The 21st Century Water Quality Challenges for Managed Aquifer Recharge: Towards a Risk-Based Regulatory Approach

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IAH-MAR Commission Webinar 2025.02.11

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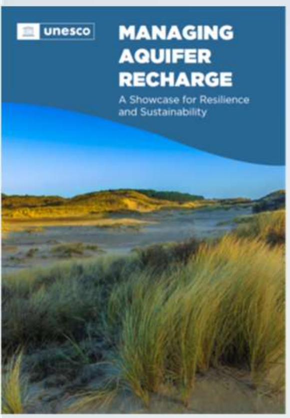
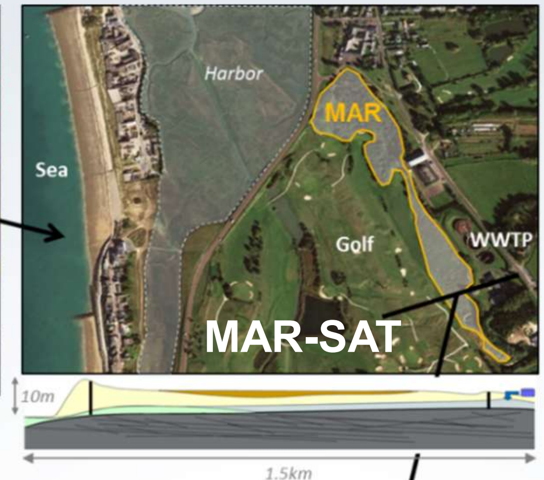
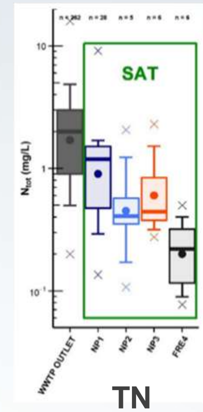
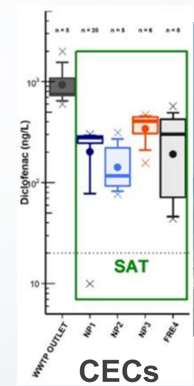
Successful Reclaimed Water MAR-SAT



Normandy, France







Purpose: Environmental ; Treated Waste Water Recharged: 500 – 5000 m^3 per day

Picot-Colbeaux et al. (2021). Case Study 17: Sustainable coastal MAR-SAT system in Agon-Coutainville, Normandy, France in Zheng et al (eds). Managing Aquifer Recharge: A Showcase for Resilience and Sustainability, UNESCO, Paris.

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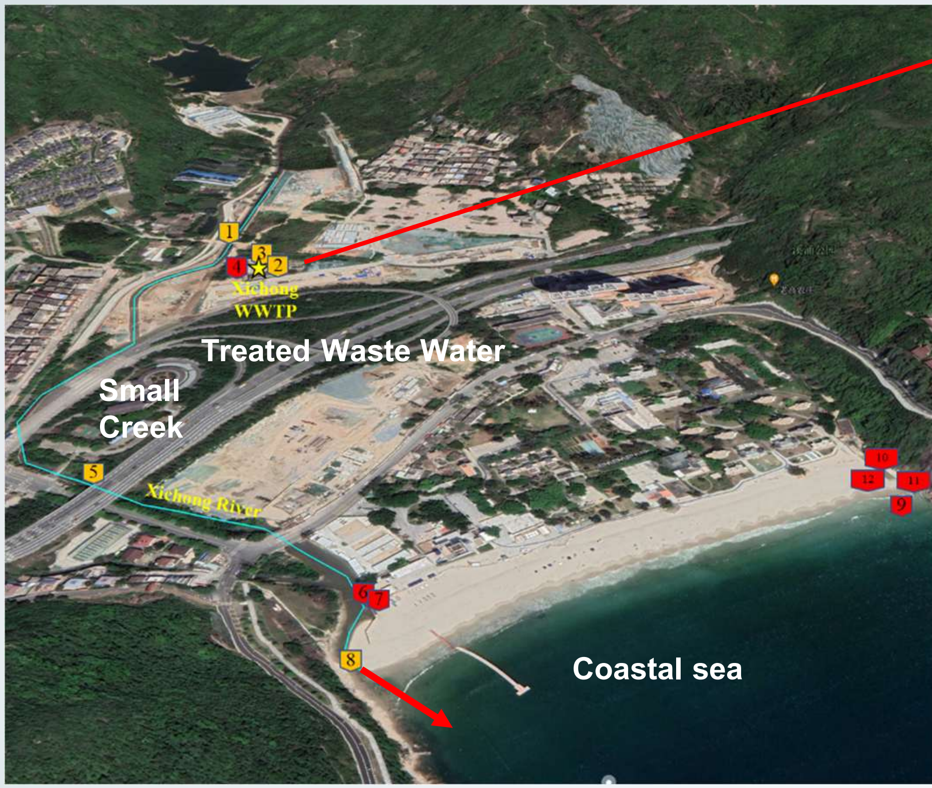
Ongoing studies to assess water quality risks for MAR



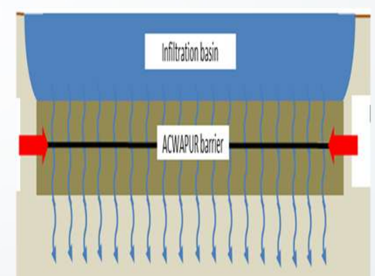
WWTP: Secondary

Shenzhen Coast

MAR:

Wetland + SAT

+ in-channel PRB



Under utilization of natural treatment ability and storage capacity of coastal brackish aquifer

Ph.D. student & post-doctoral scholar positions available to work on any aspect of water quality and health issues across the land-ocean continuum & MAR

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Outline

Incidental/Un-Managed Recharge Can Pollute Groundwater in Farms and Cities

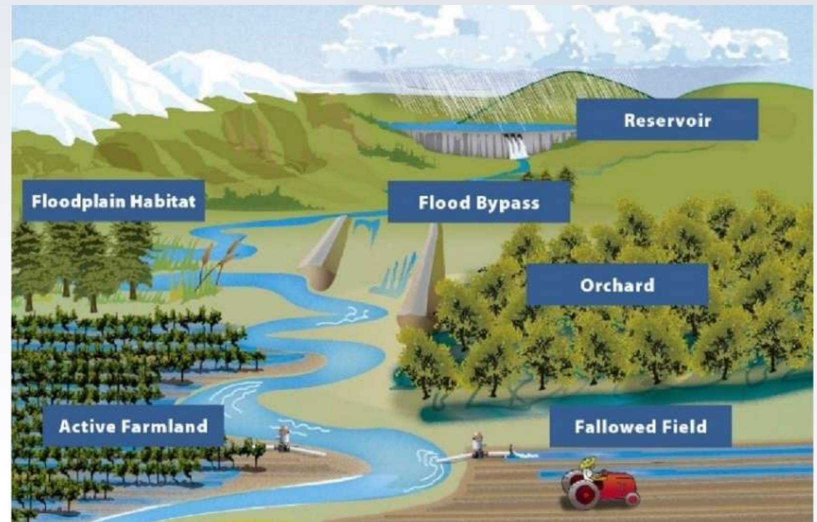
I. **2021 Groundwater Management Regulations of China (GWMRC)**

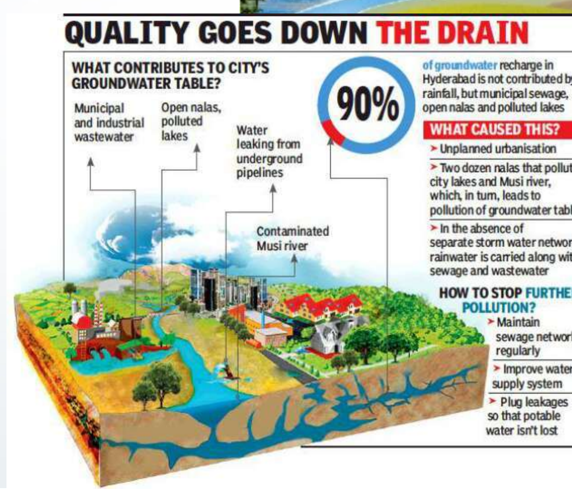
II. **Prerequisites:**

Amend GWMRC

A risk-based regulatory approach

III. **MAR to MARs**





Managed aquifer recharge **and storage** (MARs), also called groundwater replenishment, water banking and artificial recharge, is the ***purposeful*** recharge of water to aquifers with **storage time optimized** for **subsequent recovery or environmental benefit**.

Part I: GWMRC

Groundwater Management Regulations of China
published by State Council 9th Nov 2021

GWMRC地下水管理条例

10 chapters 63 articles (6 articles relevant to MAR)

Part I

第一章 总则 Chapter 1 General Principles

第四条Article 4 国务院水行政Ministry of Water Resources (MWR)主管部门负责全国地下水统一监督管理工作。国务院生态环境Ministry of Ecology and Environment (MEE) 主管部门负责全国地下水污染防治监督管理工作。国务院自然资源Ministry of Natural Resources (MNR) 等主管部门按照职责分工做好地下水调查、监测等相关工作。

第二章 调查与规划 Chapter 2 Survey and Planning

第十条Article 10 国家定期组织开展**地下水状况调查评价**工作**Conduct groundwater survey and assessment periodically**。地下水状况调查评价包括地下水资源调查评价、地下水污染调查评价和水文地质勘查评价等内容。

第十五条Article 15 国家建立**地下水储备制度Establish groundwater reserve management system**。国务院水行政主管部门应当会同国务院自然资源、发展改革等主管部门，对地下水储备工作进行指导、协调和监督检查。

http://www.gov.cn/zhengce/content/2021-11/09/content_5649924.htm

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GWMRC地下水管理条例

第三章 节约与保护 Chapter 3 Conservation & Protection

第二十八条Article 28 县级以上地方人民政府local government above county level应当加强地下水水源补给保护，充分利用自然条件补充地下水Increase groundwater recharge through better use of nature， 有效涵养地下水水源 。

城乡建设应当统筹地下水水源涵养和回补需要，按照海绵城市sponge city建设的要求，推广海绵型建筑、道路、广场、公园、绿地等，逐步完善滞渗蓄排等相结合的雨洪水收集利用系统storm water collection and utilization。 河流、湖泊整治应当兼顾地下水水源涵养river and lake restoration should consider protecting groundwater supply， 加强水体自然形态保护和修复。

城市人民政府local city government应当因地制宜采取有效措施，推广节水型生活用水器具，鼓励使用再生水encourage use of reclaimed water， 提高用水效率。

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GWMRC地下水管理条例

第四章　超采治理 Chapter 4 Mitigation of Groundwater Overextraction

第三十七条Article 37　　地下水超采区的县级以上地方人民政府应当加强节水型社会建设，通过加大海绵城市建设力度、调整种植结构、推广节水农业、加强工业节水、**实施河湖地下水回补等措施，逐步实现地下水采补平衡Implement river and lake based groundwater recharge to reach a balanced state of groundwater extraction over time**。

国家在替代水源供给、公共供水管网建设、产业结构调整等方面，加大对地下水超采区地方人民政府的支持力度。

第六十三条　本条例下列用语含义是：

地下水取水工程groundwater extraction project，是指地下水取水井及其配套设施，包括水井、集水廊道、集水池、渗渠、注水井以及需要取水的地热能开发利用项目的取水井和回灌井recharge wells for geothermal energy utilization等。

GWMRC地下水管理条例

第五章　污染防治Chapter 5. Pollution Prevention

第四十三条Article 43　　多层含水层开采、回灌地下水应当防止串层污染Artificial recharge of groundwater shall prevent cross-contamination between aquifers.

多层地下水的含水层水质差异大的，应当分层开采；对已受污染的潜水和承压水，不得混合开采。
已经造成地下水串层污染的，应当按照封填井技术要求限期回填串层开采井，并对造成的地下水污染进行治理和修复。

人工回灌补给地下水，应当符合相关的水质标准，不得使地下水水质恶化。

Artificial recharge of groundwater shall comply with the relevant water quality standards and shall never deteriorate groundwater quality.

http://www.gov.cn/zhengce/content/2021-11/09/content_5649924.htm

Part I

Recommended GWMRC Amendment

Change Chapter 4 Mitigation of Groundwater Overextraction to:

Chapter 4. Integrated Surface and Ground Water Management

第三十七条Article 37 地下水超采区的县级以上地方人民政府应当加强节水型社会建设，通过加大海绵城市建设力度、调整种植结构、推广节水农业、加强工业节水、~~实施河湖地下水回补等措施，逐步实现地下水采补平衡~~~~Implement river and lake based groundwater recharge~~ Implement managed aquifer recharge and storage to reach a balanced state of groundwater extraction over time。

~~人工回灌补给地下水，应当符合相关的水质标准，不得使地下水水质恶化。~~
~~Artificial recharge of groundwater shall comply with the relevant water quality standards and shall never deteriorate groundwater quality.~~

Establish a risk-based regulatory framework to protect the integrity of target aquifer receiving enhanced recharge. The framework is consisted of regulations, technical guidelines and standards for managed aquifer recharge and storage for each source water type.

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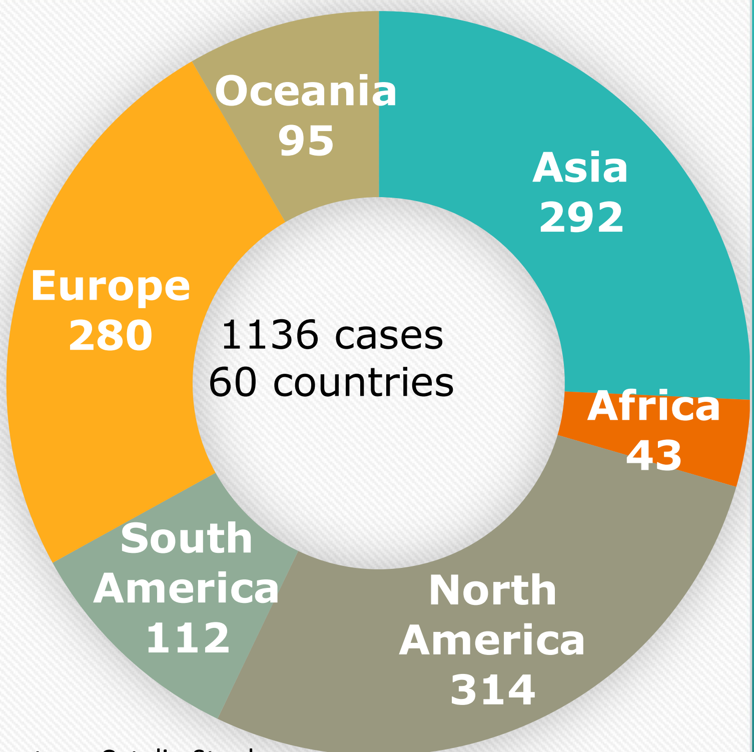
Global MAR Inventory



Courtesy: Catalin Stephan

https://recharge.iah.org/

Quantity (km³/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

P. Dillon[1,2] • P. Stuyfzand[3,4] • T. Grischek[5] • M. Lluria[6] • R. D. G. Pyne[7] • R. C. Jain[8] • J. Bear[9] • J. Schwarz[10] • W. Wang[11] • E. Fernandez[12] • C. Stefan[13] • M. Pettenati[14] • J. van der Gun[15] • C. Sprenger[16] • G. Massmann[17] • B. R. Scanlon[18] • J. Xanke[19] • P. Jokela[20] • Y. Zheng[21] • R. Rossetto[22] • M. Shamrukh[23] • P. Pavelic[24] • E. Murray[25] • A. Ross[26] • J. P. Bonilla Valverde[27] • A. Palma Nava[28] • N. Ansems[29] • K. Posavec[30] • K. Ha[31] • R. Martin[32] • M. Sapiano[33]

Why is MAR not yet an integral part of water resources management in China?

Perception of Risks

Too many unknown risks, therefore not worth taking them
Fear of using MAR to dispose of waste water
Groundwater storage is invisible

Scientific Understanding of Risks and Benefits

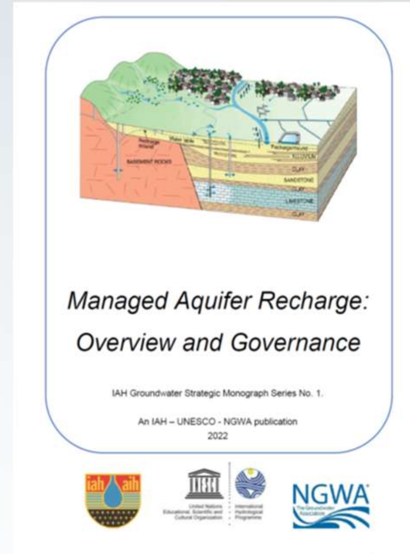
Not many investigations (n<100)
Local government implemented projects without research

Engineering Know-How

Mostly surface methods: In-channel, spreading, and induced bank infiltration
Limited role of private sector

Guidelines/Regulations/Standards

Neither national nor local government guidelines unlike Australia
Neither national nor local government regulations unlike Arizona



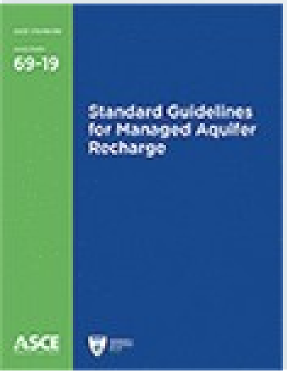
Zheng, Y., P. Dillon, W. Wang, and F. Zheng. 2016. China Needs Managed Aquifer Recharge, China Water Risks. https://chinawaterrisk.org/opinions/china-needs-managed-aquifer-recharge/

Dillon, P., W. Alley, Y. Zheng, and J. Vanderzalm (editors), 2022. Managed Aquifer Recharge: Overview and Governance. IAH Special Publication. https://recharge.iah.org/ ISBN 978-1-3999-2814-4

Part II: Prerequisites

Amend GWMRC

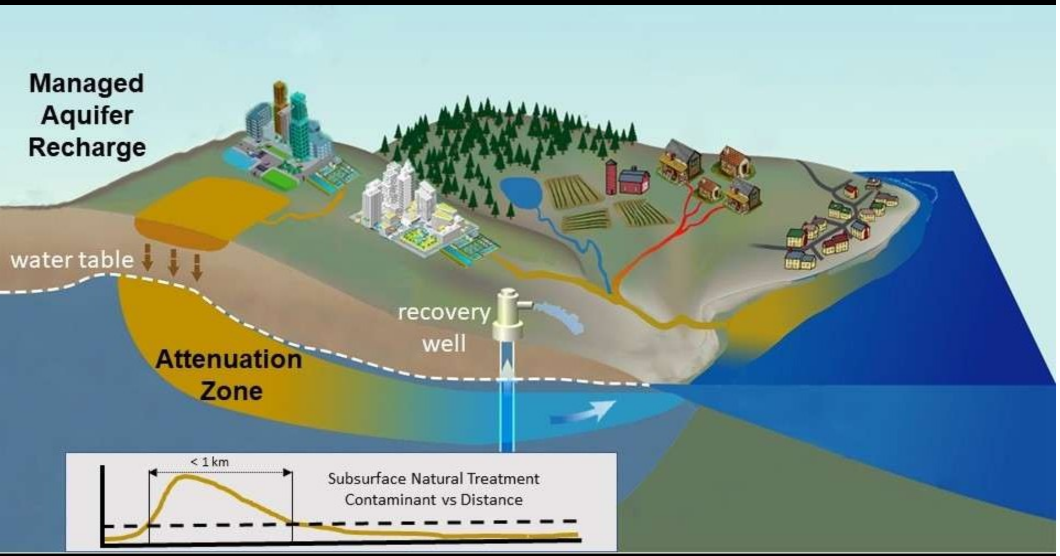
Adopt a risk-based regulatory framework



Towards a Risk-Based Regulatory Approach

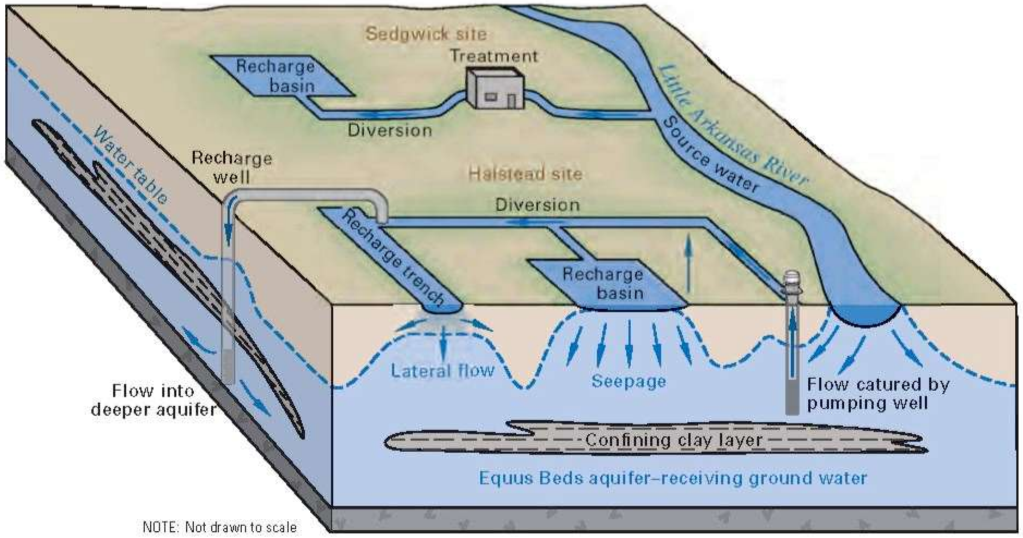
- Challenges in Governance:

water rights and water quality risks



Y Zheng, J Vanderzalm, N Hartog, EF Escalante, C Stefan (2023) The 21st Century Water Quality Challenges for Managed Aquifer Recharge: Towards a Risk-Based Regulatory Approach. Hydrogeol J. 31 (1), 31-34

Water Resource Infrastructure



Surface:

- *Recharge Basin/Ditch/Pond*
- *Soil Aquifer Treatment (SAT)*
- *River Bank Filtration (RBF)*
- *In-Channel Modification*

Sub-surface:

- *Recharge Well*
- *Aquifer Storage Recovery (ASR)*

Source Water:

- *Natural & Drinking Water*
- *Storm & Flood Water*
- *Recycled Water & Blends*

Recommendations

- ✓ MAR regulations should be part of water recycling and reuse regulations; but managing risks of reclaimed water dominant rivers in urban areas is challenging.
- ✓ A risk-based approach over a prescriptive parametric approach.
- ✓ Committee drafting the regulations should have expertise including but not limited to water resources management, waste water treatment, urban planning, agriculture, groundwater, ecology and health.

A communitarian ethic grounded in the precautionary principle.

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21st Century Water Quality Challenges

Novel chemical and biological entities ➡ unsafe operating space?

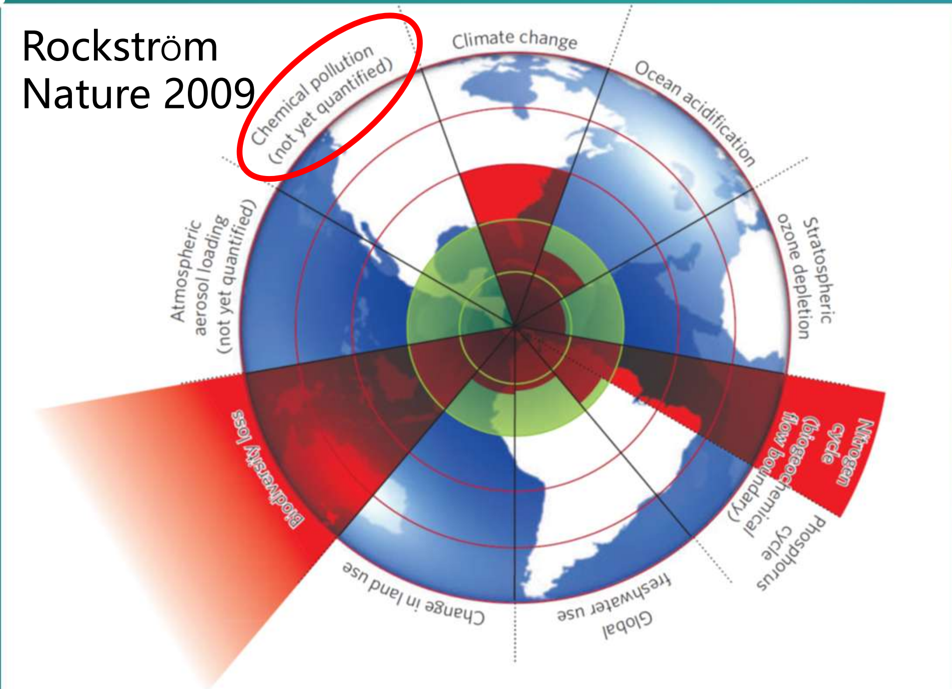
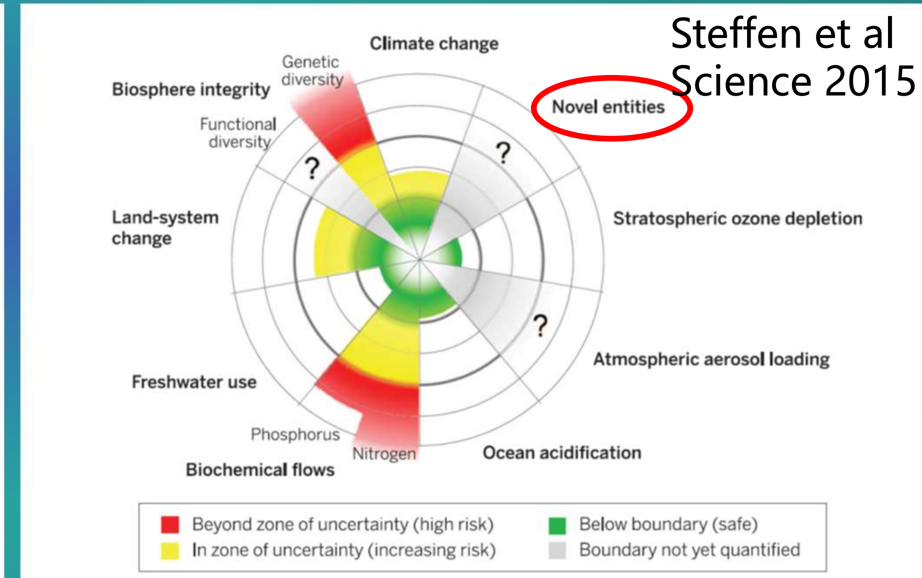


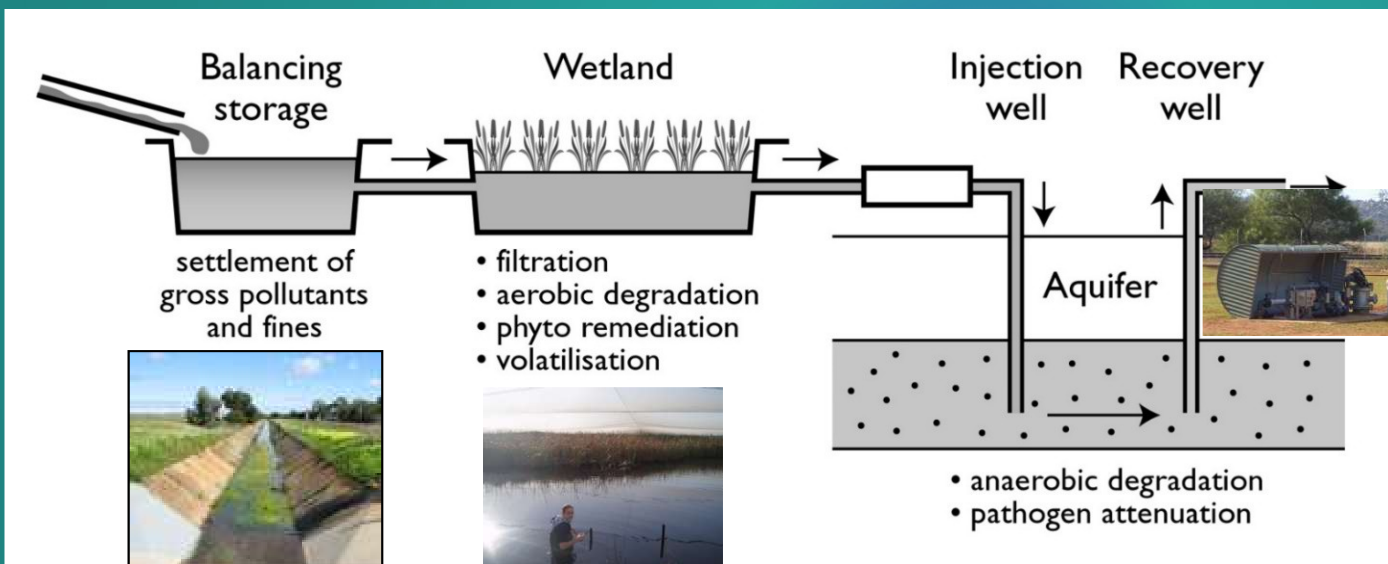
Figure 1 | Beyond the boundary. The inner green shading represents the proposed safe operating space for nine planetary systems. The red wedges represent an estimate of the current position for each variable. The boundaries in three systems (rate of biodiversity loss, climate change and human interference with the nitrogen cycle), have already been exceeded.

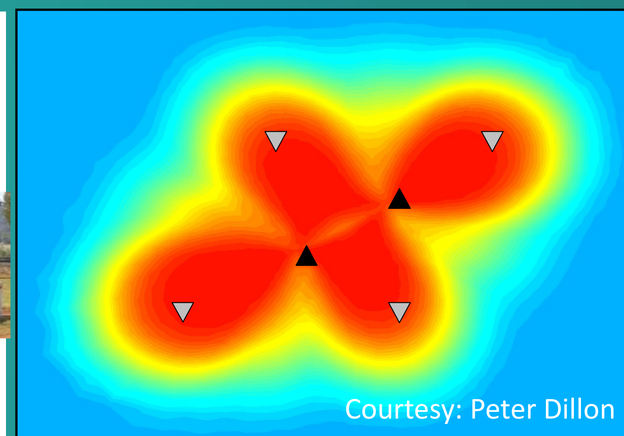


Current status of the control variables for seven of the planetary boundaries. The green zone is the safe operating space, the yellow represents the zone of uncertainty (increasing risk), and the red is a high-risk zone. The planetary boundary itself lies at the intersection of the green and yellow zones. The control variables have been normalized for the zone of uncertainty; the center of the figure therefore does not represent values of 0 for the control variables. The control variable shown for climate change is atmospheric CO_2 concentration. Processes for which global-level boundaries cannot yet be quantified are represented by gray wedges; these are atmospheric aerosol loading, novel entities, and the functional role of biosphere integrity.

21st Century Water Quality Challenges

~ 350,000 chemicals, ~80,000 in frequent use, >80% with uncertain or unknown toxicity





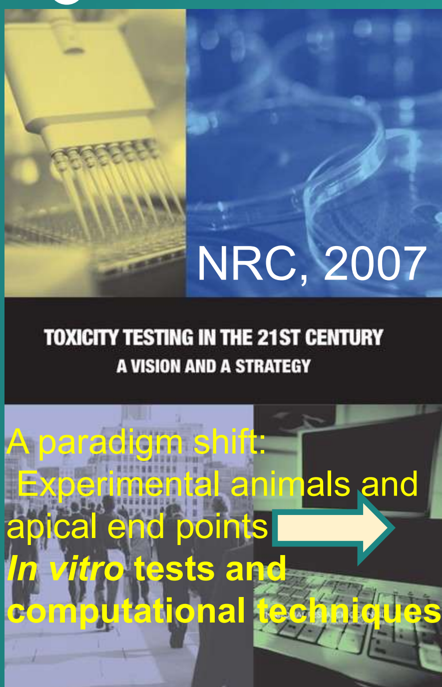
MAR regulates hydraulic retention time (storage time):
log reduction of virus, biodegradation of trace organic contaminants, etc

Page et al (2010) Wat Res

Ma, M. et al (2019) EST; Ma, Y. et al (2010) Wat Res (2021)

21st Century Water Quality Challenges

Mismatch in goals and scales of toxicology based environmental health risk assessment and systems approach based risk assessment



Validity of Toxicity Assessment: Metabolism

in vitro tests problems:

(a) modeling **human metabolism**

(b) maintaining tissue-specific function *in vitro*

(c) selecting an appropriate **xenobiotic** metabolizing system

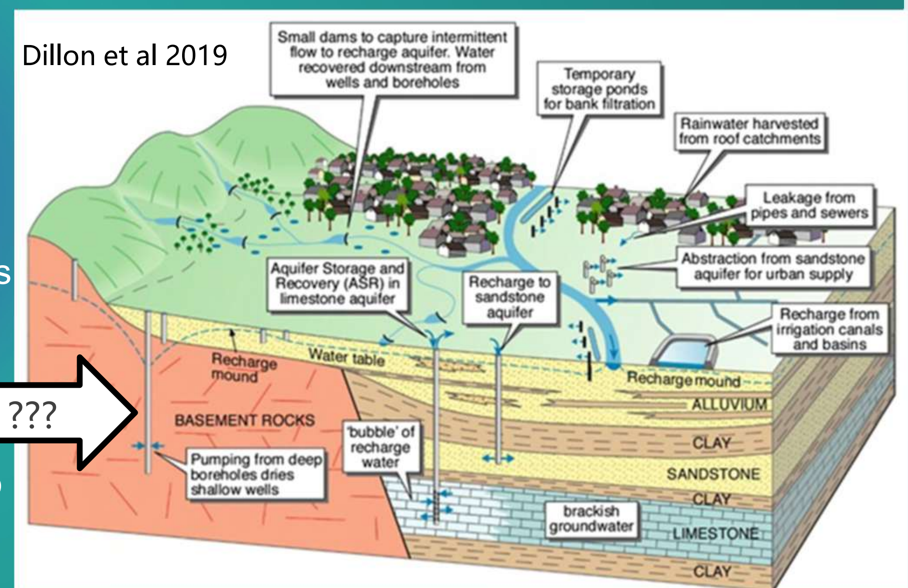
(d) keeping enzyme activity stable over time

(e) the adverse effects to toxicity-indicator cells of subcellular metabolizing fractions

(f) the testing of **mixtures** of chemicals that might require different enzyme systems

(g) the inactivation of exogenous biotransformation systems, due to exposure to certain solvents and test substance

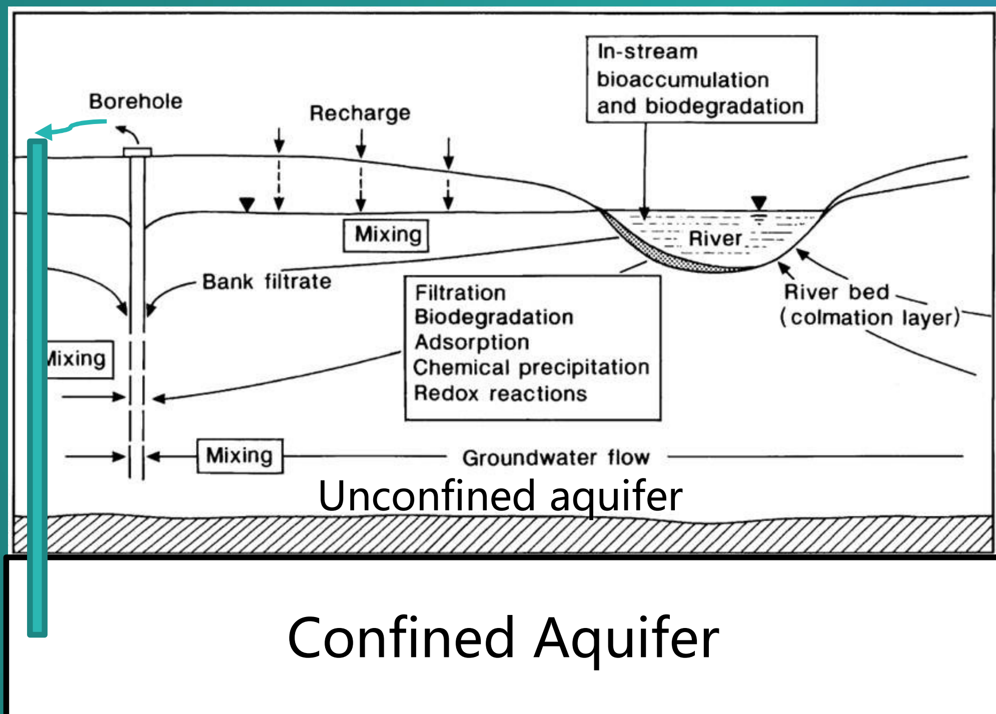
???



Priority: Human health>aquatic organisms>microbes>groundwater>soil?

21st Century Water Quality Challenges

Uncertain human and ecosystem health risks from novel entities



https://www.mar-china.geus.dk/

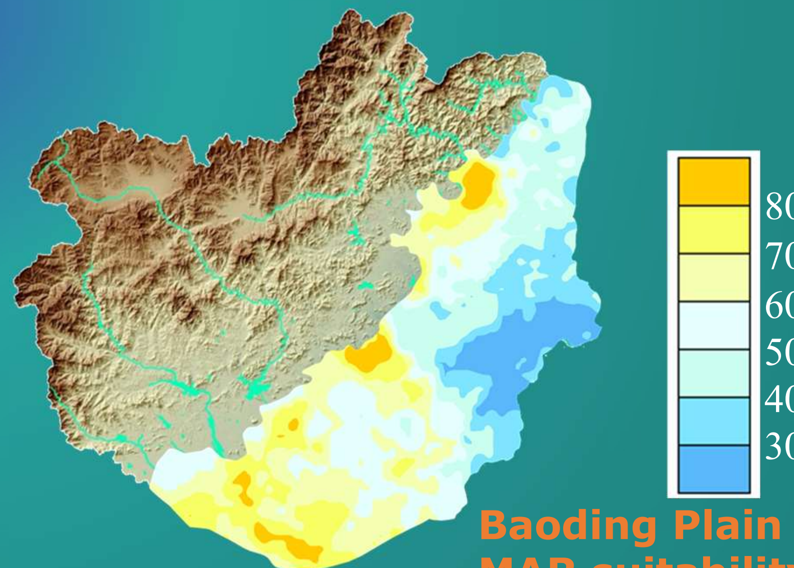
SMART

Hellauer et al (2018) J Hydrol

Redox manipulation; Berlin Germany

Sequential MAR Technology

Surface -> unconfined -> confined



Baoding Plain
MAR suitability index

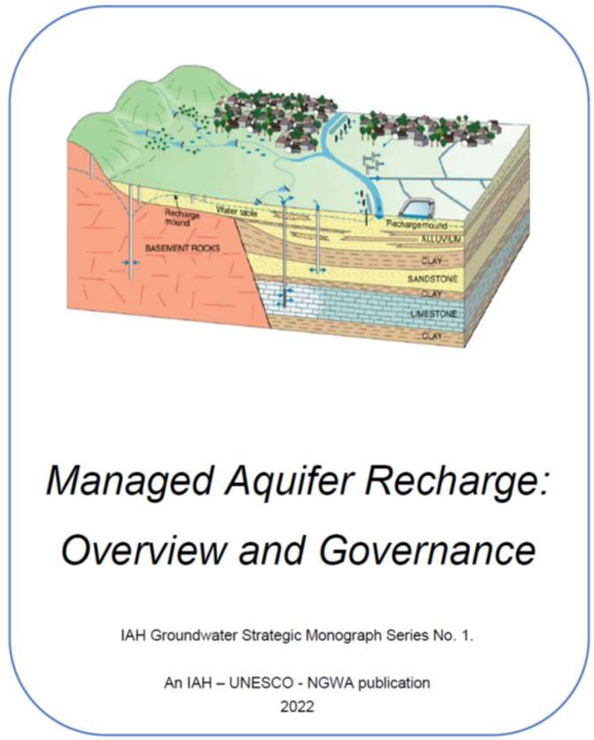
Seamlessly integrating MAR into a treatment train

Water source	① Capture	② Water treatment before recharge
Mains water	Tap into mains pipe	None or filter
Rain water	Tank	Filter
Stormwater	Wetland or basin	Wetland, MF, GAC
Reclaimed water	Pipe from water reclamation plant	DAFF, RO
Rural runoff	Wetland, basin or dam	Wetland
A different aquifer	Pump from well	None

③ RECHARGE → ④ AQUIFER STORAGE → ⑤ RECOVERY

⑥ Post treatment	⑦ End use
Disinfection	Drinking water
None	Industrial water
None	Irrigation
None	Toilet flushing
None	Sustaining ecosystems

Figure 12 - All sources of water with appropriate treatment can be used for MAR. Water treatment requirements in MAR depend on the recharge source, aquifer, recharge method, intended water use, and other preventive measures to manage risks (from Dillon et al., 2009).



Vanderzalm, J., D. Page, P. Dillon, and Y. Zheng, 2022, Considerations for Water Quality Management, in Managed Aquifer Recharge: Overview and Governance. IAH Special Publication. https://recharge.iah.org/ ISBN 978-1-3999-2814-4

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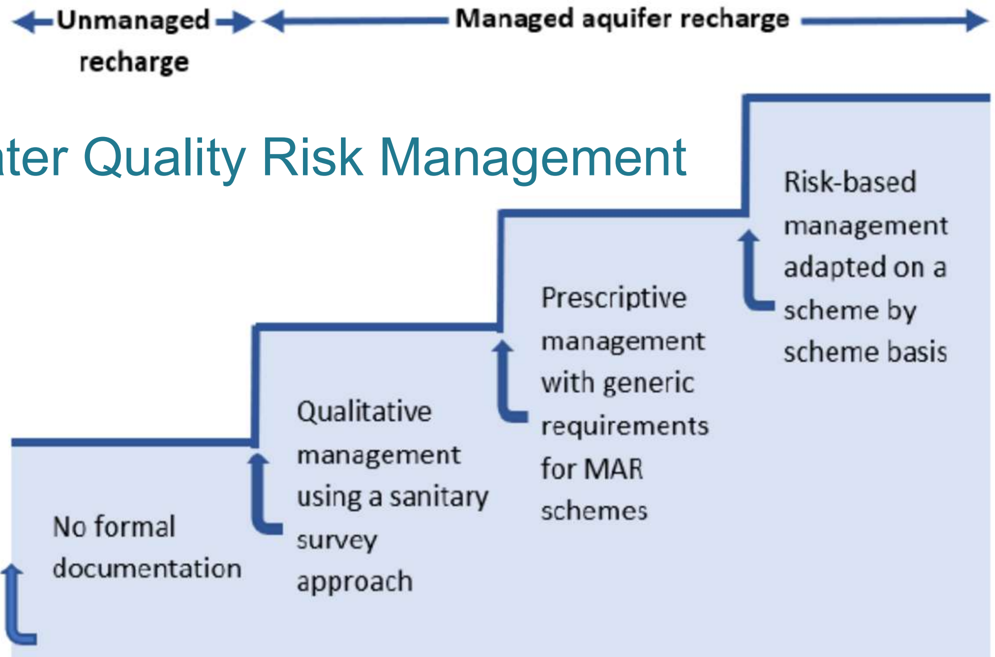
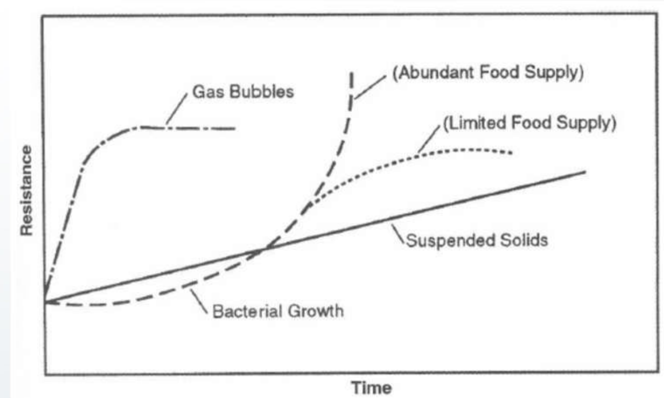
Stages of Water Quality Risk Management



Water quality focus:	Not explicit	Public health	Public health & environment	Public health & environment
Risk assessment:	None	Qualitative	Assumed generic	Quantitative
Sampling and analysis required:	None	Visual observations only	Generic analyte list	Analytes based on locally assessed risk
Level of safety:	Unknown	Safer	Safer	Safest

Figure 14 - Approaches for management of water quality in MAR progressing toward risk-based management of public health and the environment (modified from Dillon et al., 2014).

Pathogen/indicator	Removal time for 90% loss (T_{90}) (d)
Escherichia coli	0.1-1.5
Enterococcus fecalis	1-2.5
Salmonella enterica	0.7-2
Coxsackievirus	17-169
Adenovirus	28-65
Rotavirus	34-185
Cryptosporidium parvum	38-120



Typical aquifer hydraulic response for different clogging mechanisms (Pyne, 2005).

https://recharge.iah.org/unesco-iah-mar-publications

- ✓ **Cost-benefit** and **sustainability analysis** of 28 diverse Managed Aquifer Recharge (MAR) cases in operation over many years;
- ✓ Irrefutable evidence that MAR produces a wealth of benefits from **integrated management** of a wide range of **conventional and un-conventional water resources**, paving the way for global adoption to achieve sustainable development goals for water.

Sustainability Indicators
grounded by water quality risk criteria

Zheng, Y., Ross, A., Villholth, K.G. and Dillon, P. (eds). 2021. Managing Aquifer Recharge: A Showcase for Resilience and Sustainability. UNESCO, Paris, pp379. https://unesdoc.unesco.org/ark:/48223/pf0000379962

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Table 3.
Six Environmental and Three Social Indicators Established for MAR Schemes following USEPA Framework of Sustainability Indicators. Source: Own elaboration

	Score*
I. Environmental Sustainability Indicators	
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	7.6
2. The ratio of volume of recovered water vs infiltrated water on an annual basis	6.8
For large schemes, change in renewable groundwater resources in target aquifer per capita (m^3/year per capita)	1.6
A.2 Water Quality	
3. Exceedance rate based on time-series monitoring of recovered or ambient water quality parameters	7.8
4. Exceedance rate based on time-series monitoring of source water quality parameters	7.5
For large schemes, percentage use as drinking water sourced from target aquifer	3.1
B. Ecosystem Services	
5. Changes in ecological flow (m^3/yr) and improvement in water quality in ecosystem needing protection identified in a catchment water management plan	4.9
Change in peak flow (m^3/s) for MAR intended for flooding control	1.3
C. 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	7.0
No unacceptable seepage, waterlogging, discharge occurs	3.4

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II. Social Sustainability Indicators	
A. Resource Security/Human Health	
7. Clearly defined, transparent regulatory framework for MAR, preferably one that requires monitoring of resource integrity	8.6
8. Permit granting process is based on sound risk assessment aimed to protect human health	8.9
Assists resilience to adverse impacts of climate change	5.5
B. Sustainable Community/Participation/Education/Environmental Justice	
9. Systematic Institutional arrangements for public and stakeholder consultation, preferably with regular publicly available reports of scheme outcomes	7.4

*Average score by 11 participants. Score scale: Do not include 0, OK to include 4, Good to include 7, Must include 10.

Zheng et al (2021). Chapter 3. Assessment of Environmental and Social Sustainability of Managed Aquifer Recharge Case Studies. in Zheng et al (eds). Managing Aquifer Recharge: A Showcase for Resilience and Sustainability, UNESCO, Paris.

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Part III:
MAR to MARs

Managed aquifer recharge **and storage** (MAR**s**), also called groundwater replenishment, water banking and artificial recharge, is the ***purposeful*** recharge of water to aquifers with **storage time optimized** for **subsequent recovery or environmental benefit**.

Managed Aquifer Recharge in North China Plain

https://www.mar-china.geus.dk/

MAR CHINA

Home | About MAR-China | Field Sites | Modelling

WELCOME TO MAR CHINA

– Managed Aquifer Recharge in the North China Plain

The project will address the potential of utilizing "low value" reclaimed water (treated waste water) and floodwater through Managed Aquifer Recharge (MAR) to replenish the groundwater aquifers in the North China Plain (NCP) region. Our aim is to investigate how MAR can contribute to rehabilitation of groundwater aquifers. This requires an improved knowledge of the treatment and degradation processes occurring during MAR and subsequent storage. In addition, the full potential is best explored using spatially distributed hydrological modelling to quantify the effects of realistic MAR implementation through scenario analysis.

The project aims at three outcomes:

- Development of a knowledge base to access the quantitative aspects of the large scale potential of MAR as a tool for water scarcity alleviation
- Development of a knowledge base to access the water qualitative aspects of MAR in NCP
- Increase the knowledge on MAR among stakeholders, practitioners and policy makers

The aims of the object are linked to three work packages:

- WP1: Integrated hydrological modelling of coupled surface-water and groundwater systems
- WP2: Water quality improvements through managed aquifer recharge in the North China Plain
- WP3: Dissemination of results

News

The MAR-China project group got together in Copenhagen for a workshop at GEUS; August 19-23. 2019.

For more information direct to: https://www.mar-china.geus.dk/about-mar-china/activities/

The MAR-China project group attended the 10th International Symposium on

GEUS:

Simon Stisen
Jens Aamand
Julian Koch
Grith Martinsen
Jacub Modrzynski

SUSTech:

Yan Zheng
Yunjie Ma
Meng Ma
Wensi Guo
Yuxia Yang
Alex Palomo

BWSTI: Binghua Li

JinanU: Weiping Wang

IWHR: Xin He

SUSTech

Treated waste water reclaimed for landscaping & env. use

Zhu and Dou (2018)

Beijing

Shenzhen Central Park

Yr 2020

Urban reclaimed water use： 14.6 billion m^3

(23.3% of total urban supply)

Beijing: ~ 1 billion m^3

Study Site: Beiyun River in Beijing, the North China Plain: **>90%** of flow is reclaimed water.

(Geo-Environment Monitoring 2018&2019)

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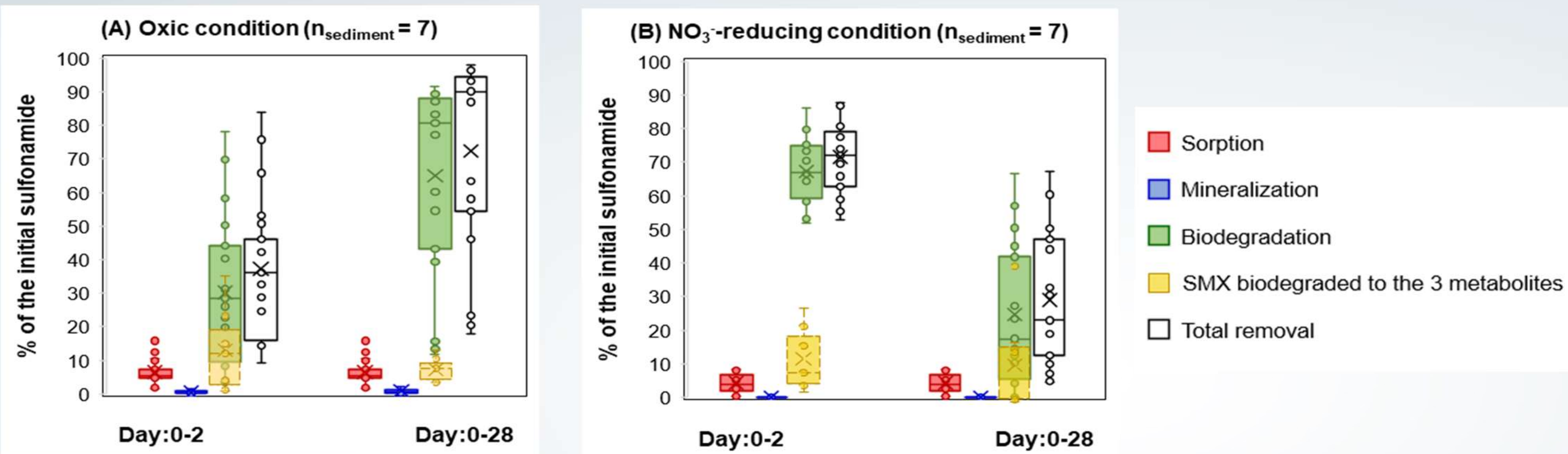
Sulfonamide Removal: biodegration >> sorption > mineralization

- Batch-1: Sorption tests; Batch-2: Mineralization tests; Batch-3: Removal tests → Biodegradation



Percentage of removal attributed to sorption, mineralization, and biodegradation during (A) oxic and (B) anoxic (NO_3^--reducing) degradation tests.

Y. Ma, J. J. Modrzynski, Y. Yang, J. Aamand, and Y. Zheng* (2021). Redox-dependent biotransformation of sulfonamide antibiotics exceeds sorption and mineralization: Evidence from incubation of sediments from a reclaimed water-affected river. Water Research. 205:117616

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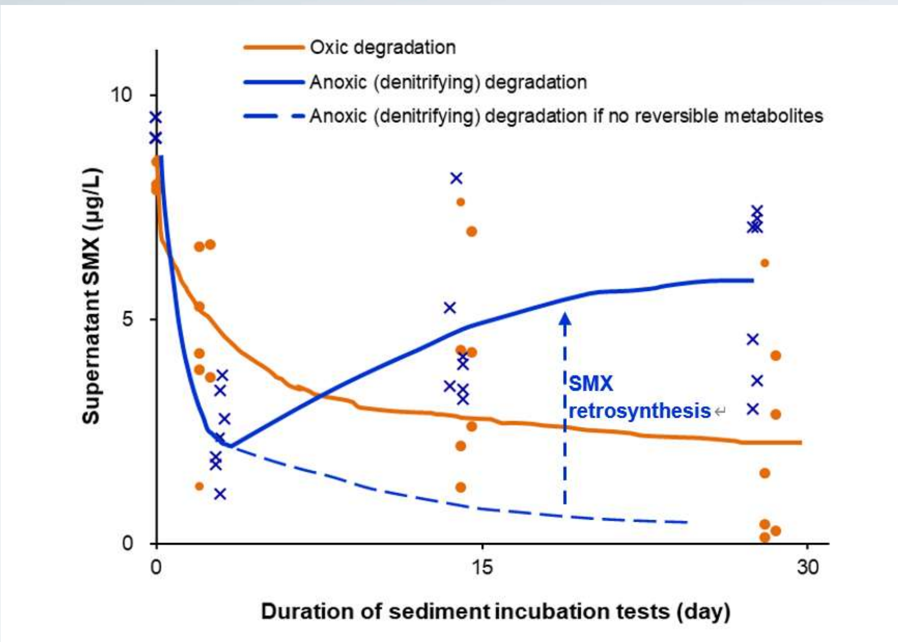
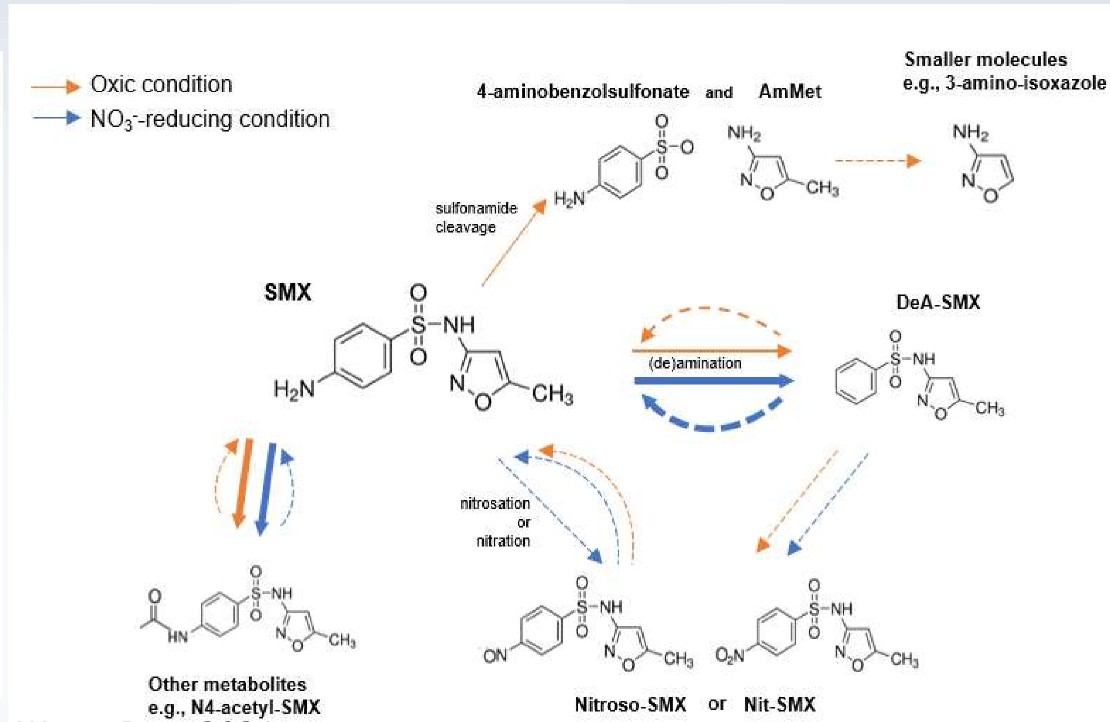
SMX Degradation Kinetics: Oxic > Anoxic





The first-order degradation kinetics *Yunjie Ma et al, Water Res. 2021*

$t_{1/2,oxic}$ = 12 ± 11 days

$t_{1/2,anoxic,\ day\ 28}$ = 69 ± 25 days

$t_{1/2,anoxic,\ day\ 2}$ = 1.1 ± 0.3 days

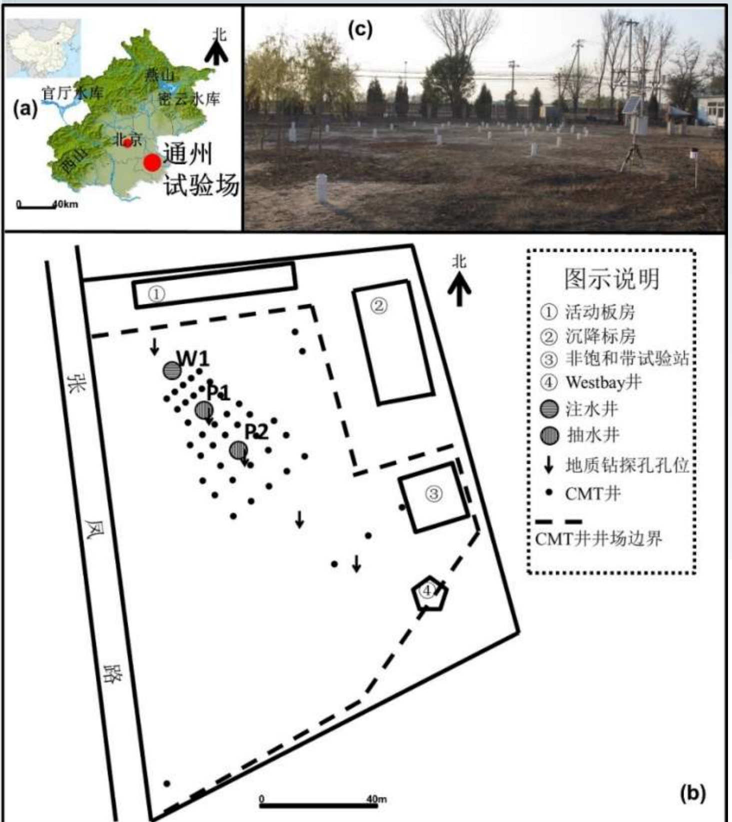
Proposed transformation processes in SMX biodegradation under oxic and anoxic conditions.

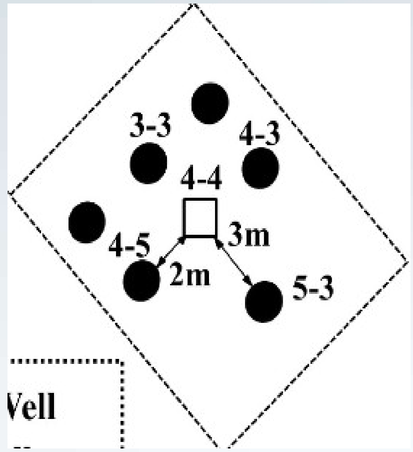
In situ experiment $t_{1/2,suboxic/anoxic}$:3.1 ± 0.2 days; 6.5 ± 0.6 days *Meng Ma et al, ES&T, 2019*

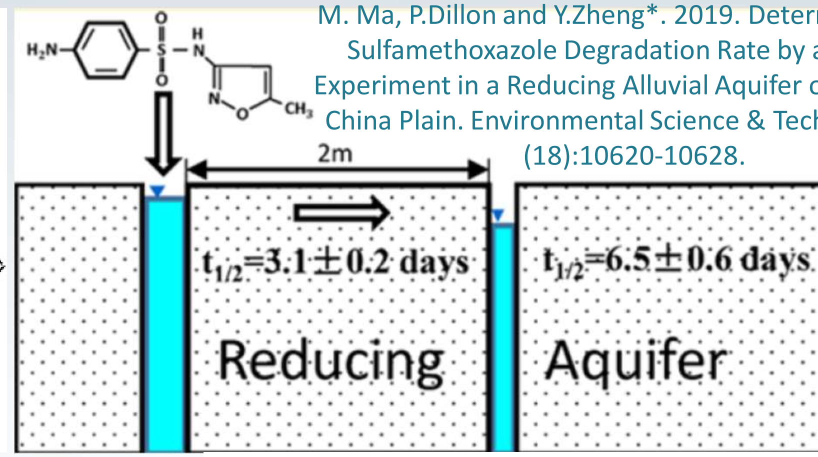
SUSTech

Sulfamethoxazole (SMX) degradation rates through *in situ* experiment

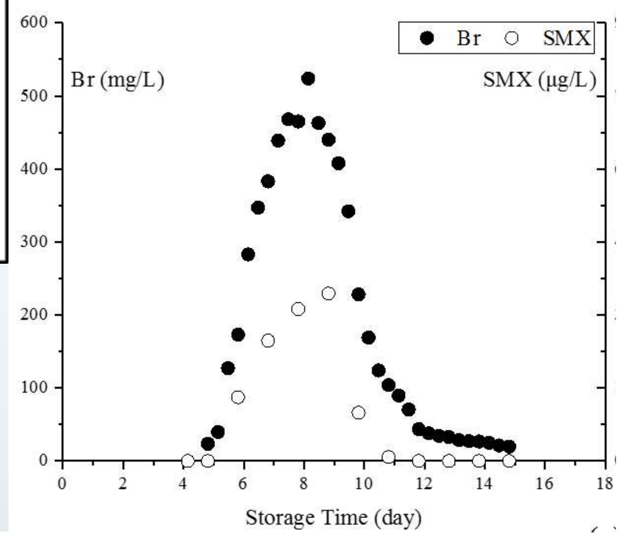
M. Ma, P.Dillon and Y.Zheng*. 2019. Determination of Sulfamethoxazole Degradation Rate by an in Situ Experiment in a Reducing Alluvial Aquifer of the North China Plain. Environmental Science & Technology 53 (18):10620-10628.

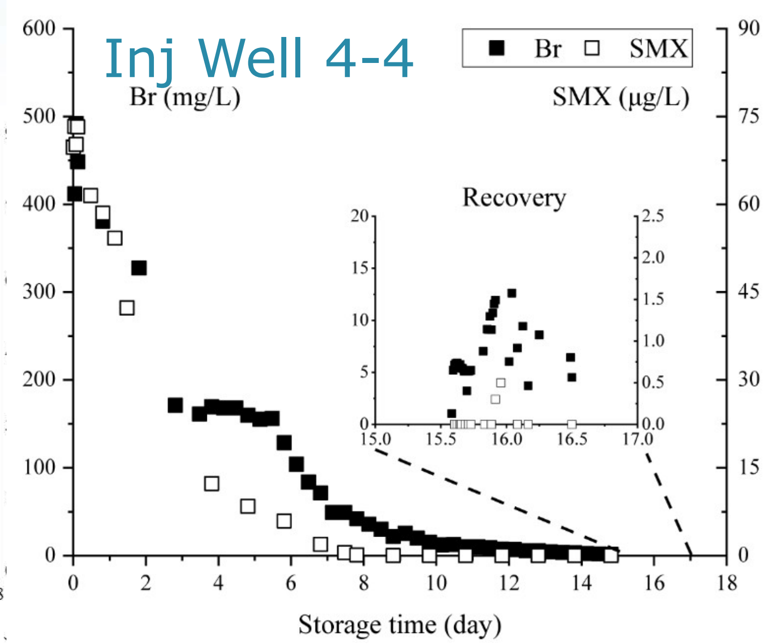




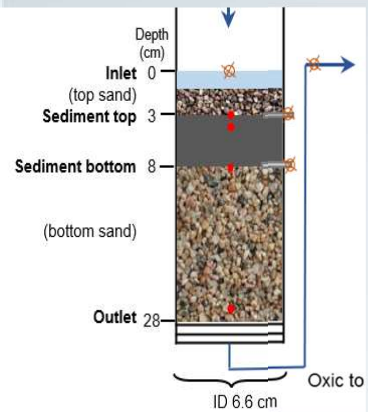


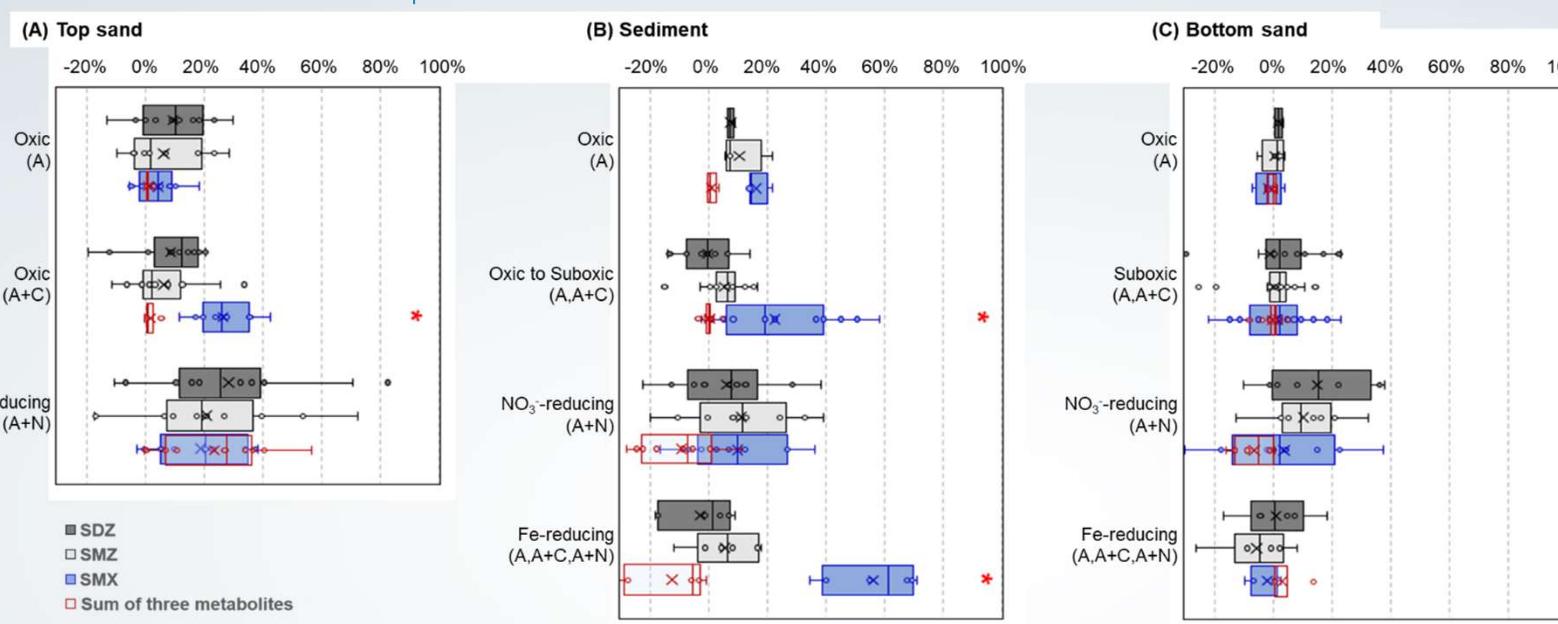
Exp Well 4-5





Removal is limited by substrates and reaction time!





Sulfonamide removal (%) of SDZ, SMZ and SMX, and the total production of three SMX metabolites (% to initial SMX concentrations) in different redox zones over 120-day infiltration.

Y Ma, M Ma, A Palomo, Y Sun, JJ Modrzynski, J Aamand, Y Zheng* (2023) Biodegradation of trace sulfonamide antibiotics accelerated by substrates across oxic to anoxic conditions during column infiltration experiments. Water Research 233, 120193

Conclusion

- Incidental recharge due to large scale reclaimed water use for landscaping and environmental flow purposes in the North China Plain is a threat to groundwater quality by introducing not-so-biodegradable **contaminants of emerging concerns** such as sulfonamide antibiotics and by mobilizing geogenic contaminant such as arsenic (not shown in this talk).

- In water-sediment systems, the removal of sulfonamide antibiotics is primarily via biodegradation involving microbes. However, it is redox-dependent**, usually incomplete with unknown metabolites**, with variable degradation kinetics **influenced by substrate availability and retention time**. Acceleration of biodegradation and full mineralization through manipulation of hydraulic retention time, primary substrates, and redox conditions etc. need to be investigated to tackle the contaminants of emerging concerns, one of the 21st century water quality challenges.

- To protect human and ecosystem health, **regulations governing water recycling will do well to address risks associated with incidental recharge**, and better yet, developed with enabling managed aquifer recharge to take advantage of natural attenuation abilities of aquifers.

Danida Fellowship Centre
- sustaining development through research and learning

国家自然科学基金委员会
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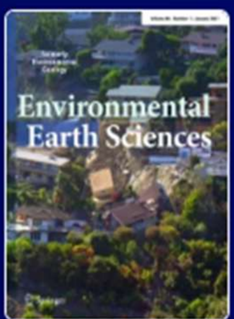
Environmental Earth Sciences

SPRINGER NATURE Journal



Overview

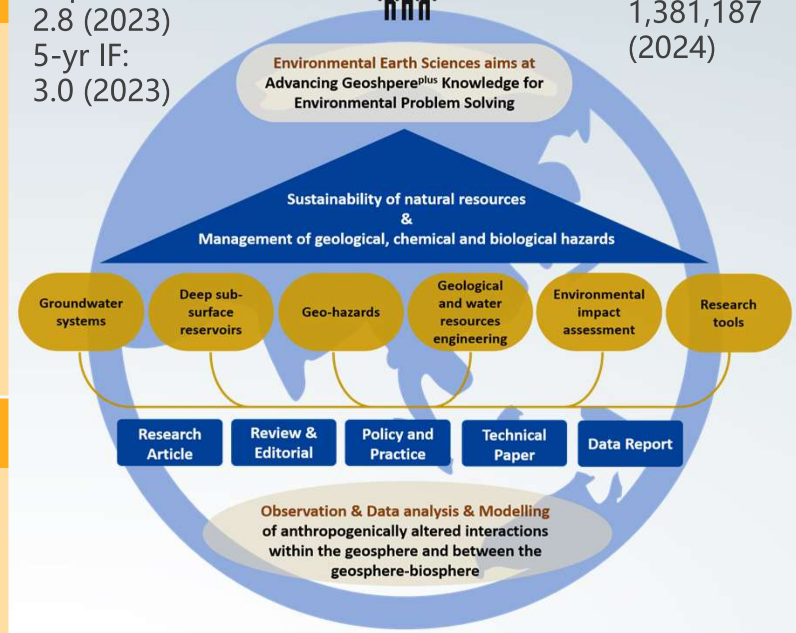
- Environmental Earth Sciences is an international journal focused on the study of anthropogenically altered interactions within the geosphere and between the geosphere–biosphere.
- Relevant areas include geophysics, geochemistry, biogeosciences, engineering geology, hydrogeology, and physical geography.

Journal Aims

Uphold geological tradition, expand outward to advance novel understanding of anthropogenically altered interactions within the geosphere and along the geosphere–biosphere nexus.

Impact factor
2.8 (2023)
5-yr IF:
3.0 (2023)

Downloads
1,381,187
(2024)



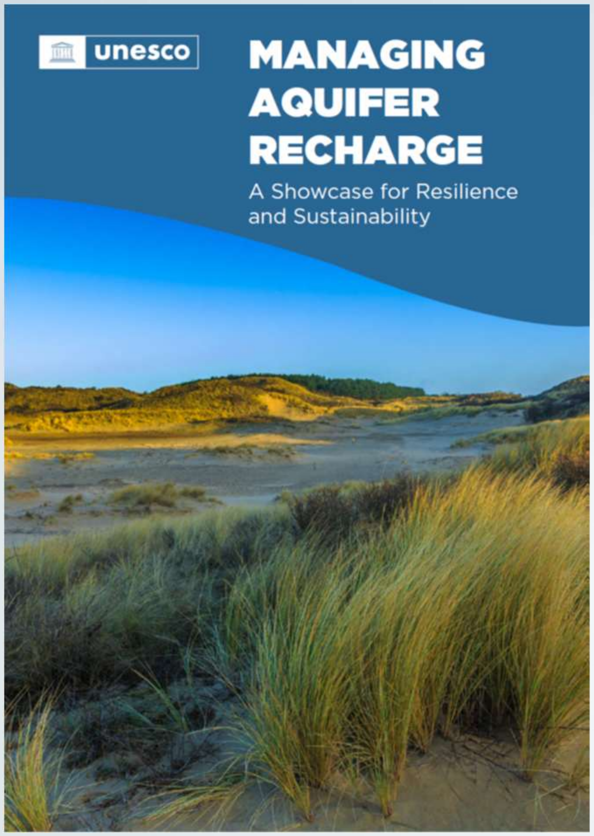
Journal Scope

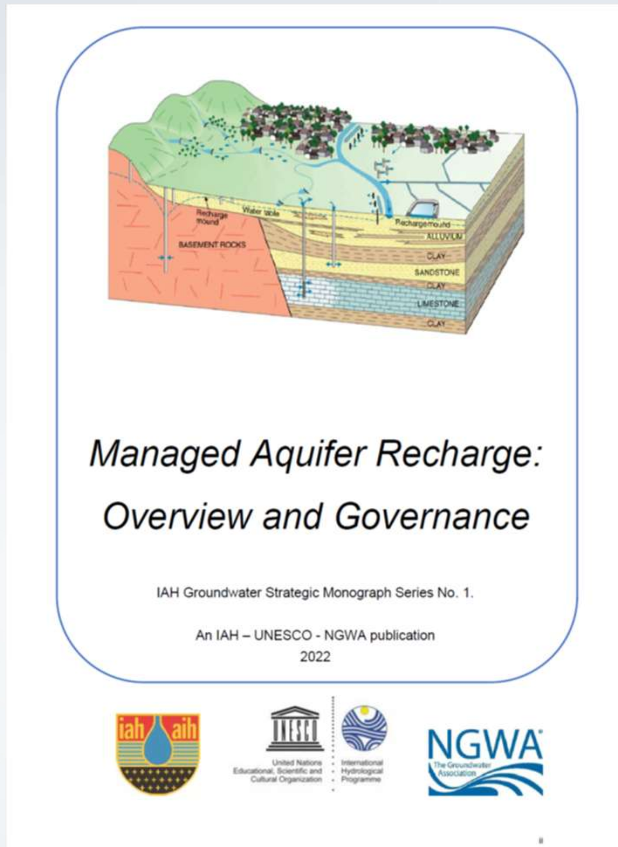
https://link.springer.com/journal/12665

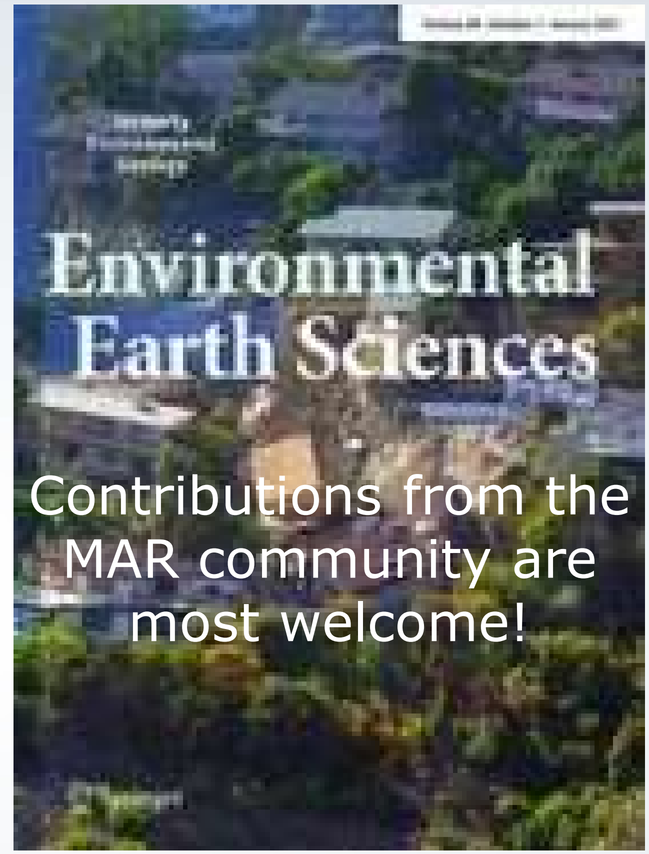
- **Groundwater systems**: the quality, quantity and sustainability of groundwater
- **Deep sub-surface reservoirs**: geothermal energy and nuclear waste disposal
- **Geo-hazards**: man-made or naturally occurring such as landslide
- **Geological and water resources engineering**: to reduce ecosystem and human health risks and to prolong sustained access to natural resources
- **Environmental impact assessment:** from a geological perspective
- **Research tools**: geophysical, geochemical and geobiological observational tools, geostatistical and geospatial methods, data assimilation and modeling methods

Editorial: Y. Zheng, O. Kolditz, B. Kolditz, Y. Ma. (2023) Environmental earth sciences: advancing geosphere[plus] knowledge for environmental problem solving, Environmental Earth Sciences 82:445, doi: 10.1007/s12665-023-11089-6

Thank You







Contributions from the MAR community are most welcome!

Acknowledgement: DANIDA, NSFC & UNESCO for funding; IAH for support.

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