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PAPER

Sixty years of global progress in managed aquifer recharge

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Abstract
The last 60 years has seen unprecedented groundwater extraction and overdraft as well as development of new technologies for water treatment that together drive the advance in intentional groundwater replenishment known as managed aquifer recharge (MAR). This paper is the first known attempt to quantify the volume of MAR at global scale, and to illustrate the advancement of all the major types of MAR and relate these to research and regulatory advancements. Faced with changing climate and rising intensity of climate extremes, MAR is an increasingly important water management strategy, alongside demand management, to maintain, enhance and secure stressed groundwater systems and to protect and improve water quality. During this time, scientific research—on hydraulic design of facilities, tracer studies, managing clogging, recovery efficiency and water quality changes in aquifers—has underpinned practical improvements in MAR and has had broader benefits in hydrogeology. Recharge wells have greatly accelerated recharge, particularly in urban areas and for mine water management. In recent years, research into governance, operating practices, reliability, economics, risk assessment and public acceptance of MAR has been undertaken. Since the 1960s, implementation of MAR has accelerated at a rate of 5%/year, but is not keeping pace with increasing groundwater extraction. Currently, MAR has reached an estimated 10 km^3/year, ~2.4% of groundwater extraction in countries reporting MAR (or ~1.0% of global groundwater extraction). MAR is likely to exceed 10% of global extraction, based on experience where MAR is more advanced, to sustain quantity, reliability and quality of water supplies.

Keywords Managed aquifer recharge · Artificial recharge · Review · Water banking · History of hydrogeology

Introduction

Over the last half of the twentieth century, rotary drilling, submersible pumps, electricity distribution, population growth and concentration in urban areas, the need for increased food production, pursuit of rural incomes and avoidance of famine have all conspired to elevate the value of groundwater as an essential resource (OECD 2015). Groundwater exploitation has grown at a rapid rate, and has challenged human capability to sustain the resource, and where climate is drying the challenge has intensified. Managed aquifer recharge (MAR), used to enhance the quantity and quality of groundwater, is a term conceived by the British hydrogeologist Ian Gale, who was the founding co-chair of the International Association of Hydrogeologists (IAH) Commission on Managing Aquifer Recharge from 2002 to 2011 (IAH-MAR 2018a). Managed aquifer recharge refers to a suite of methods that is increasingly used to maintain, enhance and secure groundwater systems under stress. River-bank filtration for drinking water supplies was well established in Europe by the 1870s and the first infiltration basins in Europe appeared in 1897 in Sweden and in 1899 in France (Richert 1900; Jansa 1952). However, 60 years ago, at the time of the formation of the IAH, human intervention to increase the rate of groundwater recharge such as drainage wells for flood relief, disposal of sewage water via septic tanks

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or seepage beneath surface-water irrigated crops, was generally unmanaged or incidental. Intentional recharge, then called artificial recharge, was rare but soon began being adopted at large scale in urban areas of California and New York in the USA, to arrest declining water levels.

Although hand dug wells and percussion drilling have been used for more than 2,000 years, the rotary drilling rig was first used in the 1880s and has evolved considerably, including reverse circulation, introduced in 1946. Also in the 1880s, the development of the AC transformer led to electrical energy distribution in the USA and Europe and ultimately reaching rural areas in developing countries through the course of the twentieth century. Then in 1928, Armais Arutunoff invented the electric submersible pump for the oil industry, whereby in the mid-1960s, this was adapted to pump water from deep wells and a disruptive technology had emerged. Until then, groundwater extraction for irrigation had been constrained by the rate at which oxen or mules could draw water from a dug well, the strength of the wind, or by the depth to which a centrifugal pump or extended shaft turbine pump could be installed. The combined availability of deep wells, electric power and electric submersible pumps radically escalated water withdrawal from aquifers and quickly reduced groundwater in storage. Between 1900 and 2008, 4,500 km^3 of depletion had occurred globally (Konikow 2011). Alarmingly, the depletion rate is still accelerating, reaching 145 km^3/year between 2001 and 2008 (Konikow 2011).

Although there is considerable uncertainty in estimates of annual groundwater exploitation and recharge, Margat and van der Gun (2013) report annual exploitation of groundwater of ~980 km^3/year in 2010, which is less than 8% of estimated global mean natural recharge (which exceeds 12,000 km^3/year; Margat 2008), but nonetheless causes substantial depletion in some areas. Hence, combining this information, groundwater storage depletion in aggregate constitutes only about 15% of groundwater extraction. The balance is composed of enhanced "natural" recharge due to steeper gradients in intake areas and reduced natural groundwater discharge with adverse consequences for surface-water resources and groundwater dependent ecosystems (Burke and Moench 2000). For comparative purposes, the global storage volume of modern groundwater is estimated at 0.8–1.9 million km^3 for groundwater aged 25–100 years (Gleeson et al. 2015) and constitutes less than 6% of the estimated total volume of groundwater. Residence time depends more on the natural discharge than groundwater extraction, but the minimum estimate for the global mean exceeds 250 years.

By contrast, the total surface-water storage in dams and lakes is two orders of magnitude smaller, 12,900 km^3 (from The World's Water 2002–2003 Data, Pacific Institute 2018), with residence times of typically a few years (average <3.3 years), giving an annual turnover of the order of 4,000–6,000 km^3. The decline in new large dams (i.e. typically >3 Mm^3 capacity; ICOLD 2018), since the 1970s (Fig. 1), represents increasing saturation and diminishing prospects as well as concerns over ecological impacts of dams, siltation of reservoirs and equity of benefits of communities downstream, particularly across political borders. It may also in part reflect the availability of alternative supplies such as desalination, which by 2005 had reached a capacity of 55 Mm^3/day (20 km^3/year; Pacific Institute 2018). In the USA, use of recycled water was reported in 2000 to be 3.6 km^3/year (7% of the sewage treated) and reuse was growing at 15%/year, and with locally high rates of recycling in Australia, Europe and the Middle East (Miller 2006); FAO estimated that 2,212 km^3 /year is released into the environment as wastewater in the form of municipal and industrial effluent and agricultural drainage water, with 80% of this untreated (UN Water

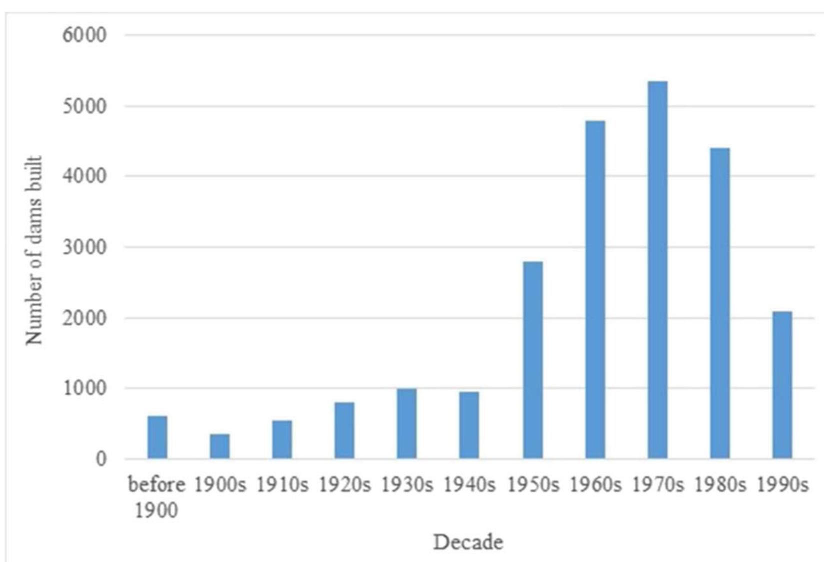

Fig. 1 Evolution of the global number of large dams built during the 20th Century (from The World's Water 2002–2003 Data; Pacific Institute 2018)

2017). The opportunities for improved treatment for more and safer reuse are very significant. Managed aquifer recharge downstream of existing dams, including through recharge releases, would offer conjunctive storage of water and the opportunity to increase dams' benefits with considerably lower financial and environmental costs than raising their height, which would also increase efficiency of water storage particularly in arid environments with low relief (Dillon 2016).

It is clear that for sustainable-water-resource utilization, stabilization of storage decline is important and there are only two means of accomplishing this for groundwater: reducing demand (through increased water use efficiency or conjunctive use with other water sources) or increasing replenishment (Dillon et al. 2012). In most locations, it is unreasonable to expect groundwater replenishment alone to reverse the impacts of excessive groundwater extraction (Dillon et al. 2009a). Managed aquifer recharge is a term for a wide and growing range of measures to support active management of groundwater resources at the local and basin level, to make more efficient use of water resources, assist conjunctive management of surface and groundwater resources (Gale 2005; Evans et al. 2012; Evans and Dillon 2018), to buffer against increasing intensity of climate extremes, particularly drought, and to protect and improve water quality in aquifers. While a few of these measures have been in use for millennia, many more have developed over the last 60 years, supported by a growing body of scientific knowledge and practical experience, fanned by the increasing pressures on groundwater systems.

This paper contains nationally aggregated estimates of annual recharge volumes and annual groundwater use. In addition, it includes global estimates of natural groundwater recharge, annual groundwater exploitation, annual volumes of desalinated and recycled water, accumulated groundwater depletion and total surface-water storage in dams and lakes. None of these quantities is subject to simple direct measurement, but the estimates rather are derived as the sum of a mix of data acquired in very different ways (including correlations and guesses) and finding different versions of the same statistic reported is not uncommon. Therefore, it has to be emphasized that the numbers shown, although being "best estimates", are subject to considerable uncertainty. The reason to show them nonetheless is that they help put the quantities of water involved in MAR in proper perspective.

Evolution of the practice of recharge augmentation

Over millennia, human endeavor has resulted in significant unintentional increases in recharge of aquifers. Typically, when forests or jungles were cleared for soil tillage, or crops irrigated with surface water, these actions have inadvertently increased groundwater recharge. Irrigation began in Egypt and Mesopotamia around 6000 BC by diversion of water from rivers, with dams and canals used from 3100 BC (Irrigation Association 2016). Watershed management interventions such as contour bunds and check dams have been used for millennia in the Middle East, Asia and South America to detain monsoon runoff, to defend against soil erosion and conserve water, and as a by-product, groundwater recharge increased. In the last half century, as agriculture has come to increasingly depend on groundwater, the resource value of the additional water has taken over as a significant driver for implementing these watershed measures, with soil conservation regarded as a co-benefit. In cities, unwanted leakages from water pipes and sewers have also recharged aquifers, since the time of the piping of the first water to cities (Sedlak 2014). Unintended and undesirable consequences of these deliberate actions include waterlogging, land salinization or groundwater pollution.

Unmanaged recharge describes where there is human intent to discharge waters into soil or aquifers but without consideration of the resource value of the disposed water, and often no thought of the impacts on groundwater quality. Stormwater drainage wells for example have been used since ~2000 years BC initially in ancient Persia (Burian and Edwards 2002). These were still being installed until the mid-twentieth century around the world, particularly in towns and cities sited on clay overlying karstic aquifers. Septic tanks are still being installed today, as a first step in village sanitation, but potentially concentrating pathogen and nutrient loads to aquifers and undermining public health where shallow wells are a source of drinking supplies. Similarly, municipalities and industries that dispose of wastewaters to sumps, injection wells or by irrigation without adequate pretreatment also pose a pollution threat.

Managed aquifer recharge is the intentional recharge of water to aquifers for subsequent recovery or environmental benefit (NRMMC, EPHC, and NHMRC 2009). The management process assures adequate protection of human health and the environment. Whereas formerly, the term "artificial recharge", has been used when the focus had been on augmenting the quantity of recharge, but with much less attention given to managing water quality, MAR means that both quantity and quality are managed effectively. As in many countries, in India where artificial recharge has been undertaken by government agencies since the 1970s, the focus has been on quantity with scant thought to water quality. It is proposed that those projects are termed "artificial recharge" until water quality is evaluated and groundwater is shown to be safe for its uses, or competently deemed so. Examples include where water recharged to unconfined aquifers is of the same quality as natural recharge, or where water quality is managed before recharge or on recovery to ensure public health and the environment are protected (Dillon et al. 2014a) and then such sites can be termed MAR (Table 1).

Table 1 Examples of groundwater recharge augmentation, showing evolution from unintentional to unmanaged and now MAR (adapted from NRMMC, EPHC, and NHMRC 2009)

Unintentional recharge enhancement	Unmanaged recharge (for disposal)	MAR (for recovery and/or environmental benefit)
• Clearing of deep rooted vegetation, or soil tillage • Spate irrigation • Irrigation deep seepage • Leakage from water pipes and sewers	• Stormwater drainage wells and sumps • Septic tank leach fields • Mining and industrial water disposal to sumps • Drainage water from construction pits	• Streambed channel modifications • Bank filtration • Water spreading • Recharge wells and shafts • Reservoir releases

Much of the development of MAR over the last 60 years has been in managing previously unmanaged recharge to improve water quality and to ensure recovered water is fit for use. In developing new techniques, fit for a wide variety of hydrological, hydrogeological and societal conditions, both quantity and quality have been improved. Initially source waters were natural waters in streams, lakes and other aquifers. These remain, despite anthropogenic influences on water quality, the largest source of water worldwide, recharged via streambed structures in monsoonal catchments in India or released from large water-supply dams in the USA for recharge via infiltration basins.

Since the 1990s, urban stormwater has been extensively harvested in South Australia, recharged and recovered via wells for public open-space irrigation, even though the storage aquifer was originally brackish. Risk assessment has been completed to enable stormwater drainage wells (unmanaged recharge) to be accepted as MAR to safely sustain groundwater-fed drinking-water supplies (Vanderzalm et al. 2014). Another source of water is dewatered groundwater, a by-product of mineral extraction, which is rapidly increasing in importance in some countries, with one example being the separate recharge of brackish and saline dewatering water for several iron ore mines in NW Western Australia to provide future mine water supplies and to protect a salina ecosystem (Fortescue Minerals Group 2011).

Since the 1970s, in California, treated sewage effluent has been stored and further treated in aquifers for subsequent use (Mills 2002). Similarly, since 2013 in Queensland, groundwater from dewatered aquifers in coal where coal seam gas (natural gas, methane) is produced, has been treated and stored in aquifers (APLNG 2012). Managed aquifer recharge gave the opportunity for these otherwise wasted waters to be considered as water resources, and in some cases paved the way for direct reuse. Evolution of treatment technologies has provided a springboard for new MAR applications. Aquifers previously too brackish for beneficial uses have been transformed into productive resources (e.g. Dillon et al. 2003).

Thermal desalination of seawater commenced in Kuwait in the mid-1950s and research investment during 1952–1982 by the US Office of Saline Water ($2 billion research in 2008 terms) facilitated the establishment of the reverse osmosis membrane industry. This matured further with continuing government and private research such that, between 1978 and 2006, improved permeability, membrane life and reduced membrane and energy costs were noted. These have increased productivity by a factor of 480 and have also advanced flash distillation and electro-dialysis techniques (UNESCO 2008). Additionally, advances in membrane technologies (Amy et al. 2017) have been a major factor in the increase in installed seawater desalination capacity to 20 km^3/year by 2005 with 75% of this occurring in the Middle East, where energy is cheap and freshwater is scarce. Groundwater recharge of the excess of supply over demand for desalinated seawater, notably in flash distillation as co-generation with electricity production, allows accumulation of reserves and improves resilience of water supply in areas with high evaporation rates. The Liwa groundwater storage reserve near Abu Dhabi, UAE, is a 50-Mm^3 example, for which Stuyfzand et al. (2017) report on water quality management.

Wastewater treatment to protect river water quality since the 1970s in USA, Europe and Asia, has made advances both in the number of plants and the level of treatment. In the early 1960s, Loeb and Sourirajan invented a cellulose acetate membrane for reverse osmosis (Visvanathan et al. 2000) enabling membrane bioreactors (MBR) to become viable in the early 1990s (Hai and Yamamoto 2011). In 2003, 66% of the worlds MBR plants were in Japan, 16% in North America, 11% in Europe, and 7% between Korea and China, with the largest plant then in Beijing producing at 80,000m^3/day. Growth in water reuse via aquifers has been primarily motivated by the need to cost-effectively secure high-quality water supplies by accumulating and drawing on buffer storages in aquifers in off-peak and peak times, seasonally or over years. The aquifer integrates existing wastewater and water infrastructure. Membrane treatments are generally well suited to maintaining flow rates in injection wells and infiltration basins and galleries, contribute to the range of pre-treatments for MAR, and complement the treatments that aquifers provide (Kazner et al. 2012).

Managed aquifer recharge overlaps with aquifer thermal energy storage (ATES) when water is seasonally recharged and recovered from aquifers via wells. There are many thousands of these systems in the Europe. Gao et al. (2017)

reviewed the performance of recent ATES systems and found energy savings of 40–90% compared with conventional sources and payback times were typically less than 5 years. The hydrogeological factors affecting efficiency were discussed by van Elswijk and Willemsen (2002) and Miotlinski and Dillon (2015). Interesting examples at municipal scale are found in the cities of Sapporo and Sendai in Japan where water from warm deep aquifers are pumped through pipes beneath footpaths and roads to melt snow and ice. As a result of groundwater depletion, the cooled water is now injected into shallow aquifers and in the summer this cool water is recovered and used in heat exchangers for air conditioning in buildings, then the warm water is reinjected into the deeper aquifer making the system sustainable (Yokoyama et al. 2002).

Quantifying the recent growth of MAR

The historical quantity of MAR is summarized in Table 2 as a result of most authors of this paper each taking responsibility for a geographic area. Generally, these estimates were produced by reference to documentation of individual projects with known starting dates and volumes, and closing dates when known, and aggregating these for incorporation into Table 2. Recharge volumes are reported as the average annual volumes for each decade to smooth out climatic variability. In most instances, recharge capacity is recorded, as relatively few sites publically reported actual annual volumes of recharge. The annual volume recharged is reported rather than volume recovered, as for water-banking systems, recovery is infrequent in comparison with recharge, and it is assumed that recharge and recovery are related over the long term.

India, the country with the most MAR capacity, has several million recharge structures (more than 500,000 in Gujarat alone; R. C. Jain, CGWB, personal communication, 2014) and 11 million more are planned (CGWB 2017), but has less than 30 structures where recharge has actually been measured and documented (Dashora et al. 2018). Information on aggregate detention capacity of streambed recharge structures and rainwater harvesting was found for Gujarat in 2012 (CGWB 2013). From studies that quantified recharge for structures with known capacities, the average ratio of mean annual recharge volume to detention capacity ranged from 1 to 2 (Dashora et al. 2018), and a conservative estimate of 1 was adopted here. For several other Indian states, aggregate numbers of recharge structures of different scales were recorded, and recharge volume was estimated using a triangular frequency distribution (that is, maximum frequency at the lower margin of each size range tailing linearly to zero frequency at the upper margin) and the same ratio for mean annual recharge to detention capacity. For states where capacities were not identified, the stated costs (CGWB 2013) of establishing recharge structures were compared with states where both capacities and costs were known and recharge volumes were estimated assuming the same ratios for detention capacity to cost and recharge to capacity. Indian programs to establish recharge structures commenced in the 1960s and government expenditure over different planning periods was known. It was assumed that the five reported states followed the national pattern, taking into account nongovernment programs that have continued since the 1960s.

Hence, the current and historical recharge estimates for India in Table 2 are for only five states that had sufficient documentation—Andhra Pradesh (includes Telangana which became independent in 2014), Gujarat, Jharkhand, Karnataka and Uttarakhand and are conservative. These states contain 18% of the national population and in 2009 accounted for 16% of national groundwater extraction (CGWB 2014). The total recharge for India could potentially be between 2 and 5 times the five-state estimated amount in 2015 (3.1 km^3/year), considering the sustained extensive but unquantified investment in recharge structures and rainwater harvesting in other states such as Haryana, Maharashtra, Madhya Pradesh, Rajasthan and Tamil Nadu (which, combined, have a further 32% of national groundwater extraction) but in the absence of factual data such estimates are currently excluded. Similarly in the USA, it is expected that MAR is under-reported in Table 2, because detailed data are limited to California and Arizona (Scanlon et al. 2016), although historical recharge in Florida, New York and Texas is included. In Germany, the Federal Statistical Agency provides summary information for public water supplies and about every 3 years since 1979 has identified the sources of water, which enables MAR including bank filtration to be quantified.

In other countries, MAR volumes are considerably smaller and estimates are derived from government reports, or more commonly by accumulating documentation of known MAR projects. The Global MAR Inventory Working Group (IAH-MAR 2018b) has consolidated information on the scope of 1200 MAR projects (Stefan and Ansems 2018) and anyone with quantitative information on other sites is invited to submit this via the MAR Portal (IGRAC 2018) to allow improved and more complete estimates in future.

Table 2 draws on many national sources of information. For some countries a national summary was produced by co-authors of this paper; the reports have been uploaded on the IAH-MAR web site (IAH-MAR 2018b) and provided with this paper as electronic supplementary material, ESM 1. These reports indicate the types of recharge, source waters used, purposes (such as water supply), subsidence prevention, and water quality improvement (such as in river-bank filtration), and describe novel practices. The table is not comprehensive, as a number of countries (reported and unreported) have known MAR facilities for which quantitative information was unavailable. Bank filtration is also accounted for

Table 2 Reported volume of MAR in 34 countries, areas or regions from the 1960s to 2015 (million cubic metres/year)

Country/region	Average annual MAR volume in the decade centred on date (Mm^3/year)						Annual gw use (Mm^3/year)[b]	MAR as % gw use	MAR as % of global reported capacity[c]	MAR vol growth (%/year[d])	gw use as % global use
	1965	1975	1985	1995	2005	2015[a]	2010	2015	2015	to 2015	2010
Austria	–	–	–	–	–	56	1,120	5.0%	0.6%	–	0.11%
Australia	79	144	185	213	257	410	4,960	8.3%	4.1%	3.6%	0.51%
Belgium	–	–	–	–	–	2.5	650	0.4%	0.0%	–	0.07%
China	20	23	23	24	56	106	112,000	0.1%	1.1%	3.6%	11.41%
Croatia	–	–	42	48	48	46	600	7.7%	0.5%	0.3%	0.06%
Czech Republic	–	–	–	–	–	22	380	5.8%	0.2%	–	0.04%
Denmark	–	–	–	–	–	0.25	650	0.0%	0.0%	–	0.07%
Finland	<1	30	35	50	55	65	280	23.2%	0.7%	9.3%	0.03%
France	20	21	26	30	31	32	5,710	0.6%	0.3%	1.0%	0.58%
Germany	–	867	766	875	765	870	3,080	28.2%	8.7%	0.0%	0.31%
Greece	–	–	–	–	–	0.3	3,650	0.0%	0.0%	–	0.37%
Hungary	–	–	–	–	–	335	370	90.5%	3.4%	–	0.04%
India (5 states only)	154	430	706	1,020	1,739	3,070	39,800	7.7%	30.9%	6.6%	4.05%
Israel	87	91	127	132	144	134	1,250	10.7%	1.3%	0.9%	0.13%
Italy	178	294	301	348	391	461	10,400	4.4%	4.6%	2.0%	1.06%
Jordan	4	9	9	13	19	20	640	3.1%	0.2%	3.5%	0.07%
Korea	–	3.7	12	46	91	146	3,800	3.8%	1.5%	10.4%	0.39%
Latin America	–	–	–	–	–	311	56,660	0.5%	3.1%	–	5.77%
Netherlands	181	240	255	241	275	262	1,600	16.4%	2.6%	0.8%	0.16%
Oman	0	0	0	6	–	84	840	10.0%	0.8%	9.9%	0.09%
Poland	–	–	–	–	–	143	2,590	5.5%	1.4%	–	0.26%
Portugal	–	–	–	–	–	9	6,290	0.1%	0.1%	–	0.64%
Qatar	<1	<1	<1	<1	37	44	260	16.9%	0.4%	8.4%	0.03%
Romania	–	–	–	–	–	7.4	630	1.2%	0.1%	–	0.06%
Serbia & Montenegro	–	–	–	–	–	9.5	580	1.6%	0.1%	–	0.06%
Slovakia	–	–	–	–	–	176	360	48.9%	1.8%	–	0.04%
Slovenia	–	–	–	–	–	9.5	190	5.0%	0.1%	–	0.02%
South East Asia	<1	<1	<1	<1	<1	5	29,270	0.0%	0.0%	–	2.98%
Southern Africa	1	2	6	6	7	10	4,500	0.2%	0.1%	5.1%	0.46%
Spain	3	8	12	60	350	380	5,700	6.7%	3.8%	10.9%	0.58%
Sweden	–	–	–	–	–	44	350	12.6%	0.4%	–	0.04%
Switzerland	–	–	–	–	–	100	790	12.7%	1.0%	–	0.08%
UK	0	0	0	5	5	5	2,160	0.2%	0.1%	–	0.22%

Table 2 (continued)

Country/region	Average annual MAR volume in the decade centred on date (Mm^3/year)						Annual gw use (Mm^3/year)[b]	MAR as % gw use	MAR as % of global reported capacity[c]	MAR vol growth (%/year[d])	gw use as % global use
	1965	1975	1985	1995	2005	2015[a]	2010	2015	2015	to 2015	2010
USA	302	494	768	1,218	2,026	2,569	112,000	2.3%	25.8%	4.7%	11.41%
Total	1,029	2,656	3,272	4,334	6,296	9,945	414,110	2.4%	100%	4.9%	42.2%
Global gw use	–	–	–	–	–	–	982,000	1.0%	NA	NA	100%
Total (km^3/year)	1.0	2.7	3.3	4.3	6.3	9.9	414.1	2.4%	100%	4.9%	42.2%

gw groundwater; – no reported data; *NA* not applicable

[a] Average annual MAR volume at 2015, based on 2011–2015

[b] Margat and van der Gun (2013)

[c] Global reported capacity is the sum of the volumes shown in this table for 2015

[d] Calculated compound growth rate from 1965 to 2015. If no data were available in 1965, data in the first year reported were used with the corresponding time duration to 2015 to calculate compound growth rate

inconsistently among European countries as reported by Sprenger et al. (2017), but where two estimates were available, the better supported estimate was used. Hence, the table is regarded as the best available conservative estimate of current national and global MAR, and its publication is intended to stimulate more rigorous reporting of MAR in future.

In the 50 years from 1965 to 2015, MAR capacity has grown from 1 to 10 km^3/year. The average annual growth rate was 4.5% for the 15 countries with reliable data in 1965 (Fig. 2) and those countries account for 34% of global groundwater use in 2010. Over the same period there was a 2.7% annual rate of growth in groundwater use for nine countries that account for two thirds of global groundwater use in 2010 (Margat and van der Gun 2013). Table 2 suggests that MAR increased by 0.5 km^3/year between 2005 and 2015 compared with the increase in groundwater use of 53 km^3/year between 2000 and 2010 for the nine reference countries reported by Margat and van der Gun (2013). Even relatively high growth rates in MAR are far from being an adequate solution to over-abstraction of groundwater. However, MAR is a management tool to consider with and complement new efficiency measures in irrigation, switching to low water use crops, conjunctive use of surface water and groundwater resources including substituting use of recycled water for groundwater, and foregoing extraction. Managed aquifer recharge viability depends on ranking the economics of these various options (Dillon et al. 2012) and social acceptance.

India (only estimated for five states) with 31% of reported global MAR capacity in 2015 and the USA (26%) account for the majority of the reported global MAR capacity. Germany ranked third with 9%, most of which is bank filtration for city water supplies that have been in use since before the 1870s (Sprenger et al. 2017). Other European countries and Australia also make modest contributions to the global total, with European contributions largely through bank filtration. Figure 3a summarizes the reported MAR volumetric capacity in 2015 by region, while Fig. 3b shows MAR capacity by region as a percentage of groundwater use in 2010 in only those countries or areas reporting MAR, as per Table 2. Although Asia, Europe and North America have the highest reported volumes of MAR there is enormous variability in MAR uptake within regions that is not explained by groundwater use alone.

Although the five states in India and the USA have high groundwater use, so do China, Latin America and South East Asia where MAR is not yet well established (Fig. 4), suggesting major opportunities for MAR in these regions. Preliminary investigations in heavily developed Chao Phraya basin of Thailand (Pavelic et al. 2012) and in the Ganges Basin of India (Pavelic et al. 2015) suggest that widespread MAR at basin scale could have a vital role in managing water variability and reducing water-related disasters (floods and droughts).

Countries with high MAR capacities in relation to groundwater use such as Germany, Italy, Hungary, and Netherlands, reflect significant long-term reliance on bank filtration in drinking water

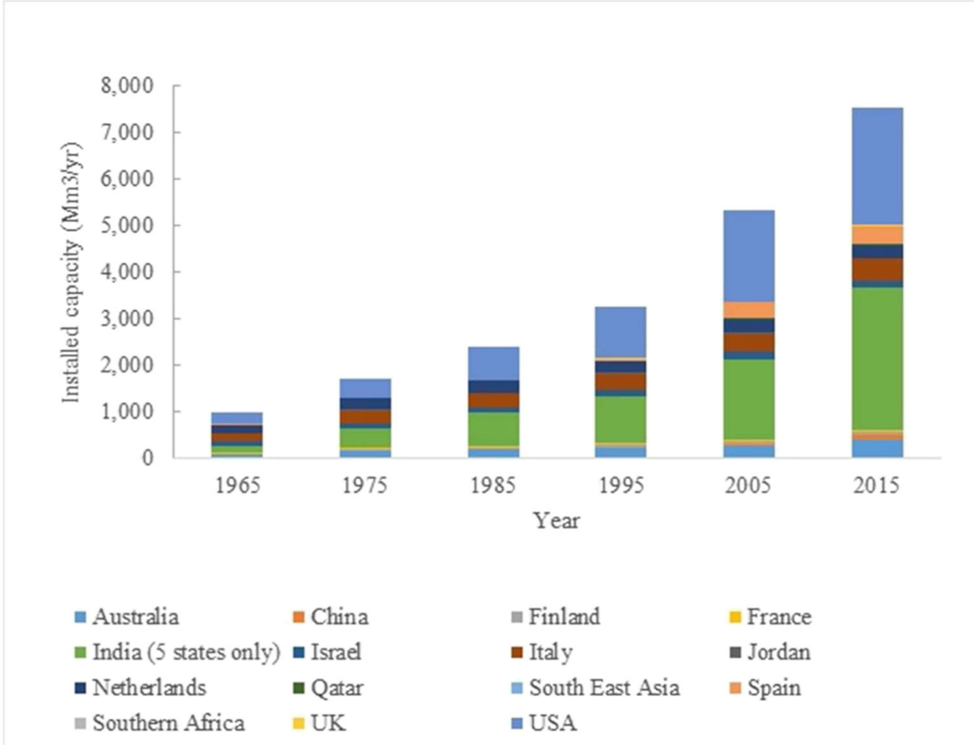

Fig. 2 International evolution of MAR capacity by decade from 1960s to 2000s and 2011–2015. This figure only includes the countries or regions where historical estimates from 1965 were available. These 15 countries/areas account for 76% of reported installed MAR capacity in 2015 and for 34% of global groundwater use in 2010. Bar stacks from bottom up follow the alphabetical order of countries as per the legend

supplies. Australia, with large MAR contributions from urban stormwater and mine water reuse, and Spain and Israel with large infiltration systems for agricultural irrigation, demonstrate growth in systems with diverse objectives. High recent growth rates (>8%/year) for MAR in Finland, Korea, Oman, Qatar and Spain show that MAR is relevant to a wide range of water-resource-management issues. The large variations in commencement and rate of uptake are thought to be more related to information exchange and capability development than to divergence of opportunities at national scales—Sprenger et al. (2017) reported considerable opportunities for uptake in Europe.

The proportion of national or regional groundwater use in 2015 that is contributed by MAR also has a wide range of values, for various reasons. Hungary and Slovakia (91 and 49%) were highest due to the historical dominance of bank filtration for urban water supplies. Other countries where bank filtration constitutes a significant proportion of groundwater use are Germany (28%) and Sweden (13%). Reporting of bank filtration varied among sites. In some cases the total annual groundwater abstraction adjacent to a stream was counted and in others this was scaled by the proportion of extraction that originated from the stream; for future consistency, the latter is recommended for reporting. In several other countries where MAR is commonly used for water quality improvement, there is also a sizable proportion of MAR to groundwater use: Finland (23%), Netherlands (16%), and Switzerland (13%). Among semi-arid to arid areas where recharge of natural water and/or recycled water is

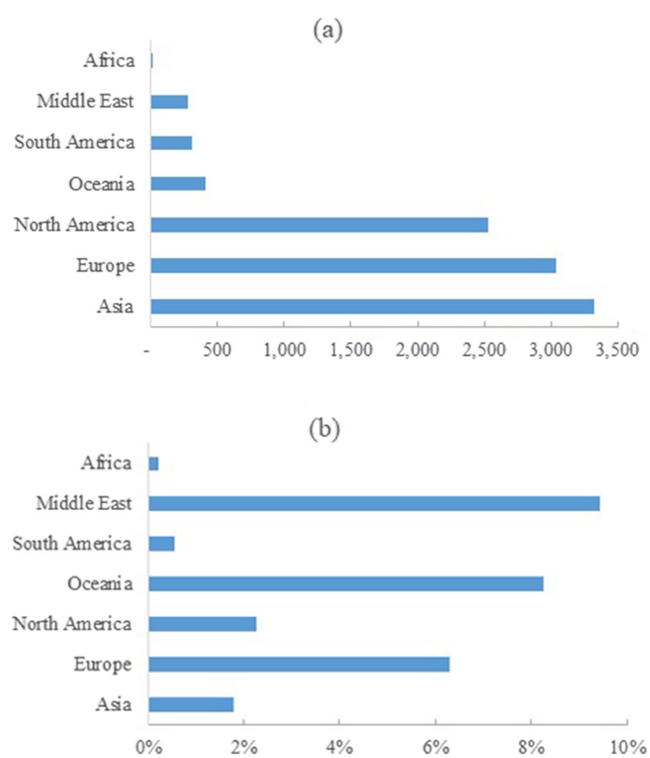

Fig. 3 Reported MAR capacity in 2015 by region expressed **a** volumetrically and **b** as a percentage of groundwater use (from Margat and van der Gun 2013) for reporting countries (or states) of each region: **a** by region (Mm^3/year); **b** by region as a percentage of groundwater use in 2010

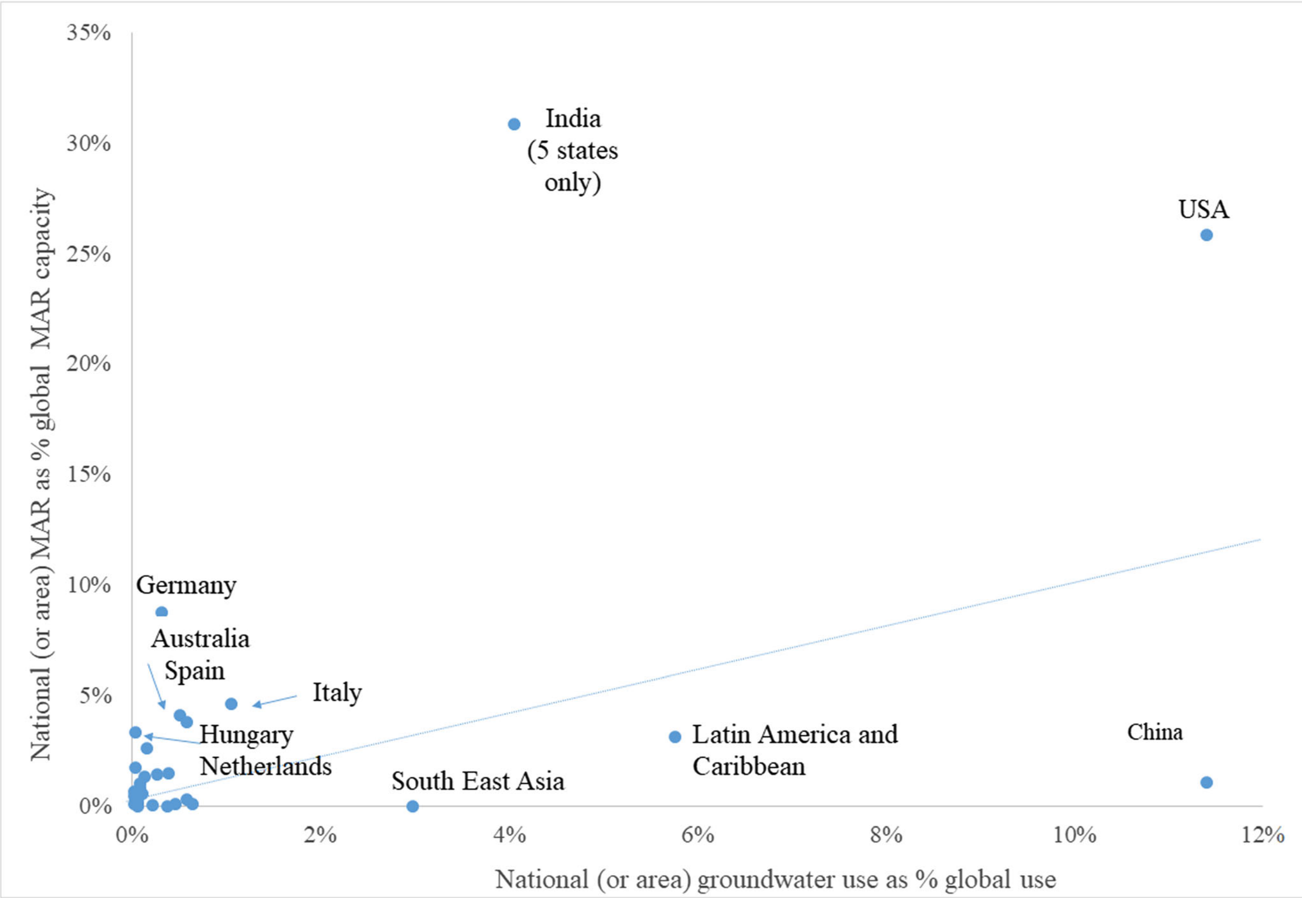

Fig. 4 National or areal MAR capacity as a percentage of reported global MAR capacity versus national or areal groundwater use as a percentage of global groundwater use

practiced, the ratio of MAR to groundwater draft varies: Qatar (17%), Israel (11%), Oman (10%), Australia (8%), 5 Indian states (8%), Spain (7%), Italy (4%) and USA (2.3%).

Notable for the very minor reported contribution by MAR and, where known, low growth rate, are Latin America and the Caribbean (0.5%), Southern Africa (0.2%), China (0.1%), and SE Asia (<0.1%). These regions cover a wide variety of climate, lithologies, and demand for drinking and irrigation water and groundwater stress (Stefan and Ansems 2018; Bonilla Valverde et al. 2018); thus, there is clearly significant potential for uptake of MAR.

Based on current application of MAR it is likely that the demand for MAR where groundwater systems are under stress would be of the order of 10% of water demand; hence the current status of MAR development (~10 km^3/year) is likely to expand to the order of 100 km^3/year. The rate of expansion will depend on having a sound understanding of the capabilities and constraints of the suite of techniques, effective risk management and knowledge of the economics of MAR in comparison with alternatives (Ross and Hasnain 2018).

Development of specific MAR techniques

A wide variety of methods are used for managing aquifer recharge, and they are addressed here in four broad categories—streambed channel modifications, bank filtration, water spreading and recharge wells; while a fifth category, runoff harvesting, used in the IGRAC MAR Portal, refers to any of these methods. The sequence followed here reflects the level of maturity of these approaches from oldest to newest, and the ramping up of research that has enabled these techniques to be refined or developed. Descriptions of the different recharge methods are given in Dillon (2005) and in Stefan and Ansems (2018) as used in the IGRAC MAR Portal (IGRAC 2018), through which all MAR projects may be reported. Figure 5 illustrates the way that the choice of MAR technique is influenced by the local hydrology, hydrogeology and ambient groundwater quality. A gallery of photographs and diagrams of various recharge techniques can be found in ESM2.

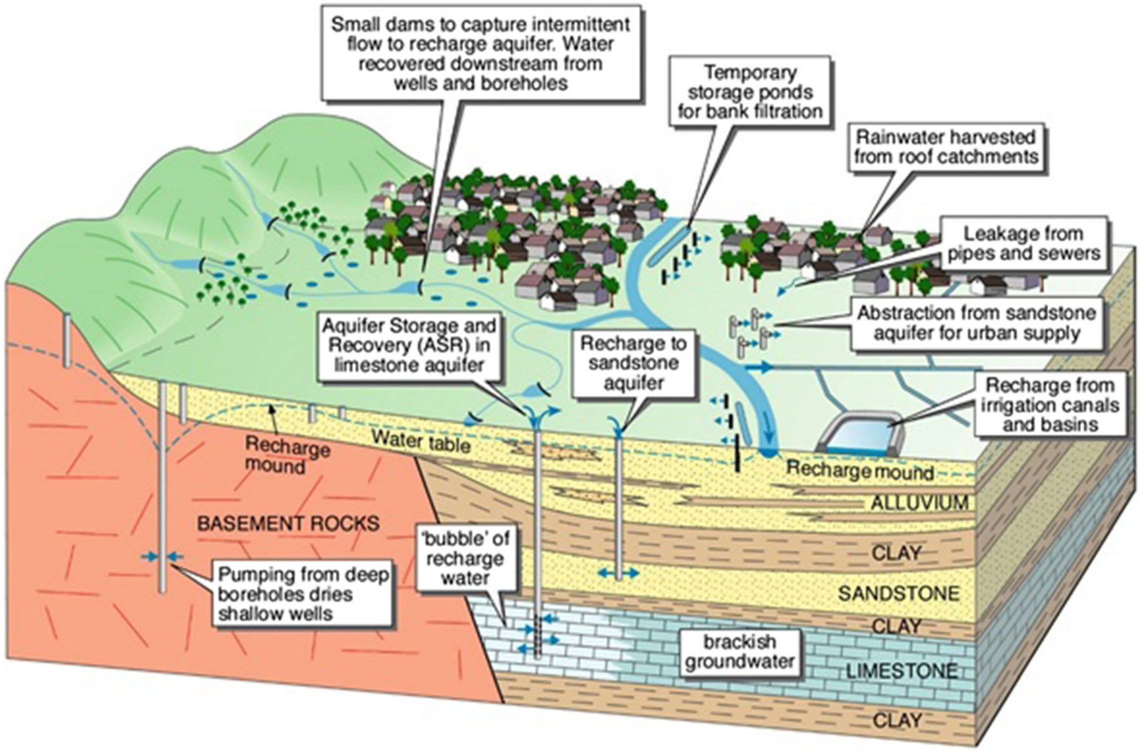

Fig. 5 Managed aquifer recharge is adapted to the local hydrology and hydrogeology, and is usually governed by the type of aquifer, topography, land use, ambient groundwater quality and intended uses of the recovered water. This diagram shows a variety of recharge methods and water sources making use 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 streambed structures, riverbank filtration, infiltration basins and recharge wells. (Adapted from Gale 2005, with permission in Dillon et al. 2009b)

Streambed channel modifications

The information on this earliest form of recharge enhancement is focussed on India, but no doubt also occurred in other semi-arid regions. Sakthivadivel (2007) reports that more than 500,000 tanks and ponds dispersed throughout India have been constructed and some are several thousand years old, as also reported for China (Wang et al. 2014). These have been used to detain surface runoff to supply water for drinking water and irrigation both directly and by infiltration to replenish aquifers. This focus is only on the infiltrated component. Gale et al. (2006) studied three streambed structures and recently Dashora et al. (2018) studied four and reviewed studies of 20 more revealing that infiltration rates from in-stream water detention are one to two orders of magnitude less than that reported for off-stream infiltration basins where flow and quality of water can be controlled. Structures need to be located in such a way that the streambed is scoured naturally by high flow, or else desilting will be required to conserve detention capacity and maintain infiltration rates. They also need to be located taking account of potential hydraulic connection with groundwater that reduces and even negates recharge, which can complicate assessment of recharge suggesting that several types of measurement methods and calculations be performed such as applied at an extensive drainage depression in southern India (Boisson et al. 2014) and Perrin et al (2012). The Indian government and NGO investment in percolation tanks to infiltrate detained monsoon runoff in drought prone areas has been enormous, and is projected to expand under an ambitious master plan for “artificial recharge” in India by a further 11 million structures in urban and rural areas at an estimated cost of US$10 billion (CGWB 2005, 2013).

The design of MAR structures has changed little since the 1960s when concrete check dams and spillways for percolation tanks were introduced and standardized through guidelines issued by state irrigation departments and the Central Ground Water Board (CGWB 2000, 2007). While there are many papers that conceptually evaluate positioning of streambed recharge structures in relation to geomorphic variables, there is a lack of field measurement and monitoring that would inform policies on MAR density within the context of catchment scale water sharing plans. Figure 6 shows a recent large-

Fig. 6 Ahin recharge dam on the Batinah Plain, Oman, constructed in 1994, is a large dam (crest length 5,640 m, crest height 8 m) with a detention capacity of 6.8 Mm^3. This is one of the 43 recharge dams, with an aggregated capacity of 95 Mm^3 constructed in Oman during the period 1985–2011 (Oman MRMWR 2012). Their purpose is to enhance aquifer recharge primarily to support irrigation; and also to protect the villages and agricultural land in the coastal zone against (previously) devastating flash floods. The dams intercept floods from a catchment with a mean annual rainfall less than 140 mm and potential evaporation around 2,000 mm/year. The detained water is released in a controlled way to recharge the aquifer zone downstream (Photo: Jac van der Gun, taken in 1995)

scale streambed structure, one of many in use in Oman, and more examples are given in ESM2.

Bank filtration

Bank filtration (BF) describes a natural process where surface-water infiltration is induced through nearby groundwater extraction. Bank filtrate can be extracted from dug, vertical or horizontal wells, drains or using other techniques. The raw water abstracted, e.g. from a production well, typically consists of a mixture of infiltrated surface water and groundwater recharged on the landside catchment. Statistics on use of bank filtrate are often not reliable because (1) there is no clear definition of the minimum travel time after which infiltrated surface water could be termed groundwater, as many water companies prefer to deliver seemingly safer groundwater to consumers, resulting in very modest reporting of numbers for BF; (2) the contribution of landside groundwater is often not known or not taken into account, resulting in the reporting of exaggerated numbers for BF. Furthermore, the term river “bank” filtration is often replaced by authors by the term river “bed” filtration to describe it more specifically (Milczarek et al. 2010) or not used at all if the abstraction scheme (e.g. drain pipe) is embedded in the riverbed. As bank filtration at most sites was and is a combination of bank and bed filtration, the term BF should be seen as a general term, which could be further subdivided into river (RBF), lake (LBF) and canal (CBF) bank (and/or bed) filtration, with RBF currently being the most commonly practiced method.

In Europe, BF systems have been in place at a large scale since 1870 (Jülich and Schubert 2001), providing about 50% of the public water supply of Slovakia and Hungary, 9% in Germany (Hiscock and Grischek 2002), 7% in Netherlands (Stuyfzand et al. 2006) and 25% in Switzerland (von Rohr et al. 2014). The city of Budapest (Hungary) is fully supplied with bank filtrate from the Danube River (Laszlo 2003) from 762 wells with a total maximum capacity of 1 million m^3/day. In the US, bank filtration systems have been in use for more than 60 years (Ray et al. 2002), including the world’s largest horizontal collector wells with single capacities of more than 150,000 m^3/day (Ray et al. 2003). Today in Europe, BF is mainly used for pre-treatment, the focus lying on attenuation of water quality variations and removal of turbidity, pathogens and organic compounds. In the US, India and Egypt, BF is mainly used to remove particles and pathogens. In some countries, including China and Italy, BF is used to prevent overexploitation of aquifers.

In the two decades following the founding of IAH, only a few publications on BF appeared in Europe, focusing on technical issues and removal of bacteria. Intensive investigations in Germany and Netherlands started after the pollution of the Rhine River by the Sandoz accident in 1986 (Sontheimer 1991) and with further development of analytical techniques for identifying trace organic compounds. In the US, RBF came into focus between 1990 and 2010 with the Environmental Protection Agency (EPA)'s Groundwater Under Direct Influence of Surface Water (GWUDISW) rules to ensure removal of pathogens (protozoa, viruses; e.g. Tufenkji et al. 2002; Weiss et al. 2005; Ray et al. 2003). Meanwhile, numerous studies have shown bank filtration to be effective in the removal and/or degradation of microorganisms, turbidity, pesticides, dissolved and total organic carbon, and organic micropollutants (e. g. Stuyfzand 1998b; Kuehn and Mueller 2000; Hiscock and Grischek 2002; Jekel and Grünheid 2005; Eckert and Irmscher 2006; Ray et al. 2003; Maeng et al. 2008; Hoppe-Jones et al. 2010; Lorenzen et al. 2010; Henzler et al. 2014; Hamann et al. 2016 and references therein).

A series of conferences and workshops on RBF was organized between 2000 and 2006 with significant support from IAH members. As a result, interest has been growing outside of Europe and the USA to implement RBF as an alternative to surface water abstraction, which faces the problems of turbidity, pathogens and increasing pollution (Ray 2008), especially in Asia. In India, a large potential for RBF was identified for the alluvial deposits along the Ganga River and various tributaries (Dash et al. 2010; Sandhu et al. 2011). Consequently, one EU-Indian and one German-Indian RBF project were started in 2005 and 2008, respectively, and the Cooperation Centre for Riverbank Filtration was established in 2007 at the RBF site Haridwar (India), which was recognized by the IAH Commission on MAR as a demonstration site in 2009. In 2011, the Indo-German Competence Centre on RBF was founded under the guidance of the National Institute of Hydrology, Roorkee, following the approval by the Indian Ministry of Water Resources. The EU-Indian project "Saph Pani" (2013–2015) included a work package on RBF (Wintgens et al. 2016). In parallel, South Korea became a leading country in Asia in constructing horizontal collector wells for RBF (e.g. Lee et al. 2009). In Thailand, a master plan for RBF was developed between 2011 and 2013 and potential areas were selected from the existing 25 river basins in the country (DGR 2013). In Vietnam, existing sites are under investigation as further use of RBF has to take into account disadvantages such as dissolution of arsenic (Postma et al. 2017) and advantages in combination with flood protection (Feistel et al. 2014). The Wakaf Bunut water treatment plant in the state of Kelantan is Malaysia's largest RBF scheme and it operates via a combination of RBF and ultrafiltration systems. The plant was commissioned in March 2013 and is capable of producing a maximum of up to 14,000 m^3/day (Chew et al. 2015). Othman et al. (2015) report on investigations at a new RBF pilot site in Sungai Perak, Malaysia, and Mauro and Utari (2011) on a pilot site on the Kurkut River in Indonesia.

Only a few BF sites are known from South America, probably as a result of sufficient (surface) water resources and information sharing limited to national journals. In English-language publications, the main emphasis was given to the removal of turbidity and bacteria (Garnica 2003; Blavier et al. 2014) and cyanobacteria (Freitas et al. 2012; Romero et al. 2014). In Australia, the potential for BF in semi-arid areas is limited, with major aspects reported including algae and brackish aquifers (Dillon et al. 2002).

In Egypt, a core group was formed in the major state water company to promote RBF along the Nile River according to the potential identified (Shamrukh and Abdel-Wahab 2008; Ghodeif et al. 2016)—an example is shown in Fig. 7. Beach wells are also used in Egypt to pretreat seawater before desalination (Bartak et al. 2012). Beach sand filtration is the abstraction of seawater via beach wells or infiltration galleries that are located along a seashore (Voutchkov 2005). Large seawater reverse osmosis plants are in operation at the Bay of Palma plant in Mallorca, equipped with vertical wells having a total capacity of 46,000 m^3/day (Ray et al. 2002), in Malta with a combined capacity of 190,000 m^3/day, and the Pemex Salina Cruz plant in North America, which uses three Ranney-type collector wells with a capacity of 15,000 m^3/day each (Voutchkov and Semiat 2008). Missimer et al. (2013) demonstrated the water quality improvements and economic efficiency of subsurface intakes for seawater reverse osmosis systems.

In countries where new BF schemes are planned, innovative methods for site assessment are needed to address major issues (e. g. Wang et al. 2016) such as induced clogging of river/lake beds (Hubbs 2006; Soares et al. 2010; Pholkern et al. 2015), prediction of attenuation rates and bank filtrate quality as well as further treatment requirements (Wintgens et al. 2016; AquaNES 2016; Sharma et al. 2012b). New technical developments are reported mainly from the US: drilling of angle wells for RBF at the Missouri River, use of an inflatable dam to enhance RBF at the Russian River (Ray et al. 2011) and construction of a tunnel with laterals beneath the Ohio River bed by the Louisville Water Company (Hubbs et al. 2003), finalized in 2011 and exceeding all known abstraction rates per km river length, leading to a high risk of riverbed clogging.

In countries with long-term BF scheme operation, recent issues and developments include: river hydrology and clogging (Martin 2013; Grischek and Bartak 2016), economic and/or technical optimization, modeling redox processes responsible for iron and manganese release and attenuation of micropollutants (Sharma et al. 2012a, b; Henzler et al. 2016), innovative sensing and management schemes (Rossetto et al. 2015), adaptation to changing conditions such as water demand and climate change (e.g. Gross-Wittke et al. 2010, Sprenger et al. 2011, Schoenheinz and Grischek 2011), measures to protect against flooding (Sandhu et al. 2018), and combination with sophisticated post-treatment techniques (AquaNES 2016)—more examples are shown in ESM2.

Fig. 7 Drilling of riverbank filtration wells at the Nile River, Luxor, Egypt, March 2018. Seasonal low river water level, frequent spills of oil and other pollutants and high turbidity during high flow cause problems in surface-water abstraction and subsequent treatment. A short distance between the abstraction wells and the river bank is sufficient to remove particles, to buffer spills and to ensure a high portion of bank filtrate and a low portion of manganese-rich land-side groundwater (Photograph courtesy of T. Grischek, University of Applied Sciences Dresden, HTWD)

Water spreading

Spate irrigation, where floodwater is spread to increase soil moisture for food production on otherwise dry cropping land, has been a widely practiced custom in semi-arid countries (Steenbergen et al. 2010), also unintentionally causing groundwater recharge. However, not until irrigation with groundwater became common in the twentieth century did the spreading of water intentionally in recharge basins begin to be used at scale. This scale-up was founded on two main strands of pioneering research initiated in Arizona (USA) with experimental tests and pilot projects in the 1960s and 1970s, and in Europe centred in the Netherlands.

In Arizona two research organizations carried out most of this work; the United States Water Conservation Laboratory (USWCL), a division of the United States Department of Agriculture, located in Phoenix, and the Water Resources Research Center (WRRC) at the University of Arizona in Tucson. In the mid-1960s, pilot recharge basins were constructed and operated by Dr. Sol Resnick (WRRC) at the foot of McMicken Dam in Phoenix. In 1967, the USWCL, under the direction of Dr. Herman Bouwer and with some assistance from the Salt River Project (SRP), constructed and operated the Flushing Meadows project, a pilot project that consisted of six long and narrow infiltration/recharge basins excavated in the bed of the Salt River. This project was followed in 1975 by the 23rd Avenue Recharge Project located adjacent to one of the city of Phoenix wastewater treatment plants. It had six recharge basins located on the north bank of the Salt River. The two USWCL projects' source water was treated municipal wastewater which was intermittently infiltrated via basins. These were operated principally to study and develop this form of water treatment and storage which became known as soil aquifer treatment (SAT).

Concurrently, the WRRC carried out research in MAR using both basins and wells. The passing of the 1980 Groundwater Act (Arizona) and the approaching completion of the Central Arizona Project Aqueduct to Phoenix in the early to mid-1980s contributed to the planning for the use of MAR to store the Colorado River (CAP) water. In 1978, the Salt River Project sponsored the first MAR symposium in Arizona. This symposium was followed by another in 1985 and from then on every 2 years. Recurring research themes were hydraulics, solute transport and modelling of MAR operations, causes and management of clogging, geochemistry of aquifer recharge, fate of pathogens and organics, and subsurface water-quality changes. There were also many case studies describing MAR projects, their role in integrated water management, economics, and progress in regulations and governance arrangements. In 1986, the Groundwater Recharge and Underground Storage and Recovery Act was passed by the Arizona Legislature (1994). This law defined the ownership of the surface water stored in the aquifer by managed recharge, and it also defined many other regulatory issues of MAR operations opening the way for the development of underground water storage facilities, mainly those storing CAP water. One of these was the city of Phoenix Cave Creek Recharge Project that would convert many of its production wells to dual-purpose injection and recovery wells to store part of its CAP water allocation. Injection and recovery of water using the same well is known as aquifer storage and recovery (ASR; Pyne 2005) and will be discussed later.

Commencing in 1986, the SRP working closely with several Phoenix area municipalities, and many members of the Arizona Municipal Water Users Association (AMWUA), planned for a large aquifer storage facility. This facility would store surplus CAP water—a site located in the dry bed of the Salt River downstream of SRP's Granite Reef Diversion Dam was selected. After several years of hydrologic, hydrogeologic, engineering and environmental studies at this site, the Granite Reef Underground Storage Project (GRUSP) obtained the necessary federal and state permits and started operating in 1994. Parallel to the efforts in Phoenix, the city of Tucson developed the Sweetwater Recharge Project to store a portion of its reclaimed water and tested one of their well fields to store treated CAP water. They followed by developing a large surface-water-spreading facility, the Central Avra Valley Recharge Project. Pima County and other water entities started planning, constructing and operating pilot recharge projects.

In the early 2000s, the Central Arizona Water Conservation District (CAWCD), now known as the Central Arizona Project (CAP), started constructing water-spreading recharge facilities in the Phoenix and Tucson areas and became the entity with the largest aquifer storage capacity. They presently own and operate four storage facilities in or near Phoenix and two in Tucson. The stored water in these projects is CAP water. To store their surplus reclaimed water and obtain credits for future reclaimed water uses, many municipalities in the Phoenix area developed their own MAR facilities. These are usually of small capacity using basins, with more entities introducing the use of vadose zone recharge wells because of land constraints. The SRP constructed and operates the New River Agua Fria Recharge Project (NAUSP) at the terminus of their canal system. This basin recharge facility commenced operation in 2008 and presently stores mostly reclaimed water from two municipalities and is also permitted for CAP water storage. The quantities of water derived from CAP and municipal wastewater was quantified in Arizona and resultant increases in groundwater levels recorded in these active management areas (Scanlon et al. 2016).

The GRUSP facility obtained a permit to store reclaimed water from the city of Mesa in 2007 and became a two-water-source-MAR operation. Aquifer storage and recovery, used by very few water utilities in Arizona, is employed when there are land limitations and also when there are unused production wells that can be retrofitted for recharge. The source water for the ASR wells is predominantly reclaimed water although some store treated and untreated CAP water. Most of the MAR facilities in Arizona are owned and operated by public utilities but there are a few with private ownership like the large MBT Ranch basin recharge facility located west of Phoenix. The increase in the direct use of CAP water has stopped the development of large capacity MAR projects in Arizona. Those municipalities which are fortunate to obtain a water right from a surface storage facility, like the town of Payson, will develop their own nonreclaimed water MAR projects; however, these will be very infrequent in Arizona's semi-arid climate. The majority of new MAR recharge facilities will be for the storage and recovery of reclaimed water. Figure 8 shows an example from Mexico that has been operating since 2007 (Humberto et al. 2018). A substantial research project on intermittent infiltration of treated wastewater (soil aquifer treatment) was undertaken by Fox (2006) and further work has progressed in Israel and Australia and is reported in Stuyfzand and Hartog (2017).

Infiltration basins were also in early use in California, commencing with dam diversions in 1928 to Saticoy spreading grounds north west of Los Angeles and used since 1954 in Orange County south of Los Angeles to assist recharge of water from the Santa Ana River and from tertiary treated wastewater (Mills 2002). Spreading basins were also developed in the Central Valley beginning in the 1960s to support irrigated agriculture (Scanlon et al. 2016). Research on clogging of basins and on water quality changes and water treatment requirements was undertaken in both Arizona and

Fig. 8 At San Luis Rıo Colorado, Sonora, Mexico, oxidation lagoons (at a wastewater treatment plant in the background), have annually discharged 8.2 Mm^3 treated water to intermittent infiltration basins (located at a distance in the middle of the photo) for more than 10 years, and in the foreground some water is starting to be used to establish constructed wetlands (Humberto et al. 2018) (Photo, April 2018, courtesy of Hernández Humberto, Organismo Operador Municipal de Agua Potable, Alcantarillado y Saneamiento de San Luis Rıo Colorado, Sonora, Mexico)

California and reported through several conference series and subsequently in the scientific literature, with summaries of various aspects given by Bouwer (1978, 2002) and Bouwer et al. (2008). In Namibia, recharge basins were constructed downstream of the OMDEL dam in 1997 to recharge an alluvial aquifer in a very arid area. The dam detains floodwater from the normally dry Omaruru River and allows settling of sediment before water is released to recharge basins to replenish the aquifer (Zeelie 2002). A similar approach is being investigated in Saudi Arabia except that ASR wells are to be used instead of recharge basins (Missimer et al. 2014).

In the Netherlands, dune infiltration was also practiced to improve the quality of river water for drinking water supplies and to buffer water supplies. Intensive research there led to improved understanding of the geochemical processes associated with infiltration systems and the consequent fate of organic material, nutrients and pathogens. The introduction of MAR systems in the Netherlands in the mid-1900s raised and continues to nurture many technical and scientific questions. In the period 1940–1975, research mainly focused on the engineering aspects of MAR systems, regarding the minimum travel time needed to remove pathogens, the attenuation of salinity and temperature fluctuations in the infiltration waters, the clogging of basins and wells, and the effects of aquifer passage on main constituents. This knowledge informed much of the handbook on artificial recharge by Huisman and Olsthoorn (1983).

In the period 1965–1985, the worsening quality of the Rhine and Meuse rivers provoked research into the behavior of macroparameters, nutrients, heavy metals and some classical organic micropollutants during detention in spreading basins and aquifer passage (Piet and Zoeteman 1980; Stuyfzand 1989, 1998a). It also stimulated research into the effects of eutrophication on algae blooms in recharge basins and on oligotrophic phreatophytic plant communities in dune valleys around them (Van Dijk 1984). It was discovered in the 1980s that rainwater lenses can form in between infiltration ponds and remote recovery systems, and that flow-through (seepage) lakes in between can disrupt these lenses and stimulate local eutrophication (Stuyfzand 1993). This research was based on multi-tracing to discern infiltrated river water from autochthonous dune groundwater (locally infiltrated rainwater). Later hydrochemical studies yielded further insight in the performance of various (potential) tracers (Stuyfzand 2010), the behavior of trace elements (Stuyfzand 2015), the behavior of organic micropollutants (Noordsij et al. 1985; Hrubec et al. 1986, 1995; Stuyfzand 1998b; Greskowiak et al. 2006; Stuyfzand et al. 2007; Eschauzier et al. 2010) and pathogens (Schijven and Hassanizadeh 2000; Schijven 2001; Medema and Stuyfzand 2002). In Israel, at the Shafdan wastewater treatment plant, soil aquifer treatment of recycled water has contributed significantly to groundwater development over many years (Schwarz et al. 2016). In Italy, since the 2016 release of a regulation for permitting MAR, the first two infiltration basins have been authorized (one of these is included in a series of photographs of infiltration basins in ESM2).

Various modeling approaches were pursued to simulate and predict the behavior of pollutants, radionuclides, bacteria and viruses, and main constituents during detention in recharge basins and during aquifer passage. One of the first such models was Easy-Leacher (Stuyfzand 1998c), which is a two-dimensional (2D) reactive transport code set in an Excel spreadsheet, combining chemical reactions (volatilization, filtration, dissolution-precipitation, sorption, (bio)degradation), with empirical rules regarding the reaction sequence. It assumes a constant input quality, flow and clogging layer conditions, but takes account of the leaching of reactive aquifer constituents. More sophisticated models were built using the MODFLOW/MT3DMS and PHREEQ-C based reactive multicomponent transport model PHT3D, including reaction kinetics (Prommer and Stuyfzand 2005; Wallis et al. 2010; Antoniou 2015; Seibert et al. 2016). On the other hand, simpler models set in an Excel spreadsheet were developed such as Reactions+, a mass balance (inverse) model to identify and quantify the inorganic mass transfer between, for instance, the infiltrating surface water and a well downgradient (Stuyfzand 2011), and INFOMI, an analytical model to predict the behavior of trace metals and organic micropollutants (Stuyfzand 1998c).

Recharge wells

Recharge wells were used as early as 600 AD in Tamil Nadu, India, to recharge rainwater collected in ponds to replenish shallow aquifers used as drinking water supplies (Sakthivadivel 2007). It is reported that thousands of these wells still exist in southern coastal areas where aquifers are brackish and are used for a variety of purposes. In northern India, step wells called *baolis*, which are impressive architectural monuments, harvested rainwater from public paved surfaces and increased groundwater supplies, at a likely risk to drinking water quality. In Turkmenistan, Central Asia, Pyne (2005) reports that for several hundred years recharge has been enhanced in an area with 100-mm annual rainfall and silty-clay soils between dunes, by construction of trenches leading to pits within the dunes and recovered from adjacent dug wells. In India, at a smaller scale, traditional household rainwater harvesting schemes have diverted rooftop rainwater into dug wells to freshen and augment water supplies in water short areas. Until the 1960s, such wells spread widely based on local knowledge and hundreds of thousands of these were implemented without government involvement. Over the last 50 years, governments have assisted the spread through provision of scientific information to improve the management of recharge.

The following account of development of recharge well systems focuses on several main areas: Israel, USA, northern

Europe and Australia. In Israel recharge wells started to be used in about 1955 (Harpaz 1971) and by 1967 there were 135 wells recharging 10 Mm^3/year, with scientific advances being recorded concurrently (e.g. Bear and Jacobs 1965). In the US, the first injection wells were established in the 1950s in California to create barriers to seawater intrusion in Orange and Los Angeles counties; ESM2 contains a diagram and photo of the current groundwater replenishment program at Orange County. Subsequent development in recharge technology led to aquifer storage and recovery (ASR), which opened opportunities in confined and brackish aquifers as well as the aquifers for which other techniques may also be used. The first ASR wellfield in the USA that is still in operation is in Wildwood, New Jersey. The wellfield began operation in 1969 and is utilized to meet seasonal peak water demands during summer months. Prior to 1969, the US Geological Survey conducted research investigations at several different sites nationwide, none of which continued in operation after the initial research program was completed, but provided the basis for further development (Asano 1985; Johnson and Finlayson 1989; Johnson and Pyne 1995; Aiken and Kuniansky 2002; Pyne 2005; Maliva and Missimer 2010). Subsequent operational projects were mostly implemented by local government agencies having a need for expansion of water supply capacity or reliability. By 1983, three ASR projects were operational in USA, including two in New Jersey and one in California. The Lake Manatee ASR project in Florida began operation in 1983 and won a major national award in 1984. Publicity from that award galvanized ASR interest and activity nationwide so that by 1995 about 25 ASR projects were operational or in development in several states.

In the late 1990s, the city of Scottsdale, Arizona, started the operation of the Water Campus Facility. This innovative project uses vadose zone recharge (VZR) wells, also called "dry wells" to store advanced-treated-municipal wastewater or treated stormwater in the aquifer. It has now operated very successfully for more than 15 years and is now widely used by many municipalities.

ASR activity accelerated during the late 1990s in, e.g. the United Kingdom, while in Florida it encountered a major setback in 2001. If arsenic is present in specific minerals in the aquifer comprising an ASR storage zone such as arseniferous pyrite, and the recharge water contains oxygen, nitrate and, e.g. chlorine or ozone, the arsenic will mobilize and may occur at concentrations exceeding drinking water standards in the water recovered from an ASR well (Stuyfzand 1998a; NRMMC, EPHC, and NHMRC 2009). Pretreatment of the recharge water to remove oxidants is effective at controlling arsenic mobilization; however, their removal tends to be complex and expensive, while post-treatment to remove arsenic is also expensive. A simple solution, which was demonstrated to be effective, e.g. in Florida, at many drinking water ASR wellfields since 1985, is to initially form and maintain an oxidized zone around the ASR well (Pyne 2005). Mobilized arsenic remains dissolved within the generally anoxic buffer zone, situated between the oxidized zone and the outer anoxic mixing zone. In the oxidized zone, most arsenic is normally precipitated or adsorbed to the aquifer matrix during storage and recovery by subsurface geochemical processes, but can be released if mixed zone water reduces either the oxidation state of the storage zone or the sorptive capacity of amorphous iron oxides (Wallis et al. 2010, 2011). Hence, ASR operations need to monitor volumes and quality stored and recovered, ensuring that none of the buffer zone volume is recovered.

By 2016 over 500 ASR wells in 175 ASR wellfields were operating in USA, spread among at least 25 of the 52 states. Most are storing drinking water; however, others are storing partially treated surface water, groundwater from different aquifers or from the same aquifer at a different location, or highly treated, purified water from wastewater reclamation projects. Aquifer storage and recovery wells are from 50 to 900 m deep in a wide variety of geologic settings, while storage is in confined, semi-confined and unconfined aquifers containing freshwater to brackish groundwater with total dissolved solids concentration up to ~20,000 mg/L. Individual ASR well yields range from ~2,000 to ~30,000 m^3/day. To date, 28 different objectives for ASR projects have been identified, the most common of which are to meet seasonal peak demands, long-term water storage (water banking) and emergency storage. Other common applications of ASR are to maintain flows and pressures at distal locations in water distribution systems, and to reduce disinfection by-products and seasonal elevated water temperatures. Most ASR wellfields meet multiple water demand and water quality objectives—an example from Florida is shown in ESM2.

In Europe, a more research-oriented approach to recharge-well development was underway during the period 1973–1982, when extensive research on the clogging mechanisms of infiltration wells was carried out by Kiwa (renamed KWR in 2006). This yielded the new clogging potential indicators Membrane Filter Index (MFI; Schippers and Verdouw 1980) and Assimilable Organic Carbon (AOC; Hijnen et al. 1998). Also, the insight was born that cumbersome clogging can only be prevented by thorough pretreatment (that included at least a coagulation step and rapid sand filtration), leading to MFI <2 and AOC <10 μg C/L, combined with frequent back-pumpings of short duration (Olsthoorn 1982; Peters et al. 1989). By the 1990s, a large-scale ASR project was operating in northern London, England, UK (Pyne 2005).

The clogging of wells or drains has always been a hot topic in MAR systems because of their extreme vulnerability. Studies by van Beek (2010) among others, revealed that infiltration basins and recovery wells in aquifer storage transfer and recovery (ASTR) systems (that is, separate injection and recovery wells) are more vulnerable to (bio)chemical clogging by hydrous ferrihydrite, whereas bank filtration wells in the anoxic fluvial plain are prone to clog by aquifer particles that are retained by the borehole wall if damaged by residual drilling muds. This growing understanding of the aquifer biogeochemical processes provided a platform to enable intelligent design to avoid these issues in well recharge systems. Much of the research methodology developed in the Netherlands on water quality, and described in the preceding section 'Water spreading', was also applied to geochemical, microbiological and organic chemical changes near recharge wells. Their use has grown in the Netherlands for drinking water supplies, in part due to tensions between use of dunes for wildlife habitat in nature reserves and for natural water filtration in public water supplies. Aquifer storage and recovery is being applied for drinking water supply only on a very small scale (Stuyfzand et al. 2012) however, it is rapidly expanding in the supply of (1) rainwater from roofs for crop irrigation in greenhouses, and (2) freshwater for irrigation of orchards (Zuurbier 2016). Other work in Europe includes evaluation and prediction, based on water quality, of the timescale for clogging around injection wells that form a barrier to seawater intrusion (Masciopinto 2013).

In Australia, ASR had captured the imagination of water managers and users particularly in urban areas, and in the early 1990s the method was in use in South Australia for harvesting winter stormwater, storing in limestone or hard rock aquifers that originally contained brackish groundwater, with effective recovery of freshwater for irrigation of parks and gardens in summer. An urban stormwater ASR research site was established in 1993 at Andrews Farm, to evaluate the effectiveness of injection and to understand subsurface processes affecting mixing and water quality. Subsequently in 1996, the City of Salisbury established at The Paddocks its first ASR project, as described in ESM2. Then in 1996–2005, the first recycled water ASR trial began at Bolivar, South Australia, and resulted in substantial advances in measurement methods, modelling and process understanding (Dillon et al. 2003; Greskowiak et al. 2005; Pavelic et al. 2006a, b, 2007; Ward et al. 2009; Vanderzalm et al. 2009; Page et al. 2010a). Both sites subsequently led to 49 ongoing ASR projects of 0.01 to 1 Mm^3/year in Adelaide (Kretschmer 2017), recharging 20 Mm^3/year and enabled ground-truthing of the Australian Guidelines for MAR (NRMMC, EPHC and NHMRC 2009) as well as their use as examples of applying the guidelines (Page et al. 2010b), combining complementary natural and engineered treatments for water recycling (Dillon et al. 2008) and expansion of MAR in Australia (Parsons et al. 2012). In 2006, a research project to evaluate the effectiveness of stormwater ASTR in brackish aquifers commenced at Parafield in the nearby city of Salisbury and by 2011 this was the hub site of major research project to evaluate the risk management requirements for use for stormwater ASR to

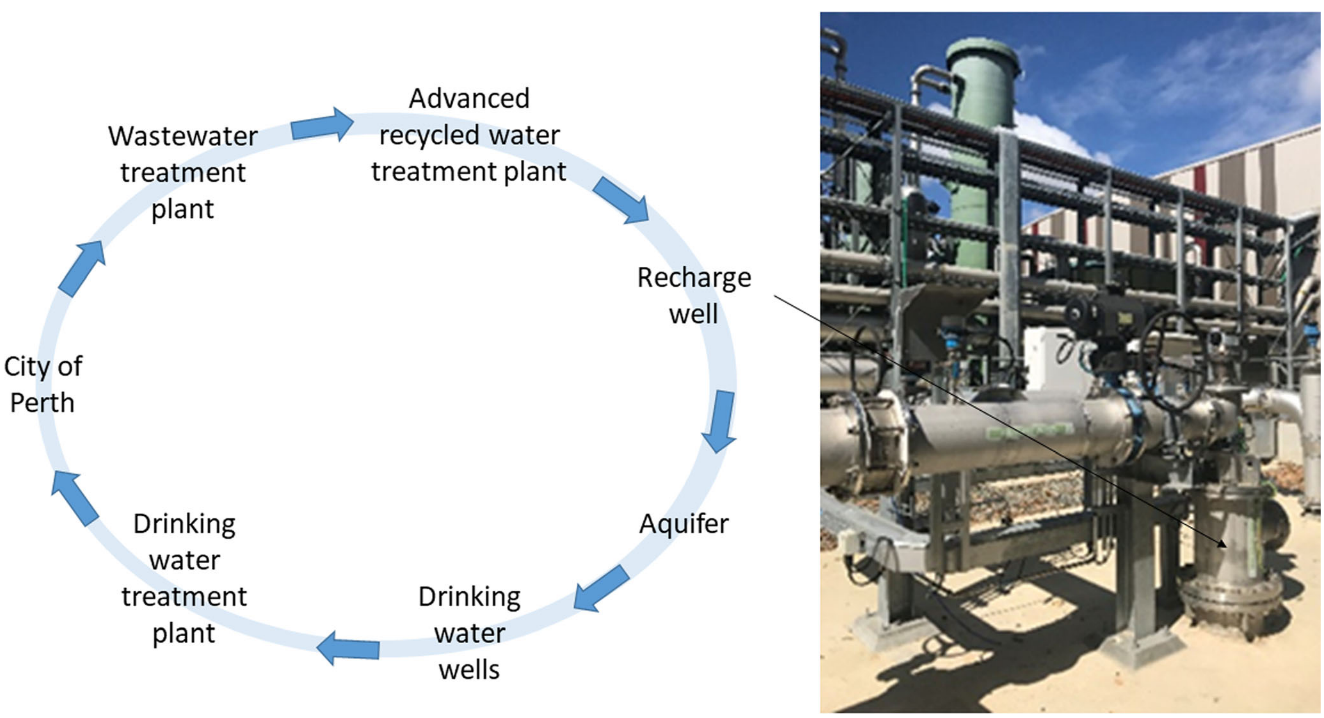

Fig. 9 Perth Groundwater Replenishment Project, Western Australia which commenced operations in 2017 at 14 Mm^3/year using advanced treated recycled water to recharge a confined aquifer that is an important contributor to Perth's drinking water supply. It will double its annual recharge by 2019 when treatment plant and a total of four wells will store water in the Leederville and Yarragadee aquifers. The project will prevent saline intrusion and allow expansion of use of the groundwater system to meet water supplies in an area experiencing a drying climate where surface water supplies have reduced over the last 40 years and population has steadily increased. (Photo and diagram courtesy of Water Corporation, Western Australia)

produce drinking water in Adelaide, and was found to have a lower cost and had higher public acceptance than seawater desalination (Dillon et al. 2014b).

Following on from the Bolivar research, Scatena and Williamson (1999) showed the potential for ASR in Perth, Western Australia, and Toze and Bekele (2009) led a study on MAR pilot projects in Perth. Subsequently the water utility undertook extensive water treatment and injection trials having deep engagement with health and environmental regulators and the public on groundwater replenishment with advanced treated recycled water. Injection wells were separate from the drinking-water-supply wells in the same aquifer. Intensive water quality monitoring was undertaken and aquifer geochemical interactions studied (e.g. Patterson et al. 2011; Seibert et al. 2016). The trials were successful on all dimensions and groundwater replenishment with recycled water was approved in 2013 as the next water supply for Perth. In 2017, the 14 Mm^3/year stage 1 of the groundwater replenishment system was commissioned (Water Corporation 2017) and its capacity will be doubled in 2019. This project won a Global Water Award in 2017 (Global Water Awards 2017) and is the first step of a plan to replenish via wells more than 100 Mm^3/year, enough to source 20% of Perth's water by 2050. Figure 9 contains a diagram and a photo of the first recharge well.

Lawrie et al. (2012), in seeking groundwater resources in a semi-arid western New South Wales (NSW, Australia), undertook extensive airborne electromagnetic studies, drilling, geomorphic, geochemical, hydrogeological and clogging studies and with an innovative integrating analysis identified several compelling opportunities for recharge enhancement via wells adjacent the Darling River near Menindee, NSW. This 10 Mm^3/year water supply for the city of Broken Hill using ASR which has been priced at less than half the projected cost of a surface-water supply, during drought would provide higher security and reduce competition for water.

Research and communications to support MAR

Considerable research in recent years has helped advance the understanding of natural processes involved in MAR and the design of any complementary engineered processes, and how to better manage such systems in a widening array of hydrogeological settings. This summary paper demonstrates the progress made in a number of areas; however, the objective of this section is not to be an exhaustive literature review and the authors recognise that many high quality and important papers are not cited. Much research is encapsulated here by reference to anthologies rather than the numerous individual specific contributions these contain.

Two significant symposia series initiated in USA have helped to bring scientific focus to the practices of MAR and help advance from trial and error approaches, and local traditional knowledge, to a scientific footing giving greater assurance of technical viability, water quality protection and improvement, environmental restoration, economic feasibility, community acceptance and resilience of systems. The Salt River Project convened the First Symposium on Artificial Recharge in 1978 in Phoenix, Arizona. This has now extended to 16 biennial symposia subsequently organized by Arizona Hydrological Society and now run jointly with Groundwater Resources Association of California and known as the Biennial Symposia on Managed Aquifer Recharge (BSMAR). In 1988, the American Society of Civil Engineers (ASCE) conducted the First International Symposium on Artificial Recharge of

Table 3 Papers, presented in the International Symposia on Managed Aquifer Recharge (ISMAR) series over the period 1988–2016, that have been published

Date	ISMAR	Location	No. of papers	Proceedings or special issues [a]	Reference
1988	ARG1	Anaheim	63	B	Johnson and Finlayson (1989)
1994	ARG2	Orlando	84	B	Johnson and Pyne (1995)
1998	TISAR	Amsterdam	83	B	Peters et al. (1998a)
2002	ISAR4	Adelaide	91	B	Dillon (2002)
2005	ISMAR5	Berlin	133	eB	Fritz et al. (2005)
2007	ISMAR6	Phoenix	124	B	Fox (2007)
2010	ISMAR7	Abu Dhabi	115	eB	Herrman (2010)
2013	ISMAR8	Beijing	122	SIJ-17	Zhao and Wang (2015)
				SIJ-12	Sheng and Zhao (2015)
				SIJ-14	Megdal and Dillon (2015)
2016	ISMAR9	Mexico City	88	SIJ-18	Stuyfzand and Hartog (2017)
				SIJ-18	Dillon et al. (2018)
All	–	–	903	B/eB-7, SIJ-79	–

[a] *B* book, *eB* e-book, *SIJ-18* special issue of a journal with 18 papers

Groundwater at Anaheim, California, that commenced what is now known as the International Symposia on Managed Aquifer Recharge (ISMAR), since IAH and UNESCO joined with ASCE in organizing these in Amsterdam in 1998. On two occasions when timing and location has been favorable, the national and international conference series have merged (in Phoenix 2007 and in Mexico City 2016). The number of papers at each symposium is shown in Table 3.

An evaluation of the topics under which papers were presented showed some perennial themes. These include the description of design, operation, management and impacts of MAR systems. Also, clogging of recharge systems and hydraulic evaluation of fate of recharged water and the ability to recover it. For clogging, in spite of huge progress in understanding mechanisms (e.g. Olsthoorn 1982; Baveye et al. 1998; Rinck-Pfeiffer 2000; Perez-Paricio 2001; Pavelic et al. 2006a, b; Wang et al. 2012; Pedretti et al. 2012; Martin 2013; Newcomer et al. 2016; Xia et al. 2018 among many others), lack of standardized predictive instruments (Dillon et al. 2016), and the previous lack of adequate water quality monitoring and geochemical, mineralogical and biological evaluations at operational sites has inhibited the formation of better predictive tools and more efficient management. A Working Group of the IAH Commission on MAR has produced one monograph on clogging (Martin 2013), and a subsequent monograph on management of clogging is in preparation to help address this.

In general, water quality is better reported in recent symposia, with geochemical evaluations now quite common, particularly for well injection systems, and there is better information on water quality improvements in aquifers particularly for organic chemicals. This new knowledge is also of value more widely in hydrogeology—for example in contaminated site remediation where introduced volumes of water and masses of constituents are normally unknown. In MAR, the stoichiometry can be explicitly defined; similarly, mixing processes and biogeochemical reactions in natural aquifer systems are generally inferred after equilibrium, whereas in MAR the kinetics of these processes are also observable at field scale. Isotopes have been used to study origin and age of ambient groundwater, mixing processes and travel times of recharged water and biogeochemical processes such as denitrification, sulfate reduction, fate of organic carbon and dissolution of minerals due to disequilibrium. The IAEA (2013) provides an anthology of methods and their numerous applications to MAR investigations.

The rates of attenuation of pathogenic micro-organisms and toxic or carcinogenic trace organic chemicals measured at MAR sites or in relevant laboratory experiments have been assembled and discussed by Drewes et al. (2008), NRMMC, EPHC, and NHMRC (2009) and Regnery et al. (2017). Large variations in attenuation rates are partially explained by environmental variables (such as temperature and redox state) and co-metabolites (e.g. labile organic carbon) and aquifer minerals (e.g. those containing iron); however, site-specific studies may be needed to meet the requirements for risk assessment and approval for reliance on aquifer treatment. The developed understanding of attenuation processes has led to the coupling of bank filtration and surface spreading to more effectively treat water through a sequence of contrasting environmental conditions. Sequential managed aquifer recharge technology (SMART) as it has been termed by Regnery et al. (2016) has now been applied at field scale in Colorado demonstrating improved degradation of some trace organic chemicals. Modelling of flow and water quality changes in MAR operations has also been extensive and a review of the range of models (unsaturated/ saturated flow, solute transport and reactions, geochemistry and clogging) and their uses in planning, design, and improving operations at MAR sites for all types of MAR are summarized by Ringleb et al. (2016). A recent example by Rodríguez-Escales et al. (2017) simulates improved degradation of organics by varying the flow fields beneath infiltration basins to vary redox conditions.

In recent years there has been increased reporting of economic impacts of MAR and governance arrangements (e.g. Megdal and Dillon 2015). Ross and Hasnain (2018) have recently proposed a systematic methodology to calculate the costs of MAR schemes and inform future investment in MAR including water-banking systems where benefits accrue in future droughts of unknown timing and magnitude.

Significant publications on MAR in the Spanish language are also available, and de la Orden and Murrillo (eds) (2009) and Escolero Fuentes et al. (2017) have highlighted advances in MAR developed and relevant to Spain and Latin America, respectively, but are also broadly applicable.

There is evidence in these papers and elsewhere of repetition of past problems of similar sites suggesting some proponents are unaware of experience previously documented. This also partially explains the prolific number of projects that are reported as “world firsts”. Clearly, these symposia could play a more valuable role in facilitating information exchange and giving opportunity for more reliable and efficient MAR, particularly to those attempting their first projects. Until ISMAR7 in 2010, all papers presented at these symposia were published in a hardbound proceedings or were available to download from the website (ISMAR5, ISMAR7). However, for ISMAR8 and ISMAR9, only abstracts and posters were published on the web and selected

Table 4 Indicative number of peer-reviewed journal papers published in the field of MAR by decade

Years	1960s	1970s	1980s	1990s	2000s	2011–2017
No. of papers	7	69	95	47	115	275

papers were extended, reviewed, revised and published as special issues of three journals and two, respectively, in an effort to document noteworthy research and investigations more comprehensively.

In the past, when literature searches were painstaking tasks, the US Geological Survey provided the very helpful service of publishing annotated bibliographies on artificial recharge including Todd (1959), Signor et al. (1970) and Weeks (2002). A SCOPUS search (May 2018) for journal papers (articles and reviews) on "managed aquifer recharge", "artificial recharge" or "water banking" in the title of the paper has shown that the number of such papers has grown considerably (Table 4); this narrow search would not have detected most papers cited in this current paper. While it is likely that papers in earlier years are under-represented by electronic bibliographic services, there has been a substantial growth in research and information sharing over the last two decades that is showing no sign of abating.

Considerable headway has been made through concerted efforts around the world, and including multinational collaborations in projects financed by the European Commission—Artificial Recharge of Groundwater (EC 2001), ArtDemo, AquaRec, Reclaim Water, Saph Pani, GABARDINE, DEMEAU, DEMOWARE, MARSOL, H2020 AquaNES, LIFE REWAT, IMPROWARE—and of the Water Research Foundation and Water Reuse Foundation of USA. There are still however knowledge gaps due to the intersection of different hydrogeology, groundwater quality and surface-water quality at each new site, although with decreasing predictive uncertainty as the number of documented sites expand. In Europe, the Action Group MAR Solutions - Managed Aquifer Recharge Strategies and Actions (AG128) was started within the European Innovation Partnership on Water, aimed at involving the principal stakeholders and small and medium enterprises (SMEs) and transferring project results into guidelines and policy to facilitate uptake of MAR.

Far more can be done with better documentation of existing operating sites, transparent reporting of problems and effectiveness of solutions. There are few sites where effects of different treatments or different aquifer properties can be compared unconfoundedly. Systematic evaluation, validation and comparison of methods to predict clogging and efficient means to manage it are still awaited. Aquifer microbiological ecosystems evaluation methods are warranted to provide a health check on sustained aquifer attenuation capacity for contaminants particularly in changing geochemical conditions. The gap in knowledge of water treatment requirements for MAR systems is closing, but could do so at a faster rate with improved risk assessments and probabilistic approaches applied to mixing processes in aquifers, and thus on recovered groundwater. The water quality and mixing aspects where MAR is used for long-term water banking and as saline intrusion barriers would be helped by improved aquifer and aquitard characterization, accounting for parameter uncertainty and density-dependent flow would also help build confidence for investment.

Methods for mapping of MAR opportunities are still diverse, and remain poorly founded in the absence of comparative information among methods and in relation to practical experience. Several areas that have been mapped are currently reported in IGRAC MAR Portal, but too often the huge value of aquifers is overlooked due to lack of awareness of their potential.

Operational performance of ASR systems is much better known than the far more abundant and longer-standing streambed modifications, essentially due to lack of basic monitoring of the latter. This warrants comparative evaluations with multiple methods across multiple sites and then investment in appropriate training of local custodians, and sharing of data to enable synthesis and feedback.

Evolution of governance of MAR

Clearly, MAR implementation is proceeding at pace, fuelled by need and with the management aspects supported by research that improves risk assessment on resource sustainability and water quality. To ensure MAR continues to generate its intended benefits and avoids excessive piezometric pressures or waterlogging, failure during drought, and pollution of aquifers, water resources management and environment protection authorities need to be familiar with the opportunities and constraints of MAR. This is most efficiently controlled by setting soundly based policies and guidelines to ensure that MAR is undertaken in a way which protects the status of groundwater and the requirements of its receptors, including the wider environment.

State policies such as in Arizona, California and Florida, have also been developed for the specific types and purposes of MAR in those states—for example in Arizona, state-supported aquifer recharge was permitted under the Underground Storage and Recovery Act, 1986, and the Underground Water Storage, Savings and Replenishment Program, 1994, in the most developed MAR regulatory system that involves three permits. "Underground storage facility permits" require that the proponent demonstrate: technical and financial capability, that the storage is hydrologically feasible, no unreasonable harm would be caused by water levels or water quality, and they have a right to the floodplain for building a detention basin. A "water storage permit" is needed to allow an entity with an excess renewable supply to store water at a permitted storage facility, and this gives the same entitlement of stored water as for its source. Thirdly, "recovery well permits" are issued to allow recovery of the equivalent volume of water stored, whereby recovery may be outside the area of hydrologic impact of the recharge, provided it is consistent with a management plan that constrains the rate of drawdown and proximal impacts.

A policy framework for MAR was developed in Australia on entitlements to use a water source for recharge, entitlement to recharge (that there is available aquifer capacity) and entitlement to recover (Ward and Dillon 2011). The entitlement to recover is transferable subject to constraints on impacts, and accounting for depreciation of stored volume particularly in brackish aquifers or those with a steep hydraulic gradient) and has standard end-use conditions relating to water use efficiency and acceptable impacts on nearby groundwater users. The framework is intended to give flexibility in use of MAR in water trading and water banking and adheres to a national system of robust water entitlements. This presents a possible model for consideration although in some jurisdictions current groundwater planning and management rules do not provide a secure entitlement to recover water stored in aquifer or allow recovery after an extended time period (beyond 3–5 years; Ross 2017).

Australian national guidelines for MAR (NRMMC, EPHC and NHMRC 2009) are the only risk-management-based guidelines that conform with the World Health Organization's water-safety-planning approach and assure protection of human health and the environment. They not only apply to all types of source waters, aquifers, recharge methods and end uses of water, and account for water quality changes within the subsurface, but they also follow a staged approach starting with a desktop assessment, investigations, commissioning, and monitoring and reporting to provide a pathway to demonstrating that risks are effectively managed. Water quality hazards addressed, based on results of recent research include the following—pathogens, inorganic chemicals, salinity and sodicity, nutrients (nitrogen, phosphorus and organic carbon), organic chemicals, turbidity and particulates, and radionuclides. These guidelines also address hazards associated with pressure, flow rates, volumes and groundwater levels, contaminant migration in fractured rock and karstic aquifers, aquifer dissolution and stability of well and aquitard, aquifer and groundwater-dependent ecosystems, and energy and greenhouse gas considerations. Nine examples of applications of these guidelines applied to case study MAR projects (Page et al. 2010b) have assisted uptake. Risk-based guidelines are data intensive and so "a stepping stone" guideline for water quality for MAR in India was produced for "natural" water sources using visual observations within a water-safety-planning framework applied at the village level (Dillon et al. 2014a).

Capone and Bonfanti (2015) reviewed European legislation regarding water policy and groundwater quality protection relevant to MAR. The Water Framework Directive and the Groundwater Directive recognize MAR as a water management tool which may be used for supporting the achievement of good groundwater status, but require member states to enact their own policies in relation to the application of MAR, respecting as a minimum the "prevent and limit" requirements of the directives, which entails taking all reasonable measures to ensure the prevention of pollutants reaching groundwater (European Commission 2007). The reviewers found differences among established national legislations and a lack of a comprehensive legal framework dealing with MAR schemes in each surveyed member state. In Italy, regulation was issued in 2016 requiring compliance with the EU Water Framework Directive through two stages of project development and at least 1 year of monitoring regarding quality and quantity.

In the USA, the US Environmental Protection Agency (USEPA 1974) has explicit federal provisions encompassed in the "Underground Injection Control Regulations and Safe Drinking Water Act" that apply in each state unless the state has its own regulations that are at least as strict. These cover the requirements for design of injection wells and the quality of water that may be injected and the monitoring to be undertaken. The "Safe Drinking Water Act" also has provisions to protect drinking water sources that envelope infiltration systems, and for which some soil attenuation capacity in the unsaturated zone is considered. In general, these apply not only to the quality of recharge water but also include allowance for changes in water quality that may occur due to travel time and distance in an aquifer, including metals mobilization and attenuation. Monitoring is required so that water quality changes can be detected. ASCE Environmental and Water Resources Institute is currently revising its guidelines on MAR, intended for release in 2019, which will advise proponents on how to develop MAR projects.

In India there is a government manual on artificial recharge (CGWB 2007) which specifies how to plan, design, monitor levels and water quality and evaluate the economics of recharge augmentation by streambed recharge structures and urban rainwater harvesting. For natural water sources, a water quality guide to MAR in India was developed based on UN Water Safety Planning approach, and capable of use based on visual observations by trained villagers (Dillon et al. 2014a). China and New Zealand are both considering the development of health and environmental guidelines and policy frameworks for MAR.

It is evident that the governance frameworks need attention in many countries to ensure that MAR is sustainable and protects groundwater quality. Monitoring of existing operations and maintaining a public repository of site information, reports and data is a fundamental starting point for providing assurance of effective operations and for developing the information to assist future uptake of MAR including research and governance.

Conclusions and next steps

In a period of 60 years, there has been remarkable growth in MAR and a growing awareness of its potential to replenish over-allocated aquifers, restore brackish aquifers, and even enable energy recovery. However, the rate of growth of MAR has not kept pace with the global rate of groundwater depletion, and much more needs to be done in levering from MAR to facilitate demand management and engage communities in cooperative management of groundwater resources. Development of MAR has occurred at different rates among and within countries for various reasons, including aquifer availability for MAR, the level of awareness and confidence in MAR among water stakeholders, and having clear approval processes. While the currently reported annual volume of MAR is only 1% of global groundwater use, in some countries it is considerably higher (especially where bank filtration is practiced), suggesting that global opportunities are only just starting to be tapped.

The growth in research has enlarged the MAR repertoire, especially using wells, widened the types of source waters for recharge, reduced the costs of water treatment for sustainable operations, improved the quality and quantity of recovered water, and given greater certainty for safe and efficient operation of MAR systems. In spite of these advances, there remain a number of basic steps that would improve efficiency of investment in MAR and underpin the uptake of MAR where this is currently low. These can be expressed in the categories of extending case study information to include economic evaluations, extending research on fundamental processes to better site, design operate and monitor MAR operations, and translating scientific evidence into governance arrangements for water allocations and water quality protection.

Documenting exemplary case studies (particularly those relevant for developing countries, such as compiled by Tuinhof and Heederick 2003) and through symposia discussed earlier, should instill confidence among those who are yet to apply MAR so that, if good practices are followed for site selection, investigation and implementation, it will be reliably successful. Current efforts to form a global inventory of MAR (Stefan and Ansems 2018; IGRAC 2018) will help with identification of geographically and typologically proximal MAR sites for those considering locally pioneering projects. More work is needed to document the costs and benefits of MAR (e.g. Ross and Hasnain 2018), including work in relation to alternative water supplies or places of storage and in identifying scenarios where MAR is likely to produce the least-cost water supply and greatest benefit accounting for all objectives, including current economic externalities such as resource and environmental benefits. In particular, considering the promise of riverbank filtration, this lacks assessment of costs and benefits. Similarly, considering the proposed magnitude of investment in streambed modification and distributed detention, evaluation is warranted at the catchment scale, accounting for maintenance and environmental flow requirements and downstream benefits and costs. National monitoring and research programs are warranted, initially sized at 2–10% of the planned investment in new recharge infrastructure, in order to steer this investment to maximise net benefits. Recharge structures have greater potential to be used to reinforce irrigation community expectations and efforts at reducing demand on groundwater, through a range of water and soil conservation measures.

While much research on subsurface physical and chemical processes in MAR has been valuable for informing solutions to local problems, more could be done to synthesize what has been learned and extend the benefits. Standardizing methods to assess and predict clogging and treatment and remediation requirements to manage it, and of methods to cost-effectively validate the fate of viruses in aquifers under a wide range of scenarios will help advance MAR. Current MAR research that warrants continuing includes—innovations to optimize ASR systems in brackish to saline aquifers (e.g. Ward et al. 2009; Zuurbier 2016), optimizing ASR systems for drinking or rainwater storage by reducing adverse water-sediment interaction (Antoniou 2015), improving water-spreading-systems capacity to cope with variable and intermittent inflows and changing redox conditions, while protecting wet dune valleys and reducing water quality problems. There will be an ongoing need to determine and predict the behavior of emerging priority pollutants such as pharmaceuticals, personal care products, new pesticides, flame retardants and nanoparticles for use in risk assessments.

Some documents now exist at the national level in only a few countries that provide guidance for health and environmental protection at MAR operations. This could be extended and made easier through use of modern sensor networks and data acquisition and control systems to facilitate decision support and risk analysis. A few jurisdictions have governance requirements that improve security of water resources entitlements generated through MAR, and documenting this experience would provide guidance on the effectiveness of alternative candidate regulatory pathways elsewhere. More regulatory effort in building water security through MAR for longer-term water banking, and in conjunctive use of dams and groundwater could create extra value out of existing dams. Furthering the knowledge of downstream impacts of MAR operations in catchments is needed. Most countries need governance frameworks strengthened to ensure that MAR is sustainable and protects groundwater quality and generates benefits for all members of groundwater-dependent communities, particularly during drought. Fundamental steps include monitoring of existing operations and keeping a public repository of site information, to assist new MAR developments and the formation of effective evidence-based governance arrangements.

There will be a continuing need to share new knowledge on MAR widely, using seminars, training workshops, linking with planners, local governments, community groups and water users to ensure that appropriate investigations are made before construction and that operators fully understand the challenges. For micro-scale systems such as rainwater harvesting there needs to be adequate local technical support to avoid potential problems. There is much to be done and IAH will have an ongoing role with other organizations in advancing MAR. The IAH Commission's goal is to make all new MAR projects sustainable and safe, based on sound scientific evidence, thereby providing a pathway to increased confidence and wise use of MAR within the groundwater management portfolio, and ultimately maximizing its appropriate use.

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Electronic Supplementary Material - Hydrogeology Journal

Sixty years of global progress in managed aquifer recharge

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ESM1: National or Regional Summaries of Managed Aquifer Recharge

These national summaries, prepared especially for synthesis in the journal paper by members of a Working Group on 60 years history of MAR of the IAH Commission on Managing Aquifer Recharge, contain much more detail than could be included in the global summary. They give a snapshot in time prepared between 2016 and 2018 of the history of the development of MAR in these countries and serve as an enduring record. These summaries are also accessible for the foreseeable future at https://recharge.iah.org/60-years-history-mar . It is intended that when other countries produce summaries they will be placed on that web site, along with possible future updates of these current summaries.

There is also ESM2, a second set of electronic supplementary material to this paper, which consists of a small photo gallery of MAR projects with concise explanations to give those new to MAR an appreciation of the wide range of methods and applications.

ESM1 Contents:

Country or Region	*Authors*	*Date*	*Page Number*
Australia	Peter Dillon	2016	3
China	Weiping Wang and Jinchao Li	2016	7
Croatia	Kristijan Posavec	2017	13
Finland	P. Jokela, V. Kurki and T.S. Katko	2017	15
France	M. Pettenati, G. Picot-Colbeaux and A. Togola	2017	18
Germany	Gudrun Massmann	2017	21
Israel	J. Schwarz and J. Bear	2016	25
Italy	R. Rossetto	2017	28
Jordan	Julian Xanke, Jochen Klinger and Nico Goldscheider	2017	32
Korea	Kyoochul Ha	2017	34
Netherlands	Pieter Stuyfzand	2016	36
Qatar	Abdulaziz A. Al-Muraikhi and Mohamed Shamrukh	2017	42
South East Asia	Paul Pavelic	2016	46
Southern Africa	Ricky Murray	2016	51
Spain	E. Fernández-Escalante	2016	54

Recent inventories of MAR have been published in the 'Special Issue on Managed Aquifer Recharge in Integrated Water Management' in *Sustainable Water Resources Management* (a Springer journal). These include a global summary and a paper on Latin America and the Caribbean :

Stefan, C. and Ansems, N. (2018). Web-based global inventory of managed aquifer recharge applications. Sustain. Water Resources Manag. 4, (2) 153-162. https://link.springer.com/article/10.1007/s40899-017-0212-6

Bonilla Valverde, J.P., Stefan, C., Palma Nava, A. da Silva, E.B., Pivaral Vivar, H.L. (2018). Inventory of managed aquifer recharge schemes in Latin America and the Caribbean. Sustain. Water Resour. Manag. 4 (2) 163-178. https://doi.org/10.1007/s40899-018-0231-y

Further details on MAR sites around the world can be found on the International Groundwater Resources Assessment Centre (IGRAC) MAR Portal at https://www.un-igrac.org/special-project/mar-portal

MAR in Australia

by Peter Dillon

2016

Hon Research Fellow, CSIRO, Adjunct Chair NCGRT, Flinders University SA

Co-chair IAH Commission on MAR

Managed aquifer recharge currently makes only a small contribution to water resources development in Australia, estimated at ~400 Mm^3 (Table 1) that is 8% of approximately 5,000 Mm^3 national groundwater use (Harrington and Cook 2014). However through storage for use of associated groundwater and urban stormwater it is a very significant enabler of more environmentally benign expansion of iron ore mining, the coal seam gas industry and urban development. Scaling up of groundwater replenishment with recycled water for potable supplies has recently commenced due to significant cost savings with respect to seawater desalination.

When Perth was first settled by Europeans in 1829 roof runoff was drained into sumps and basins and infiltrated the sandy soil to reach the unconfined superficial aquifer. The scale of unmanaged recharge grew as the village grew into a city with paved roads and planning regulations mandated drainage sumps. With the establishment of Managed Aquifer Recharge Guidelines (2009), a WA Operational Policy for MAR (2011) and water sensitive urban guidelines developed by councils (eg South Perth 2012) this can now be regarded as MAR and is estimated at ~200 Mm^3/yr.

The first intentional recharge began in 1965 on the Burdekin Delta of central Queensland where surface infiltration of river water using sand dams, pits and channels augmented groundwater irrigation supplies to grow sugar cane in a coastal area and prevent saline intrusion. Two parallel recharge systems were run, the North and South Burdekin Water Boards were cooperatively managed by cane growers who opted to invest in building and maintaining recharge systems rather than face potential cuts in consumption otherwise imposed by government to protect the aquifer. In 2015 the Boards were amalgamated and the combined systems have continued with a mean annual recharge of ~40Mm^3 with year to year fluctuations depending on needs for direct use.

A national conference on Artificial Recharge (Volker 1980 ed.) in Townsville near the Burdekin Delta helped give exposure to the scheme and pioneering research on algal growth, clogging, groundwater modelling and design and operational performance of recharge structures. The conference helped catalyze formative MAR development elsewhere in Australia. Among these were, in South Australia, aquifer storage and recovery in the Bremer River irrigation area and recharge releases from a new reservoir in the Little Para River upstream of the northern Adelaide Plains (Dillon 1984). In north-west Western Australia, Opthalmia recharge dam and four basins were built at Newman, in south-east Queensland recharge weirs were built on the Callide and Lockyer Rivers, and in Victoria recharge basins were established near Geelong, to augment groundwater supplies to a growing urban area (Parsons et al 2012).

Ironically, recharge basins built downstream of the Ophthalmia Dam constructed in 1981 as part of a conjunctive storage scheme to support mining operations and the local community were not used because the dam was so effective in recharging the aquifer (~12Mm^3/yr) with detained water (WA Department of Water 2009). This was a great advantage in an area with annual evaporation of 3m/yr. Lack of awareness of the potential for MAR in Australia was a deterrent to progress, but where projects were established and successful they soon became replicated in their local area.

With a growing appreciation of the potential value of urban stormwater and reclaimed water in the 1990s as an outcome of the Commonwealth Clean Seas and Better Cities Programs, there was a need to also identify the water quality issues associated with MAR with these water sources. CSIRO worked with partner organizations including state departments, water utilities and local government to develop demonstration projects and to apply the principles of Australia's National Water Quality Management Strategy (NWQMS) to produce water quality guidelines for MAR that protected human health and the environment. Following review these were adopted by the Council of Australian Governments as 24th NWQMS document (NWQMS 2009). They are the first risk-based guidelines on MAR, account for all types of source waters, aquifers, recharge methods and end uses of water and allow for water quality changes, both improvements and deteriorations, in the aquifer between recharge and recovery. Subsequently some historical drainage wells have come under a revised management regime that accounted for water quality risks and are now considered as having transitioned from unmanaged to managed aquifer recharge.

Water entitlement issues associated with managed aquifer recharge were addressed in the National Water Initiative framework of entitlements, allocations and use conditions for each phase of harvest, recharge, recovery and use (Ward and Dillon 2011) that enabled fully articulated set of rights and responsibilities to mesh within existing groundwater and surface water management plans. Two states have adopted this framework within their water resources policies and other states are giving consideration.

Table 1: History of managed aquifer recharge in Australia (in $10^6 m^3$/year)

Decade	Total	Infiltration systems				Recharge wells			
		Rivers	Aquifers	Urban storm-water*	Recycled water	Rivers	Aquifers	Urban storm-water	Recycled water
1961-1970	79	10		69					
1971-1980	144	40		104	0	0			
1981-1990	185	53		130	0	2		0	0
1991-2000	213	53		156	0	2		2	0.2
2001-2010	257	53	3.5	182	0.6	0.1	0	17	0.2
2011-2015	410	53	3.5	208	1.8	0.1	113	29	1.5

* derived from estimates based on population, metropolitan area, impervious fraction, rainfall, runoff coefficient and proportion of runoff effectively recharged. Others values are based on measured data.

Uptake of MAR had been slow in Australia although following release of the MAR Guidelines there has been strong public acceptance and very rapid growth particularly in the resources industries and also by local government and water utilities as they identify opportunities for MAR to contribute to their portfolio of water management activities. Surprisingly there has been minimal effort in enhancing recharge in rural areas for agriculture since the foundational project that has operated effectively for 50 years. There are diverse drivers for MAR in Australia as revealed in the results of a national survey of 135 groundwater professionals in May-July 2015 (Fig 1). The dominant reasons given are to increase water security in drought, to meet growing demand for water and to mitigate decline in groundwater levels.

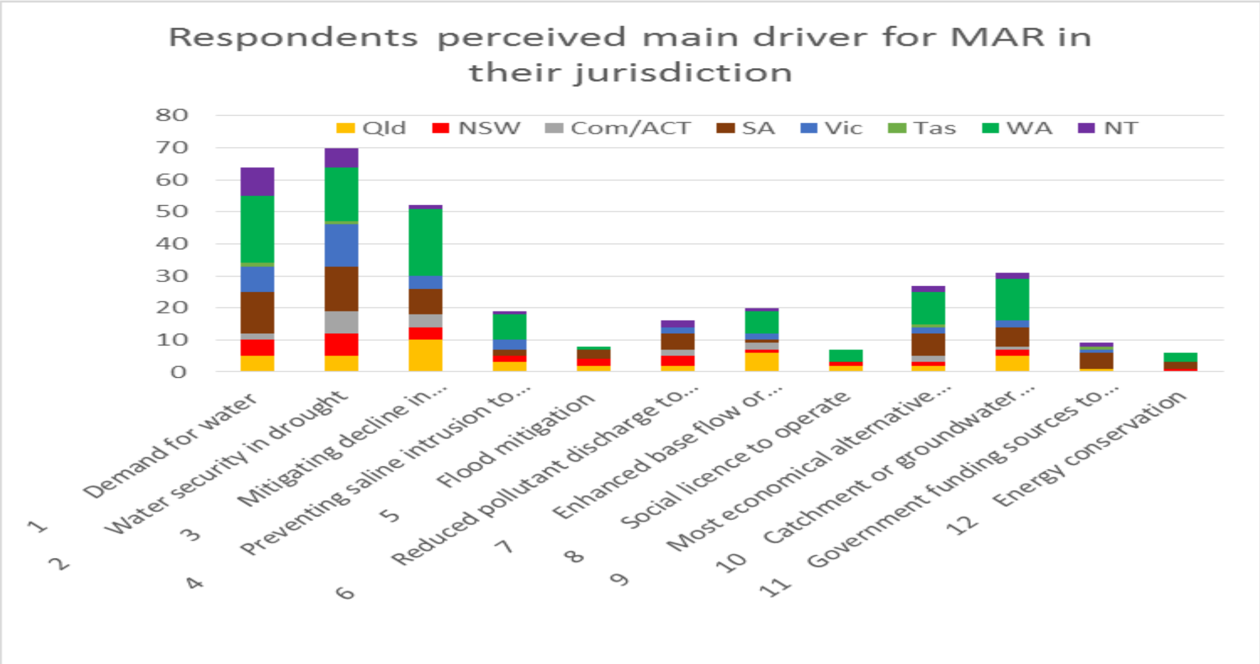

Figure 1. The main drivers for MAR perceived by 135 Australian respondents in a survey May-July 2015.

Two national symposia Volker (ed) (1980) and Sharma (ed) (1989) and International Symposium on MAR (ISAR4) (Dillon (ed) (2002) have been the dominant symposia in this field in Australia, and Australian authors have made significant contributions to ISMAR symposia since. Australian groundwater symposia conducted by IAH since 1994 have invariably included several papers on MAR and since 2000 this has also been reflected in OzWater and water recycling symposia conducted in Australia by IWA and AWA. At least twelve training courses and workshops have been run by NCGRT and its predecessor CGS since 1996 in various cities and encouragingly, two thirds of respondents to the survey claimed they had experience in MAR. There is now a MAR-Hub cluster of companies (http://marhub.net.au/) which collectively have experience in the full spectrum of MAR design and operation from hydrogeology to water treatment, systems integration, risk management, SCADA systems and wetland and water sensitive urban design. They are keen to apply their expertise internationally.

Research publications have largely focused on water quality in support of MAR guidelines and to lay the foundations for future updating of guidelines based on improved knowledge of the fate of pathogens and nanoparticles, and aquifer microbial ecology and fate of organic chemicals, natural organics and inorganics in relation to transitional thermal and geochemical conditions in aquifers and on development of robust field validation testing procedures. Clogging and its management also require improved predictive capabilities and development of comparative laboratory tests and field methods to optimize overall costs of operations and give greater assurance on preventative requirements.

Currently growth in MAR in Australia is soundly based and is expected to make a greater contribution than sea water desalination in the longer term due to lower costs. When the full benefits and costs of alternative water supplies are evaluated, it is expected that MAR will be increasingly adopted in Australia and could ultimately contribute 16% or more of national groundwater supplies.

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MAR in China for 60 Years

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China has a long history in managed aquifer recharge (MAR). The development was divided into 3 stages based on the summary combined with typical MAR projects since 1956, including the first stage applied for industrial energy saving, controlling urban land subsidence and augment agricultural water supply from 1949 to 1978, the second stage for ecological protection and augment of urban water supply from 1979 to 2000 and the third stage for multi-source MAR. In addition, geothermal reinjection and ground source heat pump are also effective use of MAR from 2001 to now(Weiping Wang et al, 2014).

1. The first stage

Groundwater recharge through deep tube wells located the geological conditions of coastal, alluvial, piedmont plain and karst aquifer with cooling water or tap water since 1960s for air-conditioning or heating and controlling land subsidence through Shanghai, Tianjin, Beijing, Shijiazhuang, Xi'an and Nanchang cities etc, characterized by factories being investors, beneficiaries and government being guide. For example, Shanghai city which represents a typical development of MAR for the first stage is located in the Yangtze River Estuary where the deep Quaternary sedimentary covers the area underlying carbonate rock layer, relying entirely on groundwater as urban water supply so resulting in land subsidence with a maximum ground drop depth of 2.63m in 1965. At the same time, five cotton mills in Shanghai carried out injection test with 4 different water sources and recharge techniques of intermittent injection, continuous and intermittent lifting, subsequently observing the groundwater level and land subsidence for many times. the result shows that groundwater recharge through tube well can not only alleviate to increase groundwater level and effectively control land subsidence but solve the problem of pumping groundwater, offering new cold source and heat source for factories with aquifer, that is water was recharged into aquifer in winter while exploited in summer and water was recharged into aquifer in summer while exploited in winter. In 1966, groundwater recharge was done through 134 of deep wells in more than 70 factories of the city at the same time so that average groundwater level raised more than ten meters and ground level up 6mm that meant it is first time to appear phenomenon of ground level rising until it had been fallen several decades(Weiping Wang et al, 2010). Since then, the techniques of groundwater recharge were improved constantly in Shanghai and achieved result showed that the underground water level rising from -10 m to -1.5 m in 1970, the land subsidence being stable at between 0 and 5 mm by 1990 (Yi Liu, 2000), the total amount of groundwater recharge with tap water of 100×10^6 m^3 in Shanghai by 2000, the annual average of groundwater recharge of 20×10^6 m^3 and urban land subsidence being controlled effectively (Shiliang Gong, 2006; Yi Liu, 2000).

In rural area of North China Plain, artificial recharge of groundwater were widely applied through wells, ponds, ditches and basins in order to increase replenishment of the groundwater and ensure the agriculture with bumper harvest and stable production, characterized by farmers putting as free labor, government gave subsidence to these projects and collective economy benefited. For example, the irrigation district of Renmin Shengli Channel in He'nan province adopted a method of combination of well and channel, which use channel water for irrigation and recharge groundwater during the dry seasons, while use well water in contrast. In 1975, the irrigated area reached 300,000 hectare and the water table was maintained at 2m, the saline land area decreased and grain yield increased year after year. Now the module, groundwater recharge through channels diverting surface water and guaranteeing agriculture harvest by pumping groundwater through wells, has been widely applied in larger irrigation districts of diversion Yellow River water in Shandong and He'nan province. The way to be developed, for example, in Huantai county and Yanzhou county of Shandong province and Hebei province, where the water network of all rivers and ditches connection throughout the county were built to retain water by rivers and ditches, infiltrating to recharge groundwater and forming larger groundwater reservoir which played an important role in combating droughts of 1970s. In addition, practical intercepting underflow project in semi-arid and arid region were constructed to alleviate the contradiction between supply and demand of water resources effectively and strengthen the agricultural drought resistance. For instance, Alxa League city of Inner Mongolia has built 70 intercepting underflow projects since 1970s. Among them, the largest one in Alxa Zuoqi resolved tens of thousands of people's drinking water with 90L/s of daily water supply. Intercepting underflow project is an effective measure to exploit and utilize groundwater of river way and valley plain in hilly area (Qinde Sun et al., 2007; Honggu Luo, 1981).

2. The second stage

6 underground reservoirs to prevent salt water intrusion were built to prevent seawater intrusion in Shandong peninsular since 1990s, characterized by mostly government investing and farmers and factories being beneficiary. For example, the Huangshui River Underground Reservoir with total reservoir capacity of 53,59 million m^3, which was composed of a underground cement wall of 5842 m long and 10 m deep combating salt water intrusion and storing groundwater ,6 sluices retaining surface water when flood period 2,518 infiltration wells and 448 infiltration trenches directing flood water into aquifer. What is more, there is a serious water shortage in partial downstream plains. Since 2000, some reservoirs have turned into integrated ecological type instead of flood control and water supply merely. For example, the water in Taihe reservoir in Zibo City of Shandong province in dry seasons is discharged to supply downstream groundwater source by riverbed infiltration.

3. The third stage

Various water sources could be storied in MAR, such as urban stormwater, reclaimed water, foreign water transferred from the other basin such as Yellow River or Yangtze River, which were recovered for drinking water supply or agricultural irrigation, characterized by more experimental pilot project and larger scale of practical projects invested by government. For example, the first urban reclaimed water recharge project in China, Gaobeidian Groundwater Recharge Pilot Project in Beijing, which was completed in 2003 with 200m^3/d of design recharge amount composed with combination of a basin and rapid infiltration shaft system(Guichun Yun et al., 2004) that led to the first state standard of *Municipal wastewater reclamation and reuse and the quality of recharging water（GB/T19772-2005）*. The pilot project though wetland treatment and basin infiltration with municipal reclaimed was done in Zhengzhou city of Henan province in 2002 and recovered water can be used for fishery, industry and agriculture (Menggui Jin et al., 2009). For another example, a pilot project of karst aquifer recharge with urban treated roof water was established in Jinan in .2011. Continuous monitoring shows that both quality of roofwater and groundwater basically met groundwater quality standard with a recharge amount of 2000m^3 until 2015(Weiping Wang et al., 2015). In addition, the project of MAR through channel infitration with local surface water released from upstream reservoir and Yellow River water pumped along Yufu River of Jinan, Shandong was implemented to augment groundwater and improve drinking water in 2014, with annual released water quantity of 5,000-7,000 million m3 from 2014 to 2015. There is same project of MAR along Chaobai River with reclaimed water and Yangtze River water was implemented in Beijing(Ji Liang et al., 2013;Fandong Zheng et al.,2015). Furthermore, geothermal reinjection and ground source heat pump are also effective utilization of MAR. In recent years, ground source heat pump (GSHP) technique developed quickly. In 2009, the *Technical code for ground-source heat pump system (GB50366-2005)* was issued, which contributed to the development and application of GSHP technology.

There are some typical MAR projects since 1960s in Table 1 and symposiums on MAR in Table 2 as follows:

Table 1. Typical Projects on MAR in China since 1960 (Uncompleted statistics)

City/ county/ province	Region	Character	Aquifer	Types	Source water	End use	Date	Operation or not	Volume (m^3/yr)
Huantai	Wuhe River	Practical	Pore	Water spreading of open channel-under tunnel	Runoff in river	Irrigation	1962		
Shanghai	Urban area	Practical	Pore or karst	ASR, ASTR	Cooling water or tap water etc.	Energy saving and preventing land subsidence	1965	Yes	20×10^6
Tianjin									
Beijing									
Shijiazhuang									
Xi'an									
Nanchang									
Huantai	Piedmont plain	Practical	Pore	Water spreading of network of connected channels/diches/ponds	Runoff in the river	Irrigation	1970s		
Yanzhou									
Tengzhou									
Shandong and Henan Province	Yellow River flood plain	Practical	Pore	Water spreading of network of connected channels/diches and irrigation	Yellow River water	Irrigation	1970s	Yes	
Inner Mongolia	Arid and semi-arid area	Practical	Pore	Intercepting dam	Local groundwater runoff	Rural human and livestock drinking water and irrigation	1970s	Yes	2.85×10^6
Shanxi Province									
Hebei Province									

<table>
<tr><th>City/ county/ province</th><th colspan="2">Region</th><th>Character</th><th>Aquifer</th><th>Types</th><th>Source water</th><th>End use</th><th>Date</th><th>Operation or not</th><th>Volume (m^3/yr)</th></tr>
<tr><td>Longkou</td><td colspan="2">Balisha River</td><td>Pilot</td><td rowspan="6">Pore</td><td rowspan="6">Underground dam</td><td rowspan="6">Exceed flood water in the river</td><td rowspan="6">Agricultural, industrial and drinking water use</td><td>1987</td><td>Yes</td><td>0.6×10^6</td></tr>
<tr><td>Qingdao</td><td colspan="2">Shiren River</td><td>Practical</td><td>1991</td><td>Yes</td><td></td></tr>
<tr><td>Longkou</td><td>Huangshui River</td><td rowspan="4">Estuary</td><td>Practical</td><td>1995</td><td>Yes</td><td></td></tr>
<tr><td>Qingdao</td><td>Dagu River</td><td>Practical</td><td>1998</td><td>Yes</td><td></td></tr>
<tr><td>Laizhou</td><td>Wang River</td><td>Practical</td><td>1999</td><td>Yes</td><td>31.9×10^6</td></tr>
<tr><td>Yantai</td><td>Dagujia River</td><td>Practical</td><td>2000</td><td>Yes</td><td></td></tr>
<tr><td>Zibo</td><td colspan="2">Zihe River</td><td>Practical</td><td>Pore and Karst</td><td>Recharge release</td><td>Local surface water</td><td>Drinking and industry water</td><td>2000</td><td>Yes</td><td></td></tr>
<tr><td>Beijing</td><td colspan="2">Gaobeidian wastewater treatment plant</td><td>Pilot</td><td>Pore</td><td>Combination of well and basin</td><td>Reclaimed water</td><td>Augment groundwater</td><td>2002</td><td></td><td>73×10^3</td></tr>
<tr><td>Zhengzhou</td><td colspan="2">Suburban</td><td>Pilot</td><td>Pore</td><td>Wetland, water treatment system and Basin</td><td>Reclaimed water</td><td>Irrigation</td><td>2007</td><td></td><td>113×10^3</td></tr>
<tr><td>Beijing</td><td colspan="2">Chaobai River</td><td>Pilot</td><td>Pore</td><td>Natural channel</td><td>Multiple sources of Yangtze River water and reclaimed water</td><td>Drinking water and industry water</td><td>2012</td><td>Yes</td><td></td></tr>
<tr><td>Jinan</td><td colspan="2">University of Jinan campus</td><td>Pilot</td><td>Karst</td><td>ASTR</td><td>Roof water</td><td>Drinking water</td><td>2008</td><td>Yes</td><td>700</td></tr>
<tr><td>Linqing</td><td colspan="2">Yellow River flood area</td><td>Pilot</td><td>Pore</td><td>Spreading of open channel-underground performed pipe-shaft</td><td>Yellow River water</td><td>Irrigation</td><td>2014</td><td>Yes</td><td>20×10^3</td></tr>
<tr><td>Jinan</td><td colspan="2">Yufu River</td><td>Practical</td><td>Pore and Karst</td><td>Natural channel</td><td>Multiple sources of local surface water and Yellow River</td><td>Drinking water and keep springs flowing</td><td>2014</td><td>Yes</td><td>50×10^6</td></tr>
</table>

Table 2 Symposiums on MAR in China

Conference	Location	Date	Website
China-Australia Managed Aquifer Recharge (MAR) Training Workshop	University of Jinan, Jinan, China.	October 27-31, 2008	http://china-mar.ujn.edu.cn/
8th International Symposium on Managed Aquifer Recharge - ISMAR8	Tsinghua University, Beijing, China.	October 15-19, 2013.	http://china-mar.ujn.edu.cn/
The Role of Managed Aquifer Recharge in Water Resources Management in China: A Practical Guide for Piloting and Upscaling	Peking University, Beijing, China.	September 7, 2015	http://hydro.pku.edu.cn/

China obtained a great achievement on MAR used for land subsidence control, energy storage, geothermal utilization, prevention of seawater intrusion, augment of urban water supply, agriculture irrigation and alleviation of agricultural disasters etc. However, there are still many problems. It is needed to develop multiple feasible, convenient and economic techniques of MAR fitting to local hydrogeological conditions, prepare guidelines of MAR and management regulations together by establishing demonstration projects, making MAR standardized and the guidelines perfect led by Ministry of Water Resources, Ministry of Environmental Protection and Ministry of Land and Resources jointly.

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MAR in Croatia

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https://recharge.iah.org/60-years-history-mar

Managed aquifer recharge (MAR) is not discussed often in Croatia since groundwater reserves generally satisfy demand for water. Hence, the need to manage aquifer recharge is not pronounced. Nevertheless, there are some springs used for public water supply which require enhanced recharge during periods of hydrologic drought as well as public wellfields deliberately positioned near rivers in order to, either enhance the capacities of pumping wells through river bank filtration, or diminish wellfield protection zones which in many cases occupy urban areas.

Quaternary alluvial aquifers, typical in the northern part of Croatia which is situated in the southwestern part of the Pannonian basin, are mainly recharged by rivers Sava and Drava. Although river Drava is regulated with hydropower plants (HPP's) on one smaller upper tributary, the majority of the flow of the rivers Sava and Drava is still unregulated with respect to structures such as dams or weirs. Therefore the rivers not only recharge aquifers but also drain them during low flow periods (Posavec *et al*., 2017). Alluvial aquifers, mainly composed of sands and gravels are generally characterized by high hydraulic conductivities, ranging from 10^{-5} m/s (~1 m/d) in eastern parts of Croatia to 10^{-2} m/s (~1000m/d) in western parts. Such high hydraulic conductivities enable intensive aquifer recharge as well as aquifer discharge. High aquifer discharge potential therefore makes MAR inefficient in many cases. At the same time, high aquifer recharge potential as well as relatively thick alluvial deposits, make positioning of the pumping wells less demanding. Therefore, in many cases there was no need to position the wells near the river in order to utilize river bank filtration.

A study by the Croatian Geological Survey (2009) on assessment of state and risk of groundwater bodies indicates that artificial recharge of aquifers by recharge wells or channels is not present in the Pannonian part of the Republic of Croatia . Nevertheless, some wellfields located in the City of Zagreb, Croatia's capital (population of ~800,000), have been placed knowingly within the proximity of the river Sava with the intention that a proportion of the extracted water would be induced recharge from the river. Further, a structure was built in the river Sava, weir TE-TO. Although the intention of building weir TE-TO was not to increase aquifer recharge, it was one of the consequences which therefore indirectly increased the abstraction potential of some wellfields and the proportion of the water derived from the river. Therefore, this proportion of groundwater pumped at some Zagreb wellfields and derived from the river can be considered as bank filtration (MAR) (Table 1).

Table 1. Estimated volume of Managed Aquifer Recharge (bank filtration) (Million cubic metres/year)

Annual MAR volume in the decade centred on date (Mm^3/y)				**Annual Groundwater use (Mm3/y)**
1985	**1995**	**2005**	**2010-15**	**2010**
42*	48*	48*	46*	600**

*derived from measured data on abstraction and estimated percentage of abstracted volume gained from river bank filtration ** based on Zagreb Water Supply and Sewage Company data on abstraction for the City of Zagreb, ~125 Mm3/y (Hidroprojekt-Ing and Sl-Consult, 2014). Extrapolated for the entire region of Croatia.

The hydrogeology of the southern part of Croatia is characterized by karst aquifers and water is supplied mainly from springs. Managed aquifer recharge is generally not a common approach with some exceptions. One such exception and the first attempt in Croatia of managed aquifer recharge in karst aquifers is at the Gradole Spring located in Istria, and used for public water supply. Gradole Spring was artificially recharged from water accumulated in Lake Butoniga and pumped into sinkhole Čiže located in Tinjanska Draga. This resulted in a significant increase of spring discharge (Faculty of Geotechnical Engineering, 2009). From the late 1980's to early 2000's, an average 0.873 Mm^3/y was pumped from Lake Butoniga and discharged into the sinkhole Čiže. The maximum volume was pumped in year 1990 (2.8 Mm3/y) and the minimum was reached in year 1995 (0.1 Mm3/y) (http://www.ivb.hr/naslovna-hidden/30-akumulacija-butoniga). Although this solution was inefficient with respect to energy consumption required to pump water from Lake Butoniga situated at 40 m a.s.l. up to the sinkhole Čiže situated at some 350 m a.s.l., it helped to increase the discharge of the Gradole Spring during summer dry seasons. Later on, a water treatment facility was built at Lake Butoniga, which enabled direct distribution of drinking water to consumers and made further MAR actions unnecessary.

Another attempt of managed aquifer recharge of karst aquifers was done also in the late eighties on the island Krk by building the water storage Ponikve. Although managed aquifer recharge resulted with increase in groundwater quantity available, it also deteriorated the groundwater quality, due to which the concept was abandoned (Faculty of Geotechnical Engineering, 2009). Another aspect of MAR was related to construction of HPP's i.e. accompanying storages. Although detouring of rivers in order to build storages had a negative impact on downstream karst aquifer systems, it also helped in stabilizing the flowrate of some springs (Faculty of Geotechnical Engineering, 2009).

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Managed aquifer recharge in Finland

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In Finland the selection of the appropriate source(s) of raw water for urban water supply has been debated for more than a century. In rural areas ground water has traditionally been drawn from wells and springs for domestic use, whereby the needs of dairy farming also largely promoted common piped water supplies. The first managed aquifer recharge (MAR) system in Finland was used in Vaasa on the western coast in the late 1920s, and its use was also considered in Helsinki. Yet, the decision by Tampere to give up the ground-water option in 1920 encouraged other cities to use surface water, as ground-water deposits in Finland are generally fairly small. After WWII, surface water was adopted even by cities with available ground-water resources. (Katko 2016, 58)

After the establishment of the National Water Administration in 1970, the use of ground water became predominant, and around the same time, wider use of MAR started. In spite of its many advantages the use of ground water for community water supply is no longer automatically considered the best option, since the current aim is to keep all water sources as clean as possible. The debate between surface and ground-water use seems, however, to continue. (Katko 2016, 58)

By the 1960s and 1970s surface water had often become polluted, but efficient water pollution control and wastewater treatment have improved its quality dramatically. Yet, Finnish waters contain natural organic matter (NOM; humus) and are also soft, since the bedrock contains only a little calcium. Therefore, surface water needs more complicated treatment, often chemical, to meet domestic water quality requirements. (Katko 2016, 59)

During the last few decades, Finnish community water supply has increasingly relied on natural ground water and MAR as raw water source (Table 1). Currently, their combined share of the water supplied is some 67%. The share of MAR alone is roughly 17 %, including bank filtration. However, potential ground-water areas and places for ground-water recharge are sparsely situated. Thus, large city centres, with their increasing need for fresh water supply, are obliged to withdraw ground water from afar, often crossing municipal borders. (Katko, 2016)

The main objective of MAR in Finland is the removal of NOM from surface waters. A typical MAR procedure consists of the infiltration of surface water into an esker with subsequent withdrawal of the MAR-treated water from wells a few hundred meters down-gradient. The infiltrated water should have a residence time of at least approximately one month before withdrawal to provide sufficient time for the subsurface processes needed to break down or remove humic substances.

There are currently 26 MAR plants in Finland and, in addition, a few plants are being planned. The MAR plants are operated continuously, also during winter. Basin infiltration is used most often, whereas sprinkling infiltration was initiated in the mid-1990s. Sprinkling infiltration includes an aboveground pipe network through which water is distributed on top of natural forest soil. Well infiltration or well injection is applied only in a couple of MAR plants in Finland. However, new infiltration wells are being planned and tested. (Jokela & Kallio 2015)

Table 1. History of MAR in Finland (approximate values)
Raw water is taken from lakes and rivers.

Period	MAR production (10^6 m^3/a)	Infiltration methods
1961 - 1970	< 1	basin (the first MAR plant started in 1970)
1971 - 1980	30	basin, dug well, bank
1981 - 1990	35	basin, dug well, bank
1991 - 2000	50	basin, sprinkling, dug well, bank
2000 - 2010	55	basin, sprinkling, well, bank
2011 - 2015	65	basin, sprinkling, well, bank (share < 10 %)

Most of the Finnish MAR plants do not have pretreatment and raw water is infiltrated directly into the soil. During a MAR process in an unconfined esker aquifer NOM is removed by physical, chemical, and microbial processes. Most of the NOM removal takes place in the saturated ground-water zone.

Most often, total organic carbon (TOC) concentrations of the raw waters vary roughly from 6.5 to 11 mg/L and after MAR the TOC concentrations of the abstracted waters are approximately 2 mg/L. The overall reduction of organic matter in the treatment (with or without pretreatment) is thus 70–85% (Jokela et al. 2017).

Mechanical pretreatment can be used for clogging prevention. Turbidity of the Finnish lakes used as raw water does not necessitate pretreatment in basin and sprinkling infiltration, however, pretreatment in well infiltration needs to be judged separately. River waters may have high turbidity requiring pretreatment. Natural conditions in esker aquifers are generally aerobic. Biodegradation of NOM in the saturated ground-water zone consumes dissolved oxygen. The higher the NOM content, the higher the dissolved oxygen consumption. If dissolved oxygen concentration in the ground-water zone sinks low enough, conditions for dissolution of iron and manganese from the soil increase. Iron and manganese dissolution may be avoided by the addition of chemical pretreatment for the raw water to cut the NOM content. According to the results from selected MAR plants, raw waters with TOC content up to at least approximately 8 mg/L are infiltrated without any considerations of chemical pretreatment. A higher share of natural ground water provides more dissolved oxygen. However, aquifer properties, including the soil composition, vary locally and have influence on the MAR process. (Jokela et al. 2017)

Eskers in Finland are glaciofluvial formations which were commonly deposited by streams in tunnels beneath the ice during the final deglaciation of the Scandinavian ice sheet. Typically, an esker consists of 20 to 50 m of gravel and sand that is covered by a thin humic soil layer (<10 cm). Eskers are preferred areas for potable water MAR treatment. However, they can also be centers of population, considered recreational areas or nature conservation sites, or they can be sources for extraction of gravel. When MAR plants are being planned, these interests may conflict. Public participation is an important feature of MAR planning in Finland (Jokela & Valtonen 2010, Kurki & Katko 2015). Sprinkling infiltration and well infiltration can be attractive for areas not suitable for the construction of basins, e.g., eskers with slopes, and forest areas having recreational values with restrictions on tree cutting. When sprinkling infiltration or well infiltration is used, there is no need to dig and construct basins and direct physical effects on the landscape are reduced. Recreational values, including minimizing the effects on landscape, are often emphasized in public participation.

Recycled water is not used at Finnish MAR plants. The MAR process removes pathogens efficiently, both bacteria and viruses. Risks of contamination of the recharge process are reduced by the choice of good quality raw waters and protection of the recharge areas from external, possibly harmful activities (such as gravel extraction or handling of petroleum). Before distribution to the trunk mains, water is disinfected by ultraviolet (UV) radiation, chlorination, or both, and, when necessary, the alkalinity and hardness are adjusted.

However, conventional ground-water management approaches, drawing from expert-based instrumental rationality, seem often to be insufficient for successful project planning and implementation. Based on an exhaustive study on two large MAR projects in Finland, Kurki (2016) suggested that in ground-water governance the core should be in collaborative rationality while some of the tools can be obtained from rationalistic expert-based planning. Thereby project legitimacy should be gained through joint knowledge production as well as interaction where addressing stakeholders' interests could help in finding mutual gains and new options for collaboration (Kurki & Katko 2015). Thus, water experts should be more facilitators rather than holders of the only legitimate source of knowledge, and the stakeholders like partners rather than informants.

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Managed Aquifer Recharge in France

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In France 67% of the volume of drinking water in France is produced by groundwater. For industrial and agricultural purposes, 40% of water supply comes from groundwater. French water regulations are fixed by the European Water Framework Directive (WFD) that defines the legal framework supporting the commitment to protect and restore water quality and aquatic environments.

"Good chemical status" of an aquifer is achieved when contaminant concentrations are not higher than the standards fixed by the WFD for groundwater. "Good quantitative status" of groundwater is achieved when the volume of water withdrawn is not higher than the renewal capacity of the water body and when the connected surface ecosystem health is maintained.

In 2013, 90.4% of the 645 identified groundwater bodies in France were in a good quantitative status but only 67% of them were in good chemical status (ANSES 2016).

With the constant population growth combined with climate change, the management of groundwater resources in France is mostly focused on water conservation and enhancement of natural recharge of aquifers (*eg*. hill reservoirs). But these actions are not sufficient to face water scarcity in some localities, and Managed Aquifer Recharge (MAR) could be an interesting and efficient way to maintain and improve groundwater quality and quantity.

Centralised governance of MAR practice in France is not established. However French regulation allows MAR on a case-by-case basis by prefectural authorization most often in the context of preventing saline intrusion or to meet the need of seasonal water demand as required depending on climatic conditions.

According to the WFD, the good status of the water bodies affected by MAR must be preserved. In France, the sources of water for enhancing recharge are mainly surface water (river) that is put into infiltration ponds.

Table 1 shows the major MAR sites in France. This shows there is considerable experience since the 1950s and there have been occasional periods of quite active development in the 1960s, 1980s and 2000s. A map showing MAR sites in France is found in Casanova *et al* (2016).

Table 1. ARTIFICIAL RECHARGE OF GROUNDWATER SITES FROM SURFACE WATER IN FRANCE

SITE	Starting date of operation	Artificially recharge water volume ($Mm^3\ y^{-1}$)	Recharge system
Donzere Mondragon	1952	$8.5m^3/s$*	Injection wells
Croissy sur Seine	1965	30.0 [a]	Infiltration ponds
Appoigny	1968	0.4 [b]	Infiltration ponds
Flins-Aubergenville	1980	8.0 [a]	Infiltration ponds/Bank filtration
Durance river	1980	5.0 [a]	Infiltration ponds
Vessy	1980	10.0 [a]	Infiltration ponds
Houlle Moulle	1983	4.4 [c]	Infiltration ponds
Flammerans	1997	6.6 [a]	Injection wells
Verneuil sur Seine-Vernouillet	2009	0.7 [b]	Infiltration ponds/Bank filtration
Hyères-les-Palmiers (France, Var)	2015	0.65 [b]	Infiltration ponds

* data in $m^3\ y^{-1}$ not available, [a] maximum capacity, [b] estimated annual value, [c] annual mean during activity period (still operating French major sites from Wuilleumier and Seguin, 2008; SIGESSN)

The Croissy-sur-Seine site can be cited as a pioneer in terms of MAR in France (Casanova et al., 2013). This site was put in operation in 1959 in order to increase the quantity of water withdrawn from the chalk aquifer for drinking water purposes (Detay, 1997). The Seine river water after pre-treatment is infiltrated into the aquifer through 9 infiltration ponds. The 12 hectares of replenishment basins help sustain 31 wells. 20 to 30 Mm^3 per year of water are infiltrated in the aquifer. Moreover, a bank filtration recharge system is coupled with infiltration ponds from Seine River under pumping wells action.

Since 2015, the active management of the main water resource of the city of Hyères-les-Palmiers (France, Var) has been developed to prevent saline water intrusion of the Bas Gapeau hydrosystem (AQUARENOVA project). This system is based on a real-time abstraction control, based on a continuous monitoring of water level and conductivity on specifically localized piezometers. The hydraulic gradients method shall optimize abstraction without risking saline intrusion (detected early 2000). In winter, aquifer recharge is operated by infiltration ponds, abstracting coastal river Roubaud water, in order to form a freshwater piezometric dome exploited in summer (Duzan *et al.,* 2016).

It is quite difficult to estimate the total amount of groundwater replenishment by MAR in France and Table 2 is based on the factual information of Table 1 and assumes that average annual recharge is approximately half the annual maximum capacity where actual volumes are unknown.

Table 2. Estimated volume of MAR in France over the last 60 years

Decade	Annual volume of MAR (10^6 m^3/y)
1951 - 1960	?
1961 - 1970	20
1971 – 1980	21
1981 – 1990	26
1991 - 2000	30
2001 - 2010	31
2011 - 2015	32

Recently, the French Agency for Food, Environmental and Occupational Health & Safety (ANSES) published opinion on the health risks related to MAR (2012-SA-0255) and put emphasis on MAR solutions using surface waters or treated wastewater to mitigate the decrease in French groundwater resources in the future. The quality of groundwater must be preserved during MAR practices and particularly to guarantee quality compatible with production of drinking water, without needing to use additional treatments funded by local authorities and consumers. ANSES recommends developing studies of MAR sites in France to ensure sustained quality of recharged groundwater and to better characterise the hazards to humans.

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MAR in Germany

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According to the Federal Statistical Authority of Germany (FSA, 2013), public water supply in Germany relies on groundwater extraction (60,9 %), spring water (8,4 %), lake and dam water (12,2%) and river water (1,2 %). The remaining 17,4 % originate from MAR, whereby 8,6 % is bank filtrate and 8.8 % is defined as "recharged groundwater", consisting mainly of intentionally recharged surface water. In 2013, the public water supply produced ~5000*10^6 m³ of water out of which ~3500*10^6 m³ were domestic water provided for households and small businesses. According to these numbers approximately 870*10^6 m^3/year were abstracted via MAR. Surface water is the main source of MAR in Germany, recharged intentionally, for example via basins, or indirectly via induced bank filtration. MAR in Germany is generally done to achieve water quality improvements of the surface water used as a source, i.e. as a pre-treatment step, and to some extent also to preserve deeper groundwater resources. Since only a small fraction (~3 %) of the total amount of water available annually is required for the public water supply (Grischek et al., 2010), quantitative reasons for MAR are of lesser importance and strict legal regulations mostly impede the use of storm- or treated wastewater as well as the use of injection wells.

Table 1. Development of MAR in Germany and groundwater use

Annual MAR volume in the decade centred on date (Mm^3/y)						Groundwater Use (Mm^3/y)	MAR as % groundwater use	MAR as proportion of drinking water supply
1965	1975	1985	1995	2005	2010-15	2010	2010-15	2010-15
n.a.	867	766	875	765	872	3,077	28.2%	17.2%

The federal statistical agency in Germany collects the data only every 3 years. Data is based on public water supply only and was available from 1979 only for the years: 1979, 1983, 1987, 1991, 1995, 1998, 2001, 2004, 2007, 2010, and 2013.

Bank filtration has a long tradition in Germany. Amongst the sites exploited longest are those of the Düsseldorf-Flehe Waterworks on the River Rhine (Schubert, 2002), the Dresden-Saloppe Waterworks on the River Elbe (Grischek et al., 2010) and those of the Berlin Water Company along the lake-type extents of the rivers Spree and Havel in Berlin (Stadtentwicklung Berlin, 2016), all having provided drinking water since the 1870s. According to Lenk et al. (2006), decreasing river water qualities halved the amount of drinking water produced by bank filtration in former Western Germany between 1970 and 1990 and many sites were abandoned because of increasing chemical and organoleptic problems. Nowadays the water quality of major rivers has improved, possibilities for bank filtration are reviewed and new sites have been launched again (Lenk et al., 2006). Of the large river catchments in Germany, rivers within the Elbe (21 %) and Rhine (8,5%) catchments have the highest share of water originating from bank filtration in terms of % of total water production and also the largest total amount of water produced via bank filtration (Elbe:

189*10^6 m^3/year; Rhein: 140 *10^6 m^3/year; FSA, 2013). A literature review on bank filtration sites in Germany by Lenk et al. (2006) illustrates the clustering of sites identified as having >50 of bank filtrate in abstraction and observation wells in the Rhine and Elbe catchments (figure 1).

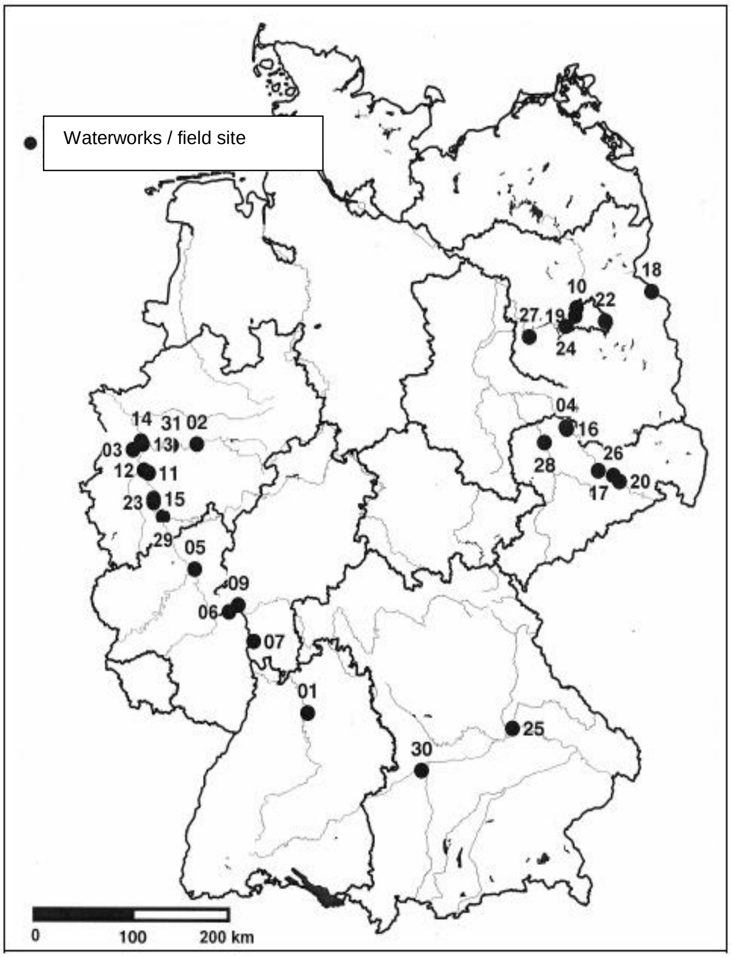

Figure 1: Water companies and field sites that were identified as having >50 of bank filtrate in abstraction and observation wells and studied in a large review on European bank filtration (Lenk et al., 2006).

In recent years, research on bank filtration in Germany has strongly focused on the behavior of organic trace pollutants during underground passage and a detailed report on the attenuation efficiency of the sub-surface for organic trace pollutants during bank filtration was presented by Schmidt & Lange (2006). Intensive research has, for example, been conducted regarding the semi-closed water cycle of Berlin, were 70% of the groundwater abstracted for drinking water purposes originates from bank filtration or infiltration via ponds and the fraction of treated sewage in the surface water courses is relatively high (e.g., Ziegler et al., 2002). Results from the NASRI and successive projects could show that most organic trace pollutants present in the surface water are readily removed, but a number of compounds behave persistent (e.g. Wiese et al., 2011). Overall, results also showed that the first meter of flow (i.e. the infiltration zone/river or lake base) is most efficient in removing trace pollutants and amongst other factors, redox conditions and temperatures strongly affect degradation (e.g. Burke et al. 2014). One of the largest challenges when assessing and quantifying organic trace pollutant attenuation during bank filtration and any other form of MAR is the transferability of attenuation parameters (such as first order degradation rate constants) between sites. This is mostly still impossible (e.g. Henzler et al., 2014; Nham et al., 2015; Hamann et al., 2016) and therefore prohibiting precise predictions on trace pollutant behavior at newly launched sites.

MAR with treated wastewater or stormwater is uncommon in Germany, the only exceptions being the cities of Braunschweig, where treated wastewater has been irrigated continuously for over 50 years onto agricultural fields (Ternes et al., 2007) and Wolfsburg, which irrigates ~$4*10^6$ m³/year of treated wastewater onto agricultural soils (WEB, 2014). In these two exceptional cases, MAR is practiced as soil-aquifer treatment and aims at stabilizing groundwater levels in addition to irrigation and fertilization of crops used for energy production.

Elsewhere in Germany the practice of treated or formerly even untreated sewage irrigation, which often lead to unintentional (and rather unmanaged) aquifer recharge, has been abandoned. A prominent historical example of "sewage farming" is the capital city Berlin, were untreated sewage was applied directly onto fields above unprotected aquifers from 1876 to the 1980s (Hass et al., 2012). Often, the remainders of this unintentional MAR practice continue to contaminate groundwater downstream of the former sewage farms (Scheytt et al., 2000; Richter et al., 2009; Hass et al., 2012).

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Artificial Recharge of Groundwater in Israel

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Artificial recharge of groundwater aquifers (AR), performed through infiltration ponds and through recharge wells, has been practiced in Israel since the 1960's as an important component of the integrated management of surface and groundwater (Schwarz,1980) for the following objectives:

1. Seasonal storage of excess surface water in the National Water Supply (NWS) system, which carries water from the Jordan sources in the north to the central (coastal) regions.
2. Reclamation of over-exploited aquifers,
3. Utilization of rainwater runoff and flash floods, where surface storage is unavailable.
4. Soil – Aquifer Treatment (SAT) of sewage treatment effluents, aimed at the removal of residual contaminants by filtration and adsorption on the aquifer's solid skeleton, by upper soil aeration and by long retention time in the aquifer.

The NWS system, inaugurated in 1964, supplies water for domestic, industrial and agricultural purposes. It conducts and integrates Jordan River surface water, through Lake Kinneret, with groundwater from the coastal sandstone and mountain limestone aquifers, which are the major groundwater basins in Israel. Since 1964, AR has been implemented for seasonal storage, as part of the NWS's operation, to increase the yield during years of high demand and low rainfall. The water carried by the NWS is recharged both into the Coastal (sandstone) and Mountain (limestone) aquifers.

In the first years of the NWS system, AR was implemented also for the reclamation of the sandstone Coastal Aquifer, which had been heavily overpumped prior to 1964. In fact, already in 1958, while planning the NWS, AR experiments were conducted in order to establish the capacities of AR facilities and to investigate the fate of the recharged water as it spreads in the aquifer.

AR has been implemented within the framework of the NWS system through spreading grounds, by dedicated (single purpose) wells, and by dual purpose wells operating alternately for pumping water to the water supply system and for AR.

AR of flash floods started in the 1960's in two of the main coastal River Basins by diversion to specially constructed spreading basins.

SHAFDAN is the main Waste Water Treatment Plant (WWTP) in Israel. Presently, it is serving a population of 2 million people in the Greater Tel-Aviv Region. Within the framework of this project, effluents of a conventional secondary WWTP are delivered to SAT/AR facilities, composed of percolation ponds, in a dedicated portion of the Coastal Aquifer, These ponds are surrounded by pumping wells. The pumped water is delivered through a separate pipeline system for irrigation in most Southern Israel farms, replacing fresh water supply.

The evolving role of AR can be traced in the records of the Hydrological Service (Weinberger et al 2012). Recently, the role of AR as a storage procedure has declined due to the replacement of water from the NWS by reclaimed sewage as the main source of irrigation water and the introduction of sea-water desalination. In recent years, most of AR is of reclaimed sewage effluents. Table 1 shows the development of AR in Israel since 1960.

Table 1: Artificial recharge in Israel since 1960 (in $10^6 m^3$/year)

ARTIFICIAL RECHARGE OF GROUNDWATER IN ISRAEL [$10^6 m^3$/year]

Decade	Total	Wells		Spreading Grounds		
		Limestone	Sandstone	Sandstone		
		Water Supply System		Water Supply System	Floods	SAFDAN Reclaimed Sewage Effluents
1961-1970	87	18	36	14	20	
1971-1980	91	32	27	15	17	10
1981-1990	127	18	42	12	9	46
1991-2000	132	5	11	13	15	89
2001-2010	144	3	2	6	14	119
2011-2013	134	0	0	1	10	122

AR operations have posed challenges which called for theoretical and field research (TAHAL, 1969, Schwarz *et al*, 2016). This research led to the development of planning tools. For example, research provided a better understanding of the process of mixing in the aquifer of water of different qualities (the Kinneret water being more saline than aquifer water), and produced tools for calculating the quality of pumped water (Bear and Jacobs, 1968). Another challenge was to overcome the clogging of soil beneath infiltration ponds and around screens of recharge wells (e.g. Rebhun and Schwarz, 1968).

The main challenges of AR that required intensive research and studies aimed at establishing diagnostic and remedial methodologies were:

1. The travel and mixing in the aquifer of recharged and indigenous water.
2. The impact of AR on the quality of pumped water in dual purpose wells and in nearby pumping wells.
3. Clogging and capacity degradation of recharge wells and spreading basins.
4. Contamination of AR wells.
5. Proper design and maintenance of AR facilities.
6. Cost allocation of AR operations within the National Water Supply System

At present, Israel's water economy is characterized by the introduction of large scale sea water desalination within the framework of the NWS system. AR of this water is required, but it raises new economic and technical challenges that are currently under intensive research.

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Managed aquifer recharge in Italy

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Italy has a long history of managing aquifer recharge. In Venezia, man-made water-banking of rainfall in the soil dates back to the end of the middle-age as the main source of drinking water (Vanzan Marchini, 2009). Rainwater was harvested and then conveyed to city "squares" (*campi*). These were filled with sand and stored all the harvested water that then drained through the sand medium to supply a large well (with its characteristic "*vera*") in the middle of the square. There is also substantial recharge enhancement from traditional means such as river weirs and wells near the embankments of surface water bodies. These techniques are detailed in M. Canavari Engineering Geology Primer (1928). Unintentional incidental enhanced recharge through excess irrigation also occurs as elsewhere in the world. However, in the last 60 years other forms of intentional artificial recharge in Italy have occurred only at experimental or demonstration level. Since 1969, 40 experimental pilots have been established, but not yet made a major contribution to water supply. So, it may be said that in spite of the long history in some locations, aside from riverbank filtration, managed aquifer recharge in Italy is still in its early stage of development.

While in Italy water scarcity is a major issue in the southern part of the country, the bulk of the pilots are located in the northern area (Fig. 1). The aim of these pilots is to maximize natural storage in aquifers, combat saltwater intrusion and to improve water quality. Infiltration ponds comprise the most widespread method followed by dry wells, with Forested Infiltration Areas being the most innovative type. These are rural areas where farmers store water while growing trees (for wood production), by using irrigation channels during the non-irrigation season. However, Induced River Bank Filtration (IRBF) is by far the largest managed aquifer recharge scheme currently used, even though it is not widely recognized as such, and the hydraulic connection between the surface water body and the aquifer is often disregarded by practitioners and technicians in governing authorities. It is crudely estimated that more than 400 Mm^3 of drinking water is supplied from IRBF wells. This estimate is based on the assumptions that IRBF schemes exist at rivers where average yearly discharge is higher than 30 m^3/s and that an average of 10 Mm^3 per scheme are then used.

Since the beginning of 2010, some projects on managed aquifer recharge were co-financed by the European Commission mainly through the LIFE program (TRUST - Tool for regional - scale assessment of groundwater storage improvement in adaptation to climate change (Marsala 2014); AQUOR - Implementation of a water saving and artificial recharging participated strategy for the quantitative groundwater layer rebalance of the upper Vicenza's plain (Mezzalira *et al.* 2014); WARBO - Water re-born - artificial recharge: innovative technologies for the sustainable management of water resources; Nieto Yabar *et al.*, 2012). Nearly all of them, use the terminology of artificial recharge instead of MAR. The evolution of MAR capacity in Italy is shown in Table 1.

In 2014, the Regional Authority of Emilia Romagna started a pilot on the Marecchia River fan to alleviate water scarcity in the Rimini area resulting from recurrent drought periods (Severi *et al*. 2014) using a recharge basin. The pilot was terminated two years later after having recharged about 2 Mm^3 while currently awaiting permitting of the full-scale plant.

One of the main characteristics of these pilots is that they are focused on site characterization, investigation and hydrodynamics issues, while little attention is generally paid to water quality aspects. In many cases, a very small number of piezometers (in some cases only one) are set in place in order to monitor recharge effects. This is a critical point, and unless addressed has potential to turn public perception of MAR from an opportunity to a threat to ground-water. Within the EU FP7-ENV-2013 MARSOL project (Demonstrating Managed Aquifer Recharge as a Solution to Water Scarcity and Drought; www.marsol.eu), a dedicated focus was posed on water quality issues at the 15 Mm^3/year IRBF plant in Sant'Alessio (Rossetto *et al*. 2015), demonstrating that IRBF may constitute a reliable (when care is paid to water quality aspects) and important source of water.

Table 1. Evolution of MAR in Italy

Decade	Induced River Bank Filtration (Mm^3/yr)	Other forms of MAR (Mm^3/yr)	Total (Mm^3/yr)
1961-1970	172	6	178
1971-1980	258	36	294
1981-1990	301	0	301
1991-2000	344	4	348
2001-2010	387	4	391
2011-2015	430	31	461

IRBM are estimated values only, based on population growth. Other forms of MAR values are derived from cited reports. This represents about 8% of total domestic water supply in Italy in 2012 (5000Mm^3/yr).

The main barrier to development of aquifer recharge in Italy has been until 2016 the lack of a piece of legislation on licensing MAR plants. While recharge of aquifers has been allowed since September 2013, as foreseen by the EU Water Framework Directive (EU, 2000), the regulation on licensing and permitting MAR plant (*impianti di ricarica della falda in condizioni controllate*) was promulgated only in June 2016 (DM 100/2016). This piece of legislation strongly focuses on monitoring issues, especially regarding water quality. The above-mentioned Emilia Romagna MAR plant, following the permitting application, is now under consideration to become the first Italian operational MAR scheme conforming to this framework. A new MAR pilot is under development within the EU LIFE REWAT (sustainable WATer management in the lower Cornia valley through demand REduction, aquifer REcharge and river Restoration) in Tuscany.

So far, there is growing interest in this low-cost, potentially low-energy technique, as it may constitute a valid alternative to traditional water treatment or allow conjunctive management of surface-water and ground-water bodies. At the same time, lack of knowledge at the level of intermediate governing bodies, as well as among professionals, is preventing the application of these techniques. For example, MAR plants, even though more economic and environmentally benign, are overlooked in favour of building of small surface water reservoirs. Therefore, dissemination of MAR scientific findings and technical know-how among governing authorities and the general public is crucial for the application of MAR techniques.

Finally, it is of utmost importance to identify the financial instruments to set up and sustain these water infrastructures, so as to guarantee routine operations and maintenance, and thereby opening a new market in the water sector.

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Figure 1. Locations of MAR experimental sites in Italy

Managed aquifer recharge in Jordan

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Managed aquifer recharge (MAR) has been practiced in Jordan since the 1960s and is firmly anchored in the national water strategy (MWI 2016) with the main goal to augment groundwater availability. Schemes for flood water recharge have been implemented and treated wastewater is proposed to be used in the future. However, the latter is only allowed to be recharged to aquifers that are intended for irrigation and not for drinking water purposes. In such cases, the use of reclaimed water for MAR is controlled by the standard regulations and legislations (MWI 2001) which preset the maximum concentration for diverse parameters. Further considerations by the Ministry of Water and Irrigation (MWI) may adapt these standards in order to achieve a more flexible approach for individual MAR sites, e.g. to allow the recharge of less treated wastewater to aquifers of poor quality that are still suitable for irrigation purposes (MWI 2001).

MAR is mainly performed using percolation reservoirs, recharge and release dams, and by injection wells (Xanke *et al.* 2015), both into alluvial deposits and limestone aquifers. In some cases, the reservoirs showed high infiltration rates despite being constructed with the primary purpose of surface storage (e.g. Shueib dam, Kafrein dam). However, heavy sediment loads, as a result of the sparse soil cover in these desert catchments, reduce the life span of many of the reservoirs by causing a loss of the storage capacity and a reduction in infiltration rates. As yet there are no applicable solutions to avoid the sedimentation. There is also a high risk that the outlets of the recharge and release facilities, such as at Wala dam, may become blocked by sediments. This has occurred for some conventional dams between the early 1960s and the early 1990s (Steinel 2012).

Table 1 List of dams in Jordan used for MAR (modified after Steinel 2012; Riepl 2013; Hadadin 2015; Xanke *et al.* 2015).

Location	Period of operation	Mean annual infiltration (MCM)	Initial and current storage capacity (MCM)	Geological formation (labeling)	MAR techniques/ Comment
Wala dam	2002 - today	*6.7	9.3/7.7	Limestone (A7)	percolation reservoir, injection wells
Shueib dam	1968 - today	**0.7	2.5/1.43	Alluvial deposits	percolation reservoir
Kafrein dam	1968 - today	n.a.	8.5/6.0	Alluvial deposits	percolation reservoir
Wadi Madoneh	2003 - today	n.a.	0.09	Limestone (A7)	4 recharge and release dams
Wadi Butum	2011 - today	n.a.	0.47	Limestone (B4)	3 percolation reservoirs
Sultani dam	1962 - n.a.	n.a.	1.2	Limestone (B2/A7)	percolation reservoir/clogged
Qatrana dam	1964 - n.a.	n.a.	4	Limestone (B2/A7)	percolation reservoir/clogged
Rajil dam	1992 - n.a.	n.a.	3.5	Limestone (B4/B5)	percolation reservoir/clogged
Siwaqa dam	1993 - n.a.	n.a.	2.5	Limestone (B2/A7)	percolation reservoir/clogged

*2002-2012; **2001-2009

A successful example of MAR is the Wala reservoir, where about 6.7 MCM/a, on average, infiltrate into the underlying karst aquifer. The water is abstracted at the 7 km downstream Hidan wellfield and contributes about 11.7 MCM/a, on average, to the drinking water supply of Jordan's capital Amman, Madaba city and smaller communities in the immediate surroundings (Xanke *et al.* 2015). Further comprehensive hydraulic and numerical studies have been done by Xanke *et al.* (2016), which revealed a decrease of the mean groundwater table on the long-term as a result of accumulating sediment in the reservoir and the associated reduction in the infiltration rate. In the case of the Kafrein and Shueib dams, the natural seepage from the reservoirs augment groundwater availability for irrigation purposes in the Jordan Valley, but only the water balances of the Shueib dam has been calculated by Riepl (2013) to be about 0.4 MCM/a in average. However, in the most cases the recharge rates are not well documented.

Further research in Jordan is commissioned by the MWI (Steinel *et al.* 2016) to evaluate the potential of MAR in porous aquifers (Steinel 2012).

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MAR in Korea

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In South Korea, which depends heavily on surface waters for water resources, there has been interest in the development of indirect water intake systems, such as riverbank filtration, in order to solve problems such as water quantity variability and water pollution. The development of riverbank filtration in Korea is mostly operated by municipalities in relatively small and medium sized facilities in Gapyeong, Haman, Iryong, and Daesan areas. A facility currently under construction has the capacity of 180,000 m^3/day, and it is scheduled to be completed in 2017. And, the Korea Water Resources Corporation is carrying out large-capacity Nakdong riverbank filtration business of 68,000 m^3/day in Changnyeong area (K-water, 2016).

The annual amount of groundwater use in South Korea reached 3,807 Mm^3 in 2010 (Ministry of Land, Transport and Maritime Affairs, 2011). Water supply by managed aquifer recharge totals 146.4 Mm^3 per year, accounting for 3.8% of total groundwater use. Riverbank filtration accounts for 89.1 Mm^3/year and underground dams and 57.3 Mm^3/year. Six underground dams have been developed and competed in the 1980s and 1990s, of which 5 are used for agriculture and 1 is used for drinking water (Ministry of Land, Transport and Maritime Affairs, 2012).

In Jeju Island, reservoirs for flood mitigation have been combined with well injection systems since 2010 to produce what is called Jeju-friendly Aquifer Recharge Technology(J-ART). The system has been built in the Hancheon upstream area, and proved to be effective in intentional increase groundwater recharge by about 2 Mm^3/year (Korea Institute of Geoscience and Mineral Resources, 2011). In addition, several empirical studies have been conducted over the past decade to recirculate the abandoned groundwater for heat utilization in green house areas to replenish groundwater and reduce the groundwater drawdown (Korea Institute of Geoscience and Mineral Resources, 2011).

Table 1. Growth in volume of Managed Aquifer Recharge (Million cubic metres/year)

Annual MAR volume in Korea in the decade centred on date (Mm^3/y)						Annual Groundwater use (Mm3/y)	MAR as % groundwater use
1965	1975	1985	1995	2005	2010-15	2010	2010-15
	3.7	12.4	46.0	91.3	146.4	3,807	3.8%

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History of managed aquifer recharge in The Netherlands

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General overview

In the Netherlands, unmanaged aquifer recharge started in the early 1900s with the centralized disposal of sewage water in large cesspools, the disposal of groundwater from deep construction pits, and the irrigation of some polder areas where watertables declined due to e.g. groundwater abstraction for drinking water supply.

Currently, there are -- for drinking water supply -- 13 ‘intentional’ basin artificial recharge (BAR), 2 aquifer transfer recovery (ATR), 1 ASR and 23 River Bank Filtration (RBF) systems. They contribute about 17, 1, 0.1 and 6% to a total annual production of 1,100 Mm^3 of drinking water in the Netherlands, respectively.
In addition, there is a rapidly growing number of small-scale ASR systems for agricultural water supply, which store rainwater from the roof of greenhouses or fresh surface water. Urban runoff is increasingly being decoupled from sewage systems and introduced directly into local infiltration ponds or subsurface systems.

Artificial recharge through basins (BAR)

BAR started on a large scale in the coastal dune area, with later expansions inland (Fig.1, Table 1). The reasons to recharge the dune area were to: (i) reverse the severe salinization due to groundwater mining for drinking water supply of cities such as Amsterdam and The Hague; (ii) continue with producing drinking water from the dunes, benefitting from the existing infrastructure; and (iii) reverse the severe decline of groundwater tables in the dunes, which are considered a major nature reserve where wet dune valleys are essential to maintain biodiversity.

The dune infiltration involves a pretreatment near the intake, transport to the dunes, recharge and recovery in the dunes, and a post-treatment. In the period 1965-1975 , public opposition against BAR in the dunes was roused by ecologists who discovered serious eutrophication phenomena in plant communities in and around infiltration ponds. This led to gradual optimizations of the BAR systems through the NESTOR (NEw STyle Of Recharge) approach, which aims at reducing the adverse effects of dune infiltration on nature (Peters et al. 1998).

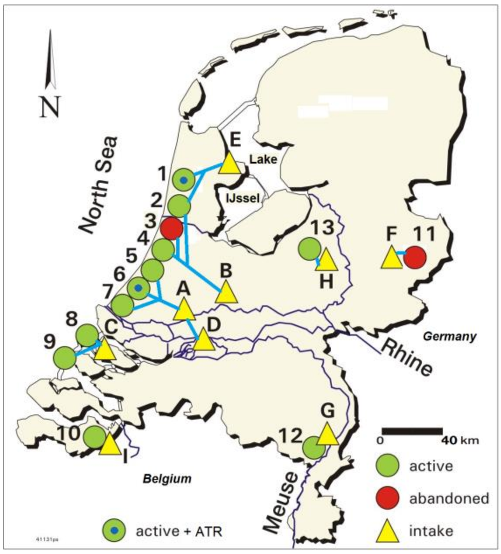

Fig. 1. Location of 11 operational and 2 abandoned BAR production sites in the Netherlands, together with their surface water intake points. On sites 1 and 6 also ATR is applied. Further information in Table 1.

Table 1. Some details on the 13 BAR production sites of which 2 were abandoned, with their surface water intake points.

Site in Fig.1			Start		Intake	Recharge		Pretreatment	System $
No.	Near city	Name	grwater	BAR	Fig.1	Source	Mm3/a	#	Inf / Recovery
1	Castricum		1924	1957	E + (B)	Lake IJssel	25	B+R+C	C/W
2	Wijk aan Zee	Kieftenvlak	1885	1975			17		C/W
3	Overveen	Groot Olmen	1898	1975-1999 †	B	Rhine R.	1	R	B/W
4	Zandvoort	Leiduin	1853	1957			52		C/C+D
5	Katwijk	Berkheide	1878	1940	D or A	Meuse or Rhine R.	25	B+R	B/C+D+Q+W
6	Scheveningen	Meijendel	1874	1955			47		B/D+W
7	Monster	Solleveld	1887	1970			7		B+C/W
8	Ouddorp	Oostduinen	1934	1955	C	Rhine/Meuse estuary	3.5	R	C/D+W
9	Haamstede		1930	1978			3.7		P/W
10	St. Jansteen		1936	1944-1998 ‡	i	Brook	2		C/W
11	Enschede	Weerseloseweg	1892	1952-2004 †	F	Canal	5.5	B+R+pH	B+C/W+Q
12	Heel	Lange Vlieter	-	2002	G	Meuse R.	15	S	P/W
13	Epe		1954	1999	H	Brook	1-2	S	B/W

#: B = detention in basin or abandoned meander loop; C = Activated carbon filtration + O3 + UV
R = sedimentation or microfiltration + coagulation + RSF; S = sedimentation
$: B = Basin; C = Canal; D = Drain; P = Pit; Q = horizontal well; W = vertical well. ‡ : since 1998 for industry

ATR and ASR

In the Netherlands, Aquifer Transfer Recovery (ATR) utilizes separate wells for infiltration and recovery at 100-200 m distance, mainly for continuous production of drinking water, but also to store some volume. In 1990 after many trials since the 1930s, 2 systems were put in operation (Fig.1), where ~4 Mm3 of highly pretreated surface water is annually feeding about 20 recharge wells on each location.

Aquifer Storage Recovery (ASR) is being applied for drinking water supply only on a very small scale. ASR is, however, rapidly expanding in the supply of (i) rainwater from roofs for crop irrigation in greenhouses, and (ii) freshwater for irrigation of orchards (Zuurbier 2016).

River Bank Filtration (RBF)

The first river bank filtrate was pumped for public drinking water supply in the Netherlands, probably in 1879 along the Rhine River at pumping station Nijmegen (Site 42 in Fig.2). In 1950 15 well fields pumped 11 Mm3 and in 2014 23 pumping stations produced 59 Mm3 of Rhine bank filtrate. In 1998 the first Meuse bank filtrate was pumped near Roosteren (site 80 in Fig.2).

The quality deterioration of the Rhine River, especially in the period 1920-1975, had at least 3 impacts on the preparation of drinking water from Rhine River water: (a) a switch in the period 1928-1962 from the direct intake and treatment of river water, to the pumping of Rhine bank filtrate on 10 stations; (b) the closure of 17 well fields pumping Rhine bank filtrate in the period 1944-2000; and (c) extension of the classical treatment (aiming at removal of iron, manganese, ammonia and methane), with processes removing organic contaminants.

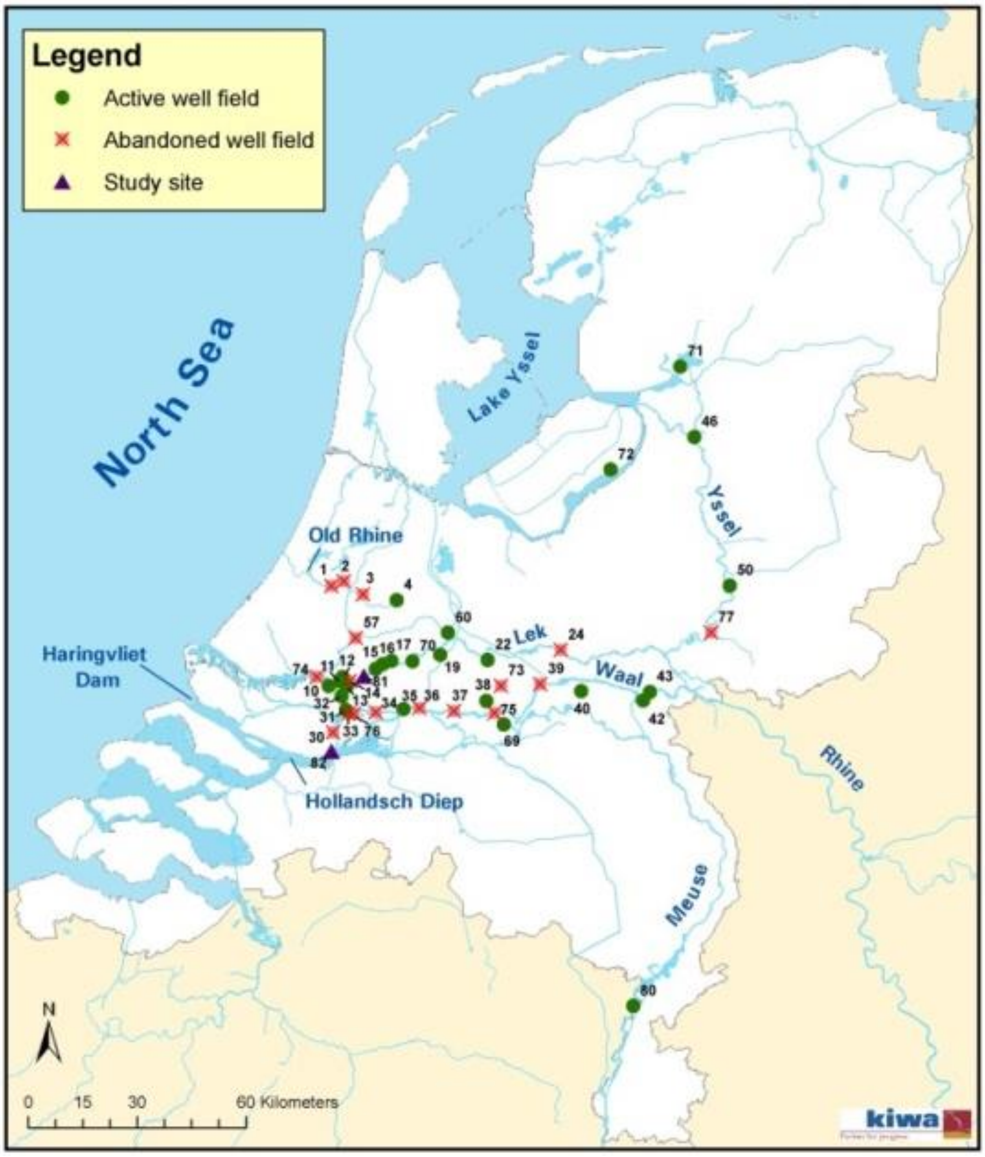

Fig. 2. Location of all public supply well fields pumping >10% river bank filtrate in the Netherlands, with distinction between active and abandoned sites.

Research

The introduction of MAR systems in the mid 1900s raised and continues to nurture many technical and scientific questions. In the period 1940-1975, research mainly focused on the engineering aspects of MAR systems, regarding the minimum travel time needed to remove pathogens, the attenuation of salinity and temperature fluctuations in the infiltration waters, the clogging of basins and wells, and the effects of aquifer passage on main constituents. This knowledge fueled the bulk of the handbook on artificial recharge by Huisman & Olsthoorn (1983).

In the period 1965-1985, the worsening quality of the Rhine and Meuse Rivers provoked research into the behavior of macroparameters, nutrients, heavy metals and some classical organic micropollutants during detention in spreading basins and aquifer passage (Piet & Zoeteman 1980; Stuyfzand 1988, 1998a). It also stimulated research into the effects of eutrophication on algae blooms in recharge basins and on oligotrophic phreatophytic plant communities in dune valleys around them (Van Dijk 1984). It was discovered in the 1980s that rainwater lenses can form in between infiltration ponds and remote recovery systems, and that flow-through (seepage) lakes in between can disrupt these lenses and stimulate local eutrophication (Stuyfzand 1993). This research was based on multitracing to discern infiltrated riverwater from autochthonous dune groundwater (locally infiltrated rainwater). Later hydrochemical studies yielded further insight in the performance of various (potential) tracers (Stuyfzand 2010), the behavior of trace elements (Stuyfzand 2015), the behavior of organic micropollutants (Noordsij et al. 1985; Hrubec et al. 1986, 1995; Stuyfzand 1998b; Stuyfzand et al. 2007; Eschauzier et al. 2010) and pathogens (Schijven 2001; Medema & Stuyfzand 2002).

Various modeling approaches were pursued to simulate and predict the behavior of pollutants, radionuclides, bacteria and viruses, and main constituents during detention in recharge basins and during aquifer passage. One of the first models was Easy-Leacher (Stuyfzand 1998c), which is a 2D reactive transport code set in EXCEL spreadsheet, combining chemical reactions (volatilization, filtration, dissolution-precipitation, sorption, (bio)degradation), with empirical rules regarding the reaction sequence. It assumes a constant input quality, flow and clogging layer conditions, but takes account of the leaching of reactive aquifer constituents. More sophisticated models were built using the MODFLOW/MT3DMS and PHREEQ-C based reactive multicomponent transport model PHT3D incl. reaction kinetics (Prommer & Stuyfzand 2005; Wallis et al. 2010; Antoniou 2015). On the other hand, simpler models set in Excel spreadsheet were developed such as Reactions+, a mass balance (inverse) model to identify and quantify the inorganic mass transfer between for instance the infiltrating surface water and a well downgradient (Stuyfzand 2010), and INFOMI, an analytical model to predict the behavior of trace metals and organic micropollutants (Stuyfzand 1998c).

In the period 1973-1982, extensive research on the clogging mechanisms of infiltration wells was carried out by Kiwa (renamed KWR in 2006). This yielded the new clogging potential indicators Membrane Filter Index (MFI; Schippers & Verdouw 1980) and Assimilable Organic Carbon (AOC; Hijnen et al. 1998). Also, the insight was born that a cumbersome clogging can only be prevented by a thorough pretreatment (incl. at least a coagulation step and rapid sand filtration) leading to MFI < 2 and AOC <10 μg C/L, combined with frequent backpumpings of short duration (Olsthoorn 1982; Peters et al. 1989).

The clogging of recovery wells or drains has always been a hot topic in MAR systems, because of their extreme vulnerability. Studies by Van Beek (2010) revealed among others, that BAR and ATR systems are more vulnerable to (bio)chemical clogging by hydrous ferrihydrite, whereas RBF wells in the anoxic fluvial plain are prone to clog by aquifer particles that are retained by the borehole wall if damaged by residual drilling muds.

The current research is mainly on the following key topics:

- Optimizing ASR systems in brackish to saline aquifers (e.g. for agriculture) by reducing bubble drift and bubble buoyancy, and thereby raising the recovery efficiency (Zuurbier 2016),
- Optimizing ASR systems for drinking or rain water storage by reducing water-sediment interaction (Anthoniou 2015),
- Determining the capacity of BAR systems to cope with intake stops, while minimizing the potential damage to wet dune valleys and reducing water quality problems due to e.g. changing redox conditions.
- Determining and predicting the behavior of emerging priority pollutants such as pharmaceuticals, personal care products, new pesticides, nanoparticles etc.
- Identifying weak points in BAR systems where pathogens in the infiltration water or from land bound animals can survive on their way to the recovery system.

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Historical Overview of Enhanced Recharge of Groundwater in Qatar

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Introduction

Qatar occupies a peninsula which projects into the Arabian Gulf and occupies an area of 11,627 km^2. Qatar has a warm desert climate with mild winters and hot summer. The mean annual rainfall is approximately 70 to 80 mm. Qatar is known for its scarcity of renewable water resources. Until 1953 the population of Qatar was entirely reliant on groundwater for its potable and agricultural water. In 1953 the first desalination plant was commissioned and the country's desalination capacity has been increased over the years so that in 2017, almost all water demand for municipal and industrial use is produced by desalination. However, water for agricultural irrigation is almost entirely derived from pumped groundwater. In 2013, the volume of groundwater pumped for agricultural use was estimated to be 218 Mm^3. This abstraction resulted in a small decline in water level together with an associated deterioration of water quality (MoE 2009). Managed aquifer recharge with natural waters is estimated at almost 10.7 Mm^3/yr and so significantly augments the estimated natural recharge (rainfall and irrigation return) of 75Mm^3/yr. There is managed recharge of deep aquifer with stormwater and recycled water in urban areas which is estimated at almost 33 Mm^3/yr. Thus total managed aquifer recharge contributes about 44 Mm^3/yr which has reached 17% of the total groundwater use of 260 Mm^3/yr in 2010 (Margat and van der Gun 2013) and there is potential for further expansion of MAR.

MAR Projects and Efforts

Eccleston and Harhash (1982) have described the hydrogeology of Qatar. The extent of the aquifers of Qatar has been subdivided into two main hydrologic provinces: Northern and Southern. Smaller groundwater provinces have subsequently been added to this conceptual model, the Abu Samra, Doha and Aruma Groundwater Basins. The main aquifers where MAR is practised in Qatar are the Eocene-age Rus Formation and the underlying Paleocene-age Umm er-Radhuma (UER) Formation. In some areas these two layers are interconnected and in hydraulic continuity to the extent that they can be considered as forming a single aquifer (Abdel-Wahab et al. 2008). There are two small members which are Simsima Member; and Abarug (Dammam) Member.

The bulk of the aquifer recharge in Qatar is derived from rainfall; other recharge inputs include urban recharge (mainly restricted to the area of Doha) and agricultural irrigation returns which are isolated throughout the country. Two different types of recharge mechanism are generally recognized in Qatar. Direct or diffuse recharge from widespread infiltration of rain water at or near to the point where rain falls. The second one is localized recharge (also called indirect or focused recharge) where surface water runoff accumulates in localized depressions with no surface water outlet. Previous estimates have shown that the contribution from focused recharge appears to be the most important recharge mechanism in Qatar being, on average, 4 to 9 times greater than diffuse recharge (Kimrey 1985, Entec 1994 and MoE 2009). This is considered to be due not only to the concentration of surface runoff in the depressions, but also due to the elevated storage capacity and permeability of the bedrock underlying the depressions.

In 2009, a significant project was carried out in Qatar to study the artificial recharge of aquifers (MoE 2009). To augment the natural recharge, a total of 313 passive recharge wells as identified by MoE Study have been installed across Qatar. The recharge wells installed in Qatar are 'passive' gravity recharge wells in which no active injection is undertaken and water accumulated above ground-surface enters the recharge well and infiltrates into the aquifer under the force of gravity. 166 of these recharge wells to enhance natural recharge from rainfall have been identified as occurring within depressions and the remaining 147 recharge wells outside of depressions. To facilitate modeling of rainfall-runoff-recharge, the SWAT2005 model has been applied. Analysis of groundwater level data from 44 recharge wells in Qatar for the period 2001 to 2007 and injection tests from 27 recharge wells show that capacity for a recharge well to infiltrate surface water varies widely. Recharge well infiltration capacity has been determined from 30 injection tests.

Modeling results indicate that the 161 existing recharge wells which are included in the model contribute 10.7 Mm^3 to groundwater recharge in an average hydrological year in addition to the natural recharge which the model calculates as being 75 Mm^3. The model has been used to estimate the optimal number of recharge wells required to enhance and infiltrate all surface water accumulations within 5 days after the most extreme rainfall event in the average hydrological year. Using only those depressions that were retained after applying the selection criteria to determine the most favorable depressions in non-urban areas, the model predicts that 1502 recharge wells are required to inject all the ponding water generated during the largest storm (~20 mm) in an average hydrological year within a 5 day period. It is observed that there are already 114 of those 161 existing recharge wells in the depressions selected as being the most favourable (thus, 1,388 additional recharge wells are required). Model indicated that 47 existing recharge wells are not required in the optimal total number of recharge wells. The managed aquifer recharge contribution of both the optimum and current number of recharge wells (i.e. 1,549 wells) for the average year would amount to 33.5 Mm^3, as shown in Figure 1. A plan to construct more recharge wells has been produced but implementation is not yet decided.

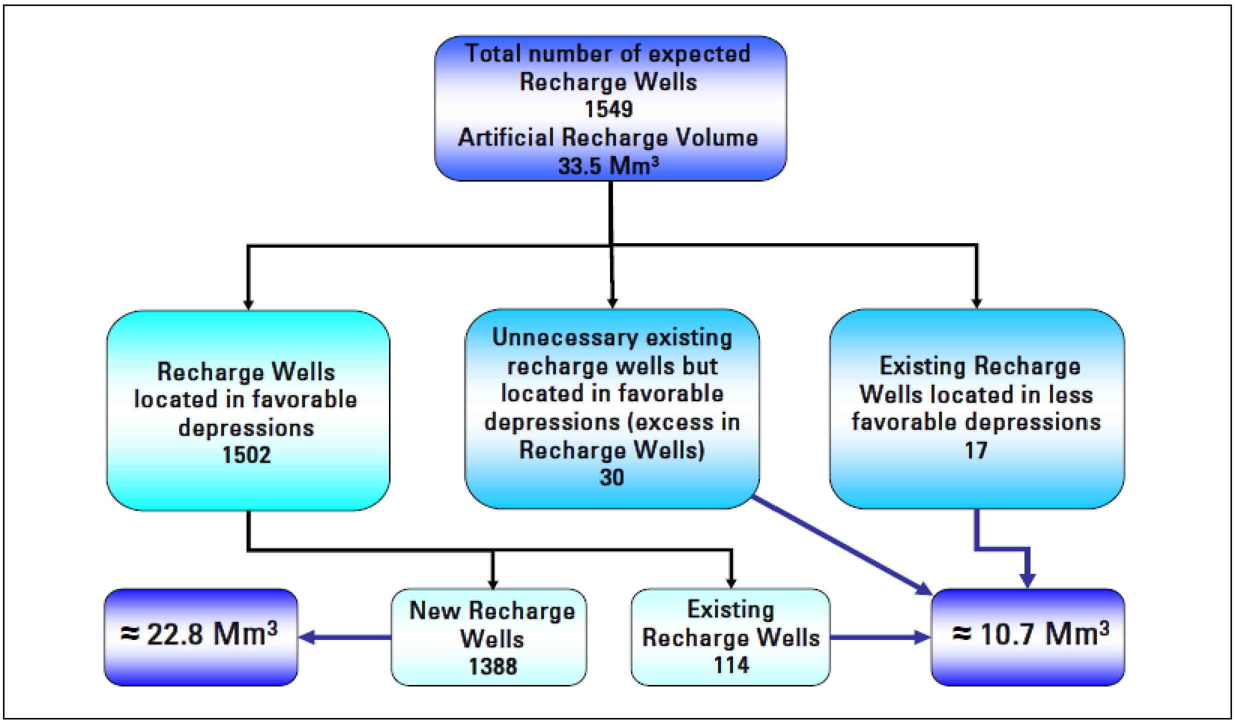

Figure 1. Optimal number of recharge wells and quantity from MoE 2009 Study

A sensitivity analysis indicates that the cost-benefit of any future recharge well array is highly dependent on the permeability of the sub-surface, the allowed time of ponding of water in depressions, the selection of favorable depressions, and the storm rainfall amount used in the design. It is important to note that the model results show that the potential for managed aquifer recharge is similar in the southern and northern parts of Qatar although this is dependent on the rainfall distribution (MoE 2009).

Two other types of MAR are implemented in the urban area of greater Doha. Excess recycled water (mainly high quality treated effluent) and collected stormwater combined with surficial groundwater are recharged using deep wells. This managed practice started in 2008. The main objective of this recharge is to dispose the excess recycled water and to improve the quality of deep groundwater. Recharged water is of better quality than the groundwater in the receiving aquifer. For example, Total Dissolved Solids (TDS) in recharged water is 1,100-6,000 mg/l which is considerably fresher than the deep groundwater having 15,000-25,000 mg/l TDS. This practice of urban MAR is in an experimental phase, with precise environmental monitoring and is seen as a temporary solution until it is evaluated. Ongoing work continues to assess and evaluate this MAR practice in urban areas in Qatar. There is continuous monitoring of quantity and quality of both the recharged water and the receiving environment (i.e. deep groundwater between 100 and 400m) and shallow groundwater (i.e. less 50m). 3D groundwater simulations are applied to help in this assessment of managed recharge in the urban area.

Current Types of MAR in Qatar

As mentioned above, there are three types of MAR in Qatar. The first type is the recharge wells in depressions in non-urban areas to augment the natural rainfall recharge in north and south groundwater basins. The second is the use of deep recharge boreholes in Doha basin for disposal of relatively fresh recycled water. The last involves the recharge via deep boreholes in Doha basin for temporary disposal of the collected urban stormwater combined with surficial groundwater after necessary treatment. This temporary disposal is helping to improve the quality of deep groundwater by reducing its salinity. Table 1 shows the recharge amounts of the three categories.

Table 1: History of managed aquifer recharge in Qatar (in 10^6 m^3/year)

Period	Recharge wells			Total
	Rainwater and stormwater (non-urban area)	Recycled water (urban area)	Stormwater and shallow groundwater (urban area)	
1981-1990	5.3	0	0	5.3
1991-2000	8.0	0	0	8.0
2001-2010	10.7	26.0	0	36.7
2011-2015	10.7	31.0	2	43.7

Data derived from MoE 2009 study and from Qatar government internal reports.

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MAR in Southeast Asia

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The level of progress in MAR in Southeast Asia is considered to be limited (Table 1). This review could only identify a handful of case studies worthy of note. Literature based on general discussions or on hypothetical modelling has not been considered. Across the region, there has been a tendency for applying deep recharge methods (wells) over surface methods (basins) owing to an absence of favorable shallow geological conditions in targeted areas or limited access to land. Most studies have been carried out in Thailand, with a lesser number carried out in Vietnam, Malaysia and Indonesia.

The earliest known work dates back to the early 1970s in Thailand where a pilot injection trial was carried out in response to land subsidence issues in the Bangkok metropolitan area due to heavy groundwater withdrawals resulting in groundwater quality deterioration and increased flood risk. The trial, carried out by government hydrogeologists, experienced two major sets of problems – high rates of aquifer clogging due to inadequate pretreatment of source water and rapturing of overlying clay layers due to excessive injection pressures (Ramnarong, 1989). Subsequent tests in a nearby area, carried out two decades later by local academics involved eight months of recharge testing which yielded successful results as evidenced by observations of rebound in pore pressures in adjacent aquitards (Phien-wej et al. 1998).

Efforts to test the viability of ASR in a coastal province of the country (Rayong) in the early 2000s was unsuccessful, once again due to irreversible well clogging (Pavelic et al. 2010). This result may be attributed to a degree of institutional memory loss on behalf of the government hydrogeologists, although international technical assistance was also provided.

A more concerted program of ASR testing extending over two phases from 2008 to 2014 was carried out in the Central Plains of Thailand (Sukhothai province) to address groundwater overexploitation caused by high groundwater use for agriculture. This testing has concluded that high levels of system maintenance are needed to address inherent well clogging problems (Bral et al. 2015).

Basin recharge methods based on harvesting wet season river flows were applied in an alluvial floodplain setting of Phitsanulok province between 2008-2011 to restore depleted groundwater levels in irrigation command areas. This was the first known trial of its kind in Thailand and one of the first in the region. A stage-wise, integrated approach was followed covering site suitability mapping, recharge system performance, hydrology & numerical modelling, hydrochemistry and cost-benefit analysis. Results of the trial appeared to be technically and economically promising (Nadeeet al. 2012; Pavelic et al. 2012; Srisuk et al. 2012; Uppasit et al. 2013). The large land area needed for wetland pretreatment of canal water prior to the recharge step may be a constraint unless methods with lower areal footprints can be identified. The study provided the foundation for the development of technical guidelines of a range of different MAR technologies to be applied (Chusanatus et al. 2012).

MAR assessments have been carried out in the coastal sand dunes of Binh Thuan province in Vietnam to examine the role of MAR in mitigating drought impacts by restoring groundwater storage capacity and improving ecosystems. Whilst extensive baseline studies of the water resources were carried out to characterize the baseline hydrology and hydrogeology of the area, it would appear that the project did not advance to the stage of conducting pilot recharge testing (Thoa et al. 2008; Hoanh et al. 2013).

Small scale testing of recharge into dry wells with rainwater to restore depleted groundwater levels and control impacts of land subsidence has also been applied in the highly water stressed Bandung basin in West Java, Indonesia. It was proposed that implementation should focus on industrial areas where large roof areas could be harnessed (Taufiq, n.d.). In Batu Pahat district, Malaysia, a favorable feasibility assessment led to the recommendation of recharge testing to boost groundwater storage in area of high demand and flooding. The documentation available suggests that the pilot testing had yet to proceed (Tjahjanto et al. 2008; Musa et al. 2009).

Enabling conditions for MAR

MAR has received minimal interest in SEA, with cases limited to feasibility studies or trial. The enabling conditions for consideration of MAR would appear to be three-fold, namely:

i) pressing groundwater quantity or quality issues
ii) local technical expertise in groundwater and an appropriate institutional setup to allow human and other resources to be mobilized
iii) links to international networks and institutions

The importance of these 3 pre-requisite is exemplified for several of the case studies described above (Table 2). By deduction, this also serves to explain the absence of MAR experience in countries such as Laos, Cambodia and the Philippines where problems are either not apparent, or unable to be addressed with current technical capacity. Singapore, with the most highly developed economy contrasting with the lowest per capita water availability in the region, has invested heavily in rainwater harvesting and water recycling in order to reduce its dependence on imports from Malaysia. This appears not to have extended down to harnessing the storage potential of underlying aquifers.

There are no known cases of MAR moving beyond feasibility studies or trials into larger scale, long term schemes. The rationale for this is possibly more case specific and diverse. In the case of the ASR trials carried out in Bangkok, whilst recommendations were made for larger-scale testing, policy mechanisms other than MAR ultimately provide more expedient and were found to successful in addressing the subsidence issue across the Bangkok metropolitan area (Foster, 2002). Raising the profile of MAR and its merits under specific contexts, has not yet advanced to the policy level in SEA and has remained largely within the scientific community. It is the role of the scientific community to change the perceptions of the policy makers that water resources problems do not justify the exploration into technologies which are not yet mainstreamed and therefore risky.

Table 1. Compilation of MAR case studies in Southeast Asia

No.	Site	Project type	Objective	Aspects covered	Problems faced	Impacts achieved	References
1	a) Bangpoon (1972) b) AIT campus (1993-94), Pathumthani province, Thailand	pilot injection trials (single injection well)	restore depleted GW levels and control impacts of land subsidence	aquifer characterization, well hydraulics, ground movement	- rupturing of overlying clay - clogging when untreated canal water was used	- policy mechanisms other than MAR proved successful in addressing the subsidence issue	a) Ramnarong, (1989) b) Phien-wej et al. (1998)
2	Nong Taphan, Rayong province, Thailand	pilot ASR trial	trial ASR technology using treated canal water	aquifer characterization, recharge performance & well clogging	- trial abandonment due to excessive well clogging		Pavelic et al. (2010)
3	Sawankhalok, Sukhothai province, Thailand	pilot trial (multiple ASR wells)	restore depleted GW levels in an irrigation command area through recharge of wet season river flows	aquifer characterization, recharge performance & well clogging, hydrochemical tracing, solute transport modelling	- well clogging even with physioco-chemical treatment requiring high levels of system maintenance		Mallonee, (2013) Bral et al. (2015) Mungkang et al. (2015)
4	Ban Nong Na, Phitsanulok province, Thailand	basin recharge pilot trial	restore depleted GW levels in irrigated areas through infiltration of wet season river flows	site suitability mapping; recharge performance & clogging; hydrology & numerical modelling; hydrochemistry; cost-benefit analysis	- large land area sacrificed for wetland pretreatment of canal water	- foundation for guidelines to be developed over the wider area affected by similar problems - led to new work being initiated on MAR for co-managing floods and droughts	Chusanatus et al. (2012) Nadeeet al. (2012) Pavelic et al. (2012) Srisuk et al. (2012) Uppasit et al. (2013)
5	Hong Phong district, Binh Thuan province, Vietnam	basin recharge pilot trial	arrest drought impacts and restore GW storage capacity and improve ecosystems	hydrological and hydrogeological characterization, hydrochemistry, modelling	- project carried out extensive baseline studies of the water resources but does not appear to have recharge the piloting stage		Thoa et al. (2008) Hoanh et al. (2013)
6	UTHM campus, Batu Pahat district, Malaysia	pilot recharge trial	boost groundwater storage in area of high demand and flooding	aquifer characterization (geophysics, grainsize, analytical modelling)	- feasibility assessment was favorable but pilot testing had yet to proceed		Tjahjanto et al. (2008) Musa et al. (2009)
7	Bandung Basin, Indonesia	pilot recharge of dry wells	restore depleted GW levels and control impacts of land subsidence	pilot recharge, laboratory test of pretreatment, risk assessment modelling		- roof water harvesting in industrial areas proposed, following treatment (zeolite) to neutralize pH of rainwater	Taufiq, (n.d.) Fildebrandt et al. (2003)

Table 2. Enabling conditions for MAR implementation

No.	Country	Problem	GW expertise / institution	International linkages
1-4	Thailand	GW depletion and/or land subsidence	Department of Groundwater Resources (formerly Department of Mineral Resources)	Intl technical assistance, IAH
5	Vietnam	drinking/domestic/agricultural water provision in drought prone areas	Vietnamese Academy of Science and Technology (Institute of Geophysics, Institute of Geological Sciences)	Vietnam Atomic Energy Commission, UNESCO (Jakarta office), University La Sapienza (Italy)

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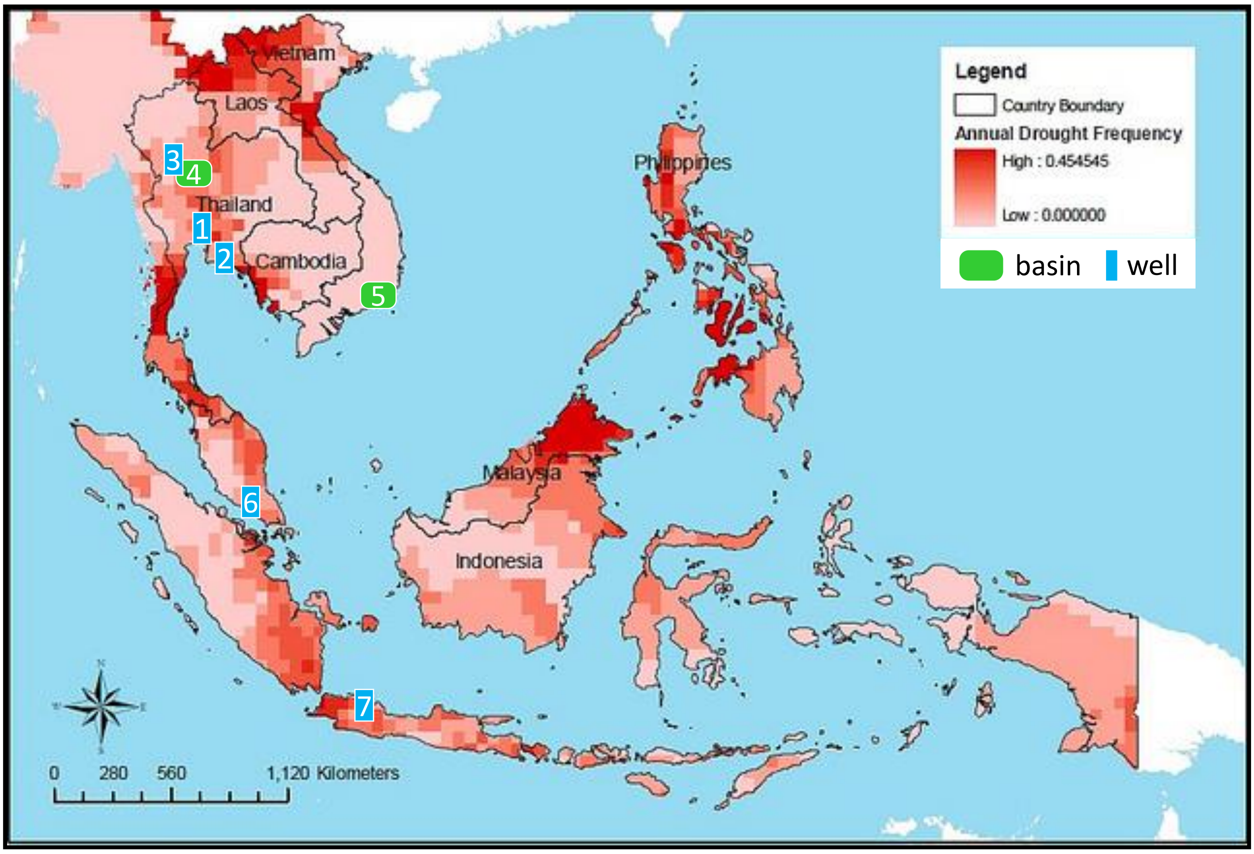

Figure 1. Map of MAR trial sites in SEA, identified according to recharge technology. Base map is taken from Yusuf and Francisco, (2009)

An overview of Managed Aquifer Recharge in Southern Africa

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MAR is not a new concept in Southern Africa. In the early-mid 1900s sand storage dams were constructed in stages in Namibia for the storage of water in artificial "aquifers" (Wipplinger, 1953), and in South Africa, the Atlantis scheme near Cape Town started infiltrating storm run-off and treated waste water in 1979 (DWAF, 2010a). In addition to these, farmers over the years have built numerous earth dams for the purpose of enhancing groundwater recharge. In recent times, there have been three major contributions to the advancement of MAR in the region. It started with a surge of research in the late 1990s and early 2000s (Murray and Tredoux, 1998 and Murray and Tredoux, 2002) which had two significant spin-offs: The construction of a major borehole injection scheme for the City of Windhoek, Namibia; and the South African government developed and rolled-out its national MAR strategy.

Southern Africa is dominated by hard-rock hydrogeology, so the research focussed primarily on assessing the feasibility of recharging these fractured aquifers. One of the identified test sites was in Windhoek, Namibia, where a successful MAR scheme could prevent the construction of a 700 km pipeline to the nearest perennial river and save the city the vast costs associated with major surface water transfer schemes.

Besides being the cheapest water supply option for the city, the Windhoek's MAR scheme is of particular interest because it involves large-scale borehole injection and recovery in a highly complex, fractured quartzite aquifer. Prior to this scheme, MAR had not been practiced anywhere in the world at a large scale in complex geological environments – the risk of losing water was generally considered too high. By undertaking a comprehensive feasibility study it was demonstrated that water losses would be negligible if designed and operated correctly (Murray, 2002). As a result the scheme was built and has been under permanent expansion since the first injection boreholes were commissioned in 2005. Its current injection capacity is 420 m^3/hr and with the new boreholes that have been drilled, this will increase to over 1 000 m^3/hr.

South Africa's MAR strategy (DWAF, 2007 and DWS, 2010b), like all comprehensive strategies, sets out objectives and tasks required to meet the objectives, and so far a number of the tasks have been completed. Examples of resources produced as part of South Africa's MAR strategy are:

- A check-list for implementing successful MAR projects (DWA, 2009a)
- A national map of potential MAR areas in South Africa (DWA, 2009b)
- Guidelines for planning and authorising MAR schemes (DWA, 2010c)
- Examples of MAR feasibility studies (DWA, 2010d).

Besides the larger schemes of Windhoek and Atlantis mentioned above, a few small-medium scale MAR schemes have been implemented in South Africa (mostly borehole injection), and a number of feasibility studies have been conducted with the intention of implementation in the near future. In addition to these a major feasibility study was undertaken for the Botswana government with the aim of assessing the value of MAR for the more industrious eastern part of the country (Murray, 2012 and Lindhe, et al, 1014). In most cases, the main purpose of MAR in Southern Africa is to augment water supplies and to enhance water security. Two schemes, however, are for mine water disposal in order to comply with environmental regulations. In these cases, it is not permitted to dispose surplus water from the mines' dewatering processes on the land surface, so aquifer recharge has become the alternative, and as a by-product, local farmers benefit from it. Table 1 presents an estimate of MAR volumes since 1960.

Table 1. Growth in Managed Aquifer Recharge 1965-2015 (in million cubic metres / year)

Date	Atlantis	Polokwane	Windhoek	Williston	Kolomela	Total
1965	0	1	0	0	0	1
1975	0	2	0	0	0	2
1985	2.7	3	0	0	0	5.7
1995	2.7	3	0	0	0	5.7
2005	2.7	4	0	0	0	6.7
2015	2.7	4	2.83	0.09	0.65	10.3

While the current scale of MAR activities is very small in Southern Africa, the potential for up-scaling is huge. The additional storage that could potentially be gained over and above natural groundwater storage if MAR was implemented in all prime MAR areas is South Africa is estimated to be 7.9 billion m^3 (7 944 million m^3) (DWAF, 2007). Considering that South Africa uses an estimated 2.7 billion m^3/annum (2 723 million m^3/annum) (DWA, 2016) it is evident that MAR practices on a large- and wide-scale could substantially enhance the country's water security.

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Managed Aquifer Recharge in Spain

by E. Fernández-Escalante
2016

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Managed Aquifer Recharge or artificial recharge (there is not still consensus on terminology in Spain) has been applied intentionally, according to chronicles, since the 12th century on the South slopes of Sierra Nevada Mountains. MAR devices used for irrigation are called *"careos"* Fernández-Escalante *et al.*, 2005) and some authors attribute their origin to the Muslim period whilst others state it was originally from the Roman era. Interestingly, they have many aspects in common with the Peruvian *"amunas"* of the pre-Columbian period.

In the early 1960's a pioneering large diameter recharge well was constructed in Barcelona by the water supply company (Custodio, 1986) as a complementary source for urban supply, starting a new phase in the classical Integrated Water resources Management (IWRM) schemes in Spain.

By the late 1980´s well-documented use of infiltration wells in Daimiel National Park were underway for environmental restoration. These were to mitigate the serious impact of drought on the wetlands and related ecosystems and to decrease the risk of the aquifer provisionally declared over-exploited due to the high pumping rate for irrigation.

At the same time the Spanish Geological Survey (IGME) drilled a deep borehole in the bank of Esgueva River (Valladolid) to test deep infiltration and injection (De la Orden *et al.*, 2003). Also some infiltration ponds were built related to an iron ore mine in Granada, further broadening MAR applications.

In the 1990´s several projects were carried out, testing the feasibility of the different MAR types in different areas. A detailed description for most of these sites can be found in DINA-MAR, 2009 and http://www.dina-mar.es/post/2010/04/29/documentacion-tecnicanoticias.aspx.

In addition new investments were made in short duration R&D projects, with the big disadvantage that many of these were abandoned after the supporting funds finished.

Currently there are more than 32 different MAR projects scattered around Spain (figure 1), with diverse facilities and methods to enhance recharge. Most of these activities were promoted by agents such as the Spanish Ministry of Agriculture by means of Tragsa Group, the Spanish Geological Survey (IGME) and the Catalonian Water Authorities, broadening the historical uses.

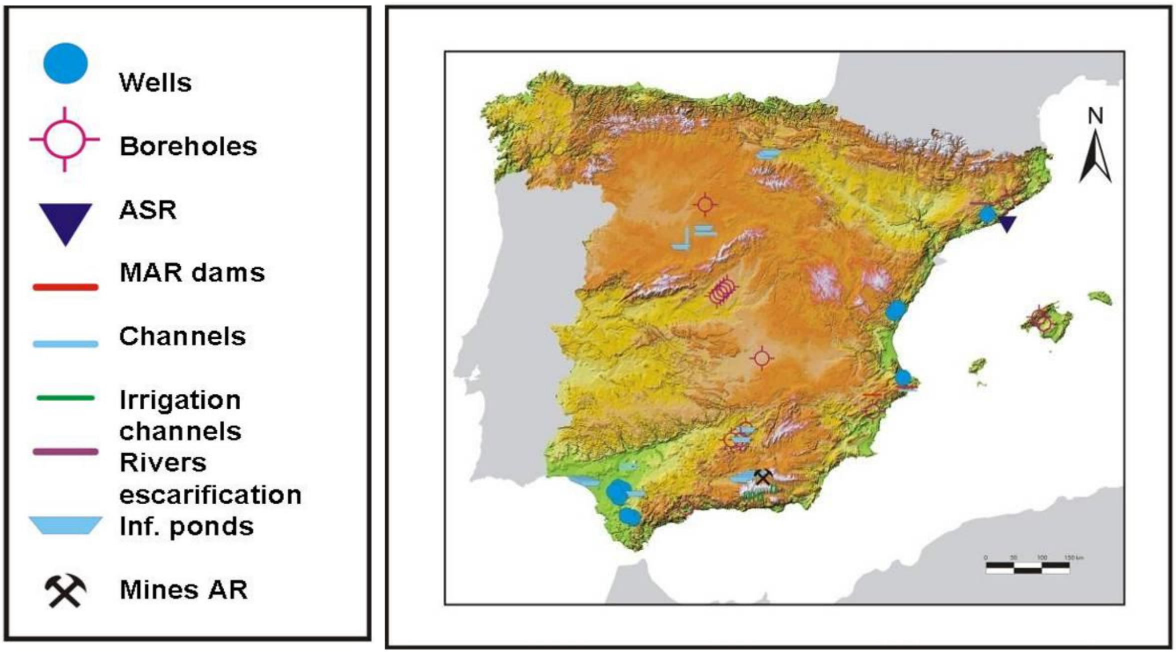


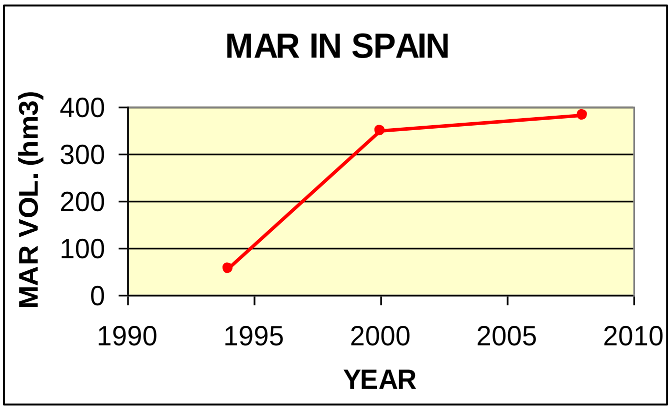
Figure 1. MAR facilities inventory in Spain, modified from DINA-MAR, 2009.

In general there are good examples of application for mining in the Southern area (Andalusia; Alquife; Cobre las Cruces). In the central area there are abundant canals and infiltration ponds for MAR. For example, starting in 2002, Los Arenales aquifer is the biggest large scale MAR area in Spain actively involving many agro-industries and becoming good examples of cooperation between farmers and researchers and Public-Private Partnerships (PPP). The deepest boreholes for ASR have been drilled in the big cities (Barcelona since 1969 and Madrid since 1995) so as to enhance reliability and increase supply of urban water. Along the Mediterranean Arc are many examples of detention structures such as dykes, check dams and dams to slow down the floods called "gotas frías" that are common in the Mediterranean area, diverting high flows to recharge aquifers.

According to Fernández (2018) the biggest volume of intentional recharge infiltrated into the aquifer is conducted by about one thousand dykes and dams constructed along the upper catchments of river basins, to reduce flash-floods and their devastating effects. Although these facilities (constructed by the Institute for the Nature Conservation, ICONA, since the 1950´s) have multiple uses, they retain water and considerably enhance the natural recharge by about 200 Mm^3/year.

Among all the examples reported, the vast majority were promoted by the public sector. Among the exceptional private initiatives it is worth mentioning those at Marbella and Majorca Island. The official estimate of the annual volume of water recharged via MAR in Spain has grown from 50 to 60 Mm^3/y (LBAS, 1994) to 350 Mm^3/y (LBAE, 2000).

In 2008 the total volume of MAR in Spain was about 380 Mm^3/year (DINA-MAR; 2009). About three quarters of this was by means of these dykes and check dams in the upstream sections of the river basins, especially on the East coast. Some of these facilities were developed around the year 2000 for intentional recharge by institutions such as Diputación de Alicante.



(1994, LBAS)	**50-60**
(2000, LBAE)	**350**
(2008, DINA-MAR)	**380**

Figure 2. Artificial recharge of groundwater in Spain [$10^6 m^3$/year]

According to the catalogue of European MAR applications for 23 countries DEMEAU (2014) classified according to 10 different MAR types (Figure 3) the biggest number of sites are in the Netherlands and in Germany, and Spain is the country with the biggest diversity with 8 of the 10 different MAR types represented.

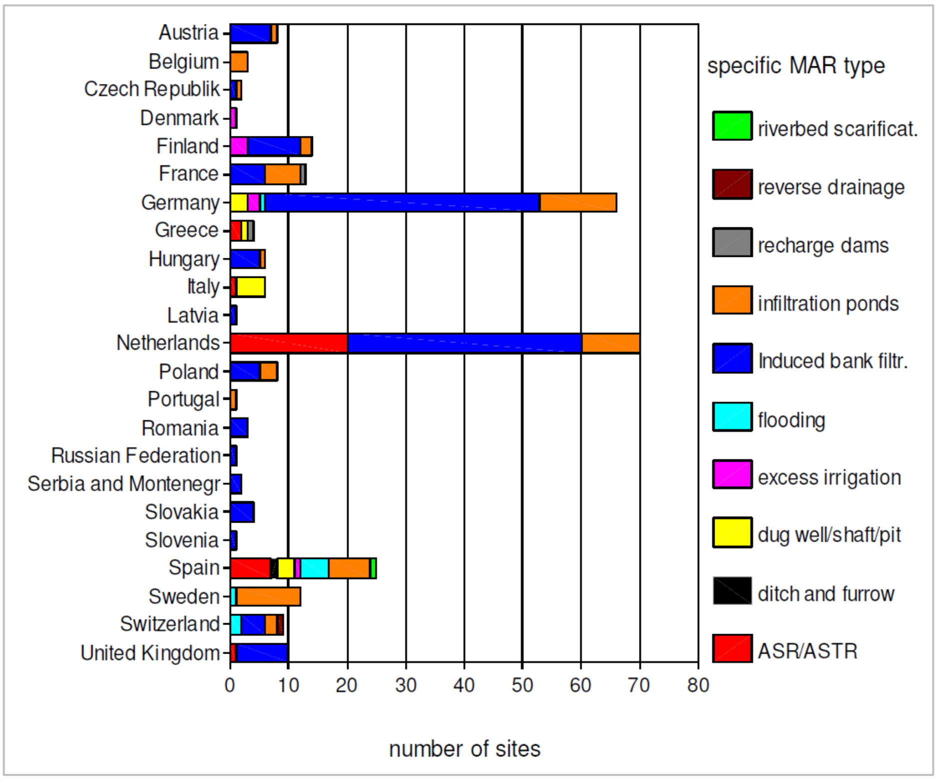


Figure 3. MAR sites *vs* MAR types for 24 European countries (DEMEAU, 2014).

A large number of MAR activities or demonstration sites using reclaimed water from waste water treatment plants (WWTP) have spread throughout Spain (Figure 4). Important experience is being gained in Costa Brava (e.g. Port de la Selva) and in Barcelona airport area, where saline water intrusion is inhibited by means of reclaimed water recharge in Llobregat river delta.

In summary, MAR has been present in Spain for several centuries and today there is a great variety of MAR facilities, that makes Spain an excellent country to visit to observe different working examples of most types of MAR. It is also worth mentioning there are more than 24 MAR facilities envisaged (especially for Ebro and Guadalquivir river Basins) in the second generation of Basin Plans, already published, which are commitments of the Spanish Government with their citizens and with the European Commission.

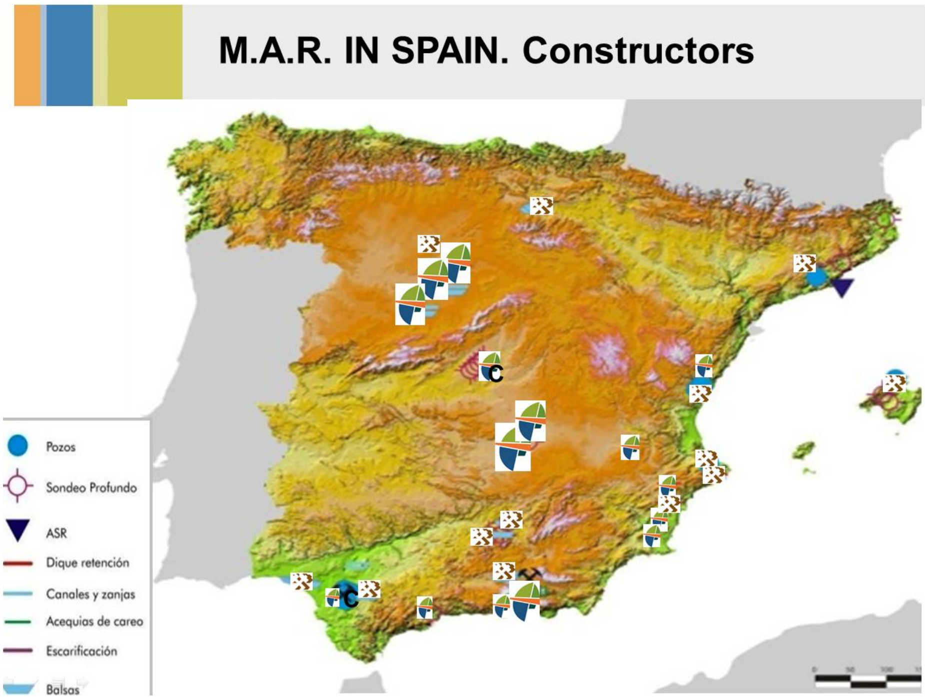


Figure 4. Map of MAR sites in Spain (DINA-MAR, 2009).

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International Association of Hydrogeologists

Commission on Managing Aquifer Recharge

This is one of IAH's family of Commissions and Networks

Aims

IAH's MAR Commission aims to expand water resources and improve water quality in ways that are appropriate, environmentally sustainable, technically viable, economical, and socially desirable. It will do this by encouraging development and adoption of improved practices for management of aquifer recharge. through:

- increasing awareness of MAR among IAH members and the greater groundwater community;
- facilitating international exchange of information between members;
- disseminating results of research and practical experience;
- informing policy development that enables benefits of MAR to be realized;
- facilitating members to conceive, undertake and deliver joint projects of international value.

Actions

To do this we have :

- resources on the IAH-MAR web site and a publications repository
- an email list that you can join from the IAH-MAR website
- working groups to undertake specific international projects
- symposia including ISMAR and workshops
- links to national networks

How to join

Join the email list at https://recharge.iah.org/ (its free) and on average circulates less than 8 emails a year.

Join a working group (cost is free but there is an assignment to do as a contributor to an international project team) https://recharge.iah.org/working-groups

Come along to a Plenary Session (free and no obligation) at an IAH Congress or at an ISMAR Symposium to discover how IAH-MAR could be helpful for you or your colleagues.

We encourage you, if you find this Commission useful, to also join IAH (this has annual subscription fees and you receive Hydrogeology Journal, IAH Book Series, newsletters, discount registration to IAH Congresses and ISMAR Symposia)

Electronic Supplementary Material - Hydrogeology Journal

Sixty years of global progress in managed aquifer recharge

Dillon, P., Stuyfzand, P., Grischek, T., Lluria, M., Pyne, R.D.G., Jain, R.C., Bear, J., Schwarz, J., Wang, W., Fernandez, E., Stefan, C., Pettenati, M., van der Gun, J., Sprenger, C., Massmann, G., Scanlon, B.R., Xanke, J., Jokela, P., Zheng, Y., Rossetto, R., Shamrukh, M., Pavelic, P., Murray, E., Ross, A., Bonilla Valverde, J.P., Palma Nava, A., Ansems, N., Posavec, K., Ha, K., Martin, R. and Sapiano, M. [* pdillon500@gmail.com]

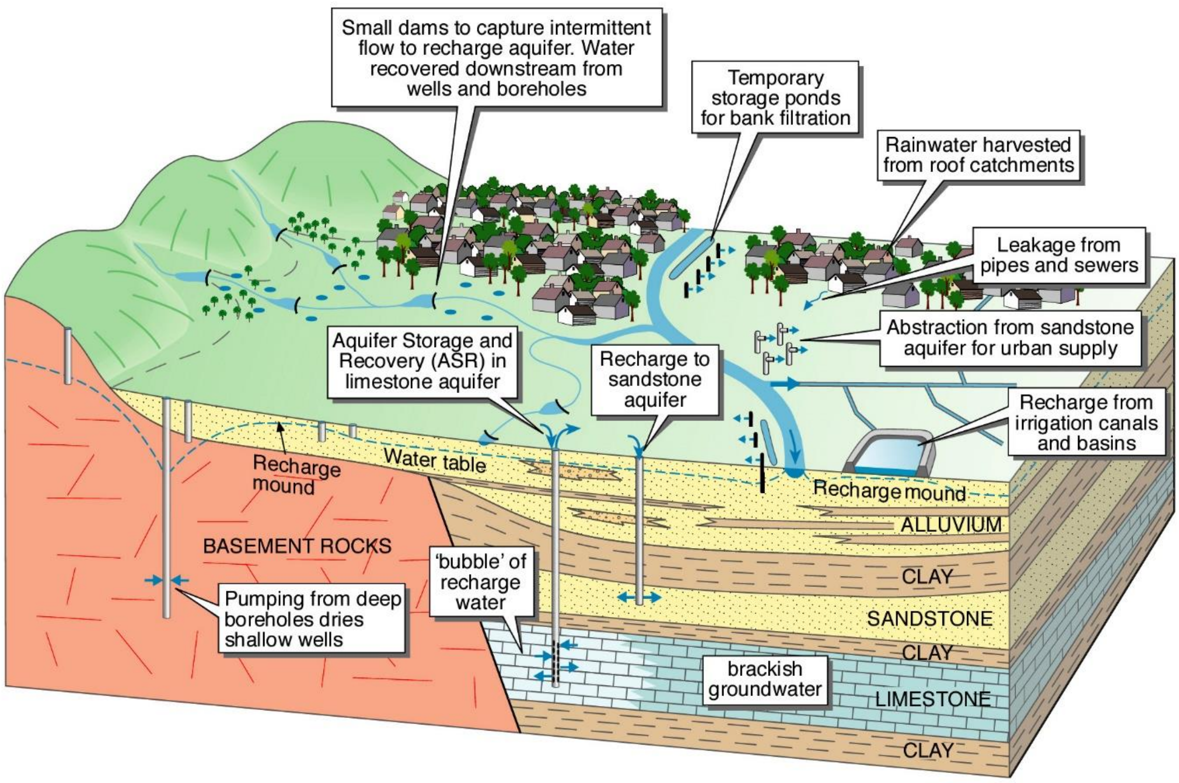
ESM2: Photographs of managed aquifer recharge projects

This photograph gallery was collated especially for the journal paper by members of a Working Group on 60 years history of MAR of the IAH Commission on Managing Aquifer Recharge. Captions contain brief descriptions of the projects and these are intended to be a useful educational resource to illustrate the variety of methods used for MAR, for a range of purposes, water types and end uses.

This is in addition to ESM1, which is an anthology of national histories on MAR.

ESM2 Contents:

Type of managed aquifer recharge	*ESM2 Page No.*
A diagram showing a variety of MAR methods used	2
Streambed channel modifications	3
Bank filtration	5
Water spreading	8
Recharge wells	14



Managed aquifer recharge is adapted to the local hydrology and hydrogeology, and is usually governed by the type of aquifer, topography, land use, ambient groundwater quality 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 streambed structures, river bank filtration, infiltration basins and recharge wells. (*Adapted from Gale, 2005, with permission in Dillon et al 2009*)

Dillon, P., Pavelic, P., Page, D., Beringen H. and Ward J. (2009). Managed Aquifer Recharge: An Introduction. Waterlines Report No 13, Feb 2009. 65p.
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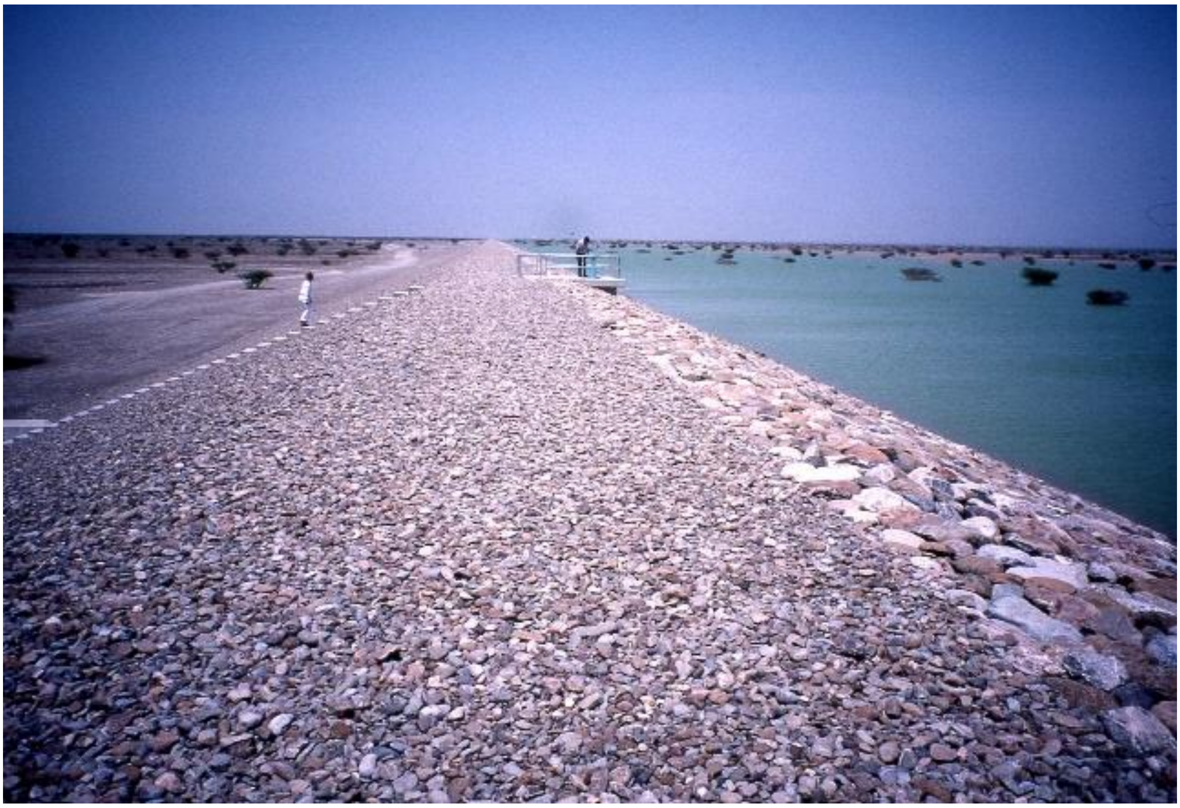
https://recharge.iah.org/files/2017/01/Gale-Strategies-for-MAR-in-semiarid-areas.pdf (accessed 12 Mar 2018)

Streambed channel modifications

Photo 1.1 Percolation tank construction near Baramati, Maharashtra, India, in the 1970s with women carrying murum and clay one bowl at a time to patiently construct the designed embankment. (*Photo from Agricultural Trust Baramati*).

Sand dams in the Burdekin River, Queensland, Australia, to spread water and increase recharge to aquifers used for irrigation supplies. Recharge channels and pits are also used in this area. About 40 Mm^3 has been recharged annually since the 1970s. (*Photo courtesy of Keith Bristow, CSIRO*).



Ahin recharge dam on the Batinah Plain, Oman, constructed in 1994, is a large dam (crest length 5640 m, crest height 8 m) with a detention capacity of 6.8 Mm^3. This is one of the 43 recharge dams, with an aggregated capacity of 95 Mm^3 constructed in Oman during the period 1985-2011 (Oman, MRMWR, 2012). Their purpose is to enhance aquifer recharge primarily to support irrigation; and also to protect the villages and agricultural land in the coastal zone against (previously) devastating flash floods. The dams intercept floods from a catchment with a mean annual rainfall less than 140 mm and potential evaporation around 2000 mm/yr. The detained water is released in a controlled way to recharge the aquifer zone downstream *(Photo: Jac van der Gun, 1995).*

Oman, MRMWR (2012). Dams in Oman. Ministry of Regional Municipalities and Water Resources. https://issuu.com/kabirahmed07/docs/dams_in_oman (accessed 24 July 2018)

Bank filtration

River bank filtration monitoring cross-section at the River Elbe at Torgau, Germany. Since 1981, Torgau waterworks abstracts up to 150,000 m^3/day from 42 wells located along a 15 km-long river stretch. The wells are located at mean distance of 300 m from the river bank. The travel times of the bank filtrate range from 50 to >200 days resulting in an effective removal of organic trace compounds. A monitoring cross-section with observation wells between the river and the abstraction wells allows sampling below the river bed (buried membrane pumps) and from different depths of the 55 m-thick sand and gravel aquifer. (*Photograph courtesy of T. Grischek, HTWD*)

Drilling of river bank filtration wells at the River Nile, Luxor, Egypt, March 2018. Seasonal low river water level, frequent spills of oil and other pollutants and high turbidity during high flow cause problems in surface water abstraction and subsequent treatment. A short distance between the abstraction wells and the river bank is sufficient to remove particles, to buffer spills and to ensure a high portion of bank filtrate and a low portion of manganese-rich land-side groundwater. (*Photograph courtesy of T. Grischek, HTWD*)

First flood-proof river bank filtration well in Srinagar, Uttarakhand, India. After a severe flood in 2013, a concept to construct flood-proof wells has been developed (NIRWINDU project) and realized in 2017 to protect city drinking water supplies. (*Photo courtesy of F. Musche, HTWD*)

Water spreading

Percolation ponds Nahaley Menashe, Israel. Since the 1960s, flash flood waters of four wadis south of Mount Carmel have been diverted to recharge the coastal plain aquifer in the dune area, which is now adjacent to the Hadera Desalination Plant (seen in background). The average annual yield of flood water is 10–15 Mm^3. The project consists of diversion structures, conveyance channels, a settling basin with an area of 51 ha to remove sediments and three percolation basins with a total area of 48 ha. Thirty seven pumping wells that are connected to the national water supply grid encircle the recharge area. The percolation ponds are now used also to store the desalination plants excess product water outside of the flood season. (*Photo by Dr. Joseph Guttman, Mekorot water company*)

At San Luis Rıo Colorado, Sonora, Mexico, oxidation lagoons (at a wastewater treatment plant in the background) have annually discharged 8.2 Mm^3 treated water to intermittent infiltration basins in the middle distance for more than 10 years. In the foreground, some water is starting to be used to establish constructed wetlands. *(Photo, April 2018, courtesy of Hernández Humberto, Organismo Operador Municipal de Agua Potable, Alcantarillado y Saneamiento de San Luis Rıo Colorado, Sonora, Mexico).*

In Arizona, USA, the Granite Reef Underground Storage Project (GRUSP) takes surface water from the South Canal of the Central Arizona Project through a delivery canal to infiltration basins to recharge the unconfined aquifer that supplies the City of Phoenix. The facility, except for the source water canal, is totally constructed in the Salt River bed. It has been operating since 1994 and is permitted to recharge up to 115Mm^3/yr through 7 basins. (*Photo courtesy of Mario Lluria, HydroSystems Inc.*)

Basin infiltration Jäniksenlinna MAR plant, Tuusula, Finland. During winter, ice cover is formed on the basin surface, but this does not prevent infiltration. Jäniksenlinna MAR plant is used for potable water production: humic lake water is infiltrated, it travels 400–650 m in the ground with a detention time of 30–60 days. During that time, humic substances are biodegraded and/or removed by adsorption. This operation started in 1979 and comprises both basin and well infiltration with total capacity of 13,200 m^3/d. Cascade aeration helps sustain aerobic conditions that are important for aerobic biodegradation of humic substances in the soil. (*Photograph by Unto Tanttu*)

In Santiuste Basin, Segovia, Spain, water is diverted from Voltoya River MAR by a dam and 10 km of 1200-mm diameter pipe and discharges as shown to an infiltration pond that overflows into 27 km of MAR infiltration canals. The system was established in 2002 and designed for a maximum flow-rate of 100 l/s and to deliver up to 8.5 Mm^3 in each 6-month winter-spring cycle, whenever the Coca Gauge station registers over 1,200 l/s in the Voltoya River. The infiltration pond has an area of 1.4 ha, and the two canals an area of 6.1 ha. The purpose is to increase water availability for irrigation and now 28% of water used for irrigation is derived from MAR. A small amount is used for the regeneration of wet-lands (La Iglesia salt-lake). Santiuste village wastewater treatment plant water is also discharged into the MAR canal for recharge. Three artificial wet-lands have also been built to improve the purification process. Between 2002 and 2015 the total volume infiltrated was 34 Mm^3. The mean groundwater level has raised 1.47 m, resulting in 30% energy savings to pump water with respect to the previous cost. (*Photo: Enrique Fernández Escalante, March 2017.*)

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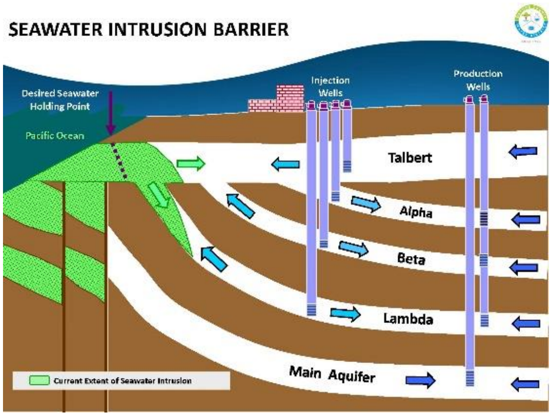
In Italy, the Suvereto infiltration basin uses flood-water and it was designed and set in operation in 2018, applying the newly issued Italian regulation on artificial recharge of aquifers (DM 100/2016). The infiltration basin is located at a pre-existing topographical low near the Cornia River in a groundwater recharge area where the aquifer is composed of gravel and sand. The river, having intermittent flow, provides recharge water during high flow periods, including floods, and when discharge is above the minimum ecological flow. The facility consists of the following elements: i) intake work on the River Cornia; ii) the inlet structure control system, managed by quality (mass spectrometer defining surface water spectral signature) and level probes, and allowing pumping into the facility at predefined head and chemical quality thresholds; iii) a sedimentation basin; iv) the infiltration area (less than 1 ha area); v) the operational monitoring system, based on a network of piezometers where both continuous data (head, temperature, electrical conductivity and dissolved oxygen) are gathered and discrete measurements/sampling performed. Depending on the climatic conditions, it is estimated that the volume of diverted surface water may vary between 0.3 and 2 Mm^3/yr. *(Photos: Rudy Rossetto)*

Recharge wells

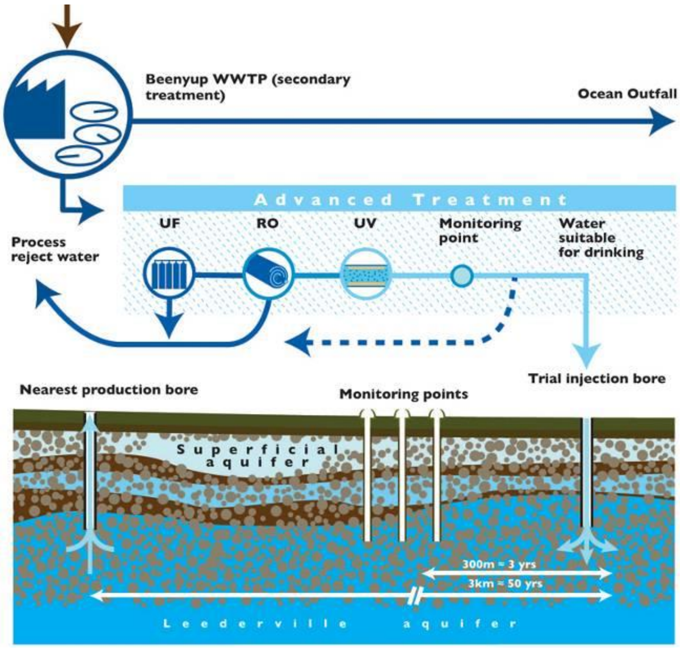
At Cocoa, Florida, USA, ten aquifer storage and recovery wells, including one in the foreground, store and recover treated drinking water using the underlying aquifer at a depth of 100 to 130 m. The volume stored below ground during the low demand period and recovered in the high demand period at Cocoa is ten times the volume of the two storage tanks behind. The unit storage cost of ASR was less than 2 per cent of the alternative cost of constructing additional tanks. (Dillon *et al* 2009; see reference details above). The system commenced operation in 1987 and has the capacity to recharge and recover 45,000 m^3/d (Pyne 2005) (*Photo: Peter Dillon*)

Pyne, R.D.G. (2005). Aquifer Storage Recovery: A Guide to Groundwater Recharge Through Wells. ASR Systems, 2nd Edition, 608p.



Orange County’s Groundwater Replenishment System (GWRS) in California, USA, is the world's largest water purification system for indirect potable reuse. This takes highly treated wastewater that would otherwise be discharged into the Pacific Ocean, and further treats it with microfiltration, reverse osmosis and ultraviolet light with hydrogen peroxide. The high-quality water that is produced meets all USA drinking water standards. The water indirectly, via aquifers, supplies 850,000 residents in an area with an annual rainfall of 360 mm. GWRS started in 2008, but was an expansion of the ‘Water Factory’ that began in the 1970s. It currently produces 0.37 Mm^3/day and will grow to 0.49 Mm^3/day by 2023. The water is injected via 23 multi-port wells into a series of coastal aquifers to prevent saline intrusion occurring as a result of groundwater exploitation. The water is also fed with water from other sources into a large number of infiltration basins. GWRS protects and improves groundwater quality and enables continuing use of the groundwater system for vital water supplies. (*Figures courtesy of Orange County Water District*)

The Paddocks constructed wetland and urban stormwater harvesting system was developed by the City of Salisbury, South Australia, and commenced operation in 1996. The scheme was conceived to mitigate flooding, to improve stormwater quality, to provide urban recreational amenity and wildlife habitat, and also to harvest water in winter for summer irrigation. On average 60,000 m^3/yr is harvested from an 80-ha urban-residential catchment and recharged (Kretschmer 2017). When water quality is suitable, stormwater is injected into a confined limestone aquifer with native groundwater salinity of 1800 mg/L, via a 164-m deep aquifer storage and recovery (ASR) well with open-hole completion. Although native groundwater salinity was too high for irrigation, ASR allows a volume of about 80% of the volume of fresh water recharged to be recovered for sustainable irrigation of parks and sporting grounds in summer via a distribution system that extends through the City of Salisbury and connects a number of stormwater ASR systems. (*Photos by Peter Dillon*)



Perth Groundwater Replenishment Project, Western Australia, which commenced operations in 2017 at 14 Mm^3/yr using advanced treated recycled water to recharge a confined aquifer that is an important contributor to Perth's drinking water supply. It will double its annual recharge by 2019 when a treatment plant and a total of 4 wells will store water in the Leederville and Yarragadee aquifers. The project will prevent saline intrusion and allow expansion of use of the groundwater system to meet water supplies in an area experiencing a drying climate, where surface water supplies have reduced over the last 40 years and the population has steadily increased *(Photo and diagram courtesy of Water Corporation, Western Australia).*