Managed Aquifer Recharge: from Global Perspective to Local Planning

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Introduction

Natural system + Irrigated agriculture + Urban development → Managed aquifer recharge (MAR)

“Intentional storage of surplus surface water in underground for later use of ecological benefits”
<table>
<thead>
<tr>
<th>Attribute</th>
<th>Storage above ground</th>
<th>Storage below ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land area required</td>
<td>large</td>
<td>very small</td>
</tr>
<tr>
<td>Proximity to the city</td>
<td>far</td>
<td>within</td>
</tr>
<tr>
<td>Capital costs</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Investigations costs</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Intake and supply rate</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Evaporation losses</td>
<td>moderate</td>
<td>low</td>
</tr>
<tr>
<td>Algal problems</td>
<td>moderate</td>
<td>low</td>
</tr>
<tr>
<td>Mosquitos</td>
<td>moderate</td>
<td>low</td>
</tr>
<tr>
<td>Mixing loses</td>
<td>none</td>
<td>none to high</td>
</tr>
<tr>
<td>Pathogen removal</td>
<td>some</td>
<td>substantial</td>
</tr>
<tr>
<td>Recontamination potential</td>
<td>moderate</td>
<td>none to moderate</td>
</tr>
<tr>
<td>Relief requirements</td>
<td>suitable valley</td>
<td>suitable aquifer</td>
</tr>
</tbody>
</table>

Source: adapted from Dillon et al., 2009
Water Risk Index

High
Low
MAR sites

Global MAR Portal
1200+ MAR sites, 60+ countries

Stefan and Ansems, 2018 | http://marportal.un-igrac.org
https://doi.org/10.1007/s40899-017-0212-6
MAR case studies by country

Number of case studies per country

<table>
<thead>
<tr>
<th>Country</th>
<th>Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>95</td>
</tr>
<tr>
<td>Brazil</td>
<td>90</td>
</tr>
<tr>
<td>China</td>
<td>130</td>
</tr>
<tr>
<td>Germany</td>
<td>73</td>
</tr>
<tr>
<td>India</td>
<td>65</td>
</tr>
<tr>
<td>Netherlands</td>
<td>71</td>
</tr>
<tr>
<td>USA</td>
<td>295</td>
</tr>
</tbody>
</table>
MAR historical development

- Spreading Methods
- Induced Bank Filtration
- Well, Shaft & Borehole Recharge
- In-Channel Modification
- Rainwater & Run-off Harvesting

Number of sites (cumulative)

- 1810's
- 1870's
- 1880's
- 1940's

Time periods:
- 1800-1809
- 1810-1819
- 1820-1829
- 1830-1839
- 1840-1849
- 1850-1859
- 1860-1869
- 1870-1879
- 1880-1889
- 1890-1899
- 1900-1909
- 1910-1919
- 1920-1929
- 1930-1939
- 1940-1949
- 1950-1959
- 1960-1969
- 1970-1979
- 1980-1989
- 1990-1999
- 2000-2009
- 2010-2015
Main MAR types

Total number of case studies (%)

<table>
<thead>
<tr>
<th>Region</th>
<th>Spreading Methods</th>
<th>Well, Shaft &amp; Borehole Recharge</th>
<th>Induced Bank Filtration</th>
<th>In-Channel Modification</th>
<th>Rainwater &amp; Run-off Harvesting</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASIA</td>
<td>24%</td>
<td>2%</td>
<td>21%</td>
<td>42%</td>
<td>12%</td>
</tr>
<tr>
<td>AFRICA</td>
<td>30%</td>
<td>7%</td>
<td>23%</td>
<td>40%</td>
<td></td>
</tr>
<tr>
<td>NORTH AMERICA</td>
<td>40%</td>
<td>3%</td>
<td>53%</td>
<td></td>
<td>4%</td>
</tr>
<tr>
<td>SOUTH AMERICA</td>
<td>18%</td>
<td>6%</td>
<td>7%</td>
<td>54%</td>
<td>14%</td>
</tr>
<tr>
<td>EUROPE</td>
<td>30%</td>
<td></td>
<td>53%</td>
<td></td>
<td>16%</td>
</tr>
<tr>
<td>OCEANIA</td>
<td>11%</td>
<td>57%</td>
<td>32%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Specific MAR types

<table>
<thead>
<tr>
<th>MAR Type</th>
<th>Number of Case Studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infiltration Ponds &amp; Basins</td>
<td>259</td>
</tr>
<tr>
<td>ASR/ASTR</td>
<td>268</td>
</tr>
<tr>
<td>Induced Bank Filtration</td>
<td>173</td>
</tr>
<tr>
<td>Subsurface Dam</td>
<td>129</td>
</tr>
<tr>
<td>Recharge Dam</td>
<td>106</td>
</tr>
<tr>
<td>Dug Well/ Shaft/ Pit Injection</td>
<td>75</td>
</tr>
<tr>
<td>Rooftop Rainwater Harvesting</td>
<td>34</td>
</tr>
<tr>
<td>Ditch &amp; Furrow</td>
<td>22</td>
</tr>
<tr>
<td>Trenches</td>
<td>18</td>
</tr>
<tr>
<td>Flooding</td>
<td>18</td>
</tr>
<tr>
<td>Reverse Drainage</td>
<td>11</td>
</tr>
<tr>
<td>Excess Irrigation</td>
<td>10</td>
</tr>
<tr>
<td>Channel Spreading</td>
<td>7</td>
</tr>
<tr>
<td>Barriers &amp; Bunds</td>
<td>3</td>
</tr>
<tr>
<td>Sand Storage Dams</td>
<td>2</td>
</tr>
</tbody>
</table>

46% from total
## Types of water source for MAR

<table>
<thead>
<tr>
<th>Water Source</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tap water</td>
<td>2.6%</td>
</tr>
<tr>
<td>Storm water</td>
<td>17.2%</td>
</tr>
<tr>
<td>River water</td>
<td>55.0%</td>
</tr>
<tr>
<td>Reclaimed wastewater</td>
<td>8.8%</td>
</tr>
<tr>
<td>Mine water</td>
<td>0.4%</td>
</tr>
<tr>
<td>Lake water</td>
<td>6.7%</td>
</tr>
<tr>
<td>Groundwater</td>
<td>8.8%</td>
</tr>
<tr>
<td>Distilled water</td>
<td>0.1%</td>
</tr>
<tr>
<td>Brackish water</td>
<td>0.5%</td>
</tr>
</tbody>
</table>
MAR objectives

Total number of case studies (%)

- **ASIA**
  - Ecological Benefits: 42%
  - Maximize Natural Storage: 45%
  - Other Benefits: 10%

- **AFRICA**
  - Ecological Benefits: 68%
  - Maximize Natural Storage: 18%
  - Other Benefits: 15%

- **NORTH AMERICA**
  - Ecological Benefits: 39%
  - Maximize Natural Storage: 40%
  - Other Benefits: 16%

- **SOUTH AMERICA**
  - Ecological Benefits: 61%
  - Maximize Natural Storage: 23%
  - Other Benefits: 5%

- **EUROPE**
  - Ecological Benefits: 18%
  - Water Quality Management: 5%
  - Management of Water Distribution Systems: 71%

- **OCEANIA**
  - Ecological Benefits: 45.6%
  - Maximize Natural Storage: 46%
  - Other Benefits: 5%
MAR objectives vs. final water source

Number of case studies

- Ecological Benefits: 6%
- Management of Water Distribution Systems: 1%
- Maximize Natural Storage: 40%
- Physical Aquifer Management: 23%
- Water Quality Management: 26%
- Other Benefits: 4%

Legend:
- Agriculture
- Domestic
- Ecological
- Industrial
MAR beneficiary sector

- **Asia**:
  - Agriculture: 26%
  - Domestic: 53%
  - Ecological: 17%
  - Industrial: 3%
  - Total: 100%
  - n = 223

- **Africa**:
  - Agriculture: 3%
  - Domestic: 73%
  - Ecological: 23%
  - Industrial: 3%
  - Total: 100%
  - n = 30

- **North America**:
  - Agriculture: 18%
  - Domestic: 58%
  - Ecological: 6%
  - Industrial: 19%
  - Total: 100%
  - n = 118

- **South America**:
  - Agriculture: 28%
  - Domestic: 58%
  - Ecological: 14%
  - Industrial: 1%
  - Total: 100%
  - n = 110

- **Europe**:
  - Agriculture: 8%
  - Domestic: 87%
  - Ecological: 5%
  - Industrial: 1%
  - Total: 100%
  - n = 257

- **Oceania**:
  - Agriculture: 19%
  - Domestic: 58%
  - Ecological: 21%
  - Industrial: 19%
  - Total: 100%
  - n = 89

Legend:
- Green: Agriculture
- Yellow: Domestic
- Orange: Ecological
- Blue: Industrial
Further readings

https://doi.org/10.1007/s40899-017-0212-6

Web-based global inventory of managed aquifer recharge applications

Catalin Stefan1 · Nienke Ansems2

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Abstract
Managed aquifer recharge (MAR) is being successfully implemented worldwide for various purposes: to increase groundwater storage, improve water quality, restore groundwater levels, prevent salt water intrusion, manage water distribution systems, and enhance ecological benefits. To better understand the role of MAR in sustainable water management and adaptation to climate and land use change, about 1200 case studies from 62 countries were collected and analyzed with respect to historical development, site characterization, operational scheme, objectives and methods used, as well as quantitative and qualitative characterization of in- and outflow of water. The data harvested was used for the compilation of a global inventory of MAR schemes, whose main goal is to provide access to existing MAR projects and techniques and demonstrate their benefits. To increase the availability and facilitate continuous update of the MAR inventory, an MAR web-based portal was developed
Further readings

Sixty years of global progress in managed aquifer recharge

P. Dillon\(^1,2\) · P. Stuyfzand\(^3,4\) · T. Grischek\(^5\) · M. Luria\(^6\) · 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\(^33\)

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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
Simple tools derived from data mining and empirical correlations

Practical implementation of analytical equations of groundwater flow

Reliable simulations using complex numerical flow models (i.e. MODFLOW)

The applications are based on a collection of simple, practical and reliable web-based tools of various degrees of complexity. The tools are either included in application-specific workflows or used as standalone modelling instruments.

EXAMPLES OF TOOLS

T07. APPLICATION-SPECIFIC SCENARIOS ANALYZER
This tool makes use of the output files of the MODFLOW-based model and uses them for the customized analysis of user-defined model scenarios
Global MAR Portal

Web-GIS portal for visualization of MAR projects and suitability maps
Saltwater Intrusion Assessment

Interactive web-based implementation of analytical equations
MODFLOW-based Groundwater Modeling

Setup, calculation, optimization and visualization of MODFLOW models
<table>
<thead>
<tr>
<th>SPECs</th>
<th>ModelMuse</th>
<th>Visual MODFLOW Flex</th>
<th>INOWAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODFLOW code</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Pricing model</td>
<td>free</td>
<td>9,000 USD</td>
<td>free</td>
</tr>
<tr>
<td>Web-based interface</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Multiple tools (over 20)</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>FEATURES</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenarios analysis</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>3D visualization</td>
<td>✗</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Shared models</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Optimization algorithms</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Cloud-based scalability</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>PACKAGES</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Analytical equations</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>MODFLOW-2005</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>MT3DMS</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SEAWAT</td>
<td>✗</td>
<td>✓</td>
<td>in progress</td>
</tr>
<tr>
<td>MODPATH</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
</tbody>
</table>
GIS-based MAR suitability mapping

Costa Rica
Bonilla et al., 2016

Iberian Peninsula
Vasquez, 2017

Guatemala
Pivaral, 2016

China
Wang, 2017

Machuca River basin
Zapata, 2015

MARSSI Index
www.ismar10.net
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Managed Aquifer Recharge: from Global Perspective to Local Planning

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