# A global perspective on the advance of Managed Aquifer Recharge

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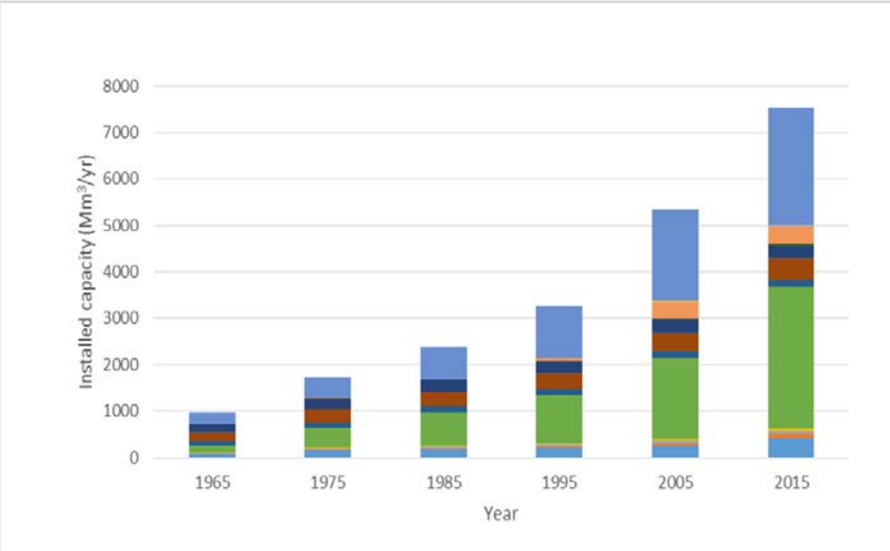
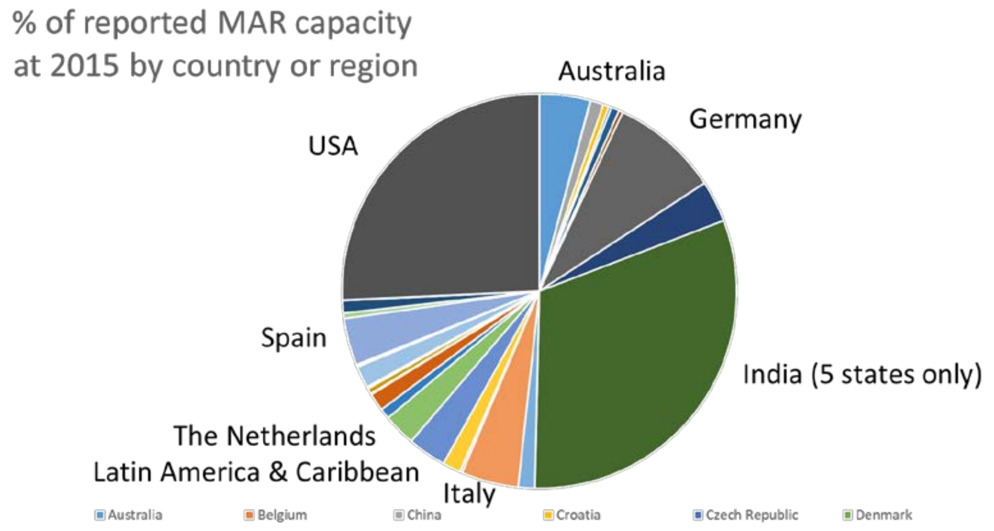
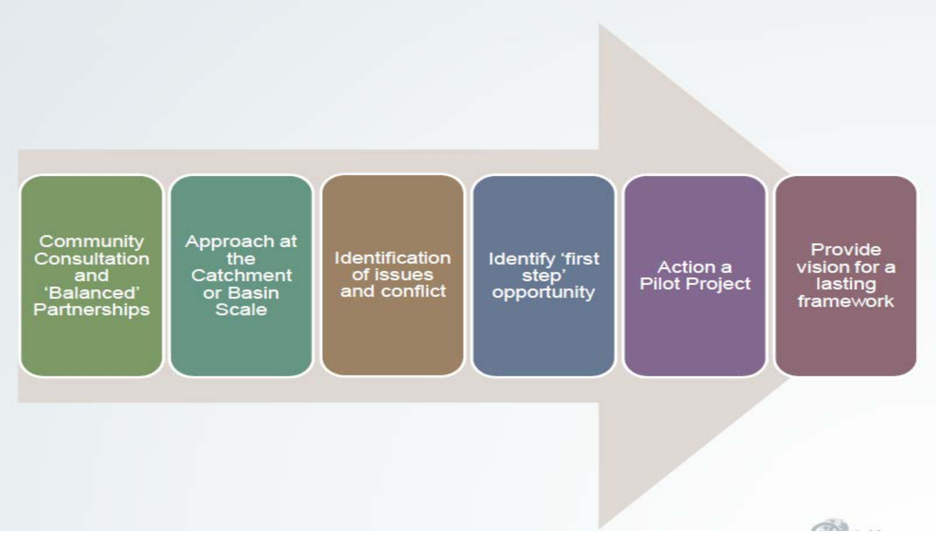
**BSMAR16 , 5-7 March 2018**



# Contents

- What is MAR ?
- How much does MAR contribute to global water supplies ?
- Progress in research
- What next?




Images courtesy of Bob Bower, WGA, Hinds/Hekeao MAR pilot project, Canterbury Plains, New Zealand

# Evolution of groundwater recharge augmentation

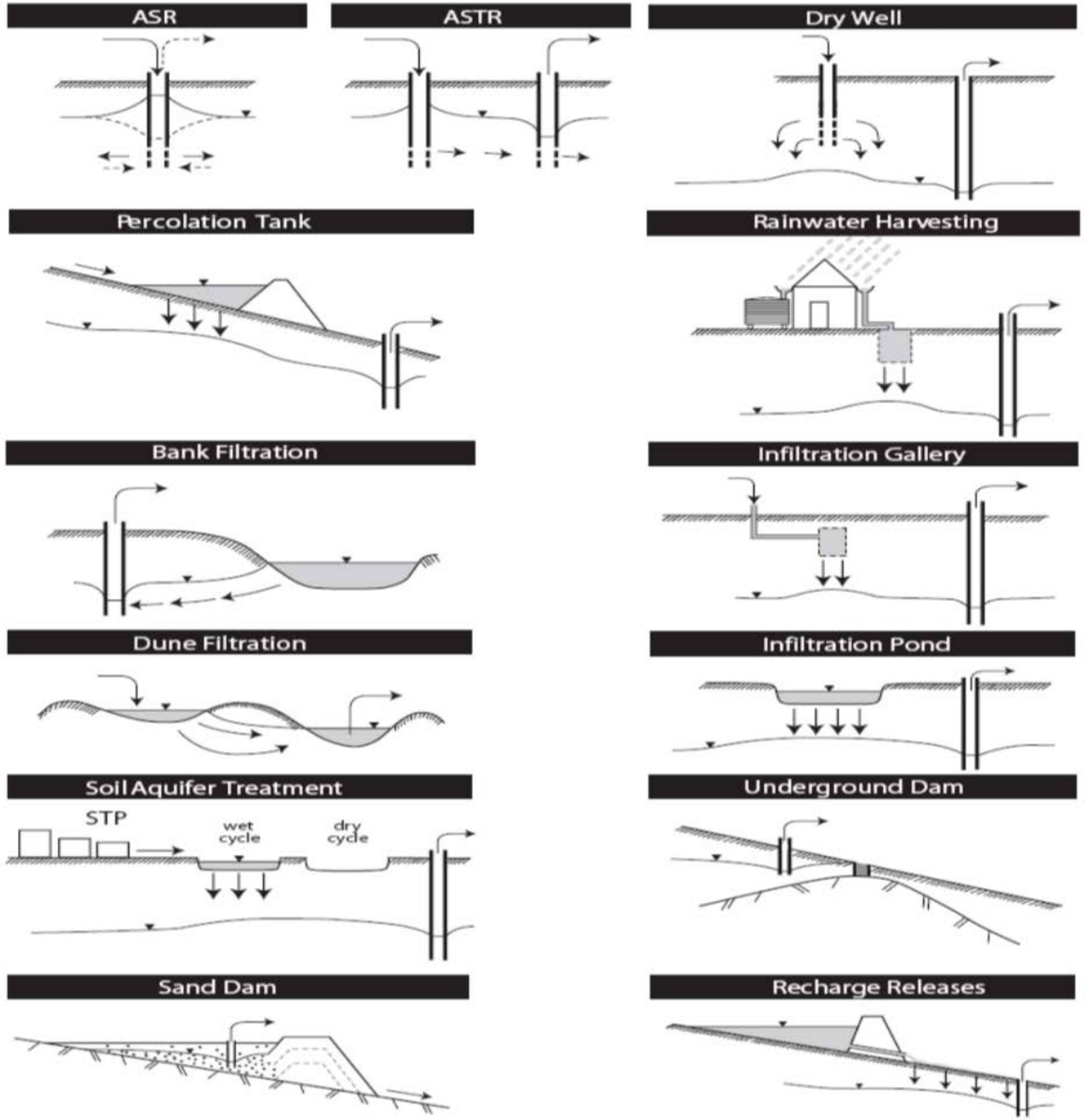
(adapted from NRMMC,EPHC & NHMRC 2009)

| Unintentional Recharge Enhancement | Unmanaged Recharge (for disposal) | Managed Aquifer Recharge (for recovery) |
|---|---|---|
| • Clearing of deep rooted vegetation, or soil tillage<br>• Spate irrigation<br>• Irrigation deep seepage<br>• Leakage from water pipes and sewers | • Stormwater drainage wells and sumps<br>• Septic tank leach fields<br>• Mining and industrial water disposal to sumps<br>• Drainage water from construction pits | • Streambed channel modifications<br>• Bank filtration<br>• Water spreading<br>• Recharge wells and shafts<br>• Reservoir releases |

# Terminology is important

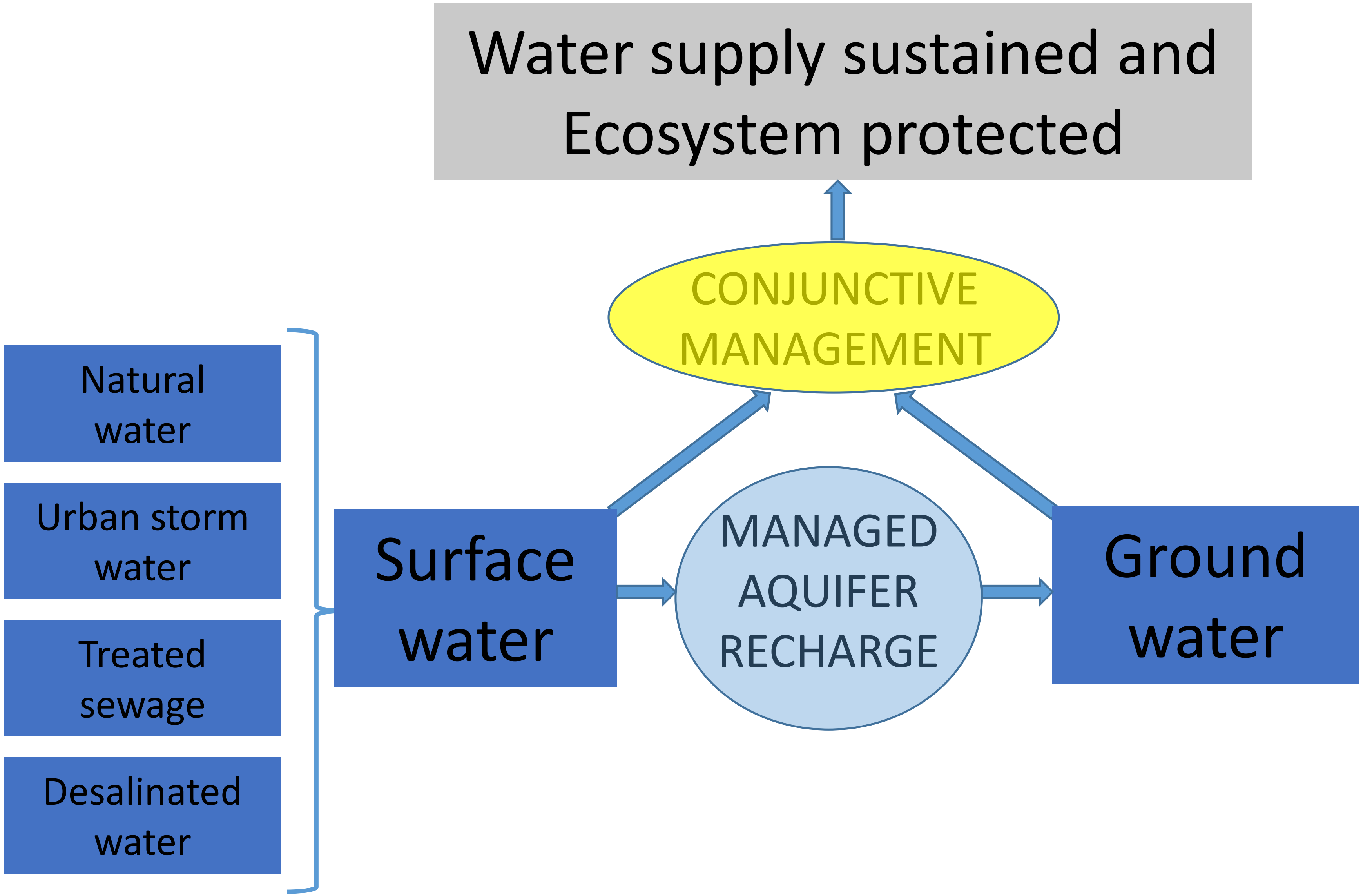
Artificial recharge – old name for MAR but still used if water quality is not being managed

Terms for types of MAR – use consistent terms because these have important distinctions for water quality regulators and we want consistent governance




Dillon (2005) Future management of aquifer recharge. Hydrogeology J , 13 (1) 313-316.

# Integrated water resources management through MAR and conjunctive use



# Reported volume of MAR in USA from 1960s to 2015

(Million cubic metres/year : 1Mm³/yr = 810.7 acre-ft = 264.2 million (US) gallons)

| Decade | Total | Infiltration systems | | | | | | | Recharge wells | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Central Valley, Kern County CA # | CAP, AZ * | Recycled water, AZ * | Orange County, CA ** | LA Montebello Forebay CA ## | Long Island, NY ## | ? | Recycled water, Orange County, CA ** | El Paso, Texas ## | Orlando, Florida, stormwater wells ## | ? |
| 1961-1970 | 243 | 0 | 0 | 0 | 150 | 15 | 56 | | 0 | 0 | 22 | |
| 1971-1980 | 423 | 70 | 0 | 0 | 200 | 28 | 96 | | 3 | 0 | 26 | |
| 1981-1990 | 703 | 250 | 0 | 0 | 250 | 33 | 120 | | 6 | 13.8 | 30 | |
| 1991-2000 | 1128 | 500 | 70 | 20 | 300 | 62 | 120 | | 10 | 13.8 | 32 | |
| 2001-2010 | 1962 | 1000 | 250 | 80 | 300 | 74 | 120 | | 92 | 13.8 | 32 | |
| 2011-2015 | 2532 | 1400 | 400 | 100 | 300 | 74 | 120 | | 92 | 13.8 | 32 | |

**Acre-ft USA: 2,050,000 CA: 1,510,000 AZ: 405,000 NY+FL+TX : 135,000**

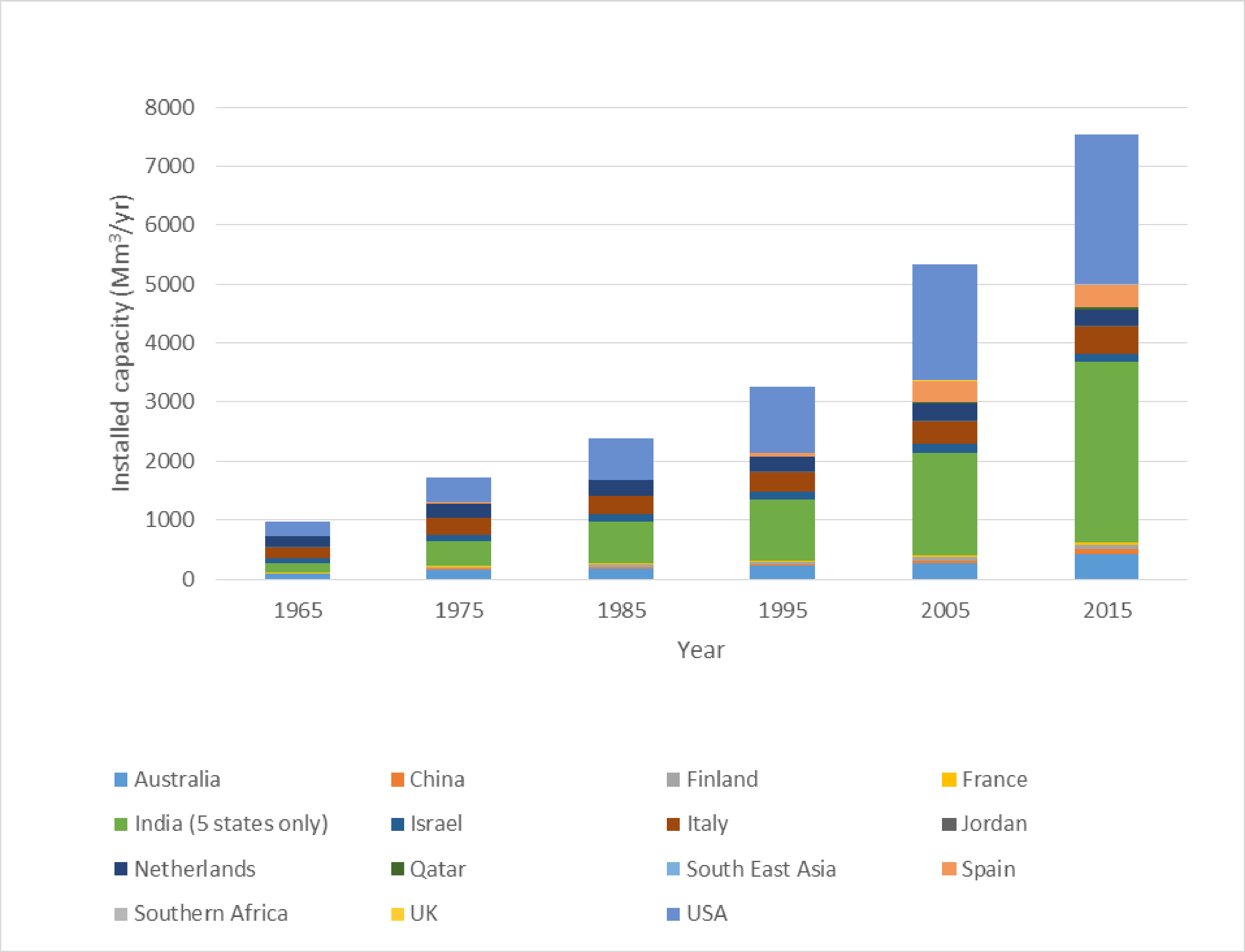
**MG USA: 669,000 CA: 493,000 AZ: 131,000 NY+FL+TX : 44,000**

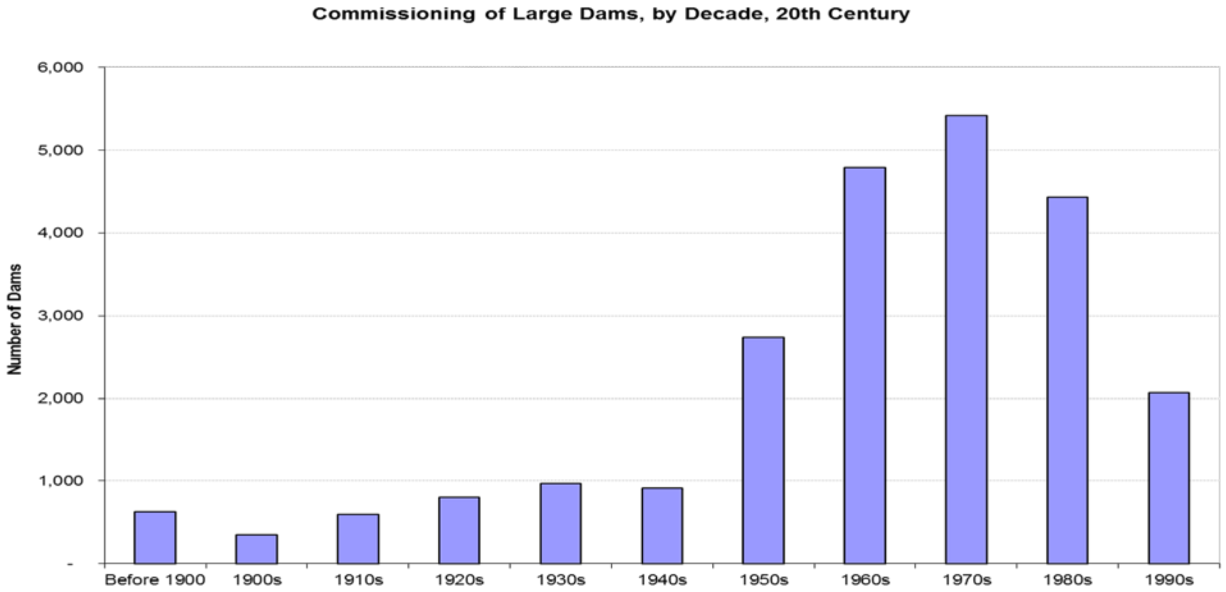
**DO YOU BELIEVE THIS????**

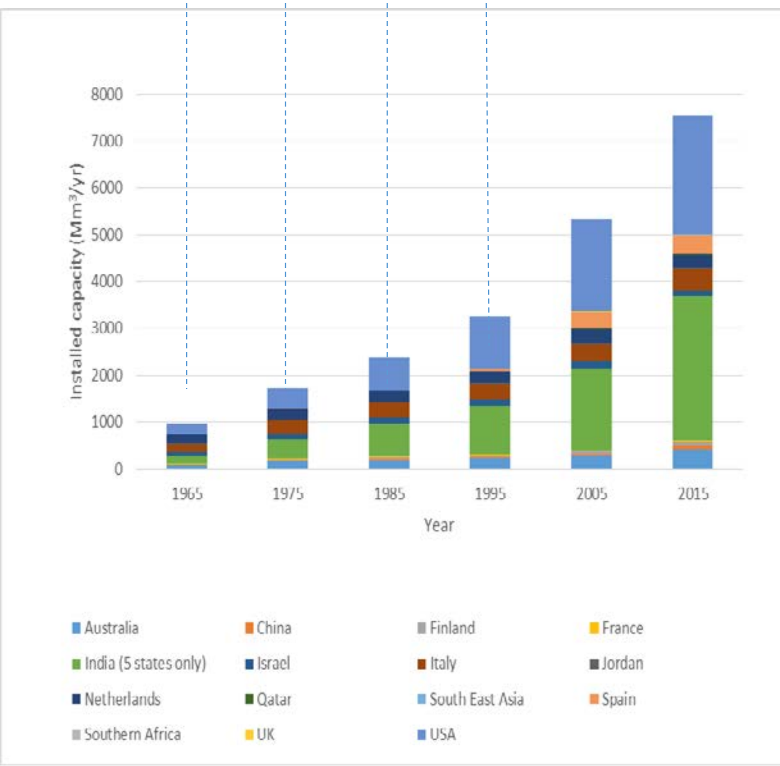
\# and * Scanlon et al (2016) Enhancing drought resilience with conjunctive use and managed aquifer recharge in California and Arizona.
** Mills (2002) The quest for water through artificial recharge and wastewater recycling. (OCWD)
\## National Research Council (1994). Ground Water Recharge Using Waters of Impaired Quality. National Academies Press.

- Most USA states are missing, and some projects are missing even in reported states. No bank filtration was reported.
- If you have figures or know someone who has summaries, please pass them on.
- Wanted: A volunteer to do a summary for each state where MAR in use or for USA ?

# Growth in MAR for 15 countries or states where its use has been documented since 1965 (accounts for 76% installed MAR capacity at 2015)

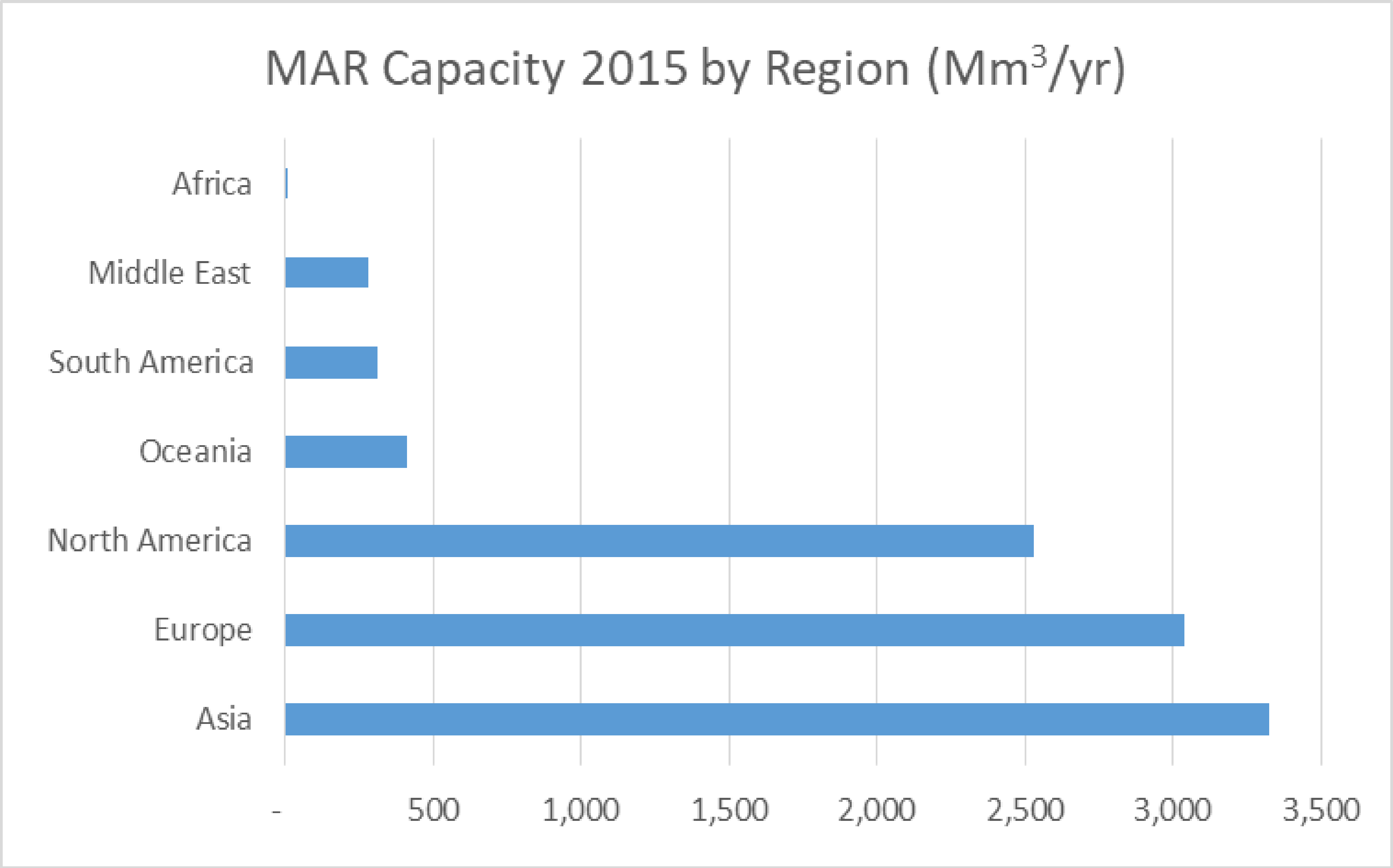


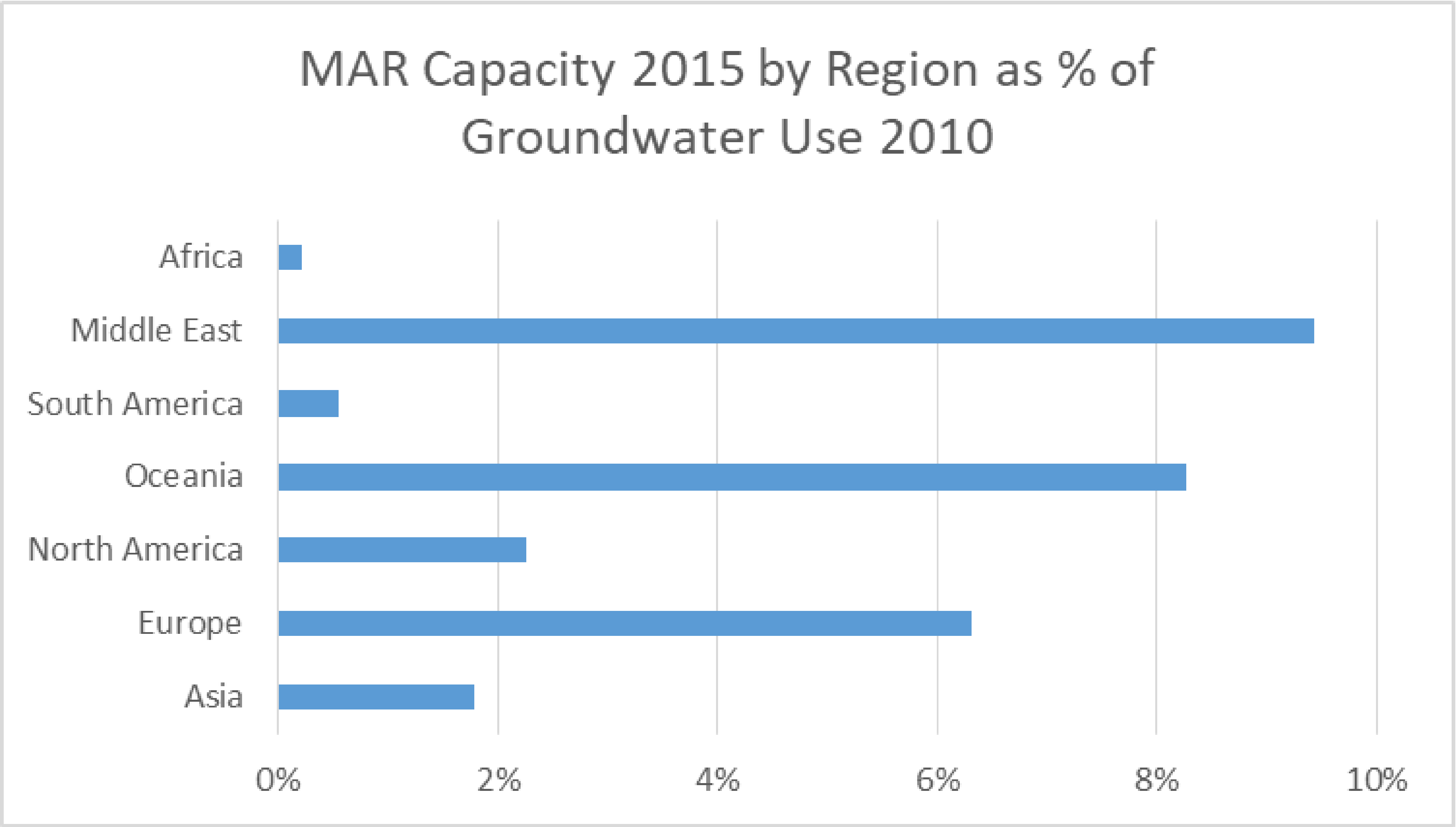


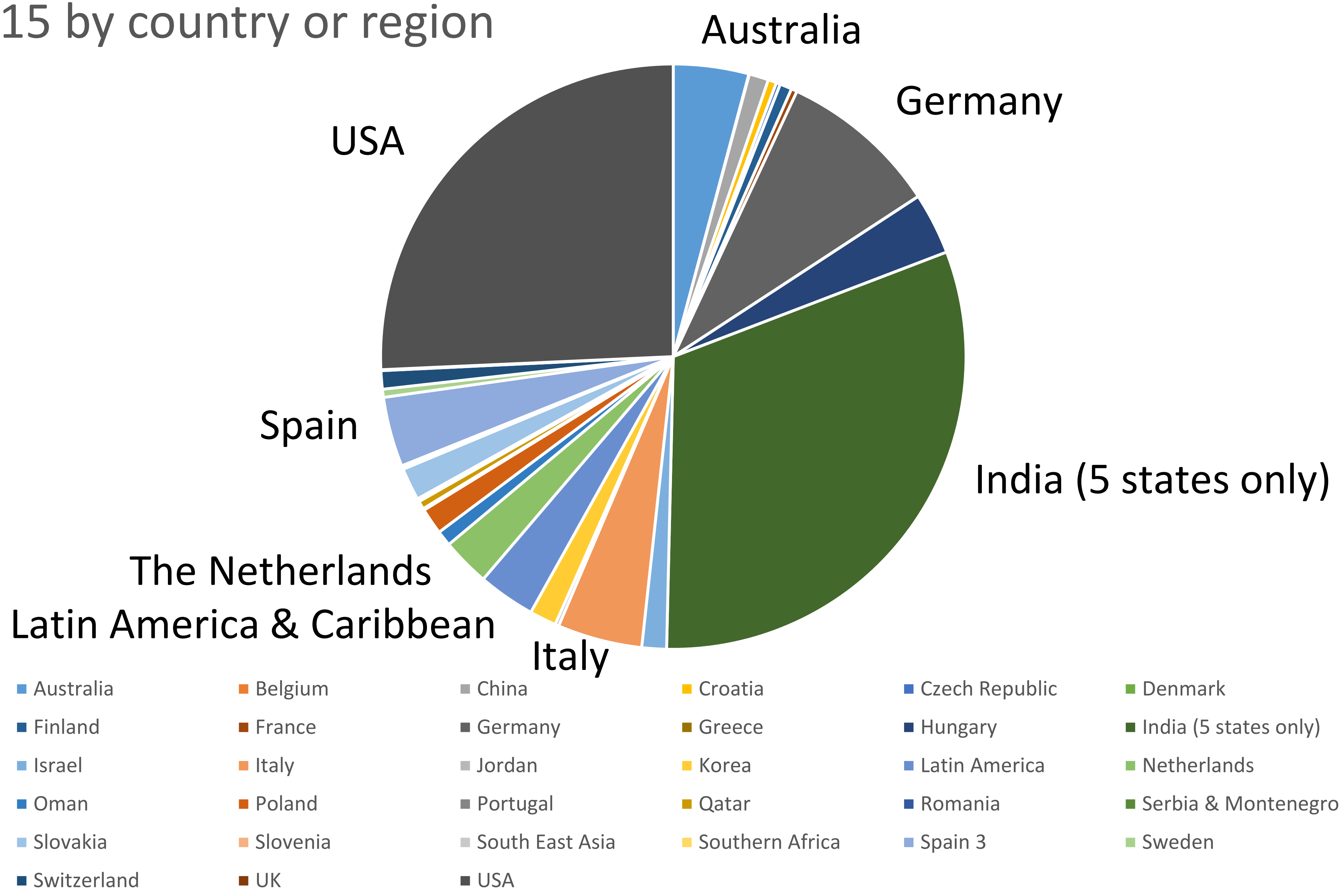

# Comparing trajectories of dams and MAR

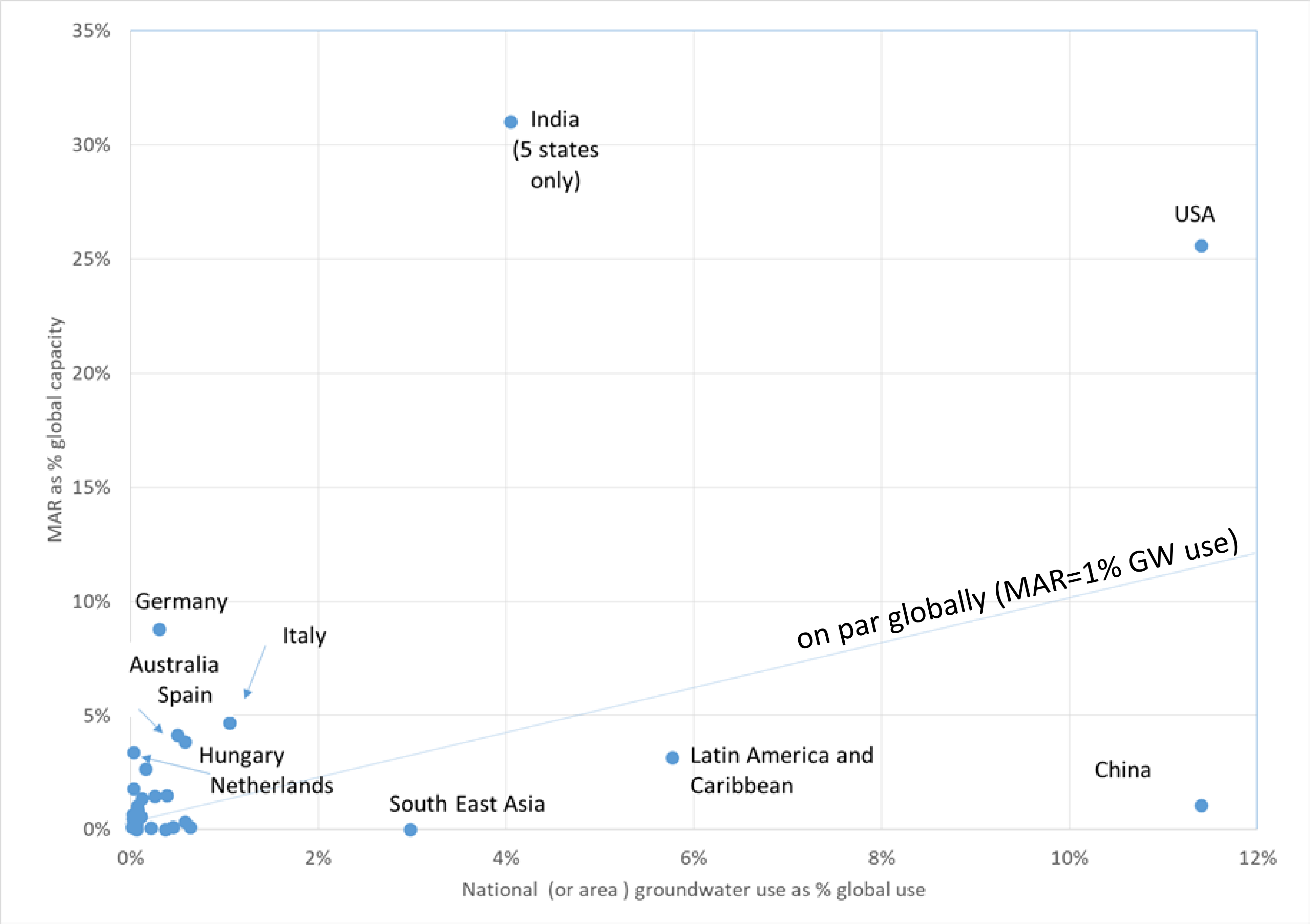
Note: scales are different and dams can facilitate MAR


MAR Capacity 2015 by Region (Mm3/yr)
Africa
Middle East
South America
Oceania
North America
Europe
Asia
-
500
1,000
1,500
2,000
2,500
3,000
3,500


MAR Capacity 2015 by Region as % of Groundwater Use 2010
Africa
Middle East
South America
Oceania
North America
Europe
Asia
0%
2%
4%
6%
8%
10%

# % of reported MAR capacity at 2015 by country or region






MAR as % global MAR capacity

Vs

GW use as % global GW use

| | Average annual MAR volume in the decade centred on date ($Mm^3/y$) | | | | | | Annual Groundwater use [1] (Mm3/y) | MAR as % ground-water use | MAR as % global capacity | MAR vol growth earliest year to 2015 %pa | Ground-water use as % global use |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Country/Region** | **1965** | **1975** | **1985** | **1995** | **2005** | **2015*** | **2010** | **2015** | **2015** | **- 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% | 8.8% | 0.0% | 0.31% |
| Greece | | | | | | 0.3 | 3,650 | 0.0% | 0.0% | | 0.37% |
| Hungary | | | | | | 335 | 660 | 50.8% | 3.4% | | 0.07% |
| India (5 states only) | 154 | 430 | 706 | 1020 | 1739 | 3070 | 39,800 | 7.7% | 31.0% | 6.6% | 4.05% |
| Israel | 87 | 91 | 127 | 132 | 144 | 134 | 1,250 | 10.7% | 1.4% | 0.9% | 0.13% |
| Italy | 178 | 294 | 301 | 348 | 391 | 461 | 10,400 | 4.4% | 4.7% | 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 | <1 | 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] | 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% |
| USA | 243 | 423 | 703 | 1128 | 1962 | 2532 | 112,000 | 2.3% | 25.6% | 5.1% | 11.41% |
| | | | | | | | | | | | |
| Total | 970 | 2,585 | 3,207 | 4,244 | 6,231 | 9,903 | 414,400 | 2.4% | 100.0% | 5.1% | 42.2% |
| Global groundwater use | | | | | | 9,903 | 982,000 | 1.0% | | | |

# Global MAR history

- MAR 10 $km^3$
- Groundwater use 1000 $km^3$
- MAR 1% GW use

- MAR growth 5%pa 0.5 $km^3$ /y
- GW Use growth 50 $km^3$ /y

# MAR in perspective

| | $km^3/yr$ | | |
|---|---|---|---|
| • Natural recharge | 12,000 | (Margat 2008) | |
| • Groundwater use | 982 | (Margat & van der Gun 2013) | |
| • Groundwater depletion | 145 | (Konikow 2011) | (18% of gw use) |
| • Managed aquifer recharge | 10 | (Dillon *et al* in prep) | (1% of gw use) |
| | | | |
| • Seawater desalination | 20 | (UNESCO 2008) | |
| • Turnover of dams | 4-6,000 | (Pacific Institute 2003) | |

# Progress in Research and Practice

**Tools have improved out of sight..**

- Computers and modelling, geostatistics, spreadsheets,
- Materials – well casing, screens, valves, pumps, drilling eg vibrocore
- Water treatment – activated carbon, ozonation, reverse osmosis, membrane bioreactor, deoxygenation
- Logging – geophysics- down hole, surface, airborne, down hole flow logging
- Monitoring and analysis – trace organics, viruses (PCR), BDOC (biodegradable dissolved organic carbon), particle size distributions, isotope analyses C, N, S, O, H etc
- Pressure transducers, probes, flow meters, loggers, SCADA – control systems
- Risk assessment methodology

**enabling greater scientific insight on and management of ..**

- Hydraulics, clogging, recovery efficiency
- Fate of constituents
- Geochemistry
- Microbial ecology

# ISMAR publications

| Date | ISMAR | Location | No. of papers | Procs or Special Issues * | Reference |
|---|---|---|---|---|---|
| 1988 | ARG1 | Anaheim | | B | Johnson A.I. (ed). (1988) |
| 1994 | ARG2 | Orlando | 84 | B | Johnson A.I., Pyne, R.D.G. (eds.). (1994) |
| 1998 | TISAR | Amsterdam | 83 | B | Peters, J. *et al* (eds) (1998) |
| 2002 | ISAR4 | Adelaide | 91 | B | Dillon P.J. (ed). (2002) |
| 2005 | ISMAR5 | Berlin | 133 | eB | Fritz B. *et al* (eds) (2005) |
| 2007 | ISMAR6 | Phoenix | 124 | B | Fox P. (ed). (2007) |
| 2010 | ISMAR7 | Abu Dhabi | 115 | eB | Herrman R. *et al* (eds). (2010) |
| 2013 | ISMAR8 | Beijing | 122 | SIJ-17 | Zhao, Xuan and Wang, Weiping (eds.) (2015) |
| | “ | “ | | SIJ-12 | Sheng, Zhuping,,Zhao, Xuan (eds) (2015) |
| | “ | “ | | SIJ-14 | Megdal S., Dillon P. (eds) (2015) |
| 2016 | ISMAR9 | Mexico City | 88 | SIJ-18 | Stuyfzand, P. and Hartog, N. (eds) (2017). |
| | “ | “ | | SIJ-18 | Dillon, Pavelic, Wang and Palma Nava (in prep) |
| All | | | 840 | B+eB-7, SIJ-79 | |

* B = book, eB = e-book, SIJ-18 = Special Issue of a Journal with 18 papers

# Indicative number of peer reviewed journal papers published in the field of MAR by decade

| Years | 1970s | 1980s | 1990s | 2000s | 2010-2017 |
|---|---|---|---|---|---|
| Number of papers | 3 | 5 | 36 | 140 | 319 |

Results of SCOPUS search Sept 2017 on “managed aquifer recharge”, “artificial recharge” or “water banking” in the title of the paper has shown that the number of papers in each successive decade has increased considerably. Papers in earlier years may be under-represented by electronic bibliographic services. (Dillon *et al* in prep)

# Information needed to progress MAR

**Information**

- Citable references on innovative projects
- Measurement of water quantity and quality at MAR sites
- Breakdown of economics of MAR sites
- Global inventory of MAR
- Maps to show potential for MAR
- Communities of practice to share experience

**Scientific advances**

- Standardised methods to predict clogging
- Standardised validation procedures for pathogen removal
- Improved prediction of contaminant removal and mobilization in aquifers
- Cheaper aquifer characterization and ecosystem indices

**Governance**

- Implementation of groundwater management plans that recognize role of MAR
- Consistent water quality guidance based on risk management/water safety plans
- Encouragement of water banking for water security in drought, climate change
- Encouragement of conjunctive use of g/w and s/w
- Strengthen IWM in urban areas, incl stormwater, treated waste water
- Link water to energy, food, and land planning to account for multi-sectoral benefits
- Support for community cooperative MAR development and maintenance


# Conclusions - the journey so far

The last 60 years has seen a huge growth in MAR based on sound interdisciplinary science.

MAR currently compensates for 5% of global groundwater depletion, and good management would see that percentage rise for two reasons.

MAR reduces net groundwater use by only 1%, and it is a trivial 0.06% in comparison with natural recharge.  However its done where it is useful and critically needed.

There are more people to feed and climate variability in many places is reducing natural recharge, increasing evaporation and water use.  **It would be irresponsible not to consider buffering of storage below ground**.  Resilient water supplies are fundamental so MAR is no longer exotic, it’s a mainstream groundwater management tool and **should be used as inducement for demand management, not as a substitute**.

***In 60 years artificial recharge has transitioned from trial and error to rigorously investigated, and  from unmanaged to managed.  Soil and aquifers that once were regarded as inert are now seen as bioreactors and aquifer hydrogeochemistry and ecology recognized as important. Monitoring and measurement capabilities have improved, and technology advanced. Success is no longer random, its expected, unless dismissed early in site investigations.***

# Conclusions - the journey ahead

**Trends:**

- More water banking for drought and water security
- More use of urban wastewaters, rural flood cropping and diffuse micro-MAR
- Engineered and natural treatment methods to complement soil and aquifer targets
- Community based MAR in alluvial systems with technical support
- Ongoing research on information gaps and synthesis of knowledge

**For IAH MAR Commission**:

- Continue to promote exchange of information of benefit to water suppliers and users, water resources managers, environmental and health regulators, planners, financial institutions and communities
- Continue to foster interdisciplinary research and sharing between researchers and all stakeholders.
- Dispel myths, and divergent policies in place around the world that are not supported by science, and encourage good practices so that all new MAR operations are sustainable.

**International Association of Hydrogeologists**

**Commission on Managing Aquifer Recharge**

IAH –MAR https://recharge.iah.org/

***Aim:*** Safe, sustainable recharge enhancement

***Methods:*** web site, publications database, email list, conferences, projects, **working groups**, workshops

***Outputs:***

- UNESCO publications – eg '*Strategies to enhance recharge in arid and semi-arid areas'* , *'..managing aquifer recharge, discharge and storage equilibrium'* ,*3Rs-Managing the groundwater buffer*
- *Working groups -Monograph on clogging (Russell Martin (ed)), governance & economics (J Water special issue 2015), MAR for development (workshop at ISMAR9, 2016), International inventory of MAR (with IGRAC and EU), Economics of MAR (Ross & Husnan 2018), 60 year history (Dillon et al in prep), MAR Guidelines (collation on web)*
- *Symposia - BSMAR 16 (San Diego USA Mar 2018) and ISMAR10 (Madrid 20-24 May 2019),*

CoChairs: Peter Dillon, Weiping Wang, Enrique Fernandez Escalante

**ALL WELCOME to access info and join working groups**

iah aih

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# ISMAR 10

## INTERNATIONAL SYMPOSIUM ON MANAGED AQUIFER RECHARGE

**Madrid (Spain)**
**2019 May 20-24th**

GrupoTragsa

Gobierno de España — Ministerio de Economía y Competitividad

Instituto Geológico y Minero de España

IWRA International Water Resources Association

www.ismar10.net