Managing Aquifer Recharge: A Showcase for Resilience and Sustainability

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Outline

1. Background and Motivation
2. Sustainability Indicator Development
3. Cost and Cost-Benefit Analysis
4. Lessons Learned and Implications

According to IAH-MAR Commission (recharge.iah.org), managed aquifer recharge (MAR), also called groundwater replenishment, water banking and artificial recharge, is the ***purposeful recharge*** of water to aquifers for **subsequent recovery or environmental benefit.**

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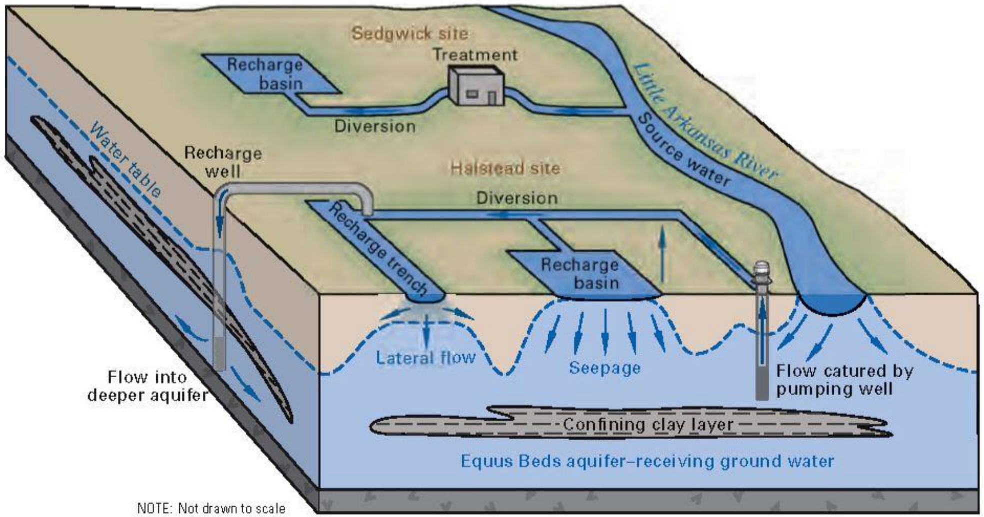
Managed Aquifer Recharge 含水层回补管理

荷兰阿姆斯特丹基于含水层回补管理（MAR）技术的绿色供水系统

土壤-含水层处理SAT技术
Soil-Aquifer Treatment



河岸带过滤RBF技术
River Bank Filtration

According to IAH-MAR Commission (recharge.iah.org), managed aquifer recharge (MAR), also called groundwater replenishment, water banking and artificial recharge, is the ***purposeful recharge*** of water to aquifers for **subsequent recovery or environmental benefit.**

根据水最终用途，通过目标补水、抽水等，人工控制含水层水循环

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Part I

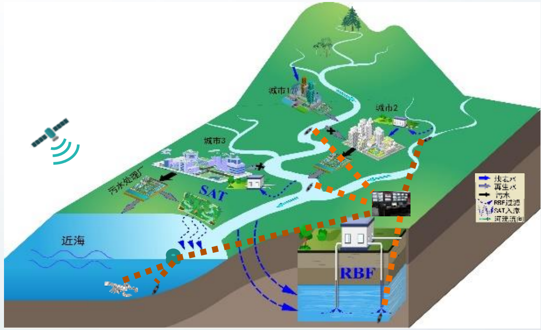
UNESCO IHP-VIII WATER SECURITY (2014-2021)

Theme (2) **"Groundwater in a Changing Environment"**

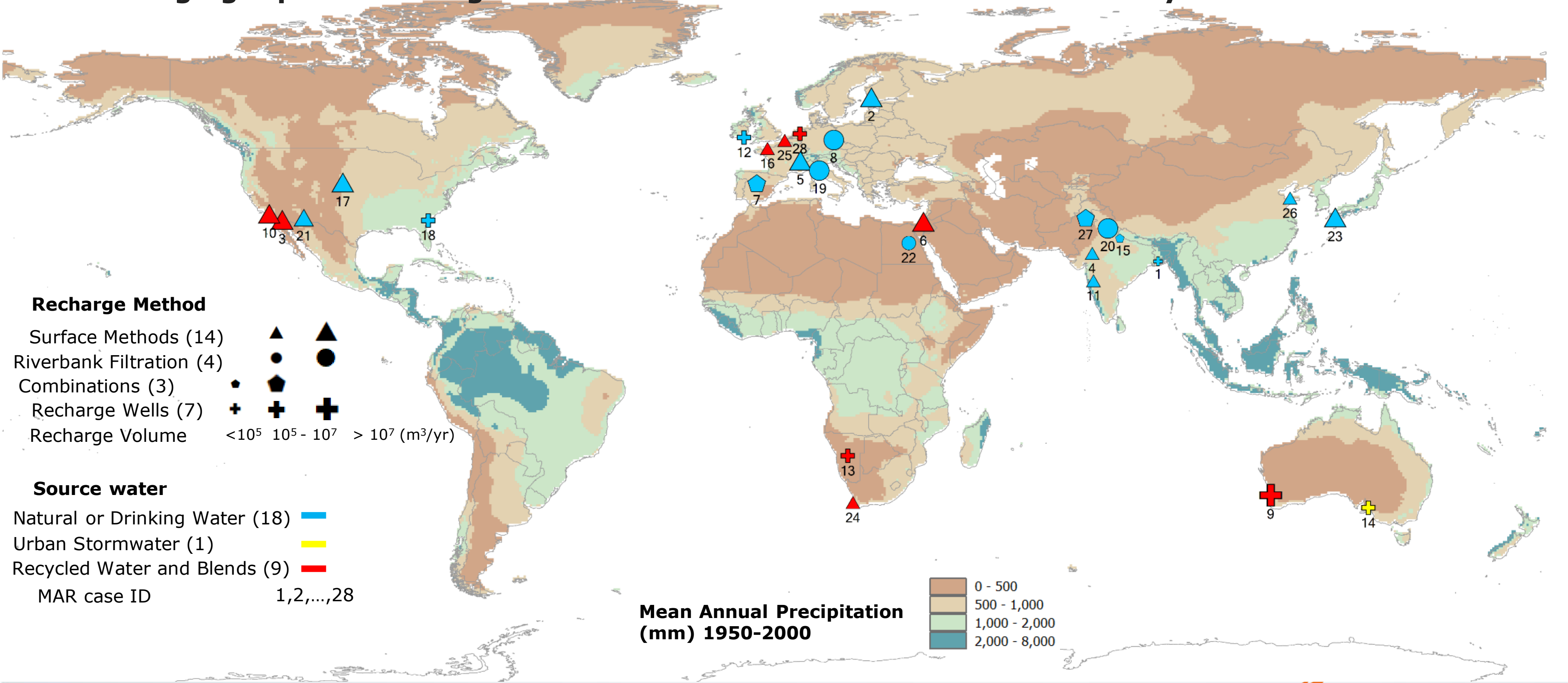
In order to **incorporate MAR to Integrated Water Resource Management**, the Focal Area "Addressing strategies for management of aquifer recharge" will

- develop and apply **methods** to assess the impact of MAR schemes on water availability and quality, social and economic resilience and local ecosystems;
- evaluate the **risks and benefits** of recycling appropriately treated wastewater and storm water for safe irrigation or drinking water supplies;
- enhance **governance** capacities, and institutional and legal frameworks to aid effective implementation.

Protecting groundwater resources is vital for achieving Sustainable Development Goals.



Locations of 28 MAR Schemes in Zheng, Y., Ross, A., Villholth, K and Dillon, P. (eds) (in press) Managing Aquifer Recharge: A Showcase for Resilience and Sustainability. UNESCO Publication



Part I

To what extent is MAR Infrastructure an economical & sustainable water resource system?

Sustainable water resource systems are those designed and managed to fully contribute to the objective of society, *now and in the future*, while maintaining their ecological, environmental, and hydrological integrity .

Source: Loucks and Gladwell (ed.) 1999. Sustainability Criteria for Water Resources Systems, UNESCO-IHP Series, Cambridge University Press, pp 137

Wanted: Outstanding examples of sustainable and economic managed aquifer recharge

UNESCO-IAH-GRIPP book on Managed Aquifer Recharge planned in 2018

Part II

Sustainability Indicator Development

Sustainability Index:

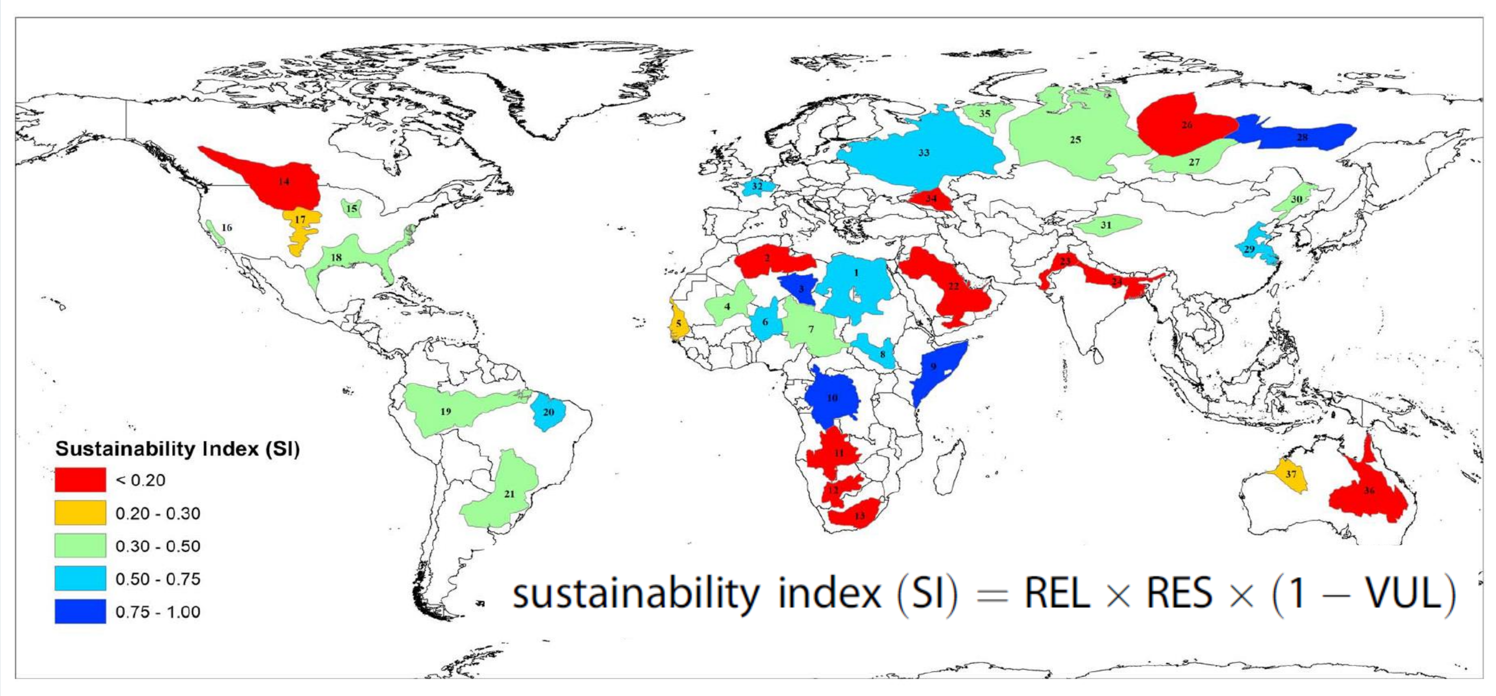
- Reliability
- Resilience
- Vulnerability

ENVISION by ASCE:

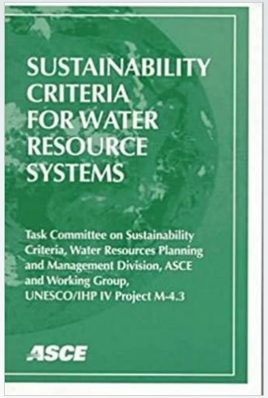
- Quality of Life
- Leadership
- Resource Allocation
- Natural World
- Climate and Risk

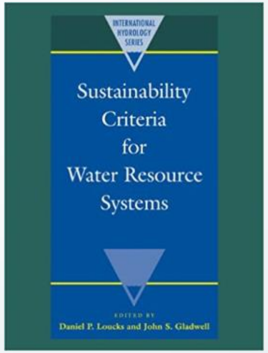
Methods to measure sustainability of water resource systems are inadequate.

Sustainability Index (SI) for the largest aquifers



Based on GRACE groundwater drought index (GGDI) 2002 - 2017





Source: Thomas et al. 2017. Global Assessment of Groundwater Sustainability Based on Storage Anomalies. *Geophys. Res. Lett.* 44:11,445-11,455.

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ENVISION: Twin Oaks Aquifer Storage and Recovery

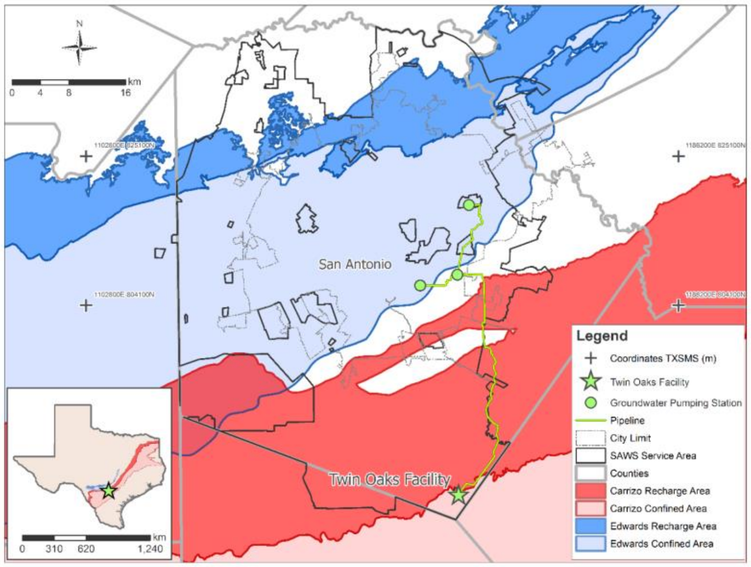
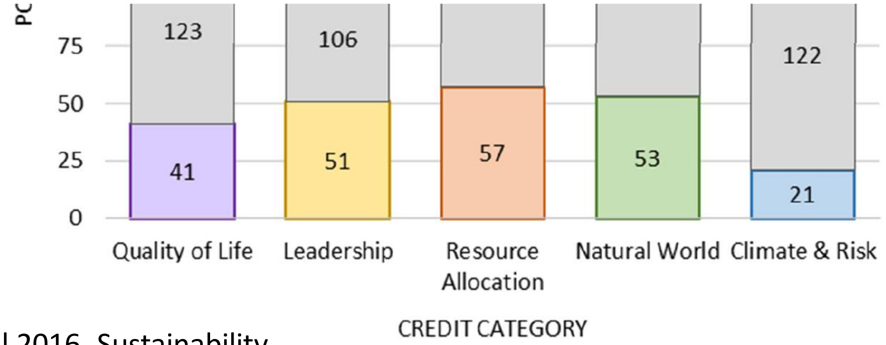


Figure 1. The Twin Oaks Facility in Bexar County, Texas. Data courtesy of SAWS, Texas Natural Resources Information System (TNRIS), Texas Parks and Wildlife Department (TPWD).

(1) Conflation of project purpose and project design
(2) No weighting of points based upon local needs
(3) Project-oriented focus omits systems scale
(4) Uneven weighting of three sustainability pillars
(5) Positive scoring overlooks negative aspects of projects



Saville et al 2016. Sustainability

Pump groundwater from the Edwards Aquifer and store it in the more stable Carrizo Aquifer for peak demand.

Conclusion: A water specific sustainability index is needed in conjunction with Envision.

Envision rates the sustainability of an infrastructure project based on 60 criteria, called credits, in five categories: Quality of Life, Leadership, Resource Allocation, Natural World, and Climate and Risk.

https://www.asce.org/envision/

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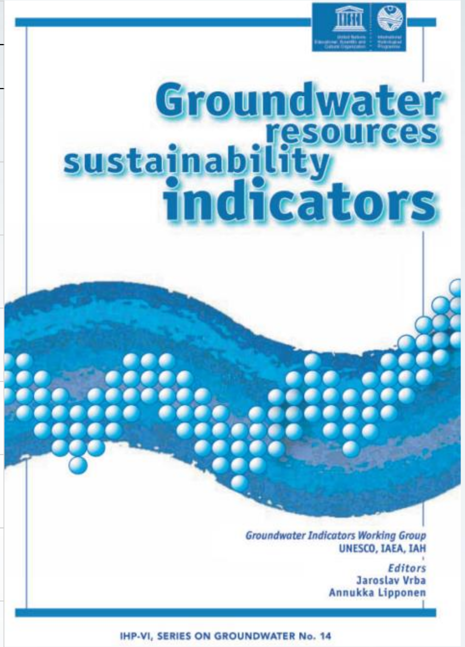
Groundwater Resources Sustainability Indicators

Table 1. Groundwater Resources Sustainability Indicators

Indicators	Category
Renewable groundwater resources per capita (m^3/year)	Env, Socio-Econon
Total groundwater abstraction/Groundwater recharge	Socio-Econ, Env
Total groundwater abstraction/Exploitable groundwater resources	Socio-Econ, Env
Groundwater as a percentage of total use of drinking water at national level	Health, Ecol
Groundwater depletion	Socio-Econ, Env, Ecol
Total exploitable non-renewable groundwater resources/Annual abstraction of non-renewable groundwater resources	Env, Socio-Econ
Groundwater vulnerability	Env, Socio-Econ
Groundwater quality	Ecol/Health， Socio-Econ， Env
Groundwater treatment requirements	Ecol/Health, Socio-Econ



To ensure resource integrity and security, groundwater quality and quantity both need protection.

Source: Vrba and Lipponen (ed.), UNESCO 2007

US EPA Sustainability Criteria

Part II

Sustainability Criteria Below are the three pillars of sustainability, each with six broad topics that relate to its respective pillar. A brief explanation and example are provided for each topic. The examples are not intended to be inclusive.

Environmental

Ecosystem Services
Protect, sustain, and restore the health of critical natural habitats and ecosystems
Example: Innovative nutrient management techniques (Green Infrastructure)

Green Engineering & Chemistry
Design chemical products and processes to: eliminate toxic hazards, reuse or recycle chemicals, and reduce total lifecycle costs.
Example: Lifecycle Assessments in molecular design

Air Quality
Attain and maintain air-quality standards and reduce the risk from toxic air pollutants
Example: Investigate potential greenhouse gas emissions reduction strategies

Water Quality
Reduce exposure to contaminants in water systems and infrastructure (including protecting source waters), optimizing aging systems, and next generation treatment technologies & approaches.
Example: Purpose driven water reuse and innovative treatment technologies

Stressors
Reduce effects by stressors (e.g. pollutants, greenhouse gas emissions, genetically modified organisms) to the ecosystem and vulnerable populations
Example: Fate of modified nanoparticles in aqueous media

Resource Integrity
Reduce adverse effects by minimizing waste generation to prevent accidental release and future cleanup.
Example: Innovative technologies and processes to prevent environmental impact

Social

Environmental Justice
Protect health of communities over-burdened by pollution by empowering them to take action to improve their health and environment
Example: Establish partnerships with local, state, tribal, and Federal organizations to achieve healthy and sustainable communities

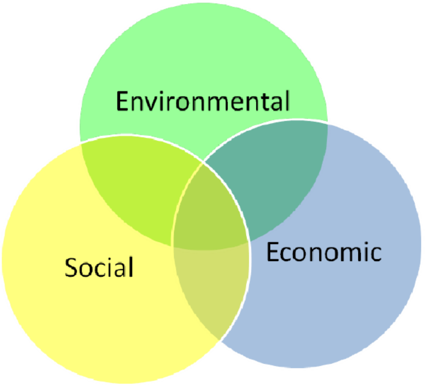
Human Health
Protect, sustain, and improve human health
Example: Parameterize model which predicts developmental toxicology

Participation
Use open and transparent processes that engage relevant stakeholders
Example: Develop database of reduced-risk pesticides for commonly used products, create greater public access and understanding about sustainability

Education
Enhance the education about sustainability of the general public, stakeholders, and potentially affected groups.
Example: Provide opportunities for students and communities to learn about sustainability

Resource Security
Protect, maintain, and restore access to basic resources (e.g. water, food, land, and energy) for current and future generations
Example: Study impact of dispersants/oil combination on natural waterways

Sustainable Communities
Promote the development, planning, building, or modification of communities to promote sustainable living
Example: Landscape with native plant species, green buildings



Economic

Jobs
Strengthen and maintain current and future jobs
Example: Promote jobs through introduction of innovative technologies and practices that provide multiple benefits to communities and the environment

Incentives
Promote incentives that work with human nature to encourage sustainable practices.
Example: Collaborative urban stormwater management approaches—Chesapeake Bay Partnership

Supply and Demand
Promote fully informed accounting and market practices to promote environmental health and social prosperity.
Example: Full lifecycle cost and benefit accounting techniques

Natural Resource Accounting
Improve understanding and quantification of ecosystem services in cost benefit analysis.
Example: Sustainability Assessments

Costs
Positively impact costs of processes, services, and products throughout the full lifecycle
Example: Strive to develop waste-free processes—eliminating need for regulation, treatment, and disposal costs throughout systems

Prices
Promote cost structures that reduce risk and premium for new technologies.
Example: Speed innovative technologies and approaches to the market

MAR sustainability indicators (from Zheng *et al* in press)

Part II

	Attribute	Indicator
ENVIRONMENTAL INDICATORS	Water quantity	1. Monitoring of groundwater table demonstrates acceptable changes over 10 years, or > 3 years with high likelihood of maintaining resource integrity 2. The ratio of volume of recovered water vs infiltrated water on an annual basis
	Water quality	3. Exceedance rate based on time-series monitoring of recovered or ambient water quality parameters 4. Exceedance rate based on time-series monitoring of source water quality parameters
	Ecosystem services	5. Changes in ecological flow (m/yr) and improvement in water quality in eco-system needing protection identified in a catchment water management plan
	Stressors	6. Energy requirements in KWh per cubic meter of recovered water, including monitoring and treating recovered water, solving clogging and low recovery efficiency issues
SOCIAL INDICATORS	Resource security	7. Clearly defined, transparent regulatory framework for MAR, preferably one that requires monitoring of resource integrity
	Human health	8. Permit granting process is based on sound risk assessment aimed to protect human health
	Community participation/ justice	9. Systematic Institutional arrangements for public and stakeholder consultation, preferably with regular publicly available reports of scheme outcomes

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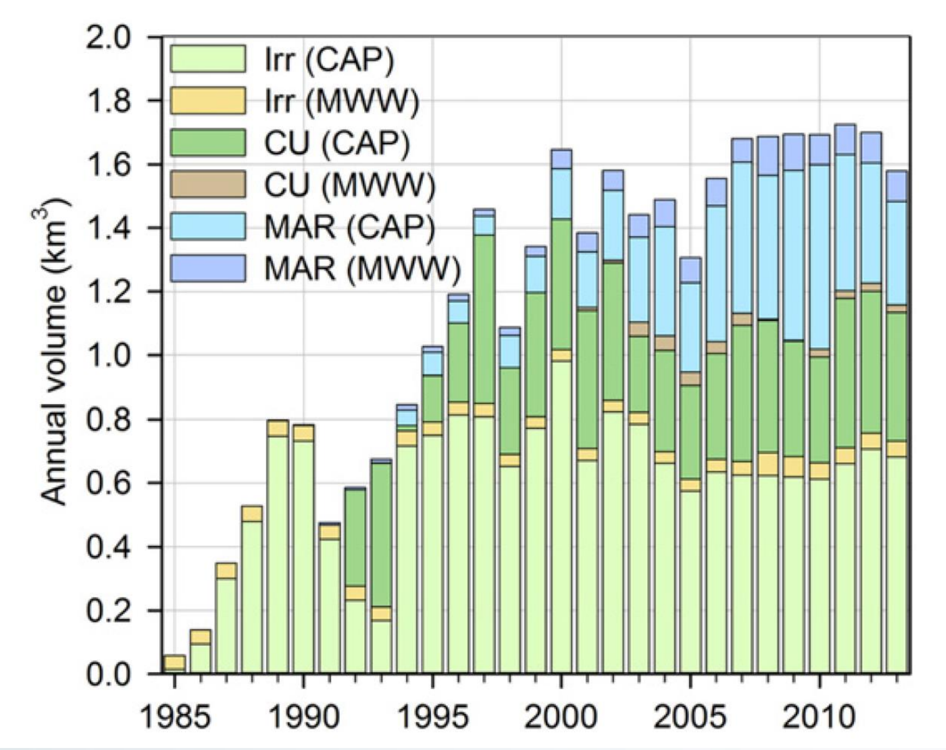
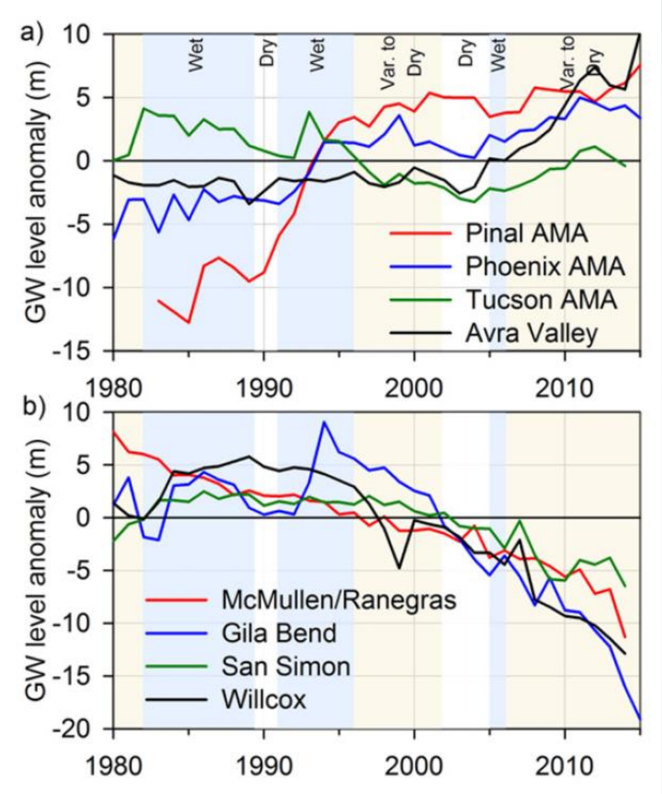
Indicator 1 - Resource Integrity
Monitoring of groundwater table demonstrates acceptable changes over 10 years





Scanlon et al. Enhancing drought resilience with conjunctive use and managed aquifer recharge in California and Arizona. ***Env Res Lett*** **11 (2016)035013**

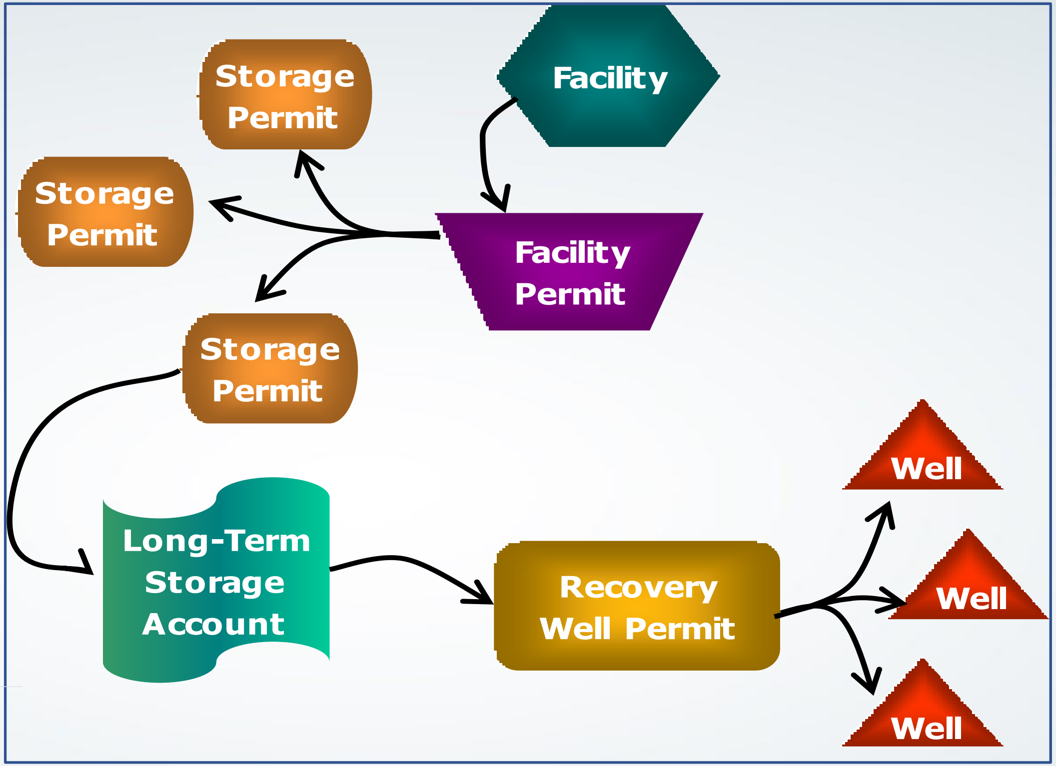
Arizona Showcase: Credits Crucial for Water Banking

Since the establishment of the **Arizona Water Banking Authority (AWBA)** in 1996, nearly 5,600 million cubic meter (MCM) of Colorado River water has been stored.

A flexible, mass-balance approach to MAR accounting:

- the future right to recover (i.e., pump) 95% of the volume that was stored;
- the ability to recover almost anywhere within the regional aquifer system;
- the ability of the recovered water to retain the legal character of the stored water.

After detailed calculation of losses, ADWR issues **Long-Term Storage Credits**



Seasholes, K. and Megdal, S. (2020) The Arizona Water Banking Authority: The Role of Institutions in Supporting Managed Aquifer Recharge. Case study 21 in Zheng et al (eds). Managing Aquifer Recharge: A Showcase for Resilience and Sustainability . UNESCO Publication, in press.

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Part III

Cost and Cost-Benefit Analysis

Levelised Cost in 2016 US$:

- the constant level of revenue necessary each year to recover all the capital, operating and maintenance expenses over the life of the project divided by the annual volume of water supply
- When recovery volumes unavailable or purpose not for recovery then annual recharge volume is used
- operating life = 30 years, discount rate = 5.0%, are used for most schemes

Benefit:

- Diverse benefits (water supply for cities and agriculture, reserve supply, water quality improvement)
- If the main benefit of a MAR scheme is additional water supply:

1) Volume of water recovered or supplied multiplied by the cost of supply;
2) Alternative cost of production (used for most schemes)

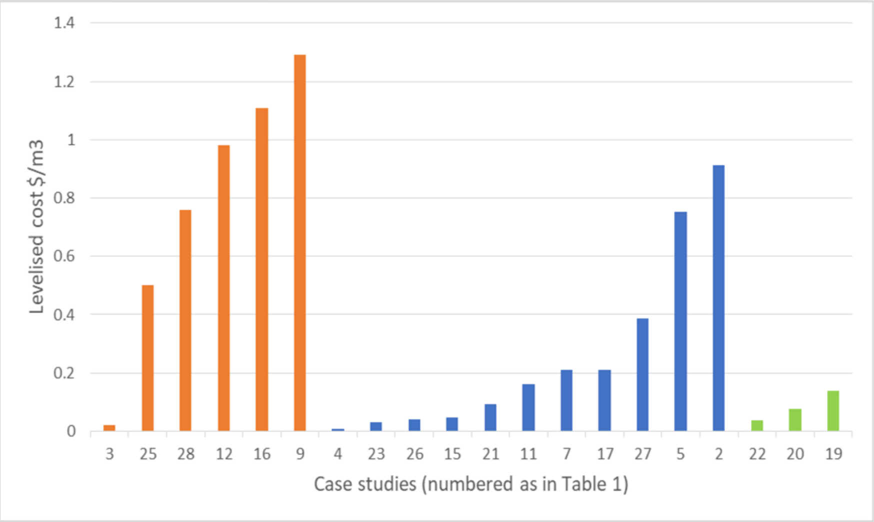
- Examples of other purposes:

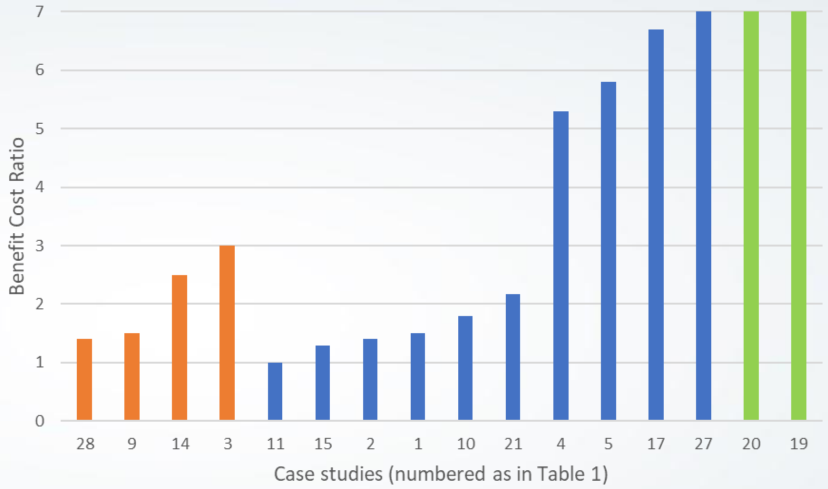
1) Net benefit from agricultural/industrial production
2) Costs of the next cheapest water treatment facility

Levelised costs (US$/m^3) Benefit : Cost ratios

Part III

Volume weighted							
Mean:	0.75	0.16	0.10	BCR	2.19	2.16	7
No of schemes:	6	11	3		4	10	2





recycled water schemes natural water schemes riverbank filtration schemes

Generally, MAR schemes achieved the same purpose at less than half the cost of alternatives.

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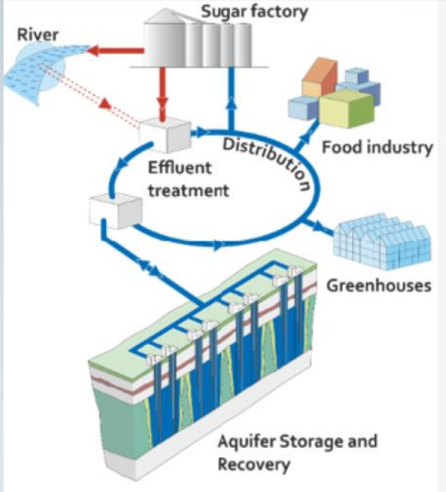


Part IV

Lessons Learned and Implications

MAR Technique:

ASR Aquifer-Storage= Recovery

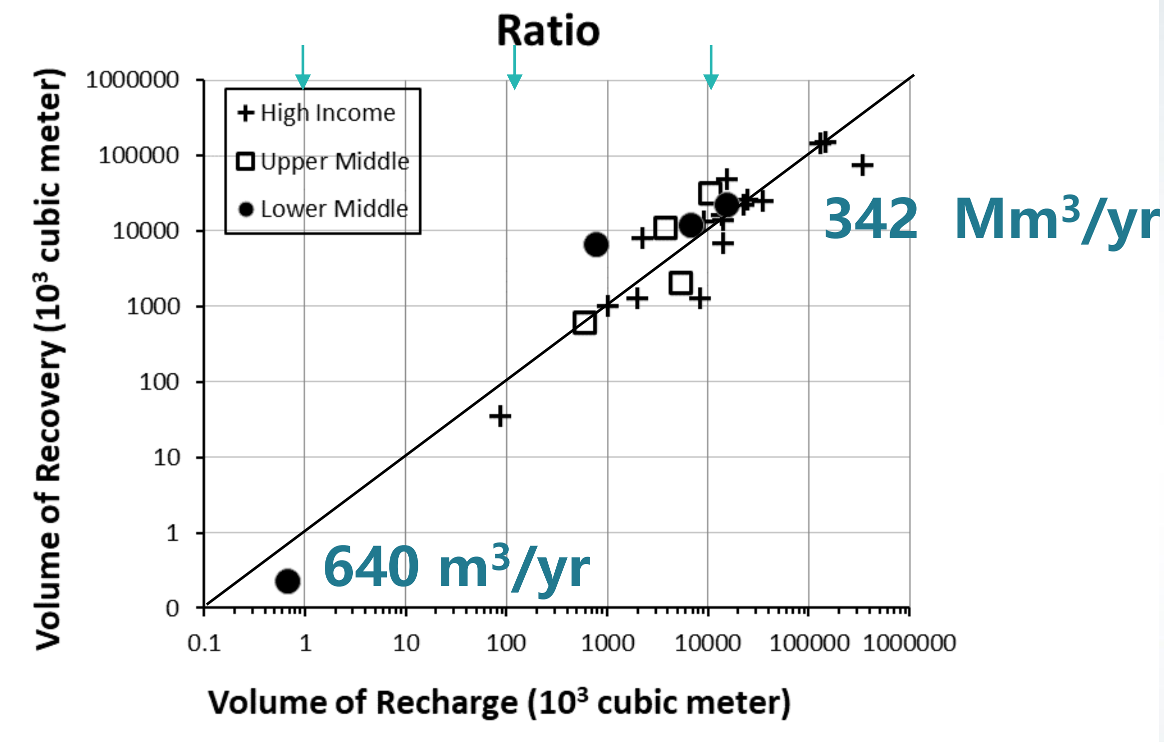
28. Zuurbier et al., Dinteloord, the Netherlands

1. Ahmed et al., Kulna, Bangladesh

Annual Recharge Volume

Part IV

Micro:<10^3 Small: 10^3 - 10^5 Medium:10^5 - 10^7 Large:> 10^7 (m^3/yr)



$V_{recovered}/V_{recharged}$ (n=26)

- Range: 0.0-8.3
- Mean: 1.4 ± 1.7

Induced Bank Filtration (n=3):

- 1.1, 1.2, 1.4

$V_{recovered}/V_{recharged}$>2 (n=5)

- **London UK for drought: 3.2**
- **Sergovia Spain for drought: 3.6**
- **Sonora Mexico for irrigation: 3.0**
- **Windhoek Namibia for drought: 2.9**
- **Rajasthan India for drought: 8.3**

Indicator 2. Resource Integrity – Water Quantity
The ratio of volume of recovered water vs infiltrated water on an annual basis

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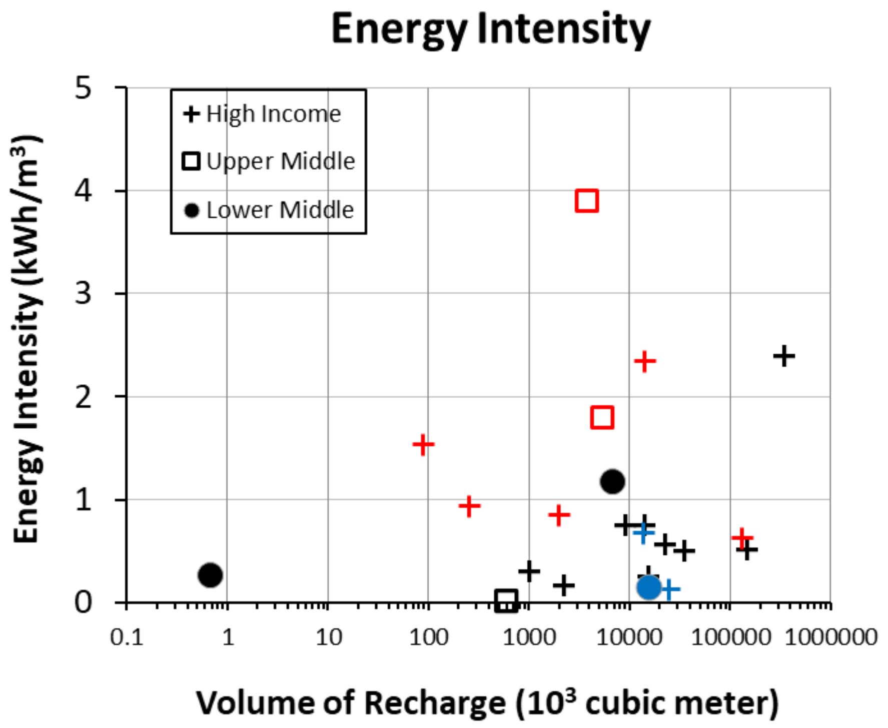
Consider and track energy intensity in design and implementation



Energy Intensity (n=23) kWh/m^3

- Range: 0.02-3.9
- Mean: 0.9 ± 0.9

Induced Bank Filtration (n=4)

- 0.13, 0.68, 0.30, 0.16

Effluent as Source Water (n=7)

- 1.7 ± 1.1

Indicator 6 - Stressor.
Energy requirements in KWh per cubic meter of recovered water, including monitoring and treating recovered water, solving clogging and low recovery efficiency issues

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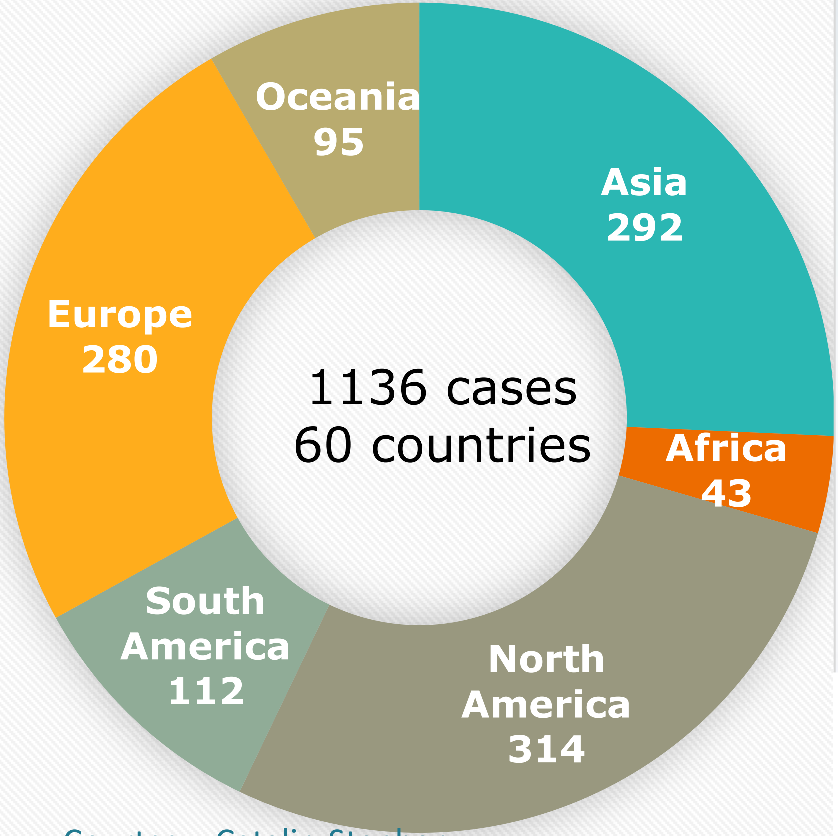
Global MAR Inventory



Courtesy: Catalin Stephan

Quantity (km^3/yr)

	Groundwater Use in 2010	MAR Quantity in 2015	%MAR of GW Use
Global	982	9.9	1.0%
USA	112	2.5	2.3%
Australia	4.96	0.41	8.3%
China	112	0.106	0.1%
India (5 states)	39.8	3.07	7.7%
Denmark	0.65	0.00025	0.0004%
Finland	0.28	0.065	23.2%

Sixty years of global progress in managed aquifer recharge

Hydrogeology Journal (2019) 27:1–30

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J. P. Bonilla Valverde[27] • A. Palma Nava[28] • N. Ansems[29] • K. Posavec[30] • K. Ha[31] • R. Martin[32] • M. Sapiano[33]

Lessons Learned and Implications

1. This documentation of evolution of **exemplary schemes**, together with the applied **toolkit of sustainability assessment and economic analysis** are rich resources for water managers considering MAR and for stakeholders of MAR projects to enhance climate resilience and other social, economic and environmental benefits of their projects.

2. Schemes from higher income countries received **better sustainability ratings primarily due to supportive regulatory systems.** Strengthening institutional capacity for regulatory frameworks for water allocation, permit granting and water quality protection are especially relevant for developing countries and localities challenged by climate change.

3. Water **quality and quantity** challenges both need to be addressed to maintain resource integrity. **Ecological flow/**ecosystem and social objectives are often secondary to other objectives and deserve more attention by MAR promoters. **Energy intensity** while important is often poorly tracked. **Community engagement** also warrants greater attention.

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- Authors of 28 case studies
- Organizations that initiated and operated these MAR schemes
- UNESCO-IHP, IAH-MAR Commission, GRIPP
- DANIDA Fellowship MAR-in-China

Acknowledgement

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BSMAR 17: Resilience through Recharge and Recovery

2020.10.07 1:30 – 2:00 PM Water Resources Management Session

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Part I

Table of Contents

Managing Aquifer Recharge: A Showcase for Resilience and Sustainability

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Do the Indicators work?

Table 2. Levels of Achievement in Envision with Modification for Sustainability Rating of Cases in this Study

ASCE Envision [2] 60 sustainability criteria in 5 categories			This Study 9 sustainability indicators in 5 categories of USEPA		
Level (+)	Performance Definition	Points for Rating*	Level (-)	Performance Definition	Points for Rating
No added value	comparable to conventional	0			
Improved	is at or above conventional	1	Degraded	is below conventional alternative	-1
Enhanced	Indications that superior performance is within reach	2	Diminished	Indications that there are risks for inferior performance	-2
Superior	noteworthy	3	Inferior	obvious poor performance	-3
Conserving	has achieved essentially zero impact	4	Harming	harmful impact in one aspect	-4
Restorative	restores natural or social system	5	Debilitating	harmful impact in all aspects	-5

*In Envision, the points possible is variable for each criterion, for example, "conserving" for "Protect fresh water availability" under category Resource Allocation (total points possible is 182) can earn up to 21 points

To simplify, this study assigns positive or negative points at a step value of 1

Part II

Higher Income -> Higher Sustainability Rating

Table 5. Sustainability Rating of MAR Cases

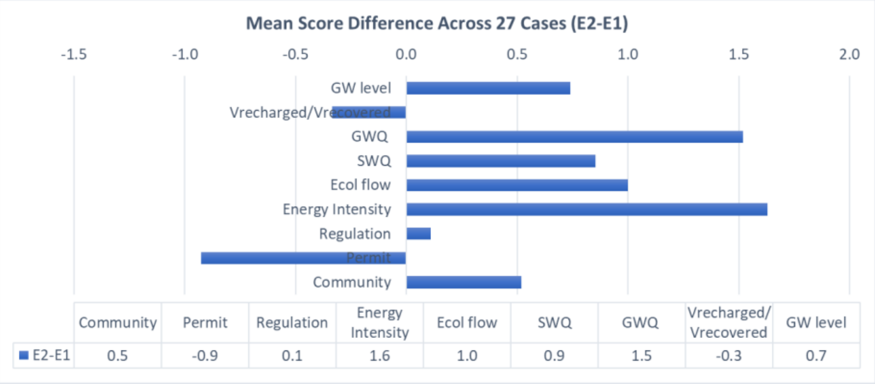
Country	Location	Rating by Two Experts	Indicator[1]: Expert Mean [2]	1 GW level	2 $V_{recharged}$/ $V_{recovered}$	3 GWQ	4 SWQ	5 Ecol flow	6 Kwh/m^3	7 Regu-lation	8 Per-mit	9 Commu nity
High Income: > 12,375				S E1 E2	S E1 E2	S E1 E2	S E1 E2	S E1 E2	S E1 E2	S E1 E2	S E1 E2	S E1 E2
Mean High Income (n=17)			***1.9***	***2.5***	***2.4***	***1.2***	***0.5***	***1.1***	***1.0***	***3.0***	***2.6***	***2.4***
Upper Middle: 3,996 - 12,375												
Mean Upper Middle (n=4)			***1.3***	***2.1***	***2.3***	***-0.1***	***-0.3***	***1.3***	***1.0***	***2.1***	***2.1***	***1.0***
Lower Middle: 1,026 - 3,995												
Mean Lower Middle (n=7)			***0.7***	***0.8***	***1.7***	***0.3***	***0.4***	***-0.2***	***1.3***	***0.4***	***0.6***	***1.5***
Min				0.0	0.0	-3.0	-1.0	-3.0	-3.0	-1.0	0.0	0.0
Max				5.0	5.0	5.0	4.0	5.0	4.0	5.0	5.0	5.0
Mean of all schemes				**2.1**	**2.2**	**0.8**	**0.4**	**0.8**	**1.1**	**2.3**	**2.1**	**2.0**

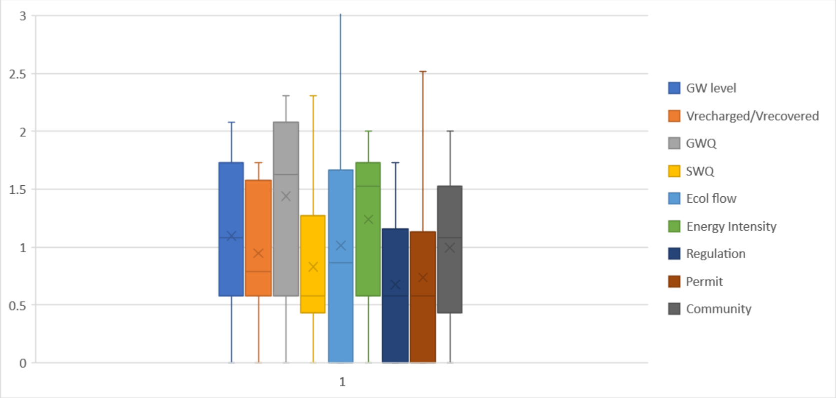
Rating

2: Enhanced

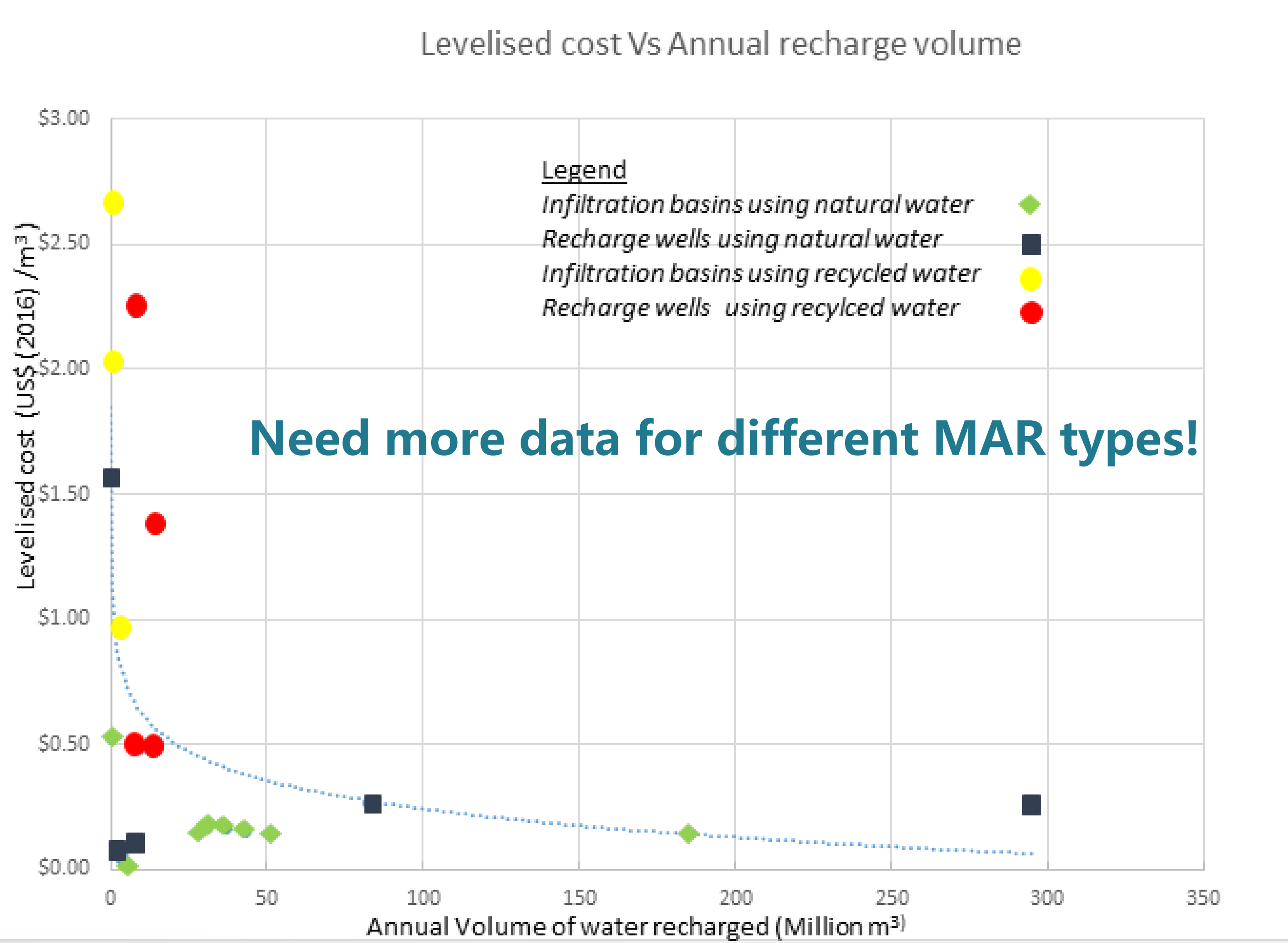
1: Improved

0: No Value Added





Part III



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10 Environmental Sustainability Indicators for MAR

A. Resource Integrity

A.1 Water Quantity

1. Monitoring of groundwater table demonstrates acceptable changes over 10 years, or > 3 years with high likelihood of maintaining resource integrity
2. The ratio of volume of infiltrated water vs recovered water on an annual basis
3. For large schemes, change in renewable groundwater resources in target aquifer per capita (m^3/year per capita)

A.2 Water Quality

4. Exceedance rate based on time-series monitoring of recovered or ambient water quality parameters
5. Exceedance rate based on time-series monitoring of source water quality parameters
6. For large MAR schemes, percentage use as drinking water sourced from target aquifer

B. Ecosystem Services

7. Change in ecological flow (m^3/yr) in ecosystems needing protection identified in a catchment water management plan
8. Change in peak flow (m^3/s) for MAR intended for flooding control

C. Stressors

9. Energy requirements to monitor and treat recovered water, solve clogging and low recovery efficiency issues are not excessive
10. No unacceptable seepage, waterlogging, discharge occurs

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4 Social Sustainability Indicators for MAR

D. Resource Security/Human Health

11. Clearly defined, transparent regulatory framework for MAR, preferably one that requires monitoring of resource integrity
12. Permit granting process is based on sound risk assessment aimed to protect human health
13. Assists resilience to adverse impacts of climate change

E. Sustainable Community/Participation/Education/Environmental Justice

14. Systematic Institutional arrangements for public and stakeholder consultation, preferably with regular publicly available reports of scheme outcomes

Please provide your feedback on the 14 indicators proposed for MAR

score with the following scale:

Do not include 0

OK to include 4

Good to include 7

Must include 10

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