Factors affecting the cost of managed aquifer recharge (MAR) schemes

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Abstract : Managed aquifer recharge (MAR) is an important technique for improving groundwater recharge and maintaining aquifer levels. There are many examples from around the world that demonstrate the advantages of managed aquifer recharge. Despite the numerous benefits and demonstrated advantages of MAR uptake has been lower than expected. The financial and economic performance of MAR is a key determinant of its global uptake. There are few studies of the financial characteristics and performance of different kinds of MAR schemes. This study contains an analysis of financial data from 21 MAR schemes from 5 countries. Although MAR schemes are highly heterogeneous it is possible to draw some conclusions about factors that affect the costs of storing water underground and recovering it for use. The costs of MAR schemes vary substantially. Schemes using infiltration and spreading basins using untreated water are relatively cheap. Schemes using recharge wells, bores and expensive infrastructure are relatively costly. When advanced water treatment is needed, this involves significant extra costs. Other key factors that affect MAR scheme costs include the range of objectives to be met, frequency of use of the scheme, hydrogeological conditions that affect infiltration rates and well yields, and the source and end use of water stored underground. Priorities for further research include additional disaggregation of capital and operating costs and inclusion of a wider range of scheme types, sources of water and countries.

Keywords**:** groundwater, managed aquifer recharge, costs, capital, operating, MAR

Introduction

The use of groundwater is increasing in many countries in response to the rising demands for drinking water supplies and food production for a growing global population. Globally groundwater is estimated to provide 36% of potable water, 42% of water for irrigated agriculture and 24% of direct industrial water supply. Groundwater supplies are diminishing, with an estimated 20% of the world's aquifers being over-exploited, leading to serious consequences such as land subsidence and saltwater intrusion in coastal areas (Gleeson et al., 2012). Careful management is needed to conserve aquifers in order to sustain groundwater use, together with exploitation of opportunities for enhanced groundwater recharge (Taylor et al 2014, Jakeman et al 2016).

Managed aquifer recharge (MAR) is an important technique for improving groundwater recharge and maintaining aquifer levels. MAR can be defined as the purposeful recharge of water to aquifers for subsequent recovery or environmental benefit. MAR has a number of advantages compared to other forms of water storage. Aquifers are widely distributed and water can be drawn from them when it is required. Aquifer storage is relatively cheap to operate and there is little evaporative loss. Managed aquifer recharge can restore over used or brackish aquifers, protect groundwater dependent ecosystems, enhance urban and rural water supplies and water quality, reduce evaporative losses and improve water supply security (Dillon et al 2009). The application of MAR is sometimes limited by slow recharge and recovery rates and groundwater salinisation and pollution, and is typically used in conjunction with other supply options (IGRAC 2007).

There are many examples from around the world that demonstrate the advantages of managed aquifer recharge. India leads the world in recharge enhancement with about 3 km^3 per year, and 0.4 km^3 per year is produced by individual sites in Hungary, Slovakia, The Netherlands, Germany, Poland and France (DEMEAU 2014). Rooftop rainwater and urban storm water have been recharged in Australia, Germany, India, Jordan, the USA and other countries with permeable soils or karst aquifers. In coastal locations including California, China and Bangladesh replenishment of aquifers using injection wells has protected urban and irrigation supplies from salinisation. Treated sewage effluent has been used to augment and secure groundwater supplies in countries such as Australia, Germany, Israel, Italy, Mexico, South Africa and Spain. Desalinated water has been used for recharge in the United Arab Emirates and the USA (Dillon and Arshad 2016).

Despite the numerous benefits and demonstrated advantages of MAR, uptake has been much lower than expected due to unavailability of strong economic feasibility analysis. The financial and economic characteristics and performance of MAR are key determinants of the global uptake of MAR (Maliva 2014), but there are few studies of the financial costs of different kinds of MAR or of the performance of MAR compared to other water supply options. Economic assessment of Australian MAR schemes (Vanderzalm et al 2015) includes seven schemes in Australia – three based on infiltration basins and four on recharge wells - which exhibit a wide diversity of costs.

MAR schemes show a great diversity of type and scale. This diversity is reflected in the wide range of costs of different MAR schemes. The costs of MAR schemes are influenced by a wide variety of hydrogeological, socio-economic and legal and institutional factors. For example, aquifer geology and soil characteristics affect water recharge and recovery rates, socio-economic conditions affect the availability and cost of labour and capital, and regulatory arrangements influence project set up costs (ASR Systems 2006, Dillon et al 2009).

This study does not attempt to analyse all of the hydrogeological, socio-economic, legal and institutional factors that affect the costs of MAR schemes. There is insufficient information about the MAR schemes included in this study to analyse all of these factors. This study has the less ambitious, but important objective of analysing the direct financial costs incurred by individual schemes and key factors that influence cost differences between schemes. These costs include the direct capital and operating costs of individual schemes, but do not include external economic and environmental costs, which are not accounted for in the scheme budget. In addition to capital and operating costs, metadata is collected for each scheme to place the financial cost analysis in context. This metadata includes scheme location, objective, period of operation (project start-up date), water source, water use, average annual influent volume and average annual extracted volume.

A global inventory of MAR schemes has been established to increase global knowledge about the implementation of MAR and to assist the planning and implementation of MAR schemes (Stefan and Ansems 2017), but the global inventory does not include financial and economic data. While it is not possible to collect financial and economic information for every MAR scheme in the global inventory, financial and economic information can be collected for some schemes. The addition of financial and economic data to the global MAR inventory would help to inform decisions relevant to the development and implementation of MAR schemes by governments, utilities, water users and other interested parties.

This study contains an analysis of financial data from 21 MAR schemes in 5 countries from the global inventory. Data on aggregate capital and operating costs is available for all of these schemes although there is only limited availability of disaggregated cost data. Data on volumes of water stored and recovered combined with capital and operating costs provides key reference material to enable future studies of cost effectiveness or cost benefit analyses of MAR. Although this data cannot by itself make the case for MAR, the data indicates the economic and other values of a wide range of MAR schemes

The study proceeds as follows. In the following section a framework for classifying MAR projects and costs is presented, building on the framework used in the global MAR inventory. The capital and operating costs of MAR schemes are analysed and factors influencing cost differentials between schemes are identified. The study ends with the discussion of the main results and suggestions about a program for further research on financial and economic aspects of MAR.

Materials and methods for assessing the costs of MAR schemes

Classification and selection of MAR schemes

MAR schemes around the world serve many different purposes, and there are many different MAR methods and technologies. In recent years, there have been coordinated efforts to classify global MAR schemes (IGRAC 2007) and European schemes (DEMEAU 2014). The global inventory of MAR schemes has been developed by a working group of the International Association of Hydrogeologist's MAR Commission (IAH-MAR) and a team of European researchers and the International Groundwater Resource Assessment Centre (IGRAC 2016) (Stefan and Ansems 2017). Data from about 1200 case studies from more than 50 countries have been collected, analysed and compiled in the first global inventory of MAR schemes (IGRAC 2016). The inventory includes information on 47 scheme characteristics including general characteristics, operational parameters, hydrogeological properties and water quality parameters. MAR schemes are classified into five main types: 1) spreading methods such as infiltration basins, 2) well, shaft and borehole recharge, 3) rainwater and run-off harvesting, 4) induced bank filtration and 5) in channel modification, with a number of sub-classifications (Stefan and Ansems 2017). The classification used in the global inventory provides a basis for classifying MAR schemes in this study. The global inventory includes key variables that

Table 1 – MAR Schemes covered by Location and MAR Type

Scheme	Country	Location	MAR Type[1] *(number of schemes)*	Water source	Scheme Objective
1-ASR-NL-ND	The Netherlands	Westland	Infiltration/ Spreading Basins (10)	Natural water	Seasonal Storage
2-ASR-NL-FM	The Netherlands[2]	Ovezande	Recharge Wells (10)	Natural water	Seasonal storage
3-RBF-IN-HD	India[3]	Haridwar	Bank Infiltration (1)	Natural water	Multi-purpose use through the year
4-SPD-US-AF	USA	Surprise Arizona	Infiltration/ Spreading Basins (10)	Natural water	Water security
5-SPD-US-HM	USA	Surprise, Arizona	Infiltration/ Spreading Basins (10)	Natural water	Water Security
6-SPD-US-LSC	USA	Marana, Arizona	Infiltration/ Spreading Basins (10)	Natural water	Water security
7-SPD-US-PMR	USA	Sahuarita, Arizona	Infiltration/ Spreading Basins (10)	Natural water	Water security
8-SPD-US-SMR	USA	Queen Creek, Arizona	Infiltration/ Spreading Basins (10)	Natural water	Water security
9-SPD-US-TD	USA[4]	Tonopah, Arizona	Infiltration/ Spreading Basins (10)	Natural water	Water security
10-IB-AU-IBWA	Australia	Mandurah, Geraldton and Esperance[5], WA	Infiltration/ Spreading Basins (10)	Recycled water	Irrigation supplies/ Replenish aquifer
11-IG-AU-PL	Australia	Perry Lakes & Floreat, WA	Infiltration/ Spreading Basins (10)	Recycled water	Ecological benefits
12-SAT-AU-AS	Australia	Alice Spring, NT	Infiltration/ Spreading Basins (10)	Recycled water	Water quality (health benefits)
13-ASR-AU-BLSA1	Australia	Bolivar SA	Recharge Wells (10)	Recycled water	Irrigation supplies
14-ASTR-AU-AG	Australia	Anglesea, Vic	Recharge Wells (10)	Recycled water	Water Security
15-GR-AU-BYWA	Australia[6]	Beenyup, WA	Recharge Wells (10)	Recycled water	Drinking water
16-IB-NZ-HN[7]	New Zealand	Near Ashburton, Canterbury Plains	Infiltration/ Spreading Basins (10)	Natural water	Ecological Benefits
17-ASR-US-SAWS	USA	Texas - San Antonio Water Supply	Recharge Wells (10)	Natural water	Drinking water
18-ASR-US-Kerrville	USA	Texas – Kerrville	Recharge Wells (10)	Natural water	Municipal water supply
19-ASR-US-EPWU[8]	USA	Texas - El Paso Water Utility	Recharge Wells (10)	Recycled water	Multipurpose use throughout the year
20-ASR-US-OR[9]	USA	California – Orange	Recharge Wells (10)	Natural water	Municipal water supply
21-ASR-US-FL[10]	USA	Florida	Recharge Wells (10)	Natural water	Drinking water

[1] Based on global data base classification. Recharge wells are also known as ASR/ASTR
[2] Schemes 1-2: Zuurbier personal communication 2016
[3] Scheme 3 Sandhu personal communication 2016
[4] Schemes 4-9: Gorey personal communication 2016
[5] A suite of five (5) schemes based on low-technology wastewater recycling. These are Caddadup, Gordon Road, Halls Head, Narngulu and Esperance.
[6] Schemes 10-15: Australian Centre for Water Recycling 2015
[7] Scheme 16: Bower personal communication 2016
[8] Schemes 17-19: Texas Water Development Board 2011
[9] Scheme 20: Hutchinson personal communication 2016
[10] Scheme(s) 21 - ASR Systems 2006 consolidated data for 11 sites

affect scheme costs such as MAR type, MAR influent source, MAR final use. However, the inventory does not include financial or economic information.

In 2016 the IAH-MAR commission established a working group on financial and economic aspects of MAR. The first task of this working group is the collection and processing of financial and economic data on MAR projects. The working group recognised that it would not be possible to collect data on more than a small fraction of the MAR schemes in the global inventory because of lack of availability or accessibility of financial and economic data. The group established a number of country contact points to coordinate the collection of cost information on MAR schemes. Information was collected for 21 schemes in five countries Australia, India, Netherlands, New Zealand, and the USA – see Table 1. These schemes correspond to three of the main classes of MAR schemes included in the global MAR inventory; spreading methods/infiltration basins (10 schemes), recharge wells (10 schemes) and bank filtration (1 scheme). Scheme selection was based on the availability of comparable information. Data is being collected for additional schemes in other countries but was not available for inclusion in this paper.

Table 2: Data sought for MAR Schemes

Contextual information	**Capital costs**
Site name	Land cost
Country	Feasibility analysis
City	Consulting services
Latitude	Construction: wells
Longitude	Construction: basins
Operator name	Construction: other storage
Operator contact	Construction: water conveyance
Year operation start	Construction: pre-treatment facilities
Year shut down	Construction: post treatment facilities
Main MAR type	Pre-operational testing
Specific MAR type	Regulatory and operational testing
Influent source	
Effluent final use	**Operating costs**
Main objective	Labour
Average annual influent volume (cubic metre)	Electricity
Average annual extracted volume (cubic metre)	Water
	Consulting services
Physical measures	Maintenance costs
Land area (ha)	Pre-treatment costs
Labour (hours worked)	Post-treatment costs
Electricity (kwH)	Depreciation allowance
Water (m^3)	
Number of wells	**Performance indicators**
Well Yield	Cost per cubic metre recharged (annual)
	Cost per cubic metre per day recovered or recovery capacity (annual)
	Cost per cubic metre supplied to end users

The data sought for each scheme is shown in Table 2 above. Key contextual variables from the global MAR database were collected to enable schemes to be classified into groups. Data was collected for annual MAR scheme capital and operating costs, and physical measures for land, labour, electricity and water use by the scheme. The physical measures allow estimation of unit costs. Total capital and operating costs were supplied for all of the schemes, and treatment costs were supplied for some of the schemes. A disaggregated breakdown of capital costs was only available for a minority of the schemes, and disaggregated operating costs were generally unavailable.

Data was collected for two scheme performance metrics; cost per cubic metre of water recharged, and cost per cubic metre recovered or recoverable. MAR schemes have varying objectives. Many schemes involve seasonal or short-term recovery of water but some facilities are aimed at providing long-term/ future reserve storage. In these cases the recovery capacity is the relevant metric. The unit cost of recovered water may be relatively high but the cost of longer term storage measured by the cost per unit of recovery capacity is relatively low, which can justify the choice of ASR compared to alternatives such as desalination (ASR Systems 2006).

Methodology for assessing financial costs of MAR schemes

Four alternative metrics were considered for comparing the costs of MAR schemes, levelised cost of water supply, water supply security insurance cost, water recharge cost and water recovery cost see Table 3.

Table 3 Alternative methods of costing MAR schemes

Method/use	**Description**	**Comments**
Capital cost, operating cost per m^3 of water recharged	\$/m3 recharged	Does not combine capital and operating costs and amortise them
Capital cost, operating cost per m^3 water recovered	\$/m3 recovered	Does not combine capital and operating costs and amortise them
Levelised cost of water supply	Amortises capital costs and operating costs over volume supplied through life of scheme \$/m3 supplied	Accounts for expected regular utilisation of supply In this paper, it is assumed that this annual utilisation is constant over the life of the project and that discount rate is known and stationary.
Water supply security insurance cost	Capital cost divided by supply capacity \$m^{3}per day	Does not include operating costs, does not account for amount of utilisation of scheme and is primarily used for water banking for water security.

Levelised cost is a widely accepted method of costing infrastructure projects. Levelised cost of a water supply project is defined as 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 water supply. Levelised costs provide an effective means to compare the costs of water from alternative projects (Dillon et al 2009). It was not possible to calculate actual levelised costs for the MAR schemes included in this study because of data gaps, in particular lack of time series of operating costs, but an indicative estimate of levelised cost could be calculated for each scheme assuming that annual operating and maintenance costs do not vary over time.
Water supply security insurance costs can be calculated by dividing the capital cost of the project by the daily supply capacity ($/m3 per day). Water supply security insurance costs were not calculated for all of the schemes in this study because most of the schemes have the objective of maintaining aquifer levels and/or providing ongoing water supplies instead of, or in addition to drought and emergency supplies. However, an example of the calculation of water supply security insurance cost is given for the San Antonio Water Supply Scheme.

Capital cost and operating cost per m^3 water recharged and water recovered adjusted for inflation provide alternative metrics that could be calculated from the data available in this study. The total capital costs and the latest available annual operating costs of each scheme are standardised in 2016 US dollars by the application of a GDP deflator and currency exchange rate. These metrics provide indicators of comparative capital and operating costs of MAR schemes, although they do not provide an integrated comparison of cost between different schemes because they do not combine capital and operating costs, or amortise them.

The financial costs of MAR schemes were processed and standardized in three steps:

1. Financial cost data (capital and operating costs) was collected for each scheme in local currency units (LCUs).
2. The capital costs of MAR schemes are available for different years ranging from 1965 to 2016. The capital cost of each scheme was converted to 2016 values by multiplying the cost by a GDP deflator which measures changes in prices of all domestically produced goods and services[11,12].
3. Local Currency Costs in 2016 were converted to US dollars in 2016. The local currency costs of each MAR scheme were converted to US dollars using exchange rate indices from IMF International Financial Statistics[13]. An additional adjustment for purchasing power parity was considered unnecessary in the case of schemes in OECD countries (20/21 schemes). An adjustment for purchasing power parity was made for the scheme from Haridwar, India[14].

An indicative figure for the levelised cost of each scheme was calculated assuming an operating life of 30 years, a discount rate of 6.67% and a capital recovery factor of 0.0779. Further details are shown in Table 4.

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[11] A GDP deflator measures the change in price of all domestically produced goods and services by dividing an index of GDP measured in current prices by a constant price index of GDP. A GDP deflator is used instead of CPI because it is assumed that the inflation of MAR construction costs is related more closely to changes in GDP than to consumer price changes. GDP deflator values are taken from IMF website. See the link below. The GDP deflator for India was obtained from the Indian Reserve Bank website.
http://data.imf.org/?sk=5DABAFF2-C5AD-4D27-A175-1253419C02D1&ss=1409151240976

[12] It was not possible to standardise operating costs across the schemes because of incomplete information about the year or years in which operating costs were collected

[13] https://www.imf.org/external/np/fin/data/rms_mth.aspx?SelectDate=2017-03-31&reportType=REP

[14] A factor of PPP at time of construction of scheme was applied. Data for the factor was obtained from the following Link: https://alfred.stlouisfed.org

Table 4: Illustrative example of calculation of MAR costs (Scheme 01-ASR-NL-ND)

STEPS	Description of variable	Unit	Cost/number	Source and Description
1	Total capital cost (LCU) at the year when scheme was constructed (2012)	Local Currency Units (Euro)	Euro 270,552	Data collected from MAR schemes
2	Index in 2012	Index	101.56	IMF GDP deflator for Netherlands https://www.statbureau.org/en/eurozone/inflation-calculators?dateBack=2012-6-1&dateTo=2016-12-1&amount=1 GDP Deflator = Index in 2016/ index in year scheme was built
3	Index in 2016	Index	104.24	
4	Apply GDP deflator	Ratio index 2016/index 2012	1.0264	
5	Total capital cost euros indexed	Euros	Euro 277,693	Total capital cost x GDP deflator (source: IMF) to bring cost to 2016 LCU value
6	Exchange rate	Euro/US$ Dec 2016	1.0541	Source: IMF https://www.imf.org/external/np/fin/data/rms_mth.aspx?SelectDate=2017-03-
7	Indexed total capital costs	(US$)	US$ 292,716	Indexed total capital cost in LCU x LCU/US$ exchange rate Source: IMF
8	Water recharged (m^3) per year	m^3	67,256	Data collected from MAR schemes through personal communication
9	Capital cost/ m^3	US$/$m^3$	US$4.35	Cost in step 7 divided by water injected per year in step 8
10	Annual operating cost	Euro	Euro 12,000	Data collected from MAR schemes
11	Indexed average operating cost	US $ 2016	12,649.20	Same steps as applied for capital costs
12	Discount rate	%	6.67%	Discount rate determined from http://depreciationrates.manager.io/ Water assets last viewed on Nov 16, 2017
13	Operating life	Years	30	Life of MAR scheme before redevelopment http://depreciationrates.manager.io/ water assets last viewed on Nov 16, 2017
14	Capital recovery factor (CRF)	Decimal	0.0779	CRF= $[r(1+r)^n]/[(1+r)^n-1]$; n = useful life (in years); r = discount rate http://pacinst.org/publication/cost-alternative-water-supply-efficiency-options-california/ last viewed on Nov 16, 2017
15	Levelised cost	US $/m3 (2016)	0.53	Levelised Cost = [(capital cost × CRF) + annual O&M costs + R&R costs]÷ average annual recharged/recovered in m^3

For each scheme the original unadjusted data for total capital and annual operating costs, the adjusted capital and operating costs, total water recharged, capital and operating cost per cubic metre water

Table 5: Costs of MAR schemes

Scheme code name[15]	Total Capital Cost ('000 LCU built year)	Annual Operating cost ('000 LCU 2016)	Capital cost (US$'000 2016)	m^3 recharged/ year '000 m^3/ year	Capital Cost/ m^3 recharged (US$ 2016)	Operational Cost/ m^3 recharged (US$ 2016)	Levelised cost/m3 Recharged (US$ 2016)
02-ASR-NL-FM	Euro 52.58	Euro 5	56	6	9.35	0.85	1.58
01-ASR-NL-ND	Euro 270.55	Euro 12	293	67	4.35	0.19	0.53
10-IB-AU-IBWA	A$ 550.00	A$ 36	403	29	14.14	0.93	2.03
16-IB-NZ-HN	NZ$ 975.00	NZ$ 138	682	4,000	0.17	0.02	0.04
11-IG-AU-PL	A$ 1,860.31	A$ 2,304	1,363	1,825	0.75	0.91[16]	0.97
21-ASR-US-FL	US$ 2,829.00	US$ 376	3,349	6,908	0.48	0.05	0.09
18-ASR-US-KR	US$ 3,000.00	-	3,393	3,661	0.93	-[17]	0.07
06-SPD-US-LSC	US$ 3,900.00	US$ 7,049	5,345	51,800	0.10	0.14[18]	0.14
05-SPD-US-HM	US$ 5,470.00	US$ 5,910	7,078	43,200	0.16	0.14	0.15
07-SPD-US-PMR	US$ 10,159.00	US$ 5,091	14,459	37,000	0.39	0.14	0.17
04-SPD-US-AF	US$ 10,750.00	US$ 4,100	14,406	30,800	0.47	0.13	0.17
08-SPD-US-SMR	US$ 11,020.00	US$ 4,309	11,972	30,800	0.39	0.14	0.17
12-SAT-AU-AS	A$ 14,171.52	A$ 962	11,608	600	19.35	1.16	2.67
09-SPD-US-TD	US$ 18,642.00	US$ 24,434	22,067	185,000	0.12	0.13	0.14
19-ASR-US-EPWU	US$ 33,635.00	US$ 3,958	38,037	13,817	2.75	0.29	0.50
13-ASR-AU-BLSA	A$ 34,300.00	A$ 3,370	25,137	9,000	2.79	0.27	0.49
03-RBF-IN-HD	IRS 112,000.00	IRS 101,240	13,529	-	-	-	-
15-GR-AU-BYWA	A$ 124,600.00	A$ 16,908	91,753	14,000	6.55	0.87	1.38
14-ASTR-AU-AG	A$ 212,165.00	A$ 7,148	154,513	7,650	20.20	0.68	2.25
17-ASR-US-SAWS	US$ 238,000.00	US$972	269,147	82,900	3.25	0.01	0.26
20-ASR-US-OR	US$ 626,741.11	US$ 18,391	722,667	294,486	2.45	0.06	0.25

15 Scheme details are shown in Table 1
16 Operating and maintenance cost includes 1.25 million of Environmental monitoring program, 0.20m of maintenance cost. Therefore, operating and maintenance cost is more than Capital cost.
17 Included in council costs, exclusive cost data not available
18 Includes water charges, hence, operating cost is higher than capital cost

recharged and indicative levelised cost are shown in Table 5. Operating costs are the most recently available annual cost figures[19].

Results and discussion: factors that influence the costs of MAR schemes

The following section contains an analysis of the factors that influence the costs of the 21 MAR schemes that are included in this analysis. The costs of MAR schemes are represented by the cost per m^3 water recharged and stored underground, and the cost per m^3 of water recovered in schemes where recovery takes place. Scheme costs generally include all of the capital and operating costs but a few schemes have relatively low costs compared to other comparable schemes because some costs such as water treatment, land, conveyance or distribution are accounted separately and/or provided free or at subsidised prices.

Overall the main factors that determine the relative costs of MAR schemes are the type of aquifer recharge and recovery technology used in the scheme and the source of water, which is linked to the end use of the scheme and the consequent amount of water treatment required. Other significant factors that affect scheme costs include the range of objectives schemes have to meet, scale of the scheme, scheme frequency of utilization and operating period, life expectancy of schemes, and hydrogeological setting including soil and aquifer characteristics. The general level of income in the region where the scheme is located is also significant since many costs, especially operating costs, are determined locally. These findings are elaborated in the following sections.

An Overview of Costs of MAR Schemes by MAR type

An overview of the recharge costs of 21 MAR schemes classified into the two MAR types and two water source types is presented in Table 6[20]. Table 6 shows the capital and operating cost (in US dollars 2016) of recharging one cubic metre (m^3) of water under different MAR types and water sources. The bank infiltration scheme (Haridwar) is excluded because there is no cost for water recharge.

Table 6 Average MAR scheme costs, by MAR type

MAR Scheme Type/ Water Source	Capital cost/ m^3 recharged	O&M cost/ m^3 recharged	Levelised cost (US$/$m^3$ recharged)
Recharged wells / recycled water (4 schemes)	$ 8.07	$ 0.53	$ 1.16
Infiltration basins / recycled water (3 Schemes)	$11.41	$ 0.84	$ 1.89
Recharge Wells/ natural water (5 schemes)	$ 3.29	$ 0.19	$ 0.45
Infiltration Basin / natural water (8 Schemes)	$ 0.77	$ 0.13	$ 0.19

[19] For Scheme 20 ASR-OR-US which has experienced several stages of development average annual operating costs were used.

[20] An average of costs from 11 MAR schemes in Florida is included and presented as a single scheme.

The data presented in Table 6 show that schemes using natural water have much lower costs than schemes using recycled water, and infiltration/spreading basins using natural water have the lowest recharge costs. In summary, there is a wide range of costs depending on the objectives and characteristics of individual schemes. These results must be treated with caution because of the small number of schemes in each category (especially infiltration and spreading basins using recycled water), but give some indication of the differential cost of recharge between different MAR types. Data on the costs of water recovered is not presented because it is not available for sufficient schemes to allow meaningful comparisons between categories.

Infiltration and Spreading basins (source natural water)
Six infiltration and spreading basins from Arizona and two from elsewhere were included in this study. The Arizona schemes satisfy regulations that require long-term water banking for drought mitigation and future use (Megdal et al 2014). These schemes do not include costs of water recovery via existing infrastructure which reduces reported costs. The costs of land and basin construction are important factors that contribute to the costs of these schemes. The more expensive schemes include the cost of land while the cheaper schemes obtain land free from local authorities. Land size, basin depth and water recharge rates also influence the relative costs of these schemes. Water and electricity are important elements of operational costs, schemes based on gravity feed are cheaper than those where electrical pumping is required. The cost of cleaning basins (including the impact of temporarily decommissioning the basin during cleaning and drying) is also significant.

Infiltration and spreading basins (source recycled water)
This category includes schemes infiltrating and recovering recycled wastewater using infiltration basins or galleries. These schemes have relatively high costs compared with infiltration of "natural" waters because of the need to treat the water so that the practice is safe and sustainable. In this study, this is the category with the highest average unit costs for recharging water related to the cost of land, level of treatment or conservative assumptions about the need to periodically reform basins. Factors influencing costs include the costs of constructing and maintaining basins, water distribution and treatment facilities, pumping costs, and environmental approvals and monitoring. Infiltration basins using recycled water have to be decommissioned for cleaning more often than basins using natural water, which increases the costs of water supplied from these facilities. The Alice Springs scheme includes allowance for costs of completely rejuvenating infiltration basins every 10 years.

Recharge Wells – Aquifer Storage and Recovery (ASR) and Aquifer Storage Transfer and Recovery (ASTR)
ASR/ASTR schemes are relatively costly compared to surface spreading methods, because of more elaborate and expensive infrastructure. These schemes require drilling of wells, and water treatment plant and other ancillary structures. The treatment required to avoid clogging of wells is higher than required for basins because wells have a much smaller aquifer contact area than basins and the attenuation capacity of the vadose zone has been bypassed. ASR/ASTR schemes based on reclaimed or recycled water require water treatment and involve rigorous environmental approvals and monitoring. The impact of water treatment on costs is examined in "Hydrogeological setting; soil and aquifer characteristics".

Bank Filtration

The Haridwar project in India has relatively low costs because of the extent of the scheme and high recharge volume. This scheme spreads over 6 hectares. This scheme has been operating since 1965. There is no cost for this river bank infiltration. The only cost is water recovery, which involves flood resistant well heads (Sandhu et al 2017)

Other factors that influence MAR scheme costs

Source and end use of water - water treatment costs

While some MAR schemes can access clean surface water or groundwater for recharge, the costs of treating water prior to recharge and/or use is one of the largest cost elements of many MAR schemes. The two main factors that influence treatment costs of MAR schemes are the source of water recharged into aquifer storage and the end use of water abstracted from storage. River water often carries sediments that need to be filtered before recharge to avoid clogging of infiltration basins or bores. Groundwater may require desalination or filtration to remove pollutants. Recycled storm water and wastewater can be partially cleaned during recharge and storage but may require additional treatment in order to meet standards for drinking and agricultural water use. (e.g. NRMMC, EPHC, NHMRC (2009)) Some of the highest cost schemes involve recharge or injection and recovery of recycled storm water or wastewater but these can still be substantially cheaper than alternative water supplies.

The range of objectives that a scheme has to meet

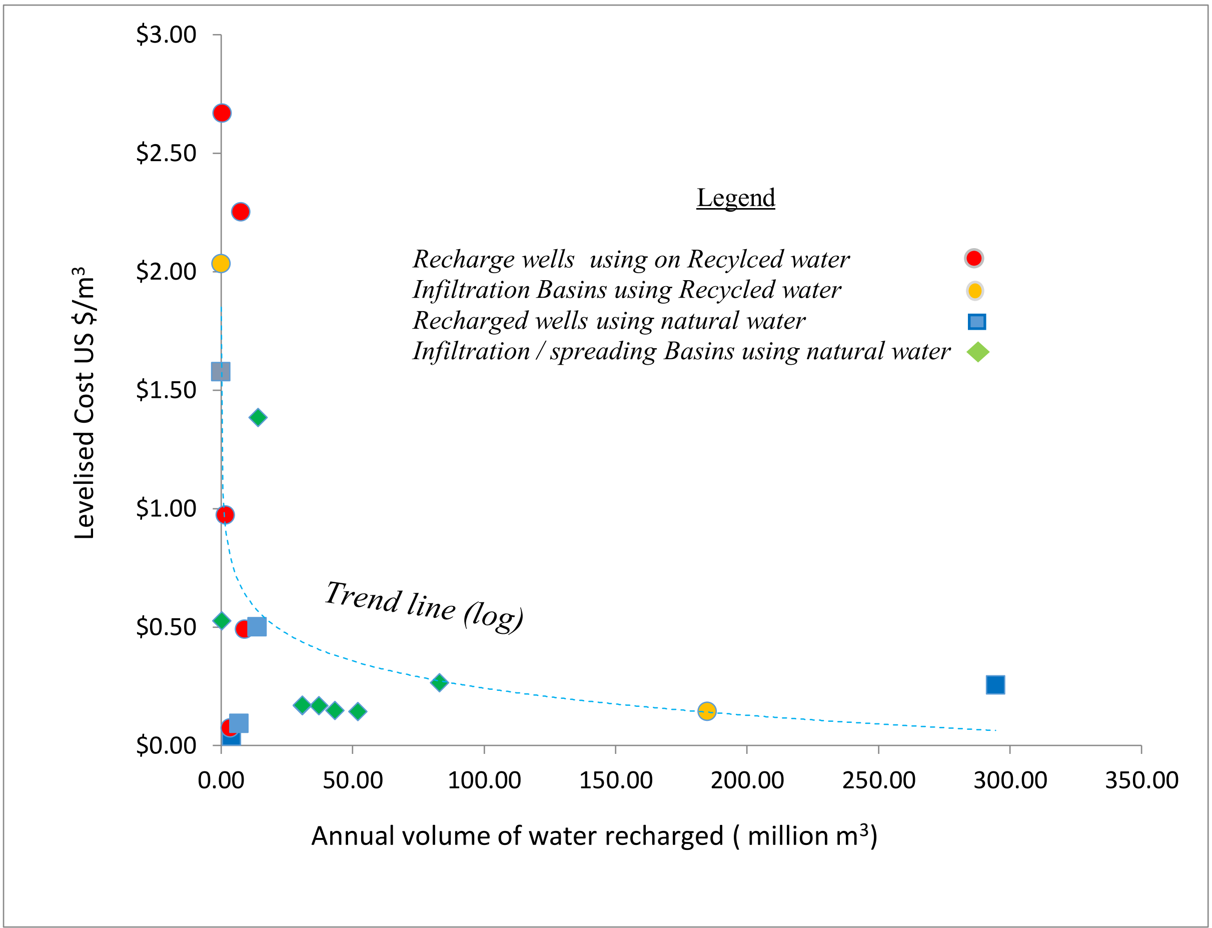
The objectives of MAR schemes are highly heterogeneous and include replenishment of groundwater, maintaining groundwater dependent ecosystems, water treatment, and supply of drinking water and agricultural water. Many ASR installations have seasonal storage as one objective, and also have other objectives such as water banking or emergency storage (Pyne 2005). Schemes with multiple objectives tend to require larger capital inputs and more infrastructure.

For example, the San Antonio Water System (17-ASR-US-SAWS) Project in Texas pumps surplus water from the Edwards aquifer to the Carrizo-Wilcox aquifer and stores it underground for drought management and emergency relief to sustain municipal users in San Antonio and address downstream environmental and other concerns during dry periods. This scheme has a recovery capacity of 227,000 m^3 per day (60 MGD) and has 29 high-capacity ASR wells, three wells pumping water from the Carrizo aquifer and a facility to treat Carrizo groundwater (MAR water only requires disinfection before use). In this case the unit capital cost of recovery capacity ($\$/m^3$ per day) is an appropriate metric to measure performance. The unit cost of recovery capacity, including design and permitting costs, wellfield facilities and wellfield mitigation program is \$ 360/m^3 per day (Texas Water Development Board 2011).

Scale of the scheme

Large schemes might be expected to benefit from some economies of scale leading to relatively lower unit costs of water recharged and recovered than comparable smaller schemes. Figure 1 plots the levelised costs per m^3 recharged against annual m^3 recharged and indicates that there is some tendency for the levelised costs of infiltration to fall as the scale of infiltration increases.

Figure 1: Levelised cost of infiltrated water compared to quantity of infiltrated water[21]



Scheme operating periods and frequency of utilisation

Some MAR schemes are established to provide a guaranteed supply of water for peak periods of use or as a contingency against extreme circumstances such as droughts. In these schemes recovery and in some cases recharge only takes place for a small number of days. Average cost per m^3 of water recovered may appear very high, but is still relatively cheap compared to other options such as surface water storage or desalination. One example included in this study is the SAWS scheme, discussed above. A further example in the USA is Wildwood, Cape May, New Jersey. They recharge water from an inland wellfield at a low rate into a coastal brackish aquifer for about 11 months per year, then recover most of it at a high rate over the July 4 Independence Day Weekend when many New Yorkers spend the weekend at Cape May. Water demands quintuple for about five days each year. A MAR unit cost in terms of US\$/m^3 recovered would be extremely high (since the volume recovered is relatively small), appearing to justify capital investment in a seawater desalination plant if the required supply rate is ignored. However, comparison in terms of US\$/m^3 per day of recovery capacity gives a much lower relative cost, justifying the use of MAR at Cape May since 1969 (Pyne 2016, personal communication).

Hydrogeological setting; soil and aquifer characteristics

Soil and aquifer characteristics affect recharge rates which are often reported to be an important driver of MAR performance and costs. Coarse-grained sand and gravel allow relatively fast recharge compared to fine-grained soils and result in lower costs per m^3 water recharged. A threshold

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One (1) scheme i.e. 3-RBF-IN-HD is not included because cost of infiltration is zero. Trend line (log scale) cannot be drawn using a zero value.

infiltration rate when infiltration basins become viable can be calculated, for example in the Lower Namoi region of Australia Basin infiltration becomes economically viable in areas with floodwater infiltration rates of 0.2m/day or more (Dillon and Arshad 2016).

Some MAR schemes are subject to losses because stored water is subject to movement during storage or mixing with brackish native groundwater and it is not possible to recover 100%. Factors affecting recovery efficiency are presented by Ward and Dillon (2011). The loss factor varies from scheme to scheme. In some schemes such as 10-IB-AU-IBWA, it is estimated to be 80% or more. In other schemes in Florida, Orange County, Texas and the Netherlands, it is estimated to range from 50-60%. At a brackish aquifer ASR site in Salisbury, South Australia, freshwater storage depreciation rate was demonstrated to be 15% per annum due to mixing and advection (Clarke et al 2015). The significance of losses for storage varies according to how long water needs to be held in storage before it is recovered. The percentage recovery rate from storage can have an important influence on scheme productivity and the costs per m^3 recovered.

Well yields are also reported to be an important driver of ASR performance. For example, the Texas Water Development Board reports that well yields are the main explanation for the range of capital costs per day of recovery capacity between US$ 132 and 528 per m^3 per day[22] for 0.23 Mm^3 recovery capacity (Texas Water Development Board 2016). The data in this study did not allow a good evaluation of the impact of well yields, and this deserves further examination in future studies.

Additional factors not covered in this study
There are a number of socio-economic, environmental legal and institutional factors that may influence MAR scheme costs which are not discussed in this study because of lack of data. The labour costs of MAR schemes will be inflated when there is lack of trained people with capacity to manage MAR projects. It is necessary to gain community acceptance of water sourced from MAR schemes. This is possible if the cost is not prohibitive and communities are given the opportunity to learn about the benefits and risks of MAR (Alexander 2011, Leviston et al 2013). The impacts of MAR schemes on water quality and the environment are not assessed in this study. The Australian Guidelines for Water Recycling: Managed Aquifer Recharge provide guidance on the management of health and environmental risks of MAR (EPHC, NRMMC AHMC 2009). Legal and institutional barriers such as the absence of ownership rights over water recovered from underground storage and the lack of accounting for evaporative loss from surface water storage can also affect the economic assessment of MAR schemes (Ross 2014, 2017, Ward and Dillon, 2011). These factors can be examined in future studies.

Conclusions and priorities for further work
MAR schemes are highly heterogeneous with a wide range of types, objectives and sizes. Although this complicates comparisons between schemes it is still possible to draw some conclusions about major factors that affect scheme costs.

The costs of MAR schemes vary substantially between MAR types. Schemes recharging unconfined aquifers using infiltration basins with untreated water are relatively cheap. Schemes using wells and / or advanced water treatment are relatively expensive.

In some cases water requires substantial and costly treatment before recharge and recovery, especially urban storm water and recycled water. Despite the expense, storm water and wastewater recycling offers lowest cost opportunities for improving water security and supplies when natural surface water and groundwater is scarce.

[22] \$0.50 and \$2.00 per gallon per day

MAR scheme costs are influenced by the range of objectives that the scheme has to meet. Some schemes are established to provide guaranteed supplies of water for peak periods or as a contingency against extreme circumstances. In such cases costs of recovered or recoverable water may be high but are still cheaper than alternatives. (Dillon and Arshad 2016; Pyne 2005)

Soil and aquifer characteristics which affect infiltration rates, and well yields can also have a major influence on MAR scheme costs, but it was not possible to thoroughly assess the effects of these variables in this study. Project operating periods and losses from storage also have a significant impact on relative scheme costs.

There are several priorities outlined below for further work on the comparative costs of MAR schemes. Collection of time series data on operating costs would enable more accurate calculation of levelised cost of water supply. Additional disaggregation of capital and operating costs would enable further analysis of the factors affecting cost differentials between schemes.

Inclusion of a wider range of studies, including a greater number of schemes from developing countries - would give a more representative picture of global MAR schemes - including rainwater harvesting and in channel modification which are not represented in this study. Many MAR schemes in developing countries use low-cost technologies and cheap water sources such as rainwater harvesting with untreated water and in channel modification.

A wider range of studies would also enable comparison of MAR schemes within particular categories, such as comparisons between infiltration basins using different sources of water and/or with different infiltration rates, and comparisons between projects using similar technologies but with different well yields. It may also allow more systematic comparison of MAR with alternative water supply, water security, water quality improvement and aquifer protection options.

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