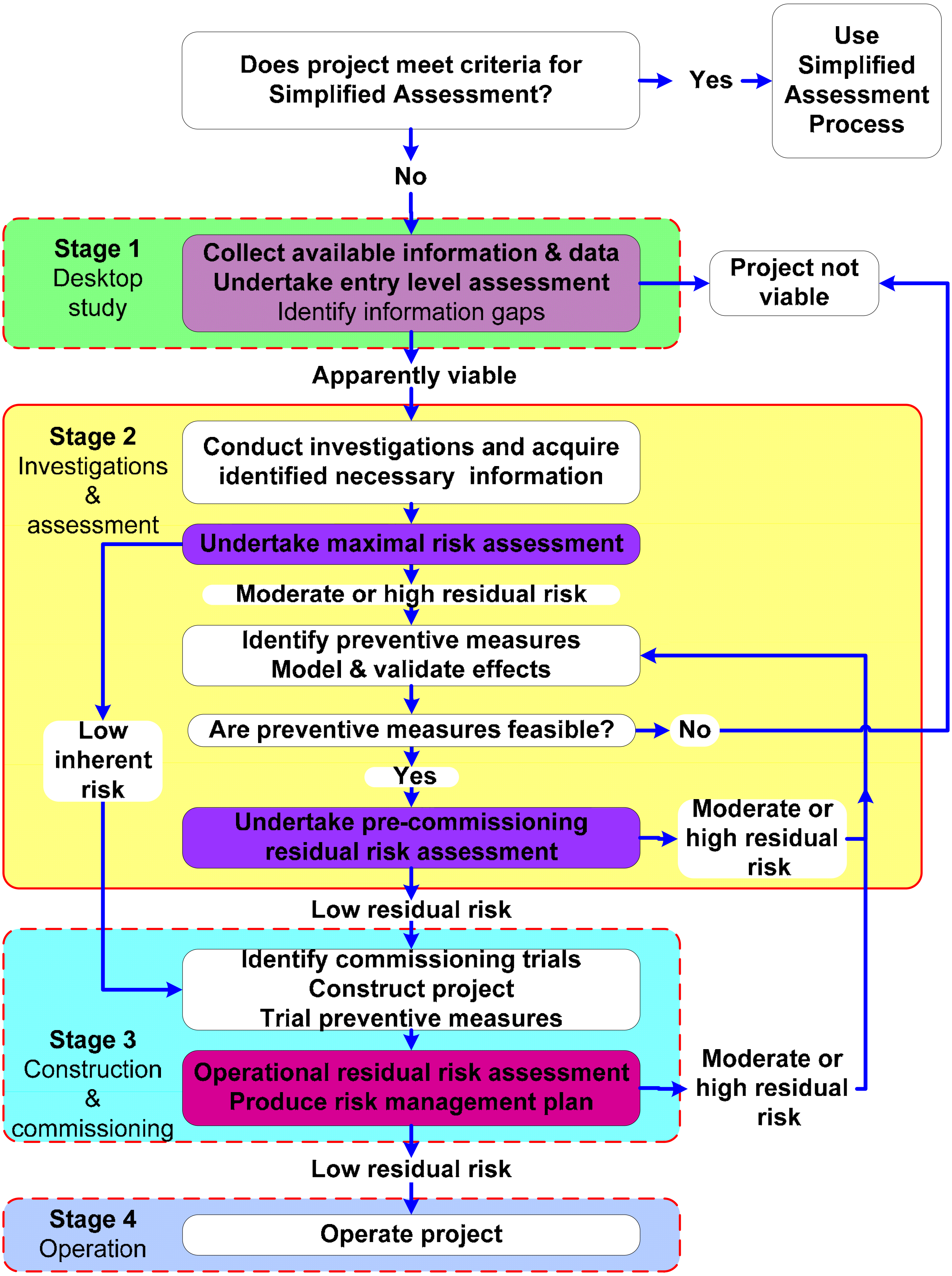


Figure 25. Stages in establishing a MAR project to meet human health and environmental needs in accordance with MAR Guidelines (EPHC, 2008) (*Source:* Peter Newland, SA EPA)

Stage 2 investigations enable risks to be assessed and the preventative measures by which they can be managed to be indentified. All 12 elements of the risk management framework quality need to be addressed. (Chapter 5 provides more detail for regulators) This requires information describing the source water quality, infrastructure and proposed operations of the project, and characterisation of the hydrogeology to demonstrate that all hazards have been addressed with sufficient supporting information for a management plan. Where further information is needed, a pilot project might be required. Stage 2 investigations result in a management plan showing how human and environmental health risks can be effectively managed in advancing to a Stage 3 trial. Often stage 2 will involve drilling one or more wells, and an aquifer test by pumping to determine aquifer properties and groundwater quality, and help identify pre-treatment needed before recharge.

At this point the risks of success will be better defined and a decision would be made on whether to invest in constructing the MAR project or in alternative water supplies. Such a decision would account for the full range of costs and benefits of all projects (as per section 3.7).

For many MAR projects the level of some risks cannot be known before implementation accompanied by suitable monitoring. Known as commissioning trials, Stage 3 monitoring provides a basis for validating assumptions and verifying operational performance of the MAR scheme. It also provides for the development of management plans for the ongoing operation of the project, Stage 4, which will require ongoing monitoring to ensure that risks to human health and environmental health are controlled.

The Guidelines for MAR, which are outlined in the next chapter, expand on the hazards to be assessed, investigation methods available, the methods and criteria used for each type of risk assessment, and preventative measures that can be used to reduce risks. Normally water quality and hydrogeological expertise will be needed to undertake these investigations and assessments with reporting to the relevant state government authority to obtain approval for Stages 3 and 4. That authority should also be approached at Stages 1 and 2 for advice on existing information, local experience and any other issues that need considering at the proposed MAR site. A table of the relevant departmental contact points in each state and territory to address queries on MAR is given at the following web address: http://www.ephc.gov.au/ephc/water_recycling.html

For small, simple projects with inherently low risks the guidelines also provide a simplified assessment process. The criteria for projects that may use this pathway are contained in the draft guidelines.

5. MAR considerations for regulators

5.1. Challenges for regulators

MAR may pose some challenging issues for regulators due to the range of considerations required. Water quantity and quality issues for both surface water and groundwater generally need to be addressed for any MAR project. This section canvases the issues presented by MAR and its potential for addressing over-allocated aquifers. Subsequently section 5.2 focuses on issues for water resources planning and regulation (the left hand side of Table 8) and section 5.3 addresses protection of human health and the environment (right hand side of Table 8).

It is recommended that the basic water access entitlement and planning regulation issues be addressed before considering water quality. Water allocation decisions will generally be based on existing information set within the context of the whole water catchment and aquifer system, and on the proposed volumes of recharge and recovery. These either result in a decision to proceed to the next step or that the proposed project is unviable, as shown in figure 24.

Table 8. Water resources management and environmental protection issues to be addressed in establishing MAR projects.

Attribute	**Quantity** **(not part of MAR guidelines)**	**Quality** **(addressed in MAR guidelines)**
Management Issue **Resource**	**Water and Storage Allocation and Entitlements**	**Human Health and Environment Protection**
Surface water	• Environmental flow requirements • Water allocation plans and surface water entitlements • Inter-jurisdictional agreements	• Catchment pollution control plan (see Stormwater Guidelines, AGWR Phase 2B and Appendix 3 of AGWR Phase 1) • Water quality requirements for intended uses of recovered water (see AGWR Phase 1 or Augmentation of Drinking Water Supplies, AGWR Phase 2A) • Risk management plan for water quality assurance (see AGWR Phase 1)
Groundwater	• Groundwater allocation plan and groundwater entitlements • Resource assessment accounting for groundwater-dependent ecosystems • Demand management • Allocatable capacity and entitlement for additional storage in the aquifer • Inter-jurisdictional agreements	Groundwater quality protection plan for recharged aquifer in accordance with Groundwater Protection Guidelines (NWQMS, 1995) • Water quality requirements for intended uses of groundwater (Water Quality Guidelines for Fresh and Marine Waters, 2000, AGWR Phase 1 or Augmentation of Drinking Water Supplies, AGWR Phase 2A). • Risk management plan for water quality assurance beyond attenuation zone, accounting for aquifer biogeochemical processes

Water quality evaluations will require more exact localised information on aquifer properties and source water quality, some of which is likely to require site-specific investigations and hence will take time and expense.   This explains the prime importance of the viability assessment of the Draft MAR Guidelines (EPHC, 2008).

In many arid areas, groundwater storage is large but natural recharge is small. When groundwater abstraction exceeds recharge, water levels drop, pumping costs increase, wells run dry, production fails, and there is economic hardship, a decline in groundwater dependent ecosystems, and social disruption. In some locations stream base flow stops, riparian vegetation dies, aquifers become saline and land subsides. The two choices for this scenario are reducing demand and/or increasing supply. Recharge enhancement used as part of integrated groundwater and water resources management strategies can contribute to both aspects.

Where there is a reduction in natural recharge due to climate change, MAR can be an effective strategy to maintain the hydrologic equilibrium. However it is only likely to be successful if demand does not already exceed historical recharge.

MAR may enable a groundwater balance to be reached with less severe demand reduction than otherwise would be required. By introducing groundwater pricing and monitoring groundwater use, communities can generate resources to invest in demand management, such as improving irrigation efficiency, or in MAR, whichever is more cost-effective. As an example, in the early 1950's the Orange County Water District in southern California, instituted a "*groundwater replenishment assessment"* (a levy on groundwater use) that paid for MAR operations that protected a coastal basin suffering from saline intrusion (Mills, 2002). Since then more than 7,000GL have been recharged with on average 270GL/yr recharged from MAR operations from three sources and this basin now sustainably supports extractions of 470 GL/yr. A competent representative entity, such as a government authority, groundwater users association or irrigation association, is needed if MAR is to be implemented as part of effective groundwater management in any basin.

5.2 Water resources planning and regulation

All Australian states and territories have water resources management policies and legislation that require water access entitlements and have introduce mechanisms for allocating water resources between different water uses and the environment. They also have regulations on licensing of drillers, issuing entitlements to extract groundwater, and some have experience in reducing allocations where entitlements exceed sustainable supply capacity of an aquifer system. However few have integrated policies or regulations concerning managed aquifer recharge, for example licensing of MAR operators, and issuing entitlements with conditions and protections to operators for storing and recovering water using aquifers.

In most urban areas groundwater abstraction for domestic use is unmanaged (and even exempted from caps on other water uses), yet where this is a viable source of supply, and exacerbated by urban mains water restrictions, groundwater abstraction generally exceeds recharge and watertable levels are in decline. Managing recharge in an aquifer where abstraction is unmanaged provides no assurance that groundwater level or pressure objectives can be achieved.

Regulation of a legion of users and rechargers of small volumes of groundwater is highly inefficient and difficult. New instruments need to be found to simplify management. This could involve methods to engender collective responsibility to prevent groundwater depletion, high water tables and pollution and to encourage awareness, monitoring and consolidated reporting. Groundwater users' associations are one vehicle to democratise groundwater management where government agencies have been ineffective alone, and could become the urban equivalent of the land-care movement, relying on volunteers to strengthen government technical and administrative roles. Standardised approvals for new wells requiring offsetting rainwater MAR operations could also help to restore groundwater equilibrium.

More severely, in those rural source water catchments where demand exceeds supply and environmental flow requirements have been established but are not being achieved, establishment of MAR projects would inevitably lead to accelerated environmental degradation by reducing downstream flows. A possible exception is where introduction of MAR would reduce total diversions and evaporation losses from off-stream surface storages and it could be clearly demonstrated that MAR would increase environmental flows.

In most urban and peri-urban areas, where impervious surfaces have increased runoff, entitlements to stormwater and reclaimed water are unclear. This may impede long term strategic investment in water recycling via aquifers. In expanding cities of the Murray Basin, that are diverting more water from streams, developers are seeking to gain rights to harvest increases in runoff for recharge and localised reuse. The development, retention and use of these "new" sources for MAR interceptions may further subtract from contributory flows to river systems which are already severely depleted. Hence the costs of reduced downstream consumptive allocations and environmental flows, accentuated in times of historically low inflows, may outweigh the benefits of reduced evaporation losses and additional storage attributable to MAR. By introducing water entitlements that are clearly defined, communicated and implemented, MAR has the potential to minimise environmental harm and even provide environmental benefits while improving overall system integrity and management.

End uses of recovered water also need consideration, as otherwise all aquifer storage capacity may be allocated to commercial projects aimed at withdrawing most water in the year following recharge. Greater community benefit may be derived by strategically storing some water to be available as drought and emergency supplies when other resources are depleted. Allocation of storage in relation to use, conditions on uses of recovered water, or scarcity pricing mechanisms are possible ways to maximise the value of both recharged water and of aquifers. This will need to recognise the quality of water on recovery and its suitability for the required uses, and in turn, this will depend on the properties of the aquifer and the quality of recharged water.

A possible framework for regulation of MAR in urban and rural areas, consistent with the national water reform agenda is outlined below for consideration by water resources managers. This follows the principles of robust separation of entitlements and allocations that have been successful in guiding rural water reform.

Governance of MAR might be typified by clearly defined separate entitlements:

> Robust separation in the Australian context, articulates a property right regime that facilitates secure, economically efficient and low cost trading and administration through time (Young and McColl, 2003a,b). Investigation of the impacts of unbundling urban water rights on a MAR industry would inform the policy options regulators face in a timely and relevant way.

- to take source water
- to store water in an aquifer
- to recover water from an aquifer, and
- to use recovered water.

Robust separation of property rights forms the foundation of the NWI market architecture. This involves a three-tiered system to allocate volumes of water efficiently over time.

Under the NWI (Clause 36-40):

1. Statutory water allocation plans are to be prepared for surface water and groundwater management units, describing how the water resource is to be shared between competing water users;
2. In developing plans, the settling of trade-offs between competing outcomes will involve judgments informed by best available science, socio-economic analysis and community input;

3. Water allocation plans are to provide for secure ecological outcomes by describing environmental and other public benefit outcomes, and by defining the appropriate water operational rules (such as the non-consumptive pool) to achieve those outcomes;
4. Water allocation plans are to provide resource security for consumptive purposes (e.g. irrigation, stock and domestic) by determining the water allocation shares for each water user in the consumptive pool, and the rules for allocating and trading water access entitlements during the life of the plan;
5. Water allocation plans also define the objectives for the use of water.

Hence water entitlements, allocations and use obligations can be managed separately and independently.

Combining these two broad concepts, separation of instruments and separation of elements, into a unified framework suggests a potentially flexible and systematic governance arrangement for MAR (Table 9).

Aquifer characteristics may determine entitlements to store as well as recover and the spatial extent of transferability of entitlements. For example on the Northern Adelaide Plains in South Australia, an over-allocated groundwater system, rechargers have typically been granted unlimited entitlements to recharge and entitlements to recover typically 80% of the cumulative volume injected. Rights of transfer of recharge credits can only be exercised in an up-gradient direction, so as not to superimpose additional withdrawal within an existing cone of depression. The 80% figure was selected on the basis that it was a typical recovery efficiency in the brackish sections of the aquifer where ASR is practised. That is 80% of the volume recharged could be recovered at a salinity acceptable for the intended irrigation use, and assigning a higher percentage would not have resulted in increased benefit to the recharge operator. The remaining 20% was considered to be of environmental benefit in reducing overdraft in the aquifer. However one license has been issued to allow a transfer of this remaining 20% recovery to a saline well which is used to top up an urban lake at Mawson Lakes over summer. The residual environmental benefit is considered to be the net freshening of the aquifer due to the average salinity of injectant being lower than that of recovered water and the net addition of water closer to the cone of depression.

Table 9: A possible policy framework based on robust separation of water rights for discrete elements of a MAR system.

Governance instrument:	MAR component			
	Water capture and harvesting	**Recharge**	**Recovery**	**Use**
Entitlement	Unit share in stormwater or effluent consumptive pool, (*ie*. excess to environmental requirements)	Unit share of aquifer's finite storage capacity	(Tradeable) extraction share a function of managed recharge.	
Periodic allocation	Periodic (usually annual) allocation rules based on a water plan. Potential for additional stormwater or effluent offsets	Annual right to raise the water table subject to ambient rainfall and total abstraction	Extraction volume contingent on ambient conditions, natural recharge and spatial constraints	
Obligations and conditions	3rd party rights of access to infrastructure for stormwater and sewage	Requirement not to interfere with entitlements of other water users and water bankers	Existing licence may need to be converted to compatible entitlement to extract (unit share).	Water use licence subject to regional obligations and conditions, for use and disposal

Australian institutional arrangements for governing urban water supplies impede the effective and efficient development of an active and sustainable MAR industry. The absence of well-defined entitlements to access stormwater, recycled water, and aquifer storage could create consequential impediments to the development of ASR, leading to ill-defined rights of water bankers, future legal disputes and potential detrimental impacts on receiving waters or groundwater dependent ecosystems. (Radcliffe, 2004, Hatton McDonald and Dyack, 2003 and ACIL Tasman, 2005). Decision makers have information to effectively manage MAR according to either regulation or market approaches.

Rural water reform provides examples of effective governance of MAR. The Angas-Bremer Basin Prescribed Wells Area is a rural area where MAR was managed with tradeable entitlements and allocations. This may provide a governance model to guide development of MAR in urban areas.

5.3. Health and environmental protection

The National Water Quality Management Strategy (NWQMS) provides the framework for guiding MAR projects so they protect human and environmental health. The MAR Guidelines form part of the water recycling guidelines and in conjunction with other guidelines address all sources of water, all methods of recharge and all end uses
(as per Figs 2-4).

The water recycling guidelines: managing health and environmental risks (Phase 1, 2006) and the Drinking Water guidelines (2004) provide the risk assessment framework on which are built the phase 2 Water recycling guidelines (Augmentation of drinking water supplies, Stormwater harvesting and reuse, and Managed aquifer recharge (Fig 22). The MAR guidelines embrace reclaimed water, stormwater, drinking water and water from other surface water or groundwater sources.

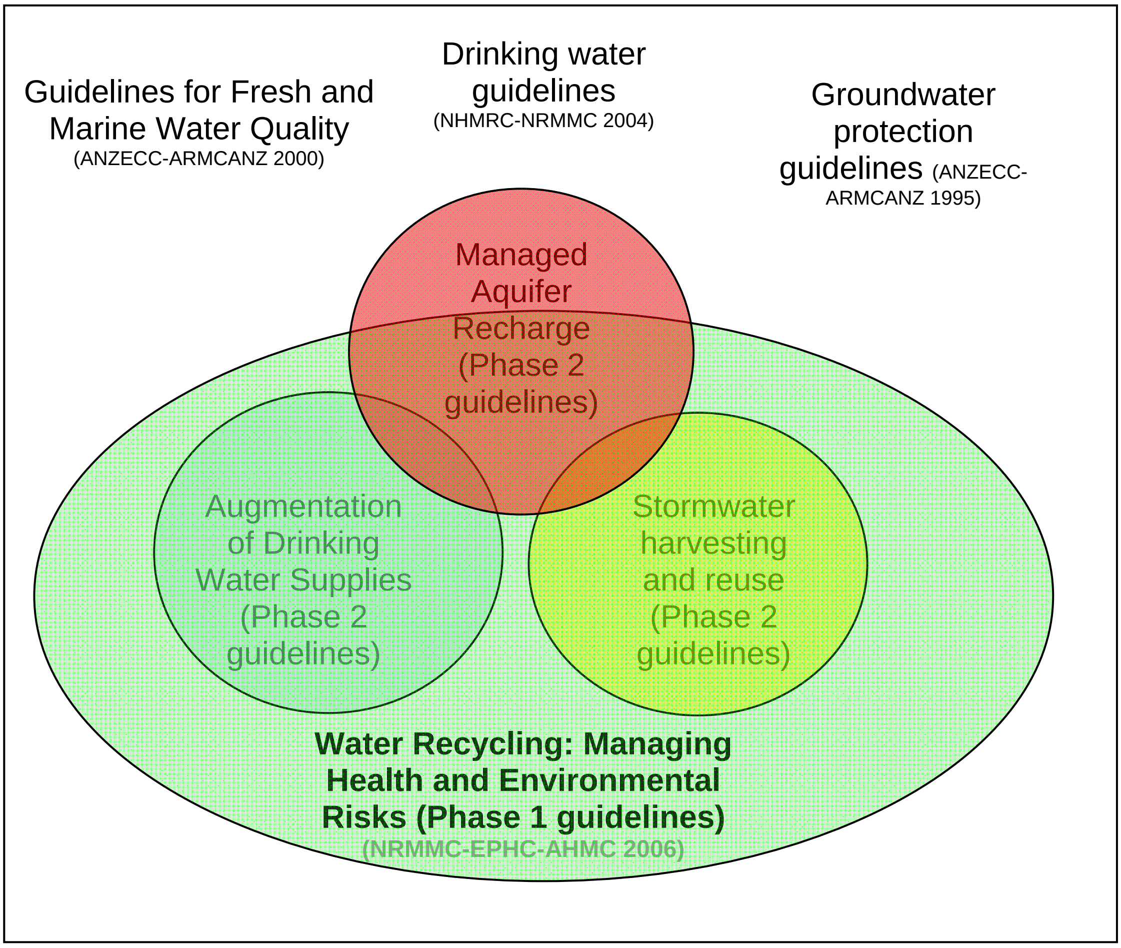


Figure 26. Relationship between MAR guidelines and the other guidelines for water recycling within the broader framework of National Water Quality Management Strategy guidelines. Note that MAR guidelines may also be used for recharge of water not considered to be recycled.

For stormwater MAR the stormwater guidelines provide hazard concentrations that should be adopted in the absence of local data on quality of source water. The augmentation of drinking water supplies guidelines provide the risk assessment process to follow if source water is recycled water and recovered water is for drinking water supplies. The Phase 1 water recycling guidelines provide the procedures to address human health and environmental risks. Guidelines for fresh and marine water quality (2000) provide the values of water quality parameters required to satisfy specified environmental values for surface water and groundwater bodies. The drinking water guidelines provide equivalent values for drinking water supplies, but focus on a systematic pro-active risk management approach to ensure that water quality always meets these values. The groundwater guidelines require that environmental values for aquifers are established taking account of ambient water quality and a public consultation process.

The risk management framework used in the MAR guidelines comprises 12 elements that fall into four main categories:

- commitment to responsible use and management of recycled water
- MAR system analysis and management, such as risk assessment and a series of preventative measures
- supporting requirements, such as employee training, community involvement, research and development, validation, and documentation and reporting systems; and
- review, including evaluation and audit processes.

All 12 elements need to be implemented for the risk management approach to be successful.

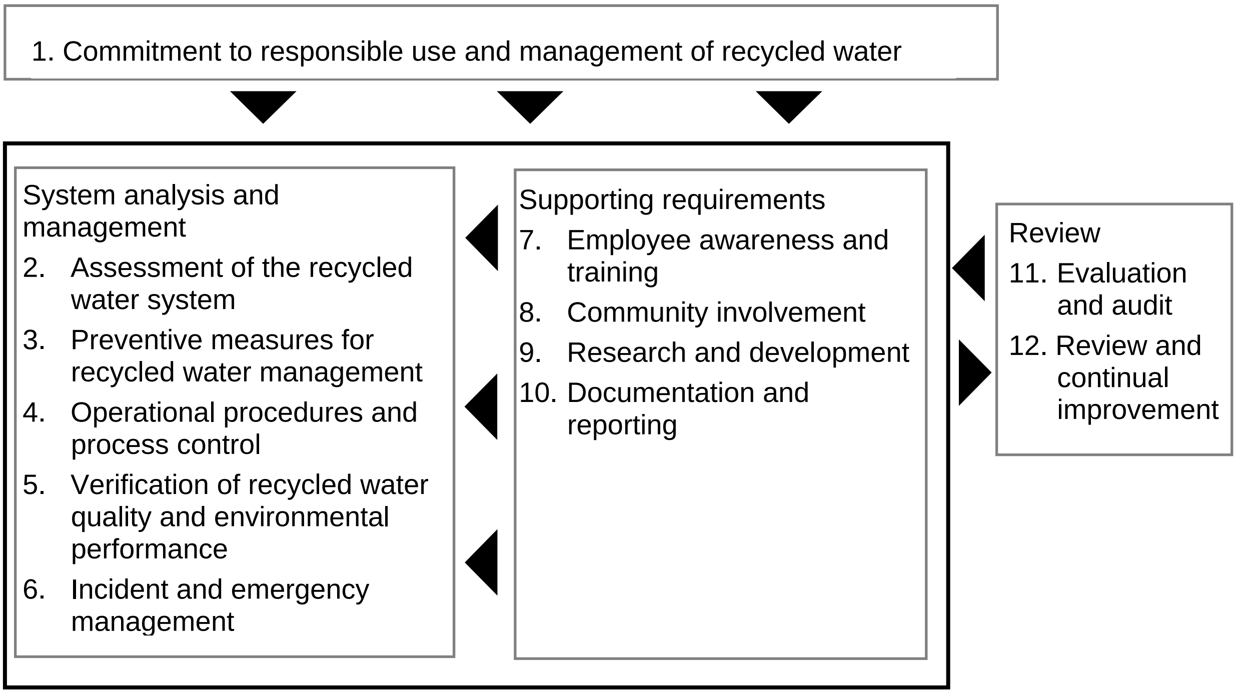


Figure 27. Elements of the framework for managing water quality and use (EPHC, 2008).

The MAR guidelines specifically aim to protect the environmental values of all intended uses of recovered water and of the aquifer beyond a transient attenuation zone, and to prevent adverse impacts. This is done by assessing potential hazards and the risks associated with each, and identifying preventive measures to manage the risks.
The hazards addressed in the guidelines are:

1. Pathogens
2. Inorganic chemicals
3. Salinity and sodicity
4. Nutrients

5. Organic chemicals
6. Turbidity/particulates
7. Radionuclides
8. Pressure, flow rates, volumes and levels
9. Contaminant migration in fractured rock and karstic aquifers
10. Aquifer dissolution and aquitard and well stability
11. Impacts on groundwater dependent ecosystems
12. Greenhouse gas emissions

For each hazard the guidelines document sources or causes, the effect on public health and environment, how it can be managed, including preventive measures, the proposed validation, verification and operational monitoring, and list the acceptance criteria for the various stages of risk assessment (Fig 25).

A simplistic view that treating water to near drinking standards before recharge will protect the aquifer and recovered water is incorrect. For example chlorination, to remove pathogens that would be removed in the aquifer anyway, can result in water recovered from some aquifers containing excessive chloroform. In some locations, drinking water injected into potable aquifers has resulted in excessive arsenic concentrations on recovery due to reactions between injected water and pyrite containing arsenic. Source water that has been desalinated to a high purity dissolves more minerals within the aquifer than water that has been less treated. Hence the MAR guidelines adopt a scientific approach that takes account of three ways that aquifers interact with recharged water:

1. Sustainable hazard removal - the guidelines allow for pathogen inactivation, and biodegradation of some organic contaminants during the residence time of recharged water in the soil and/or aquifer within an attenuation zone of finite size,
2. Ineffective hazard removal - these hazards need to be removed prior to recharge because they are either not removed (eg salinity) or removal is unsustainable (eg adsorption of any metals and organics that are not subsequently biodegraded, or excessive nutrients or suspended solids),
3. New hazards introduced by aquifer interaction (eg metal mobilization, hydrogen sulphide, salinity, sodicity, hardness, or radionuclides) - there is a need to change the quality of recharge water to avoid these (eg change acidity-alkalinity, reduction-oxidation status or reduce nutrients).

The response of an aquifer to any water quality hazard depends on specific conditions within the aquifer, including temperature, presence of oxygen, nitrate, organic carbon and other nutrients and minerals, and prior exposure to the hazard. The guideline indicates the state of current knowledge on attenuation rates of pathogens and organic compounds under a range of conditions, and provides for new local knowledge to be taken into account in assessing risks and determining sizes of attenuation zones and siting of monitoring wells.

In most aquifers, and with appropriate pretreatment of water to be recharged, the attenuation zone will be small and generally of the order of 20 to 200m from the recharge area or well. (See Fig 28.) Water that travels further has had sufficient residence time in the aquifer for attenuation of pathogens and contaminants to below the relevant guideline values for native groundwater and intended uses of recovered water.

The zone of aquifer in which water quality may be measurably affected by MAR may be larger, but in this outer domain the water quality should continuously satisfy the initial environmental values of the aquifer (Fig 28). The effects of MAR operations on hydraulic heads (pressures) may be measurable over a much larger area, especially in confined aquifers. If the aquifer is originally too saline for the uses of recovered water, a storage zone can be identified that contains water which, when recovered, is fit for its intended use (Fig 28).

The dotted line in Fig 28 marks the outer boundary of the attenuation zone. This represents the maximum separation distance between the MAR recharge structure and well(s) for verification monitoring to ensure that the ambient groundwater quality is protected. As the attenuation zone is defined only for enduring attenuation processes, on cessation of the MAR operation this will shrink and disappear as ultimately the whole aquifer will meet all its initial environmental values. Attenuation rates under various aquifer conditions are summarised in Appendices of the Guidelines and will be supplemented on the MAR guidelines website with further attenuation rates to be provided by studies designed to fill major gaps.

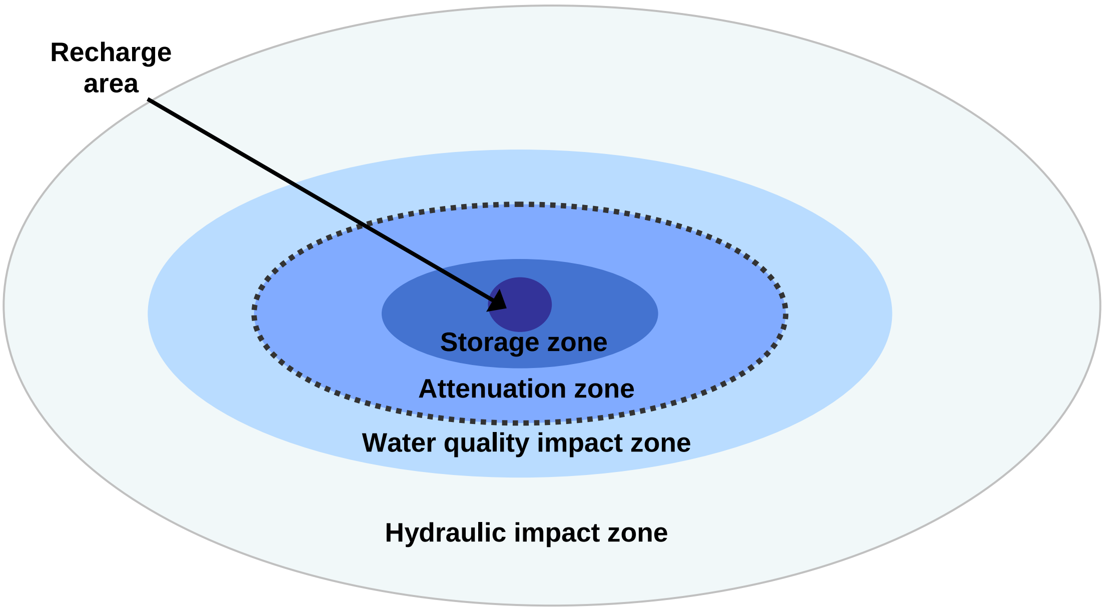


Figure 28. Schematic showing zones of influence of a MAR operation.

Guidance on other hazards such as excessive flow rates and pressures is aimed at protecting against high water tables and nuisance discharges of MAR projects in unconfined aquifers and against bursting of aquitards (confining layers capping confined aquifers).

The guidelines (in Chapter 6) also advise on the following MAR operational issues:

1. Clogging (which in low permeability aquifers can be a tighter constraint on quality of recharge water than health and environmental protection requirements)
2. Recovery efficiency (proportion of recharged water that can be recovered at a quality fit for its intended uses, which may be a constraint in brackish aquifers)
3. Interactions with other groundwater users
4. Protection against saline water intrusion
5. Operations designed to protect groundwater dependent ecosystems (GDEs)
6. Management of purge water, basin scrapings and water treatment by-products

A chapter is devoted to monitoring taking account of modern instrumentation, data acquisition systems and web-based reporting to reduce the effort and increase the information content for the purposes of ensuring that risks are managed effectively.

6. Planning for emerging MAR opportunities

6.1. Integrated urban water planning and management

If stormwater recycling via MAR is to contribute to urban water supplies, town planning will need to provide for open space essential for economic harvesting of stormwater. Such open space needs to be along drainage lines and is most effective when located over a suitable target aquifer for MAR. The capacity of the stormwater management system increases through detention, and recycling opportunities are enhanced when water sensitive urban design features are included to slow the rate of runoff and improve the quality of collected water.

If water supply planers took into account the possibility of replenishment from MAR operations at points in the distribution network (with either mains water or indirect potable recycled water) this could be used to advantage to address bottlenecks in network infrastructure. For example MAR has been proposed in balancing the Perth distribution system supplies and peak demands on either side of the Swan River to avoid a very expensive duplication of a sub-river connection.

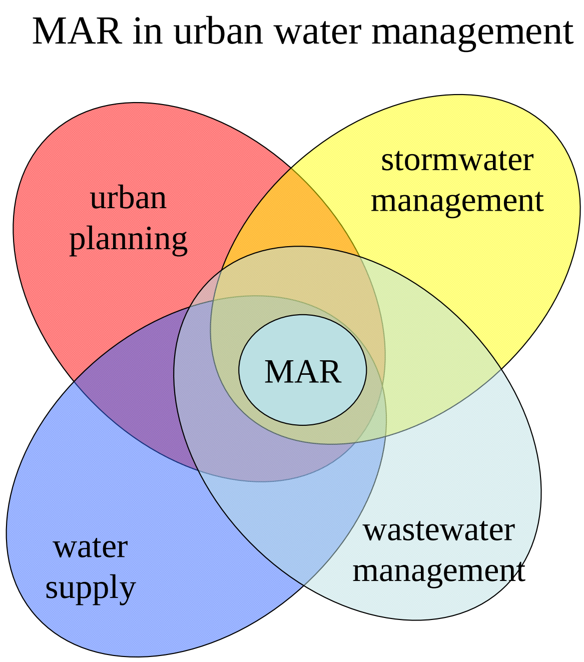


Figure 29. MAR can contribute to urban water supplies but needs to be taken into account in planning urban development and stormwater, wastewater and water supply infrastructure in order to reach its full potential.

6.2. Urban design and provision of infrastructure

Urban water supplies are paid for in two ways. The most obvious is via water rates which often have a fixed charge and a volumetric charge. The second way is through the purchase price of a residential property. For established properties this would have been a component of the initial development ("headworks") charges paid to the government utility, which were recovered by the developer on the sale of the property.

Hence if urban water consumers compare the costs of proposed alternative water supplies with only the price they pay for water via utility bills, they are neglecting to account for the headworks charge for their property that contributes to their mortgage payments and council rates. Expressed as a levelised cost of water this in some locations can rival current volumetric charges of water utilities.

A "headworks" charge is also factored into a development for stormwater costs, i.e any increase in stormwater runoff rate from the development imposes charges for augmenting and managing the stormwater system. Another approach is for the local authority to place conditions on the development to install on-site detention which restricts peak flows for storms of a given recurrence interval to no more than they would have been in the undeveloped state. Mitigation of these costs through innovative alternative supplies is only possible if these are incorporated into the subdivision design.

Real estate valuers know that residences adjacent or overlooking water have substantially higher value than those without water views. Fig 30 is a conceptual construct to demonstrate that while stormwater harvesting occupies land that then cannot be sold it can actually increase the net value of the total estate. Not every wetland need have an ASR attached, as this could be a feeder system for downstream wetlands to slow down the discharge of water from stormwater detention basins and extend the period of recharge following each storm.

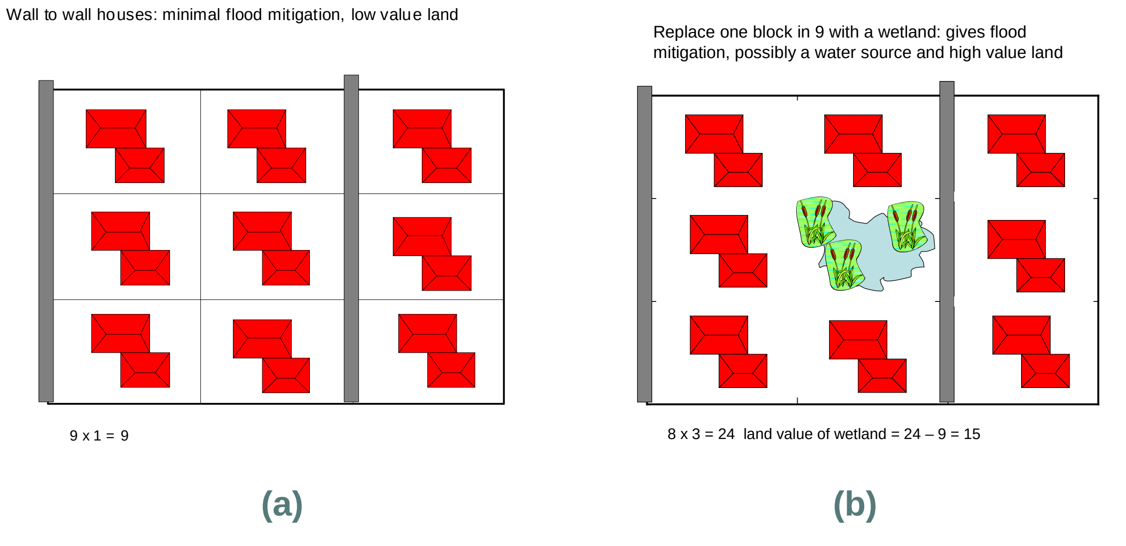


Figure 30. A nine block sector within an urban development (a) without and (b) with a wetland. If houses with a water view sell for three times the price of uninterrupted houses (source, Business Manager, City of Salisbury) the wetland more than doubles the value of the sector, and with good management importantly provides other benefits for water supply, stormwater quality, and flood mitigation downstream.

The concept of Fig 30 may also provide a model for urban redevelopment, particularly where flood prone areas could be replaced with wetlands that increase protection for surrounding land. Urban consolidation including multi-storey dwellings is likely to further increase the amenity value of open space and water views.

6.3. How water banks can be used to secure urban water

Urban water utilities are required to have entitlements for the water they take from catchments and aquifers. When proposed, new subdivisions and industries need water, the utilities' water entitlements have to be increased by the amount of the new demand. For resources that are not already over-allocated, this entitlement can be bought from other catchment water users. An alternative is to create a water bank, which can buy bulk entitlements from the most efficient water supply or conservation projects that also meet other policy objectives. These are sold to the utility or other water retailers, or possibly even directly to large customers, to enable future supplies.

In Phoenix and Tuscon in Arizona, USA, developers are required to buy 100 years' worth of water for their subdivisions, and this is added to the cost of the land. Without the water, the land cannot be sold for residential or industrial purposes, nor can the city expand, and this is now one of the fastest growing areas of USA. Developers reduce their requirement to buy water by implementing water conservation measures and establishing water recycling. The rest is bought from the water bank, and most projects involve storing Colorado River water or recycled water in the extensive drinking water-quality aquifer underlying Phoenix. This water is all required to be recoverable as drinking water. Phoenix also banks water for neighbouring Nevada for recovery to the river in times of drought. Entitlements are tradeable.

In Australia, few cities have aquifers similar to Phoenix's, but if water can be recovered from our brackish and less transmissive aquifers at drinking water quality and is fit to go into the mains, then the mains system can act as a means to transfer entitlements generated at one place to a user located at another (Fig 31).

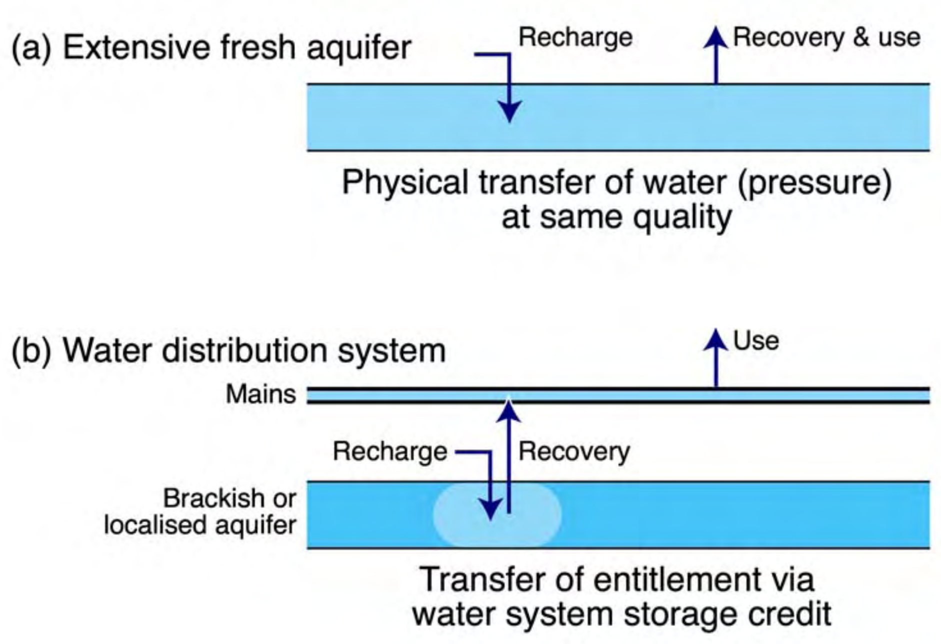


Figure 31. (a) In Phoenix the extensive fresh aquifer acts as a means to transfer credit from water recharged at one place to recovery at another, subject to water quality constraints. (b) Where aquifers are brackish or not highly transmissive, water needs to be recovered close to the point of recharge but if this is of suitable quality for replenishing water mains this can create a credit that is transferable to other points on the mains distribution system.

6.4. Opportunities for MAR in towns and rural areas

In Australia, MAR started in rural areas for protecting and enhancing irrigation supplies then progressed into cities where water prices are higher, giving more opportunity for effective recycling. As water prices rise in rural areas, MAR projects, particularly involving infiltration to unconfined aquifers when surface water allocations are available, could help increase water security in drought years for fixed-rooted crops. It is likely that sewage treatment plants will become prized sources of recycled water for irrigation, including via soil-aquifer treatment, for irrigation areas near the plants. In drier areas future pressure from cities may draw this water back into the potable supplies through investment in advanced treatment processes followed by storage in aquifers or dams.

Rural towns drawing raw water directly from rivers for drinking supplies may, where alluvium is suitable, improve quality and reliability of supplies by establishing bank filtration projects.

6.5. Emerging knowledge to increase benefits of MAR

In the last decade, pioneering progress with MAR has been substantial in Australia and internationally, and provides a firm knowledge base that is ready for application. Further evolution is anticipated as projects multiply, diversify and become larger, and research and experience grow and are disseminated.

This will be further facilitated and accelerated by;

- hydrogeological mapping to give intending proponents an initial appraisal of the potential for MAR
- demonstration projects that allow proponents and regulators to develop skills
- water resources plans that account for all costs and benefits of new alternative supplies
- greater awareness of costs of MAR in relation to alternatives
- an emerging framework for water resources planning and regulation that takes account of MAR
- confidence engendered by national guidelines for MAR
- publically accessible information on MAR to allow knowledge to accumulate
- urban planners aware of MAR allowing open space for water harvesting, and
- new institutional arrangements for investment in new sources of water.

There are likely to be increased opportunities for MAR as urbanisation grows, the climate dries in southern parts of Australia, and there are increased controls over groundwater use. Technical efficiencies and governance procedures are expected to improve (facilitated by MAR guidelines and ongoing research) providing increasing benefits from MAR. Consequently, MAR is likely to shift from being a niche technology to a standard water management method within a broad portfolio of methods that are available to urban and rural water managers across Australia.

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Glossary

activated carbon	Adsorptive carbon particles or granules that have a high capacity to remove trace and soluble components from solution.
aerobic	Pertaining to or caused by the presence of oxygen
anaerobic	Conditions where oxygen is lacking; organisms not requiring oxygen for respiration.
anoxic	Relating to or marked by a severe deficiency of oxygen
aquatic ecosystem	Any water environment from small to large, from pond to ocean, in which plants and animals interact with the chemical and physical features of the environment.
aquifer	A geological formation or group of formations capable of receiving, storing and transmitting significant quantities of water. Aquifers include confined, unconfined and artesian types.
aquifer storage and recovery (ASR)	The recharge of an aquifer via a well for subsequent recovery from the same well.
aquifer storage transfer and recovery (ASTR)	The recharge of an aquifer via a well for subsequent recovery from another well, to allow a minimum residence time in the aquifer before recovery.
aquitard	A geological layer that has low permeability and confines or separates aquifers.
artesian	When the piezometric surface (hydraulic head) of a confined aquifer is above ground surface. An uncontrolled artesian well will spurt water out of the ground.
attenuation	The reduction in contaminant or pathogen concentration as a result of treatment processes including passive subsurface treatment. This guideline focuses on sustainable treatment processes such as biodegradation. Adsorption is another attenuating process but when sorption sites are exhausted breakthrough of contaminants will occur. In these guidelines adsorption is only relied on to the extent that it extends the time available for biodegradation.
attenuation zone	The area surrounding the zone of recharge where natural attenuation takes place so that all the pre-existing environmental values of the aquifer are continually met beyond this zone. After the cessation of any MAR project the attenuation zone will shrink and disappear as all groundwater conforms to pre-existing environmental values. Verification monitoring would normally be undertaken on the perimeter of the attenuation zone, and in the recharge zone on cessation of the MAR operation.
bank filtration	extraction of groundwater from a well or caisson near or under a river or lake to induce infiltration from the surface water body thereby improving and making more consistent the quality of water recovered (eg Berlin, Germany).

beneficial use	The value of water in sustaining ecological systems as well as economic uses of water, eg as drinking water, irrigation, industrial and mining water supplies. Water quality requirements are determined by the class of beneficial use.
biofiltration	A pollution control technique using living material to capture and biologically degrade process pollutants.
capex	Capital expenditure
catchment	Area of land that collects rainfall and contributes to surface water (streams, rivers, wetlands) or to groundwater.
confined aquifer	A type of aquifer with a low permeability formation as its upper boundary, and its storage is increased by raising the pore pressure in the aquifer giving elastic compression of aquifer materials and water.
confining layer	A rock unit impervious to water, which forms the upper bound of a confined aquifer.
contaminant	Biological or chemical substance or entity, not normally present in a system or any unusually high concentration of a naturally occurring substance, capable of producing an adverse effect in a biological system, seriously injuring structure or function.
disinfection	The process designed to kill most microorganisms in water, including essentially all pathogenic (disease-causing) bacteria. There are several ways to disinfect, with chlorine being most frequently used in water treatment.
dry well	typically shallow wells where water tables are very deep, allowing infiltration of very high quality water to the unconfined aquifer at depth (eg Phoenix, USA)
dune filtration	infiltration of water from ponds constructed in dunes and extraction from wells or ponds at lower elevation for water quality improvement and to balance supply and demand (eg Amsterdam, The Netherlands).
effluent	The out-flow water or wastewater from any water processing system or device.
electrical conductivity (EC)	A measure of the conduction of electricity through water. This can be used to determine the soluble salts content. (In the absence of a regression for the local water type, total dissolved solids TDS in mg/L may be approximated as 0.6 * EC, where EC is measured in µS/cm)
environmental flows	Environmental allocation for surface water rivers, streams or creeks.
environmental values	Particular values or uses (sometimes called beneficial uses) of the environment that are important for a healthy ecosystem or for public benefit, welfare, safety or health and that require protection from the effects of contaminants, waste discharges and deposits. Several environmental values may be designated for a specific water body.
filtration	Process in which particulate matter in water is removed by passage through porous media.

granular activated carbon (GAC)	Adsorptive carbon granules (> 0.297 mm) that have a high capacity to remove trace and soluble components from solution.
groundwater	Water contained in rocks or subsoil.
groundwater dependant ecosystem (GDE)	A diverse and important component of biological diversity, taking into account ecosystems that use groundwater as part of survival. GDEs can potentially include wetlands, vegetation, mound springs, river base flows, cave ecosystems, playa lakes and saline discharges, springs, mangroves, river pools, billabongs and hanging swamps.
groundwater recharge	Replenishing of groundwater naturally by precipitation or runoff, or artificially by spreading or injection.
hazard	A biological, chemical, physical or radiological agent that has the potential to cause harm.
heterogeneity	Having different properties at different locations within an aquifer.
hydrogeology	The study of groundwater, including flow in aquifers, groundwater resource evaluation, and the chemistry of water-rock interaction, Hydrogeology is arguably the most wide-ranging sub-discipline in the Earth Sciences.
injection well	A well that admits water into an aquifer, either by pumping or under gravity.
levelised cost	Levelised costs are the constant level of revenue necessary each year to recover all the capital, operating and maintenance expenses over the life of a water supply project divided by the annual volume of supply.
mains water	Potable water from a reticulated water supply, e.g. town water supply.
managed aquifer recharge (MAR)	A term applied to all forms of intentional recharge enhancement, for the purpose of reuse or environmental benefit.
microfiltration (MF)	The process of passing wastewater through porous membranes in the form of sheets or tubes to remove suspended and particulate material. Pore sizes can be very small and particles down to 0.2 microns can be retained.
observation well	A narrow bore, well or piezometer whose sole function is to permit water level and quality measurements.
opex	Operation and maintenance expenditure
palaeochannel aquifer	Old river bed buried by newer geological deposits
passive treatment	Treatment technologies that can function with little or no operation or maintenance over long periods of time. They can function for weeks to years, even decades, with little human interference. Examples include: grassed swales, ponds, wetlands, unsaturated zone infiltration systems and aquifer storage.
pathogen	A disease-causing organism (eg bacteria, viruses and protozoa).
piezometer	A short-screened observation well used to determine pressure and/or water quality at a particular depth interval within an aquifer.

pre-treatment	Any treatment (eg detention, filtration) that improves the quality of water prior to recharge.
preventive measure	Any planned action, activity or process that is used to prevent hazards from occurring or reduce them to acceptable levels.
radionuclide	An isotope of an element that is unstable and undergoes radioactive decay.
rainwater	Water collected from the roofs of buildings.
reclaimed water	Sewage treated for a reuse (recycled water preferred).
recovery efficiency (RE)	The volume of recovered water that meets the salinity criteria for its intended uses expressed as a percentage of the volume of fresh water injected into a brackish aquifer (usually evaluated on an annual basis).
recycled water	Water generated from sewage, greywater or stormwater systems and treated to a standard that is appropriate for its intended use.
reverse osmosis (RO)	An advanced method of wastewater treatment that relies on a semipermeable membrane to separate water from its impurities.
risk	The likelihood of a hazard causing harm in exposed populations in a specified time frame, including the magnitude of that harm.
runoff	Surface overland flow of water resulting from rainfall or irrigation exceeding the infiltration capacity of the soil.
sand dam	built in ephemeral stream beds in arid areas on low permeability lithology, these trap sediment when flow occurs, and following successive floods the sand dam is raised to create an “aquifer” which can be tapped by wells in dry seasons (eg in Namibia).
source water	Water as harvested, before any treatment, prior to recharge.
stakeholder	A person or group (eg an industry, a government jurisdiction, a community group, the public, etc) that has an interest or concern in something.
storage	A natural or artificial impoundment used to hold water before its treatment and/or distribution (eg reservoir or aquifer).
stormwater	Rainfall that runs off all urban surfaces such as roofs, pavements, carparks, roads, gardens and vegetated open space.
surface water	All water naturally open to the atmosphere (eg rivers, streams, lakes and reservoirs).
tertiary treatment	Includes treatment processes beyond secondary or biological processes, which further improve effluent quality. Tertiary treatment processes include detention in lagoons, conventional filtration via sand, dual media or membrane filters, which may include coagulant dosing and land-based or wetland processes.
total dissolved salts (TDS)	A measurement of the total dissolved salts in a solution. Major salts in recycled water typically include sodium, magnesium, calcium, carbonate, bicarbonate, potassium, sulphate and chloride. Used as a measure of soil salinity with the units of mg/L.
toxicity	The extent to which a compound is capable of causing injury or death, especially by chemical means.
tracer	Any distinctive substance which can be used to quantitatively or

	qualitatively ‘fingerprint’ water.
transmissive	A transmissive aquifer can easily convey large volumes of water.
turbidity	The cloudiness of water caused by the presence of fine suspended matter.
unconfined aquifer	A type of aquifer that has the watertable as its upper boundary, and is usually recharged by infiltration from the surface.
underground dam	In ephemeral streams where basement highs constrict flows, a trench is constructed across the streambed keyed to the basement and backfilled with low permeability material to help retain flood flows in saturated alluvium for stock and domestic use (eg in Kenya).
water recycling	A generic term for water reclamation and reuse. It can also be used to describe a specific type of ‘reuse’ where water is recycled and used again for the same purpose (eg recirculating systems for washing and cooling), with or without treatment in between.
waterlogging	Saturation of soil with water.
watertable	Groundwater in proximity of the soil surface with no confining layers between the groundwater and soil surface.