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Abstract

Managed aquifer recharge (MAR) is one tool in integrated water resources management which can restore over-allocated or brackish aquifers, protect groundwater-dependent ecosystems, enhance urban and rural water supplies, reduce evaporation losses and improve water supply security. This chapter describes the ways in which MAR is used around the world and presents two Australian case studies, with a focus on economics. Aquifer storage and recovery of urban stormwater via a confined limestone aquifer is shown to provide a viable alternative to use of existing mains water or desalinated seawater for public open space irrigation. The second case study is a desk-top evaluation of the potential for recharge of harvested floodwater via infiltration basins for irrigation of cotton and faba bean crops. Based on assumptions about scale of operations, component and maintenance costs, and evaporation losses, the net benefits of infiltration basins for a range of infiltration rates were compared with those of surface water storage and of aquifer storage and recovery wells. Infiltration basins with moderate to high rates of infiltration (>0.15 m/d) had the highest net benefits and warrant testing in a pilot program. Water treatment costs make ASR with flood waters unattractive for crop irrigation, in comparison with both basin infiltration and surface storage. Selection of the most economic method of storage depends on availability of an aquifer, soil and subsurface hydraulic characteristics, available quantity and quality of surface water, land value and end use of the water. MAR is shown to offer a range of options that

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warrant investigation in comparison with conventional supply alternatives to enable the most effective water resources management to be implemented.

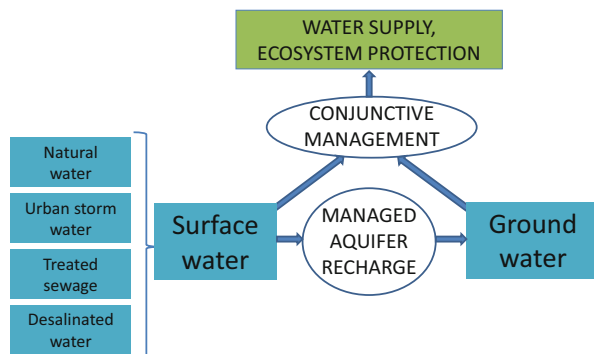
17.1 Introduction

This three-part paper describes the role of managed aquifer recharge (MAR) in integrated water management, and then provides two case studies. The first is the storage of urban stormwater for later reuse to irrigate public open space in the City of Salisbury in South Australia. This has been practised in a confined brackish limestone aquifer for 20 years and the number of aquifer storage and recovery wells continues to grow. The second case study is a desktop evaluation of the potential for storing flood water in a rural catchment to allow irrigated crop production to be expanded or to achieve environmental goals by replenishing a depleted aquifer (Rawluk et al. 2013; Arshad et al. 2012). That desktop study suggested that managed aquifer recharge via infiltration basins may be viable.

17.2 Managed Aquifer Recharge to Date

Managed aquifer recharge is defined as the purposeful recharge of water to aquifers for subsequent recovery or for environmental benefit (Dillon et al. 2009a). MAR may be used to replenish depleted aquifers, in association with demand management strategies to bring aquifers back into hydrologic equilibrium while minimising adverse impacts on livelihoods of irrigation communities. A series of examples from India and Australia are shown in Dillon et al. (2009b) that illustrate coupling MAR with demand management to achieve groundwater supplies with aquifer storage hydrologic equilibrium. Managed aquifer recharge augments groundwater with available surface water and acts alongside conjunctive use of surface waters and groundwater to sustain water supplies and achieve groundwater and surface water management objectives such as protection of ecosystems (Fig. 17.1).

Fig. 17.1 Roles of managed aquifer recharge and conjunctive use in integrated water resources management



There are countless examples around the world that demonstrate the value of managed aquifer recharge. India leads the world in recharge enhancement with about 3 km³/year, almost exclusively to unconfined aquifers through infiltration structures to help sustain groundwater supplies predominantly for agriculture and increasingly in urban areas. This volume does not keep up with groundwater storage depletion in northern India, but does help to prolong the resource and allow a window of opportunity for adaptive management. Water quality is rarely intentionally managed so it can be claimed that this recharge is not yet managed aquifer recharge. The same can be said for many parts of the world where untreated sewage and industrial effluent, stormwater or blends are allowed to infiltrate and contaminate aquifers and diminish the useable resource. If appropriately treated, this water would have supply benefits as well as environmental and health improvements.

Roof top rainwater and urban stormwater have been recharged in Australia, Germany, India, Jordan, USA and in many locations with permeable soils or karstic aquifers. There is now a progression underway from uncontrolled disposal via sumps, basins, wells and karst features to managed aquifer recharge through implementing measures to improve and protect water quality. In coastal locations in California, China, and Bangladesh replenishment of aquifers using injection wells has protected urban and irrigation supplies from salinization and in some places has been claimed to assist in mitigating against land subsidence. Treated sewage effluents have been used to augment and secure groundwater supplies in Australia, Belgium, Germany, Israel, Italy, Mexico, Namibia, South Africa, Spain, USA and elsewhere. Desalinated water is also used in UAE and USA for recharge primarily to build secure reserves of mains water. In a few locations groundwater from one aquifer is stored in another to secure supplies.

Riverbank filtration is another widespread technique to improve water quality and security of drinking water supplies. Being a low energy method for water treatment its popularity will grow as the treatment effectiveness of alluvium becomes better understood. Recharge has also been practiced for protection of groundwater dependent ecosystems (Berry and Armstrong 1997; Dillon et al. 2009c). There are many technical papers on managing aquifer recharge available from the IAH-MAR web site www.iah.org/recharge and some of these (in English and Spanish) are stored on our companion Spanish web site accessed from the same URL.

Figure 17.2 demonstrates how managed aquifer recharge can act alongside demand management and conjunctive use to bring an over-exploited aquifer back into hydrologic equilibrium. A corollary of this is that in areas where the climate is drying, causing natural recharge rate to decline and irrigation demand to increase, managed aquifer recharge may provide an adaptive strategy to help re-establish hydrologic equilibrium.

It is logical that at any location the most economic option available would be adopted first, and then the next most economic, and so on until the volume by which demand is decreased, or the volume of managed aquifer recharge or supply substitution is increased so that hydrologic equilibrium is achieved. Invariably, some strategies for increasing water use efficiency will be among the most economic options.

Figure 17.3 represents the actual sequence of options for restoring the aquifers of the Swan Coastal Plain and continuing to supply Perth's growing need for water.

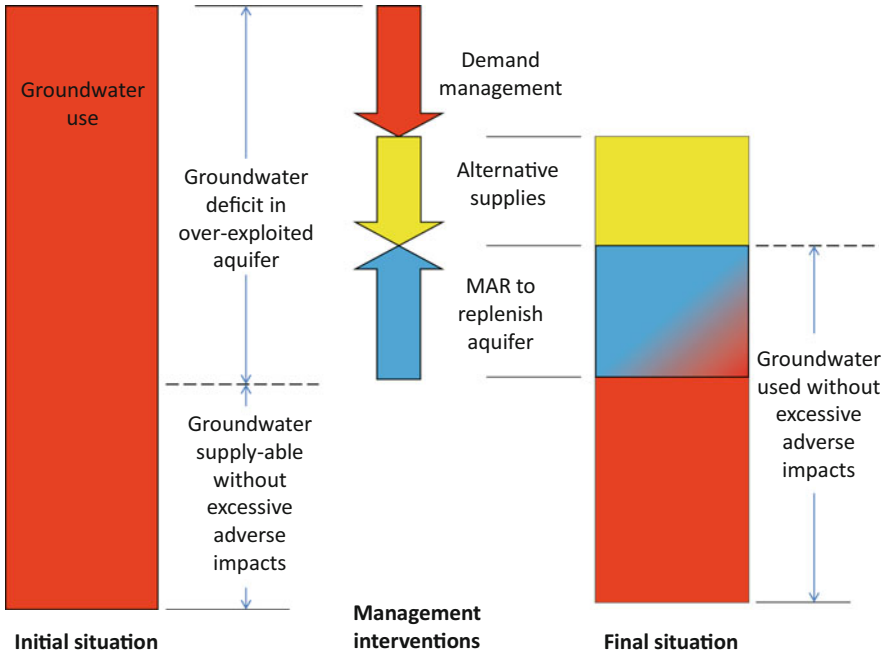


Fig. 17.2 An aquifer can be brought into hydrologic equilibrium by either reducing extraction, or augmenting supplies, either through groundwater replenishment or providing alternative supplies (conjunctive use) (From Dillon et al. 2012)

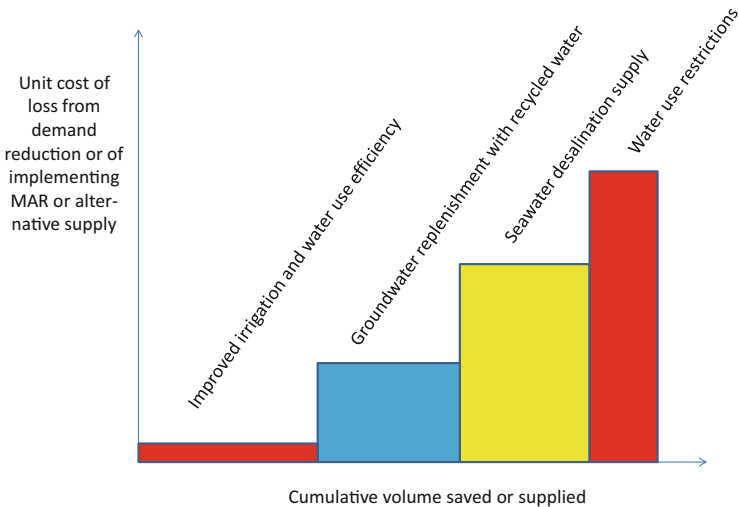


Fig. 17.3 A logical sequence of demand reduction (*red*), MAR (*blue*) and conjunctive use (*yellow*) to reign in groundwater depletion and sustain supplies (in this case for Perth, Western Australia). Options, their relative costs and volumes are location-specific. Improved irrigation efficiency is frequently the least costly option and should be implemented first (Adapted from Dillon et al. 2012)

The Water Corporation in the state of Western Australia imposed a series of water conservation measures, such as mandatory restrictions on the hours during which parks and gardens may be irrigated to avoid high rates of evaporation, and reducing the frequency of irrigation to once or twice a week. It also encouraged water efficient household appliances such as washing machines, showers, and toilets. An extensive investigation and demonstration trial of the use of recycled water for groundwater replenishment was undertaken, and the Western Australian Minister for Water announced in 2013 that this would be the next water supply for Perth, based on safety, economic efficiency and public acceptance. The value of the research was that it showed the costs of groundwater replenishment with recycled water were approximately half those of harnessing seawater desalination, the alternative (conjunctive supply) previously regarded as the cheapest acceptable source of supply. Prior to that, onerous water restrictions were the only option, and these were regarded as politically unsustainable, and caused failures in garden supplies industries.

This framework of integrated water management is used in this chapter to explore two case studies of the potential for managed aquifer recharge, one harnessing urban stormwater in a city for public open space irrigation and industrial use. The other is a desktop study for a rural area that assesses the opportunities to harvest from large floods in order to sustain agricultural irrigation. These studies focus on the economic aspects of MAR in relation to alternatives.

17.3 Potential for Managed Aquifer Recharge from Urban Stormwater in a Suburban Area of SA, Australia

The driver for this case study is not the need to reduce groundwater demand. In fact the aquifer originally contained brackish groundwater and demand was negligible prior to aquifer storage and recovery (ASR) with stormwater. The purpose of recharge was to store fresh urban stormwater runoff during wet winters and recover it for irrigation in dry summers in an area with a Mediterranean climate. The costs of MAR water supplies for local councils were cheaper than the costs of purchasing mains water from the state government-owned water utility. This supply met with the approval of the State at that time as it reduced demand on drinking water supplies and hence had a positive effect on the security of those supplies in a system that had little storage capacity and was drought-prone.

The costs of producing these supplies were calculated in AUD 2008 as shown in Table 17.1, based on data from consultants and owners of eight ASR systems with capacities between 75 and 2,000 ML/year. Costs exclude value of land occupied by wetlands used for water harvesting. In all cases the proponent of the project already owned this land. In most cases a wetland was required as a detention basin to prevent increased peak flow rates during storms as a result of new urban developments. Hence the land for the wetland was considered as contributing to the flood mitigation benefit, and the remaining costs, including wetland

Table 17.1 Mean levelised costs (in AUD 2008) for components of urban stormwater ASR projects for irrigation supplies in the size range 75–2000 ML/year (Adapted from Dillon et al. 2009a)

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

construction, were attributed to producing a water supply via ASR. Levelised cost, expressed in \$/KL, was calculated as annualised cost to amortise capital cost components over their expected working life added to the annual operating and maintenance expenses and divided by the annual volume of supply. In this case for eight stormwater ASR projects in South Australia, the adopted discount rate was 7 % and the working life of ASR wells was assumed to be 15 years, for wetland systems 25 years, and for distribution systems 50 years. It was also assumed that only 80 % of injected water could be recovered at the salinity required for its intended use.

The mean levelised cost for ASR (A\$1.12) compared favourably with independently provided figures by consultants for two seawater desalination options ranging from A\$2.45 to 3.76/KL levelised cost. The ASR energy intensity of 0.10 KWh/KL compared favourably with seawater desalination and distribution of 4.2 to 5.3 KWh/KL (Dillon et al. 2009a). That is, the mean levelised cost from the sample of stormwater ASR projects was found to be between 30 % and 46 % of that of seawater desalination, and greenhouse gas emissions were less than 3 % of seawater desalination.

Levelised costs for ASR reduced as recharge rate increased. The eight projects costed had injection rates from ~10 to ~30 L/s per well. Hence sites with higher well yields and transmissivities are preferred. For low permeability formations the levelised costs of recharge are elevated due to the capital and operating costs being amortised over smaller volumes of water and because additional water treatment may be required in order to avoid clogging of the well. An example in south-east Melbourne is reported in Dillon et al. (2010) where levelised costs of ASR exceed A\$8/KL in a formation with a transmissivity of ~1 m²/day, sustaining an injection rate of 0.4 L/s and requiring ultrafiltration and granular activated carbon filtration as pre-treatments to avoid clogging for recharge of 4ML/year.

A more recent study of stormwater recharge on the Northern Adelaide Plains (Dandy et al. 2013) revealed levelised costs of A\$1.57/KL (in 2012–2013) including land value of the harvesting facility and capital and operating costs of the distribution system for public open space irrigation. The same study found that recovery for potable use of treated stormwater had a levelised cost of between A\$1.47 and A\$2.51/KL depending on whether the water was pumped to an existing dam and treatment plant or was treated locally in a decentralised treatment plant. These costs include the costs of treatment and implementation of a risk-based management plan appropriate to the end use. Equivalent financial results for water recycling from treated sewage effluent via aquifers to various end uses will be available in 2015 from the Australian Water Recycling Centre of Excellence.

ASR sites with higher ambient groundwater salinity generally allow a smaller proportion of injected water to be recovered at a salinity that is acceptable for its intended use. This is exacerbated where native groundwater has sufficiently high salinity that density-affected flow occurs (Ward et al. 2009) and a freshwater injection lens forms at the top of the aquifer. This is difficult to recover without also entraining some of the saline water underneath. Recovery efficiency therefore also influences the levelised cost of ASR operations and needs to be taken into account wherever the native groundwater is not fit for the intended use of recovered water.

17.4 Potential of Managed Aquifer Recharge from Large Floods Events in a Rural Irrigation Area of NSW, Australia

Groundwater in the Namoi River Catchment in the Australian state of New South Wales supports an irrigation industry worth in excess of AU\$ 380 million per annum (Namoi CMA 2013). According to The Australian Cotton Grower (2012), in the wetter year of 1998/1999 about 60,000 ha of cotton were grown in the Lower Namoi, whereas in the drought year of 2003/2004 only 26,300 ha were planted due to limited surface water supplies.

In response to groundwater overdraft, State governments in Australia have reduced current groundwater irrigation entitlements in stressed aquifer systems (Smithson 2009). For the Lower Namoi Valley, a highly developed cotton irrigation district in NSW, this gradual cutback of 10 % each year, translates to a reduction of 21 gigalitres (GL)/year in groundwater entitlements for irrigation by 2015 and beyond. Reduced water availability under droughts and reduction in water allocation have significant financial impact on the farming communities.

A typical Namoi valley farm holds enough water in storage (600–900 ML) for 1 year of irrigation (Powell and Scott 2011). All irrigation water is stored and routed from surface storages before application to the field, resulting in substantial evaporation losses. On average, evaporation losses from surface water storages range between 1.2 and 1.8 m/year (Wigginton 2011), this represents a loss of approximately 35 % to 50 % of the total on-farm storage capacity.

Aquifer storage via Managed Aquifer Recharge (MAR) was investigated as a way of minimising evaporative losses and increasing farm profitability. MAR can serve the purpose of increasing groundwater storage in wet periods in order to support irrigation and environmental use of water during dry periods. The case study highlights the availability of water from high flood events that may be used for aquifer recharge and examines the financial costs and benefits of storing floodwater underground (via infiltration basins or injection wells) compared with the current method using surface storages.

Assessing the feasibility of MAR requires the integration of many types of data and information from many disciplines to assessing hydrologic, hydrogeologic, social, institutional factors and environmental risks. Carrying out a comprehensive feasibility assessment is essential; the first step in establishing an MAR scheme requires assessing the feasibility of technical and economic factors, to provide a basis for other investigations to proceed. An overview of the basic requirements and feasibility guidelines for MAR is available in Dillon et al. (2009a)

Before conducting costly technical feasibility studies through geophysical and hydrogeological investigations, a first step is to explore the potential of MAR through a desktop case study to address two questions that are of major concern to the irrigation farmers of the Lower Namoi;

- I. Is a reliable source of water for aquifer storage available? and
- II. Is underground storage financially better than surface storage?

Identifying water for the purpose of MAR will be challenging, particularly in the Murray-Darling Basin where irrigators must operate within existing entitlements to water and where flood waters are typically considered as environmental water. Under these arrangements only existing entitlements for consumptive use can realistically be considered as a source of water for MAR in rural catchments. Within existing entitlements for consumptive uses, Rawluk et al. (2013) discussed the potential sources of water for MAR in the Murray Darling Basin.

The potential sources for MAR water in the Lower Namoi may include;

- i. Water diverted from rivers under existing entitlements to take water during high floods or periods of high streamflow, known as supplementary water.
- ii. Locally captured farm run-off.
- iii. Water used in coal seam gas mining could be treated (desalinated) and reused for MAR.

In many areas of Australia, including the Lower Namoi, supplementary water and local run-off is captured and stored in farm dams for stock supply and irrigation. Currently, farm dams across the Murray-Darling Basin have a combined capacity of 2,000 GL (CSIRO 2007). Craig et al. (2005) estimated that up to 40 % (800 GL) of this storage volume can be lost each year to evaporation. Most situations in which there are opportunities for such water capture are on floodplains in the lower parts of major catchments, including the Lower Namoi. In these

situations the alluvial sediments offer storage opportunities either through surface recharge or deep injection into alluvial aquifers, depending on local hydrogeology. MAR can provide a low or no evaporation option for storage of water under these circumstances (Ross and Arshad 2013); however some water may not be recoverable, termed as recovery losses, if native groundwater is not of a suitable quality for irrigation or if there is leakage from the aquifer to other aquifers or to surface water bodies.

The Namoi River follows an irregular flow pattern with moderate to large variability in inter-annual and inter-decadal flows. Figure 17.4 highlights floods from the river flow data (1970–2008) at the Mollee gauging station where recorded mean daily flows in months during flood events in 1964, 1971, 1974, 1976, 1984, 1998 and 2000 were between 100 and 200 GL/day. This is a huge volume of water when compared to the long term median flow of 0.53 GL/day, indicated by the horizontal bar in Fig. 17.4. Such peaks could be more frequent in future under climate change (Barron et al. 2011; Chiew et al. 2011).

From the flood frequency and magnitude data, it appears that a significant volume of water could be made available for MAR provided that environmental flows and ecological requirements are met. The Water Sharing Plan (The Plan) for the Upper Namoi and Lower Namoi Regulated River Water Sources (NSW DIPNR 2003) states the extraction rules for supplementary water entitlements held by irrigators. Under The Plan, flood water that is not already allocated is assumed to be environmental water, except that holders of the supplementary access licences can extract water during the announced supplementary periods. Such access periods are typically during floods and periods of high streamflow, when dams spill and flows are in excess of licensed obligations and environmental needs (Burrell et al. 2011).

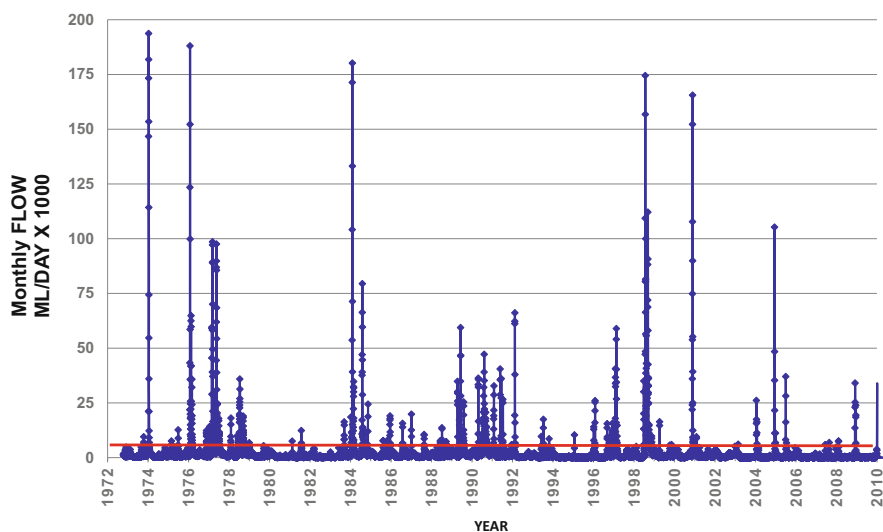


Fig. 17.4 Flood peaks in the Namoi River at Mollee (1970–2008) (Source: NSW, Office of Water 2008)

Under The Plan the volume of water that may be taken from a supplementary access event depends on the time of year. The Plan provides all the basic rules for capture of water during each supplementary event. However, the rules defining the threshold for the announcement of a supplementary access event are complex and depend on many factors. The rules in The Plan detail the various start, stop and flow triggers for different locations and the different scenarios that apply depending on the volumes of water allocations in the regulated river. In addition, the available volume of water for extraction varies for different times of the year, that is up to 10 % of the event volume between 1 July and 31 October and up to 50 % during other times. A water user is only able to extract supplementary water when, amongst other things, their supplementary water account balance is in credit.

After meeting all other requirements, supplementary access is only available when the uncontrolled flows are surplus to other needs and is only permitted in accordance with announcements made by the Minister’s Office of Water. Arshad et al. (2012) made a quantitative assessment of the volume of water from high flow events. This was achieved by analysing daily streamflow data (NSW, Office of Water 2008), from 1972 to 2012 at the Mollee gauging station.

In the absence of any published threshold volume that could be used to establish the start of a supplementary event, Arshad et al. (2012) adopted a threshold of 37.8 GL/day. This threshold was based on the peak flow of the Namoi River on 1 August 2011 at Gunnedah when the river level was more than one metre higher than the river bank (Burrell et al. 2011). With this level of inundation in the floodplain it is assumed that all the basic environmental and ecological requirements are met locally and downstream.

Figure 17.5 shows the share of irrigation and environmental water for each of the supplementary water events in the Lower Namoi from 1972 to 2012. As is indicated

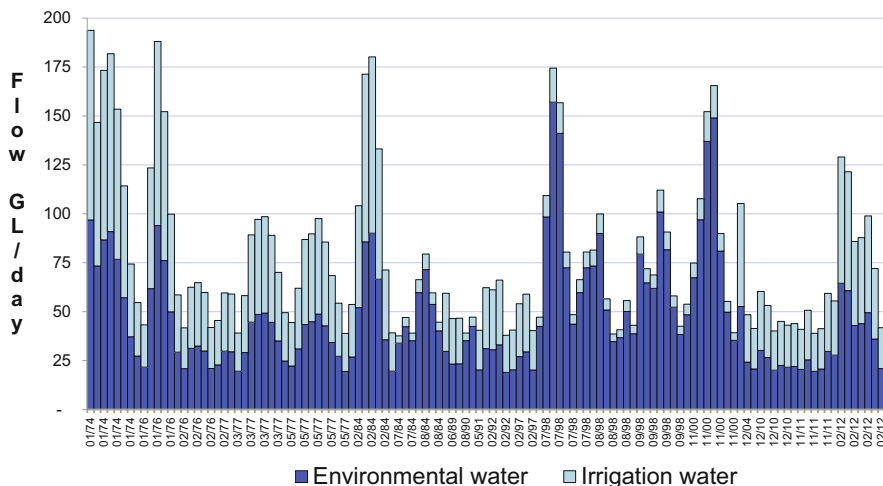


Fig. 17.5 Shares of irrigation and environmental water (1972–2012). Supplementary access set at a threshold of 37.8 GL/day, Namoi at Mollee (Data Source: NSW, Office of Water 2012)

in Fig. 17.5, in the 40 years between 1972 and 2012, there were 120 high flow events exceeding the threshold of 37.8 GL/day. These flows provided an average 85 GL of water per year for irrigation that may be available for aquifer storage which is a significant amount of water.

There is sufficient space in the main aquifers in the Lower Namoi to store this volume of supplementary irrigation water. Historical groundwater extraction, supporting the irrigation industry since the 1960s, has been in excess of groundwater recharge. This has generated a huge storage space within the alluvial aquifer. The captured supplementary water could be placed in either the shallow unconfined aquifer, or the semi-confined aquifers from which the irrigation bores extract groundwater.

Periods of high streamflow and floods offer a significant opportunity for diverting river water, and storing it in the aquifers of the Lower Namoi. However, the amount of flood water is highly variable from year-to-year, ranging from 11 GL in 1990 to 691 GL in 1977. This large variability in the volume of flood water will require temporary storages to capture, stabilise and/or treat the water before recharging it into the aquifers. Before establishing institutional mechanisms to implement MAR in Lower Namoi, a financial comparison of the costs and benefits of surface storage and underground storage using MAR would be needed.

The cost of MAR depends on number of factors such as local hydrogeology; e.g. infiltration and injection rates, cost of physical infrastructure and its maintenance, cost of acquiring source water, level of required water treatment, cost of land and cost of pumping to recover stored water. Arshad et al. (2013) carried out a cost-benefit analysis of surface and aquifer storage of 600 ML/year in Lower Namoi for a typical cotton irrigation farm. The study estimated all the irrigation related costs and benefits and compared net irrigation benefits under three different water storage scenarios: surface storage in farm dams, aquifer storage using basin infiltration, and aquifer storage using aquifer storage and recovery (ASR) wells. In a typical Lower Namoi farm all the surface water allocations, including flood water, is stored in farm dams before application to the fields.

Surface storages have significant evaporation losses reported as high as 35–45 % from surface farm dams annually (Craig 2006; Craig et al. 2005). MAR can be an option to minimize evaporation losses by storing water in aquifers and recovering that water when needed. This would allow additional land to irrigate with saved water and possibly additional farm benefits. Increased costs are however incurred on establishing MAR infrastructure and its ongoing operation and maintenance. The annual irrigation water allocation from all sources for an average cotton farm in Lower Namoi is approximately 1,350 ML. However, in this analysis we only consider and report costs and benefits of 200 ML of flood water, which is only 25 % of flood water allocation and is based on recent statutory allocations of flood water (800 ML/year) in the study area.

One limitation of the study of (Arshad et al. 2013) was that it assumed average basin infiltration and ASR well injection rates that could be possible in areas with favourable hydrogeological conditions and may be uncertain at other places due to hydrogeological heterogeneity. The following section extends the analysis by

considering a range of infiltration rates. The analysis also considers the comparative cost advantage of using an existing borehole for an ASR facility.

17.4.1 More Detailed Costings for the Case Study

Cost estimates of aquifer recharge are scarce and can vary considerably with location. Itemized costs for this study which are identified in subsequent paragraphs were estimated by combining current market rates of earthworks, services and materials for water infrastructure projects in Australia and were adjusted to the local situation and market rates in the Lower Namoi. Cost estimates were also compared with published data and technical reports including Khan et al. (2008), Dillon et al. (2009a) and Pyne (2010).

Capital costs of basin infiltration were estimated by assuming a range of infiltration rates (0.1–0.3 m/day) and calculating the required land area to achieve 2 ML of recharge per day. The target flood water harvested volume of 200 ML would generally appear in four or more episodes in a flood year. The flood water is collected and temporary held in farm dams before recharge. An infiltration pond with surface area of 1 ha and infiltration rate 0.2 m per day would recharge 50 ML of floodwater in a cycle of 25 days. For an infiltration rate of 0.1 m/day a pond with surface area of 2 ha would be required to recharge 50 ML in the same period.

The cost of underground storage primarily depends on the hydrogeological features of the target aquifer and the choice of method considered suitable to accomplish recharge. Apart from quality of source water, infiltration and injection rates can highly influence the cost of any aquifer recharge and storage facility. Bouwer (1999) provides typical infiltration rates for surface infiltration systems in the range from 0.3 to 3 m/day with relatively clean and low turbidity river water. For systems that are operated year-round, long-term infiltration rates vary from 30 to 500 m/year, depending on soil type, water quality and climate.

ASR can potentially achieve injection rates between 0.5 and 8 ML/day per borehole. In a modelling study Khan et al. (2008) assumed an injection rate of 8 ML per day per borehole for an ASR facility in the alluvial aquifers of the Murrumbidgee catchment. In the absence of accurate well injection rates based on field monitoring, Pyne (2005) observed that the injection rates of ASR increase with increasing aquifer transmissivities. For the Lower Namoi Williams (1989) reported that the main aquifers which are tapped for irrigation extraction are associated with the Gunnedah and Cubbaroo Formations with transmissivities in the range of 1,000–2,000 m²/day. The yields from bores tapping these aquifers vary up to 250 L/s in the Gunnedah Formation at depths of 60–90 m and in the deep Cubbaroo Formation at depths of 80–120 m. The shallow Narrabri Formation has transmissivities less than 250 m²/day. For this study an assumed injection rate of 25 L/s (2.2 ML/day) is considered likely for an ASR well.

The analysis assumed 40 % evaporative losses from surface storage and 5 % from basin infiltration and ASR. In the base case the only cost considered is the cost of harvesting 200 ML of flood water and the cost of annual maintenance of the farm

dam. The capital cost of basin infiltration includes the cost of earth works and laying of pipes. Ongoing costs include operation and maintenance of water harvesting and recovery and the cost of basin de-silting. An existing bore is assumed to be available for recovery after basin infiltration or for injection and recovery in ASR. The capital cost of an ASR facility on an existing farm primarily includes setting up a coagulation and filtration pre-treatment facility, with capital cost assumed as A\$ 250/ML. Ongoing operation and maintenance costs for ASR include well flushing and cleaning, flood water harvesting, water treatment and recovery. The analysis assumed a 30 year life span for surface storage and basin infiltration and 20 years for ASR and 7 % uniform discount rate for all options. All capital costs estimates are exclusive of land value.

With the additional 70 ML of water saved from evaporation through MAR, farmers in the Namoi have a choice to irrigate additional land with cotton, faba bean or some combination of the two crops that yields the highest returns. Value brought by the flood water under each option is estimated from the useable volume of flood water, after evaporative and recovery losses, times the gross margin per megalitre of mixed cropping of cotton and faba bean on equal land area. On average, for a typical lower Namoi irrigation farm average gross margins for cotton and faba bean are estimated as \$310 and \$435 respectively, averaging \$ 342.3/ML of irrigation water. Details of farm benefits are available in Powell and Scott (2011) and their estimation is in Arshad et al. (2013). Table 17.2 summarises the costs and value addition of 200 ML of flood water with each water storage option in A\$/ML.

The cost and value addition of basin infiltration depends highly on the infiltration rates; as the infiltration rates increase the capital costs decrease and value of saved water increases. Basin infiltration at an infiltration rate of 0.10 m/day proves to be uneconomical with 15 % less benefits than surface storage. With infiltration rates of 0.15 m/day basin infiltration is marginally profitable, while with infiltration rates of 0.2 m/ day and above basin infiltration becomes economically viable. The break-even point, where the added value of basin infiltration exceeds the additional costs occurs at an infiltration rate of 0.14 m/day.

In the Lower Namoi, areas with floodwater infiltration rates of 0.2 m/day and above can potentially benefit from aquifer storage of floodwater using basin infiltration. Basin infiltration systems could be piloted in areas where river-aquifer connectivity exists, particularly in zones where the river system is losing to the aquifer. Basin infiltration systems could be feasible to recharge unconfined shallow aquifers. A high cost of treatment of relatively turbid floodwaters was conservatively assumed for ASR, although testing is warranted to determine the level of treatment required for sustainable operation. Under the current assumptions even using existing wells, ASR appears to be uneconomical due to the high cost of water treatment.

In the Lower Namoi, the opportunity for aquifer storage can be advantageous for two reasons: (a) under existing rules, large quantities of floodwater are available to harvest in wet periods and can be stored underground; (b) the existing on-farm storage dams avoid the need for building temporary storage of floodwater before

Table 17.2 Levelised costs and farm benefits (A\$/ML) of Surface storage and MAR

	Unit	Surface storage	Basin infiltration rate				ASR with existing well
			0.1	0.15	0.2	0.25	
Infiltration rate (m/day)			0.1	0.15	0.2	0.25	2.2ML/day
injection rate (ML/day)			200	200	200	200	200
Volume taken under supplementary entitlement during flood event	ML	200	200	200	200	200	200
Useable volume (after losses)	ML	120	190	190	190	190	190
(a) Annualised cost of capital items	\$/ML	0	63.8	42.6	32.2	25.7	26
(b) Annual cost of operation, maintenance and management	\$/ML	26	108.5	97.9	90.5	80.7	221.7
(c) Total Annual Cost (a + b)	\$/ML	26.0	172.3	140.5	122.7	106.4	247.7
Gross value of crop \$/ML	\$/ML	342.3	342.3	342.3	342.3	342.3	342.3
(d) Value of crop that can be grown with the useable volume in each case (available water* gross value \$/ML)	\$	41,076	65,037	65,037	65,037	65,037	65,037
(e) Benefits of initial flood water (crop value/total flood volume)	\$/ML	205.4	325.2	325.2	325.2	325.2	325.2
(f) Benefits of 200 ML of flood water harvested (benefit-cost)	\$/ML	179.4	152.9	184.7	202.5	218.8	77.5
(g) Added Value % (above surface storage)		0 %	-15 %	3 %	13 %	22 %	-57 %

*multiplied by

recharging it underground. If the assumptions of this study are validated, aquifer storage using infiltration ponds would be financially viable.

17.5 Conclusion

Managed aquifer recharge can be a useful element of integrated water resource management. It can help to conserve surface water resources and improve groundwater quality (eg Adelaide case study), and minimize the evaporative losses and increase the volume of groundwater available for use (eg Namoi case study).

The economics depend on site-dependent factors. In general, recharge is least expensive where soils are permeable and aquifers are unconfined and fresh. Levelised costs may be approximately an order of magnitude less than the costs of recharge via wells. ASR is most cost efficient in aquifers that are transmissive and contain fresh or only mildly brackish ambient groundwater. It is attractive in urban areas where the value of recovered water is very high, it requires very small land area and if storing water in confined aquifers the groundwater resource is protected from overlying land uses.

MAR options have been shown to be economic in comparison with seawater desalination for urban substitutional supplies, and cheaper than use of mains water for public open space irrigation. Stormwater ASR has now been operational for 20 years in South Australia and the capacity is continually being expanded. For rural supplies the price of water is significantly lower than for urban supplies. And where infiltration rates are high and aquifers are unconfined, transmissive and contain fresh groundwater, it is possible for basin infiltration harvesting of supplementary entitlements during flood flows and their subsequent storage in aquifers to be a more efficient supply than harvesting in detention ponds alone that are exposed to significant evaporation losses. The Namoi desktop case study suggests that field validation of infiltration rates and maintenance requirements is warranted to determine the economics of MAR for flood water harvesting. Other such studies of recharge of flood waters such as Pavelic et al. (2012) in Thailand suggest that applications could potentially be very widespread.

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