Managed Aquifer Recharge

Challenge and Opportunity

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Christoph Schüth, TU Darmstadt, Germany
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Manuel Sapiano, SEWCU, Malta
MARSOL: Demonstrating Managed Aquifer Recharge as a Solution to Water Scarcity and Drought

The Mediterranean region is suffering from increasing water scarcity, which is further exacerbated by climate change, high population density, and high water consumption by agricultural, industrial, and urban uses. Not only quantity but also quality is of increasing importance, e.g., due to intensive use of fertilizers and seawater intrusion. Meanwhile, large water quantities are lost to the Mediterranean Sea as surface runoff, river discharge, discharge of treated and untreated wastewater, and as discharge of excess water from various sources during periods of low demand. This water can be used in principle for the controlled (re-)filling of exploited aquifers by artificial infiltration, referred to as Managed Aquifer Recharge (MAR).

Demonstration Sites

For the project eight demonstration sites have been selected to represent different MAR purposes and hydrogeological settings.

MARSOL follows an holistic approach, which considers different:

- Recharge water sources
- Recharge techniques
- MAR objectives

The Project

• 21 Partners
• 36 months, starting 12/2013
• Total budget – 8.0 million EUR
• EU contribution – 5.2 million EUR

MARSOL Project—Main Objectives

• Demonstrate at 8 field sites that MAR is a sound, safe, and sustainable strategy to increase the availability of freshwater under conditions of water scarcity.
• Improve the state of MAR applications to enable low-cost, high-efficiency MAR solutions that will create market opportunities for European industry and SMEs (MAR to Market).
• Promote the advantages of MAR by tailored training and dissemination programs to enable and accelerate market penetration.
• Deliver a new technology to face the challenge of increasing water scarcity in the Mediterranean region of southern Europe and other regions of the world.

Tools to Reach the Objectives

• Data collection
• Monitoring (improvement of sensors, new sensors)
• Improvement of MAR devices (planning, design, and maintenance)
• Modeling (to simulate the impact of MAR on aquifer hydrology and hydrogeochemistry)
• Scenario analysis
• Development of a Decision Support System
• Definition of guidelines and policies
• Increase of public participation within Public Private Partnership (PPP) schemes
• Market analysis on the potential market exploitation solutions.

FP-7 ENV
MARSOL
Demonstrating Managed Aquifer Recharge as a Solution to Water Scarcity and Drought (FP7-Env-2013-Water-Inno-Demo)

Start: 12.2013  
Duration: 3 years  
EU Contribution: 5.2 Mio €

The main objective of MARSOL is... With this, MARSOL aims to stimulate the use of reclaimed water and other alternative water sources to be recovered...

...sound, safe and sustainable strategy...

Australian guidelines for Water recycling, 24: Managed Aquifer Recharge (2009)
Managed Aquifer Recharge (MAR)

**Managed Aquifer Recharge** refers to different recharge techniques that allows reclaimed water to penetrate into the ground:

- percolating through unsaturated soil (**surface groundwater recharge**),

- or from below the ground, by injection or recharge wells (**subsurface groundwater recharge**).

The advantage is that reclaimed water such as treated blackwater, graywater or stormwater is not just discharged into surface waters, but reused as water for irrigation in agriculture or to intentionally recharge groundwater aquifers via MAR.
Managed Aquifer Recharge - Principles

(a) Surface spreading basin
(b) Vadose zone injection well
(c) Direct injection well

Reclaimed water for recharge

Vadose zone

Unconfined aquifer
Aquitard
Confined aquifer

Australian guidelines for Water recycling, 24: Managed Aquifer Recharge (2009)
Simplified Recharge-pumping scheme
Managed Aquifer Recharge (MAR)
Confined aquifers

In confined conditions, artificial recharge has in general to be achieved using infiltration wells as the potentiometric groundwater surface is above the confining layer.
Precipitation natural variation in Mediterranean countries:
the example of Portugal
WP12 “MODELLING"

Partners:

Portugal, Algarve:
J.P. Lobo Ferreira, Manuel M. Oliveira, Tiago Martins, Teresa Leitão (LNEC)
José Paulo Monteiro, Luís R.D. Costa (UALG), Tiago Carvalho (TARH):
Israel, Menashe: Daniel Kurtzman (Volcani)

Lavrion Greece: Laura Foglia (Geo.tu-darmstadt)

Italy, Serchio: Rudy Rossetto (SSSA), Iacopo Borsi (Tea-group)
Italy Brenta: Michele Ferri (adbve)
Spain, Madrid: Enrique F. Escalante (TRAGSA)
Barcelona: Xavier Sanchez-Vila (UPC)

Final Meeting, October 17th - 19th 2016, Leipzig, Germany
NUMERICAL MODELLING IN MANAGED AQUIFER RECHARGE

CLIMATE CHANGE IMPACT

Modification of climatological series

Emissions scenario considered in the study: A1B, which corresponds to a scenario of rapid global economic growth, and a balance between different types of energy sources - which is expected to result in precipitation and temperature changes according to the season.

<table>
<thead>
<tr>
<th>Climate Model</th>
<th>SMHIRCA_ECHAM5 Model</th>
<th>ENSEMBLES Model average rates</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2080 Horizon</strong></td>
<td>Winter: -4,7%; Spring: -37,5%; Summer: -61%; Autumn: -24,6%</td>
<td>Winter: +2%; Spring: -33%; Summer: -51%; Autumn: -27%</td>
</tr>
<tr>
<td><strong>2050 Horizon</strong></td>
<td>Winter: +4%; Spring: -15%; Summer: -26,8%; Autumn: -22,6%</td>
<td>Winter: +12%; Spring: -11%; Summer: -29%; Autumn: -15%</td>
</tr>
</tbody>
</table>

Variation rates in precipitation for A1B climate scenario

<table>
<thead>
<tr>
<th>Climate Model</th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>2050 Horizon</strong></td>
<td>Winter: +0,8°C; Spring: +0,8°C; Summer: +2,6°C; Autumn: +1,6°C</td>
<td>Winter: +1,5°C; Spring: +1,6°C; Summer: +2,5°C; Autumn: +2,0°C</td>
</tr>
<tr>
<td><strong>2050 Horizon</strong></td>
<td>Winter: +0,7°C; Spring: +0,4°C; Summer: +1,2°C; Autumn: +1,1°C</td>
<td>Winter: +1,2°C; Spring: +1,2°C; Summer: +1,4°C; Autumn: +1,5°C</td>
</tr>
</tbody>
</table>

Variation rates in temperature for A1B climate scenario

Impactos das Alterações Climáticas Relacionados com os Recursos Hídricos (2010)
WP 12: Modelling

Task 12.3: Climate change impact

An analysis of the impact of climate change in the general water budget of the areas under study will be performed using the same methodological approach using forecasts of the precipitation and temperature series (in DoW).
Task 12.3: Climate change impact

PT-2 QUERENÇA-SILVES: RECHARGE (BALSEQ_MOD) YEAR: 2100

Average yearly recharge: 245 mm/yr
83.4% Rec 1979-2009

Model HadRM2, IS92a

Average surface runoff: 100 mm/yr
87.6% SR 1979-2009

Average yearly recharge: 136 mm/yr
46.2% Rec 1979-2009

Model HadRM3, SRES A2

Average surface runoff: 59 mm/yr
51.4% Ed 1979-2009

Average yearly recharge: 186 mm/yr
63.3% Rec 1979-2009

Model HadRM3 SRES B2

Average surface runoff: 79 mm/yr
68.9% Ed 1979-2009

Fonte: Relatório LNEC 153/2012 DHA/NAS
Climate change impacts on the behaviour of aquifers and consequently on Groundwater Dependent Ecosystems

> Groundwater levels change due to groundwater recharge decrease

- Modifications in groundwater recharges amounts and periods
- Modification in groundwater flow directions
- Modification in the amount of groundwater reaching GW dependent ecosystems
- Modification on the behaviour of GW dependant ecosystems (eventually at risk)
# NUMERICAL MODELLING IN MANAGED AQUIFER RECHARGE

## CLIMATE CHANGE IMPACT

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Area (km²)</th>
<th>Total area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(GWL &lt; 0 m)</td>
<td>(0 m&lt; GWL &lt; 1 m)</td>
</tr>
<tr>
<td>Reference scenario (current situation)</td>
<td>0.1475</td>
<td>0.2038</td>
</tr>
<tr>
<td>2050 (Variation by removing the lower rainfall values for each season)</td>
<td>0.0550</td>
<td>0.2175</td>
</tr>
<tr>
<td>2050 (Constant value variation by season)</td>
<td>0.0775</td>
<td>0.2119</td>
</tr>
<tr>
<td>2080 (Variation by removing the lower rainfall values for each season)</td>
<td>0.0162</td>
<td>0.1675</td>
</tr>
<tr>
<td>2080 (Constant value variation by season)</td>
<td>0.0256</td>
<td>0.1900</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth to groundwater (2050)</th>
<th>Depth to groundwater (2080)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Current Situation" /></td>
<td><img src="image2" alt="Constant value variation by season" /></td>
</tr>
<tr>
<td><img src="image3" alt="Variation by removing the lower rainfall values for each season" /></td>
<td><img src="image4" alt="Constant value variation by season" /></td>
</tr>
<tr>
<td><img src="image5" alt="Variation by removing the lower rainfall values for each season" /></td>
<td><img src="image6" alt="Variation by removing the lower rainfall values for each season" /></td>
</tr>
</tbody>
</table>

- General reduction in natural recharge and consequent decrease of the groundwater level
- The results vary depending on the variation method of the rainfall series used in final climate change scenarios:
  - **Variation by removing the lower rainfall values for each season method** - loss of 63% for 2050 and 89% for 2080 in wetlands area (NP <0 m) and gain of 4% for 2050 and 7% loss for 2080 in the near-surface groundwater table area (0 m <NP <1 m).
  - **Constant value variation by season method** - loss of 47% in 2050 and 83% in 2080 in wetlands area (NP <0 m) and gain of 7% in 2050 and 18% loss in 2080 for the near-surface groundwater table area (0 m <NP <1 m).
MONITORING WATER QUALITY IN INDUCED RIVERBANK FILTRATION

WP8 - The case study of the Sant’Alessio MAR plant (Italy)

RUDY ROSSETTO¹, CHIARA MARCHINA¹, ALESSIO BARBAGLI¹, G. DE FILIPPIS¹, ENRICO BONARI¹, ELEONORA ANNUNZIATA¹, FRANCESCO RIZZI¹
BORSI IACOPO², PICCIAIA DANIELE²
THOMAS VIEKEN³, MANUEL KRECK³, PIETER DIETRICH³, ...
GIORGIO MAZZANTI, PAOLO MAZZONI, STEFANIA ATIANNASIO

1. INSTITUTE OF LIFE SCIENCES, SCUOLA SUPERIORE S. ANNA, PISA
2. TEA SISTEMI SPA
3. UFZ
4. PROVINCIA DI LUCCA

Supporting water utility:

GEAL
L'impianto di ricarica riverbank filtration di S. Alessio (Lucca): attività di monitoraggio e modellistica nel progetto EU FP7 MARSOL

The riverbank filtration plant in S. Alessio (Lucca): monitoring and modeling activity within EU the FP7 MARSOL project

Iacopo Borsi, Giorgio Mazzanti, Alessio Barbagli, Rudy Rossetto
...M.A.R. IS ORGANIZED (SOMEHOW) IN EUROPE
MAR BOOKS REPOSITORY… over 50 books!!

## NUMERICAL MODELLING IN MANAGED AQUIFER RECHARGE

### LITERATURE REVIEW

Several reports/articles were consulted

<table>
<thead>
<tr>
<th>Author / Project</th>
<th>Site / Study Area</th>
<th>Model</th>
<th>Scale</th>
<th>Study Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chataradong (2000)</td>
<td>San Joaquin Valley, California, USA</td>
<td>HYDRUS-2D (FDM)</td>
<td>Infiltration basin</td>
<td>Evaluation of costs of construction/operation/maintenance of artificial recharge facilities and MAR benefits</td>
</tr>
<tr>
<td>Woelfenden &amp; Koczot (2001)</td>
<td>Rialto-Colton Basin, San Bernardino County, California, USA</td>
<td>? (MODFLOW + MODPATH)</td>
<td>Aquifer</td>
<td>Determine the movement and ultimate disposition of artificially recharged water and simulate general long-term effects on water levels likely to occur as a result of using artificial recharge alternatives</td>
</tr>
<tr>
<td>Haimerl (2002)</td>
<td>Wadi Ahin, Oman</td>
<td>HYDRUS-2D (FDM)</td>
<td>Infiltration basin</td>
<td>Effectiveness of groundwater recharge dams through infiltration process simulation</td>
</tr>
<tr>
<td>Flint (2003)</td>
<td>San Gregorio Pass, California, USA</td>
<td>TOUGH2 (FDM)</td>
<td>Aquifer</td>
<td>Test scenarios for artificial recharge, conceptual model refinement</td>
</tr>
<tr>
<td>Gómez &amp; Díaz (2003)</td>
<td>Wadi Ahin, Oman</td>
<td>PMWIN (MODFLOW)</td>
<td>Aquifer</td>
<td>Simulate alternative artificial recharge process with available surplus water for containing salt water intrusion</td>
</tr>
<tr>
<td>Pliakas et al. (2003)</td>
<td>Xanthi plain, Thrace, Greece</td>
<td>PMWIN (MODFLOW)</td>
<td>Aquifer</td>
<td>Aquifer system response to MAR by exploring different scenarios</td>
</tr>
<tr>
<td>Vicente (2003)</td>
<td>Cubeta de Sant Andreu de la Barca, Spain</td>
<td>Visual MODFLOW</td>
<td>Local (small area of the aquifer)</td>
<td>Simulate artificially recharged water travel time and effects of MAR in aquifer storage</td>
</tr>
<tr>
<td>Lobo Ferreira et al. (2005)*</td>
<td>Campina de Faro, Portugal</td>
<td>Visual MODFLOW</td>
<td>Aquifer system &amp; Local</td>
<td>Aquifer characterization and MAR suitability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(MODFLOW)</td>
<td></td>
<td>Simulation of groundwater flow and salt transport, including density dependent flow at the sea-aquifer interface for the coastal aquifer</td>
</tr>
<tr>
<td>Lobo Ferreira et al. (2005)*</td>
<td>Ashdod City, Israel</td>
<td>VASP software (FEM)</td>
<td>Local (small area of the aquifer)</td>
<td>Aquifer characterization and MAR suitability</td>
</tr>
<tr>
<td>Lobo Ferreira et al. (2005)*</td>
<td>Beit Lahiya, Gaza, South Palestine</td>
<td>Visual MODFLOW</td>
<td>Local (small area of the aquifer)</td>
<td></td>
</tr>
</tbody>
</table>

* GABARDINE project
## NUMERICAL MODELLING IN MANAGED AQUIFER RECHARGE

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<tr>
<td>Santo Silva et al. (2006)</td>
<td>Planicie de Recife, Brazil</td>
<td>CODE_BRIGHT (FEM)</td>
<td>Local (small area of the aquifer)</td>
<td>Explore future scenarios, validate local well MAR structure</td>
</tr>
<tr>
<td>EPTISA (2009)</td>
<td>Aquífero Crestatx, Mallorca, Spain</td>
<td>Visual MODFLOW (MODFLOW)</td>
<td>Aquifer</td>
<td>Simulate alternative MAR methodologies, explore effects of MAR methodologies while facing a possible increase of water pumping from aquifer</td>
</tr>
<tr>
<td>Goyal et al. (2009)</td>
<td>Hisan, India</td>
<td>HYDRUS-2D (FDM)</td>
<td>Cavity-type artificial recharge well</td>
<td>Simulate drawup and drawdown of piezometric pressure heads in the aquifer storage recovery cycles of varying buffer storage volumes and residence times in a highly brackish, semi-confined aquifer under shallow water-table condition</td>
</tr>
<tr>
<td>Lobo Ferreira et al. (2009)**</td>
<td>Cap Bon, Tunisia</td>
<td>GMS (FEMWATER)</td>
<td>Local (small area of the aquifer)</td>
<td>Tests scenarios for artificial recharge, and saltwater intrusion containment</td>
</tr>
<tr>
<td>Koukidou et al. (2010)</td>
<td>Timavos alluvial basin, Thessaly, Greece</td>
<td>FLOW (FEM)</td>
<td>Aquifer</td>
<td>Characterize the regional groundwater flow system and develop appropriate models for assessing artificial recharge as a way to restore groundwater resources</td>
</tr>
<tr>
<td>Kareem (2012)</td>
<td>Jolak basin, Karkuk, Iraq</td>
<td>GMS (MODFLOW)</td>
<td>Aquifer</td>
<td>Artificial recharge through rainwater harvesting and effects in the aquifer groundwater levels</td>
</tr>
<tr>
<td>Hashemi (2013)</td>
<td>Gareh-Bygone Plain, Iran</td>
<td>? (MODFLOW + PEST)</td>
<td>Aquifer</td>
<td>Simulate the floodwater spreading system effects in aquifer groundwater levels</td>
</tr>
<tr>
<td>May et al. (2013)</td>
<td>Aquifer System of Langat Basin, Malaysia</td>
<td>GMS (MODFLOW)</td>
<td>Aquifer</td>
<td>Evaluating the effects of heavy groundwater withdrawal and artificial groundwater recharge of an ex-mining pond to the aquifer system of the Langat Basin through several scenario simulations</td>
</tr>
<tr>
<td>Handel et al. (2004)</td>
<td>-</td>
<td>HYDRUS-2D/3D (FDM) + COMSOL (?)</td>
<td>Small diameter wells</td>
<td>Explore the potential of small-diameter wells as a new ASR recharge approach for shallow unconsolidated aquifers</td>
</tr>
</tbody>
</table>

** Cooperation project Portugal (LNEC) – Tunisia (INRGREF)**
“Technical Solutions” (T.S) are not related to Managed Aquifer Recharge (MAR) technique as if it was the problem to solve. They are, to a large extent, the group of activities to increase MAR effectiveness, being MAR the solution to many related water management dysfunctions.

Q: How to increase the effectiveness of the devices and the infiltration rate?

A: Adoption of Soil and Aquifer Treatments (SATs) and other complementary techniques, such as design and management improvements applicable to existing devices

MARSOL demo sites: Experiences in 8 Mediterranean demo sites:

1- Lavrion
2- Algarve & Alentejo
3- Arenales
4- Llobregat
5- Brenta
6- Serchio
7- Menashe
8- Malta South
## Facilities inventory

### Facilities inventory

<table>
<thead>
<tr>
<th>Number</th>
<th>System</th>
<th>MAR Device</th>
<th>Logo</th>
<th>Figure</th>
<th>Photo</th>
<th>Legend</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Infiltration Pond/Wetlands</td>
<td><img src="image1.png" alt="Logo" /></td>
<td><img src="image2.png" alt="Figure" /></td>
<td><img src="image3.png" alt="Photo" /></td>
<td>Artificial wetland for recharge in Canovas, Coria, Segovia (Spain). Photo: JIRAM/EA.</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Channels and Infiltration Ditches</td>
<td><img src="image4.png" alt="Logo" /></td>
<td><img src="image5.png" alt="Figure" /></td>
<td><img src="image6.png" alt="Photo" /></td>
<td>Artificial recharge channel of the Basin of Guadalix, Segovia, Spain, operated since 2002. Photo: JIRAM/EA.</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>Infiltration Bed (Soil and Controlled Spreading)</td>
<td><img src="image7.png" alt="Logo" /></td>
<td><img src="image8.png" alt="Figure" /></td>
<td><img src="image9.png" alt="Photo" /></td>
<td>Artificial recharge by irrigation return. Photo: J. Pagés.</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>Accidental Recharge by Irrigation Return</td>
<td><img src="image10.png" alt="Logo" /></td>
<td><img src="image11.png" alt="Figure" /></td>
<td><img src="image12.png" alt="Photo" /></td>
<td>Artificial recharge by irrigation return. Photo: J. Pagés.</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>Soft Dunes Wetlands</td>
<td><img src="image13.png" alt="Logo" /></td>
<td><img src="image14.png" alt="Figure" /></td>
<td><img src="image15.png" alt="Photo" /></td>
<td>Subsurface (Colorado)</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>Infiltration Basins and Dams</td>
<td><img src="image16.png" alt="Logo" /></td>
<td><img src="image17.png" alt="Figure" /></td>
<td><img src="image18.png" alt="Photo" /></td>
<td>Artificial recharge in the basin of Atarés, Aleixos, Spain.</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>Permeable Dams</td>
<td><img src="image19.png" alt="Logo" /></td>
<td><img src="image20.png" alt="Figure" /></td>
<td><img src="image21.png" alt="Photo" /></td>
<td>Permeable dams in Benia, Spain. Photo: Tragnac.</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>Tanks</td>
<td><img src="image22.png" alt="Logo" /></td>
<td><img src="image23.png" alt="Figure" /></td>
<td><img src="image24.png" alt="Photo" /></td>
<td>Reservoir in Santa Ana river, Orange County, California. USA. Photo: A. Garcia.</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>Inverted Scouring</td>
<td><img src="image25.png" alt="Logo" /></td>
<td><img src="image26.png" alt="Figure" /></td>
<td><img src="image27.png" alt="Photo" /></td>
<td>Artificial recharge in Jaxima river, Barcelona, Spain. Photo: J. Alexandre.</td>
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<tr>
<td>10</td>
<td>10</td>
<td>Subsurface/Underground Dams</td>
<td><img src="image28.png" alt="Logo" /></td>
<td><img src="image29.png" alt="Figure" /></td>
<td><img src="image30.png" alt="Photo" /></td>
<td>Sub-surface dam in Kii, Kenya. Photo: Sander de Haan.</td>
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<tr>
<td>11</td>
<td>11</td>
<td>Drilled Basins</td>
<td><img src="image31.png" alt="Logo" /></td>
<td><img src="image32.png" alt="Figure" /></td>
<td><img src="image33.png" alt="Photo" /></td>
<td>Artificial basin, Leopold, Germany. Photo: Tragnac.</td>
</tr>
</tbody>
</table>

**Total Devices:** 25
### Facilities inventory

<table>
<thead>
<tr>
<th>#</th>
<th>SYSTEM</th>
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<tbody>
<tr>
<td>13</td>
<td>DEEPWELL AND DECOCKAGE SYSTEM</td>
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<td><img src="image1.jpg" alt="Logo" /></td>
<td><img src="image2.jpg" alt="Figure" /></td>
<td><img src="image3.jpg" alt="Photo" /></td>
<td>Deepwell in Cuzarancea aff. Napura, Segovia, Spain. Photo: E.T. Estebanez</td>
</tr>
<tr>
<td>14</td>
<td>DEEPWELL AND DECOCKAGE SYSTEM</td>
<td>DEEPWELL AND DECOCKAGE SYSTEM</td>
<td><img src="image4.jpg" alt="Logo" /></td>
<td><img src="image5.jpg" alt="Figure" /></td>
<td><img src="image6.jpg" alt="Photo" /></td>
<td>Artificial water well, Colorado, USA. Photo: DRA/MAR</td>
</tr>
<tr>
<td>15</td>
<td>DEEPWELL AND DECOCKAGE SYSTEM</td>
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<td><img src="image7.jpg" alt="Logo" /></td>
<td><img src="image8.jpg" alt="Figure" /></td>
<td><img src="image9.jpg" alt="Photo" /></td>
<td>Artificial water well, Colorado, USA. Photo: DRA/MAR</td>
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<td><img src="image12.jpg" alt="Photo" /></td>
<td>Artificial water well, Colorado, USA. Photo: DRA/MAR</td>
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<tr>
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<td>DEEPWELL AND DECOCKAGE SYSTEM</td>
<td><img src="image13.jpg" alt="Logo" /></td>
<td><img src="image14.jpg" alt="Figure" /></td>
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<td>Artificial water well, Colorado, USA. Photo: DRA/MAR</td>
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<td>Artificial water well, Colorado, USA. Photo: DRA/MAR</td>
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<td>Artificial water well, Colorado, USA. Photo: DRA/MAR</td>
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<td><img src="image23.jpg" alt="Figure" /></td>
<td><img src="image24.jpg" alt="Photo" /></td>
<td>Artificial water well, Colorado, USA. Photo: DRA/MAR</td>
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<td><img src="image26.jpg" alt="Figure" /></td>
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<td>Artificial water well, Colorado, USA. Photo: DRA/MAR</td>
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<td>DEEPWELL AND DECOCKAGE SYSTEM</td>
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<td><img src="image29.jpg" alt="Figure" /></td>
<td><img src="image30.jpg" alt="Photo" /></td>
<td>Artificial water well, Colorado, USA. Photo: DRA/MAR</td>
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<td>DEEPWELL AND DECOCKAGE SYSTEM</td>
<td><img src="image31.jpg" alt="Logo" /></td>
<td><img src="image32.jpg" alt="Figure" /></td>
<td><img src="image33.jpg" alt="Photo" /></td>
<td>Artificial water well, Colorado, USA. Photo: DRA/MAR</td>
</tr>
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<td>24</td>
<td>DEEPWELL AND DECOCKAGE SYSTEM</td>
<td>DEEPWELL AND DECOCKAGE SYSTEM</td>
<td><img src="image34.jpg" alt="Logo" /></td>
<td><img src="image35.jpg" alt="Figure" /></td>
<td><img src="image36.jpg" alt="Photo" /></td>
<td>Artificial water well, Colorado, USA. Photo: DRA/MAR</td>
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<tr>
<td>25</td>
<td>DEEPWELL AND DECOCKAGE SYSTEM</td>
<td>DEEPWELL AND DECOCKAGE SYSTEM</td>
<td><img src="image37.jpg" alt="Logo" /></td>
<td><img src="image38.jpg" alt="Figure" /></td>
<td><img src="image39.jpg" alt="Photo" /></td>
<td>Artificial water well, Colorado, USA. Photo: DRA/MAR</td>
</tr>
</tbody>
</table>
Soil Aquifer Treatment - Example

Percentage of water reuse

- Israel: 75%
- Spain: 12%
- Australia: 9%
- Italy: 8%
- Greece: 5%
- C. Europe: <1%
DEMO SITE 7: MENASHE INFILTRATION BASIN, HADERA, ISRAEL

Figure 2: Geological setting of the Menashe site and its catchment area
Soil Aquifer Treatment - Operations

Hydraulic capacity and evaporation

Infiltration basins are typically intermittently flooded
- to provide regular drying periods,
- for restoration of infiltration rates and
- for aeration of the soil.
(Between 8 hours dry-16 hours flooding to 2 weeks dry-2 weeks flooding)
→ Number of basins so that some basins can be flooded while others are drying

Annual infiltration amounts (hydraulic loading rates) typically vary from 15 m/year to more than 100 m/year.

Thus, assuming a sewage production of 100 L/person day, a city of 100,000 people, and a hydraulic loading rate of 50 m/year,

→ a SAT system for the entire sewage flow would require about 7.3 ha of infiltration basins.
MARSOL

Demonstration sites activities...
...treated waste water, river water, desalinated water, rainwater harvesting...
WP Investigation and Monitoring

Objective of the Work Package

Main objective of the workpackage is the development of sensor systems and data acquisition systems tailored for MAR sites. In particular

• optimization of tailored TDR sensors for unsaturated zone soil moisture monitoring and
• development a web based data management platform
WP4 "DEMO SITE 2: ALGARVE AND ALENTEJO, SOUTH PORTUGAL"

**PT participants:**
- Teresa E. Leitão, J.P. Lobo Ferreira, Manuel M. Oliveira, Tiago Martins, Maria José Henriques, João Rogeiro, Ana Maria Carmen (LNEC)
- Tiago Carvalho, José Martins de Carvalho, Rui Agostinho, Rita Carvalho (TARH)
- José Paulo Monteiro, Luís R.D. Costa, Rui Hugman (UAlg)

With the support of: APA Algarve, Alentejo and AdA - Águas do Algarve
WP 4: DEMO SITES - PORTUGAL

- PT1 Algarve, rio Seco (Campina de Faro aquifer)
- PT2 Algarve, rib. Meirinho (Querença-Silves aquifer)
- PT3 Alentejo, Melides (lagoon)

Regional scale water balances
WP4: DEMO SITE 2 - PORTUGAL

PT2_6 Algarve, São Bartolomeu de Messines
Rever legenda....Está em Pt. Pode-se traduzir o nome das estruturas principais e retirar o resto.

Raquel; 04/03/2016
PT2_6 Algarve, São Bartolomeu de Messines
Rever legenda....Está em Pt. Pode-se traduzir o nome das estruturas principais e retirar o resto.
Raquel; 04/03/2016
PT2_6 Algarve, São Bartolomeu de Messines

Method: Infiltration and drainage in two SAT basins

Monitoring:

- Continuous inflow and outflow monitoring of EC, pH, Redox, T
- Manual inflow and outflow sampling
- Vadose zone sampling (20 cm and 40 cm); 2 instruments in each basin
- Monitoring of pH, TSS, COD, BOD5, N total, P total, N-NH4, N-NO3, faecal coli, EC, all N forms, phosphates and sulphates (Águas do Algarve)
- Monitoring of pharmaceuticals (IWW), nutrients, major ions, B, Cu, Zn, COT, UV 254/453, SUVA
PT3_7 Alentejo, Melides (lagoon)

Melides lagoon sometimes presents pollution problems due to rice field pad activities.

A physical (sandbox) model was built in LNEC pavilions during MARSol project.

Several experiments were made to simulate soil-aquifer-treatment (SAT-MAR) processes to remove rice field pollutants prior to their discharge in Melides lagoon.
### Sources for the artificial recharge: Quantity

<table>
<thead>
<tr>
<th>Dam</th>
<th>Hydrological year</th>
<th>Depth discharge (*10^3 m^3)</th>
<th>Surface discharge (*10^3 m^3)</th>
<th>Total discharge (*10^3 m^3)</th>
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</thead>
<tbody>
<tr>
<td>ARADE</td>
<td>2000/2001</td>
<td>37 499.20</td>
<td>19 256.70</td>
<td>56 755.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ARADE</td>
<td>1995/96</td>
<td>0</td>
<td>81 255.39</td>
<td>81 255.39</td>
</tr>
<tr>
<td></td>
<td>1996/97</td>
<td>0</td>
<td>42 599.62</td>
<td>42 599.62</td>
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<tr>
<td></td>
<td>1997/98</td>
<td>8 556.65</td>
<td>113 762.30</td>
<td>122 318.97</td>
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<tr>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TOTAL (*10^3 m^3) 246 173.98</td>
</tr>
</tbody>
</table>
During the extreme drought of 2004/2005

<table>
<thead>
<tr>
<th></th>
<th>Volume of withdrawal water (*10^6 m^3)</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>23.79</td>
<td>47.31%</td>
</tr>
<tr>
<td>Urban supply of the Águas do Algarve regional system of Algarve</td>
<td>14.25</td>
<td>28.34%</td>
</tr>
<tr>
<td>Urban supply of the local municipalities</td>
<td>12.25</td>
<td>24.36%</td>
</tr>
<tr>
<td>Private users</td>
<td>Not Available</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>50.29</td>
<td>100%</td>
</tr>
</tbody>
</table>
The numerical model simulation scales at Regional scale, local scale and test site scale predicted in the projected for Demo site 2 – PT 2 Querença-Silves Aquifer
Experiment goal: assess Cerro do Bardo MAR site infiltration capacity and groundwater flow path

Recharge experiment: infiltration of 47 L/s (~170 m³/h) of water in Cerro do Bardo dug well and natural sinkholes during 90 hours (coming from a AdA well located ~1.4 km distance)

Tracer: 1000 kg NaCl
WP 4: DEMO SITES - PORTUGAL

Local scale experimental MAR site Querença-Silves aquifer

WHAT WE HAVE DONE:

Site #6: PT2 Algarve, rib Meirinho dike
- Infiltration test in the large well (April 2014)
- Large Infiltration test with geophysics (Dec 2014)
- Dike rehabilitation
- Construction of monitoring infrastructures

![Diagram of injection and recovery period](image)

![Image of injection site](image)
The remaining 33 L/s:
1. have left the well through a bypass
2. being disposed in the stream and
3. further infiltrated into the sink-holes

Depth to the water table (m)

Injection rates

47 L/s → ~0 to 21.7 L/s

~14 L/s well infiltration capacity

CB0 - Cerro do Bardo well
CR1 - Piezometer ~10 m from the well
CB2 - Piezometer ~160 m from the well

0.8 m regional groundwater increase
- Geophysical surveys (absolute (reference) and % change) -

This MAR infiltration and tracer test allowed confirming that the DEMO Site:

- Is an adequate area to infiltrate water coming from the three dams, with the surplus from wet years
- The area has a minimum infiltration capacity of 4060 m³/d (170 m³/h, compared with 35 m³/h in Campina well..., but it depends on headwater...)
- Water flows mainly towards the west direction and downwards
Finite element regional flow model of the Querença Silves Aquifer System

- SW-FW interface Scenario drought 2004-2005 simulation with different injection scenarios

Evolution of Seawater intrusion estimated at Bottom slice

Evolution of Seawater intrusion at cross-section view

Evolution of Seawater intrusion plume at 3D view
Task 4.1: Recharge water availability Campina de Faro
Rainwater harvesting (interception of precipitation in greenhouses)

Aerial view of a greenhouse complex and picture showing it’s actual drainage system.

The area is flat and is characterised by low recharge rates. In this conditions drainage is a serious problems in this area.
Task 4.1: Recharge water availability

Example of some of the wells (Noras) visited and used for Nitrate sampling.

These wells can be used for injection of water obtained from rainwater harvesting in greenhouses.

Campina de Faro aquifer system
Task 4.1: Recharge water availability (Campina de Faro aquifer system)

Rainwater harvesting (interception of precipitation in greenhouses)

- Aquifer area: 86 km²
- Average annual rainfall: 570 mm
- Greenhouses area: 2.74 km²

(by APA - Aerial view 2007/2008)

Potential rainfall harvesting:
1.63 hm³/year (20% of the average water balance - 8.3 hm³/year)

APA Algarve (Environmental Agency) maintain a detailed mapping of the greenhouses. The large diameter wells can be used to inject the water in the shallow aquifer contaminated by nitrates.

Related with WP 12 (Flow & Transport model to simulate the flushing of nitrates)
Nitrate vulnerability zone of Campina de Faro

Interim scale environmental GW quality problems

April 2008

May 2014
WP 4: DEMO SITES - PORTUGAL

Local scale experimental MAR site Campina de Faro

Legend
- Injection well
- Pumping well
- Streamlines
- PT1_1 & PT1_2 Basins

Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere
Projection: Mercator Auxiliary Sphere
Datum: WGS 1984
Units: Meter
Results from continuous monitoring (groundwater and surface water) in Rio Seco artificial recharge basins during winter time (Out.2007/Mar.2008) Carreiros test site

Natural recharge monitoring

Continuous monitoring in three piezometers

Artificial recharge experiments

Electrical resistivity assessment

May 2007
Boundary conditions

2nd kind (Neumann)
Northern boundary in contact with Limestone Cretaceous formations
Integral Flux = -0.004 m/d (all layers)

1st kind (Dirichlet)
Southern boundary (border of aquifer system and contact with marshy zones of Ria Formosa)
Specified Head = 0 (all layers)

3rd kind (Cauchy)
Rio Seco (inside model domain)
Transfer integral is set (see file) just in Layer1

Impervious zones where no boundary conditions is defined (W and E boundaries)

Boundary conditions constrains
1st kind
(constrained by max. Flux=0 m³/d)

3rd kind
(constrained by head min and max. specified values)
File: Gradientes.xls
Source/sink rate in transfer = 9.7E-04 /d
Spatial distribution and temporal analysis of the concentration of NO₃

- Temporal evolution of concentrations in individual points:
- Decrease in points to the North/ Increase to the South
- These results show the slow movement of the plume to the South (very low natural hydraulic head gradients < 1%)
Potential rainfall harvesting in greenhouses at the Campina de Faro:
1.63 hm$^3$/year (20% of the average water balance - 8.3 hm$^3$/year)
This is a simulation of the changes in the plume if this water is injected in the large diameter wells.

Steady-state MAR of greenhouse runoff in large diameter wells
Slice 1
(mg NO$_3$/l)
Finite element flow and transport model of the Campina de Faro Aquifer System

Steady-state
Current conditions

Steady-state
MAR of greenhouse runoff in large diameter wells
1.5 millions m3/year
Cross-section steady-state Current conditions 5x vertical exageration (mg NO$_3$/$l$)

Cross-section steady-state MAR of greenhouse runoff in large diameter wells 5x vertical exageration (mg NO$_3$/$l$)
Limited Groundwater resources. Causes

- Low groundwater balance: High demand (agriculture and public supply) along with low recharge.

- Seawater intrusion: thin fresh groundwater lens floating over saline water, subjected to lateral seawater intrusion and upconing effects.

Proposed solution under MARSOL

Test MAR solution – infiltration of treated wastewater surplus in deep boreholes to increase groundwater levels at Mean Sea Level Aquifer (MSLA) and create a barrier to lateral and vertical seawater intrusion.

Test Hypothesis with a 3-D groundwater numerical flow and transport model
General Considerations

Case study
The Mean sea level aquifer (MSLA) to south of the Victoria Fault (considered as a sealing fault)

Modeled area: 185.79 km²
Rainfall: 543 mm

Geology and Hydrogeology
Main formations:
- Lower Coraline Limestones (LCL)
- Blue Clay (aquitard)
- Globigerina Limestone (GL)
- Upper Coraline Limestones (LCL)

Perched Aquifer, not Included in model

Included in MSLA model limits
Numerical Model – MAR Scenarios

Model shows significant increase of groundwater levels after first year and decrease of seawater ratio, when comparing MAR vs No MAR scenarios.

Also, Particle tracking applied on the model shows that injected wastewater flows directly to sea and will not jeopardize the public supply abstraction wells.
Model shows significant increase of groundwater levels after first year and decrease of seawater ratio, when comparing MAR vs No MAR scenarios.

Also, Particle tracking applied on the model shows that injected wastewater flows directly to sea and will not jeopardize the public supply abstraction wells.
D 12.7 THE WHITE BOOK ON MAR MODELLING (MONTH 36):
UNDER DEVELOPMENT AND TO BE LINKED TO THE SC PROPOSED MARSOL BOOK
MARSOL

For more information:
www.marsol.eu or marsol@tu-darmstadt.de