Advanced Monitoring and Investigation Technologies for Managed Aquifer Recharge

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Content

Marsol Objectives

The main objectives of MARSOL can be summarized as:

- Demonstrate at eight field sites that Managed Aquifer Recharge (MAR) is a sound, safe and sustainable strategy to increase the availability of freshwater under conditions of water scarcity.
- Improve the state of the art 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 key technology to face the challenge of increasing water scarcity in southern Europe, the Mediterranean and other regions of the world.

Eight demonstration sites geographically distributed around the Mediterranean have been selected for the demonstration of different MAR objectives and technologies, and using different water sources.

MAR Objectives:

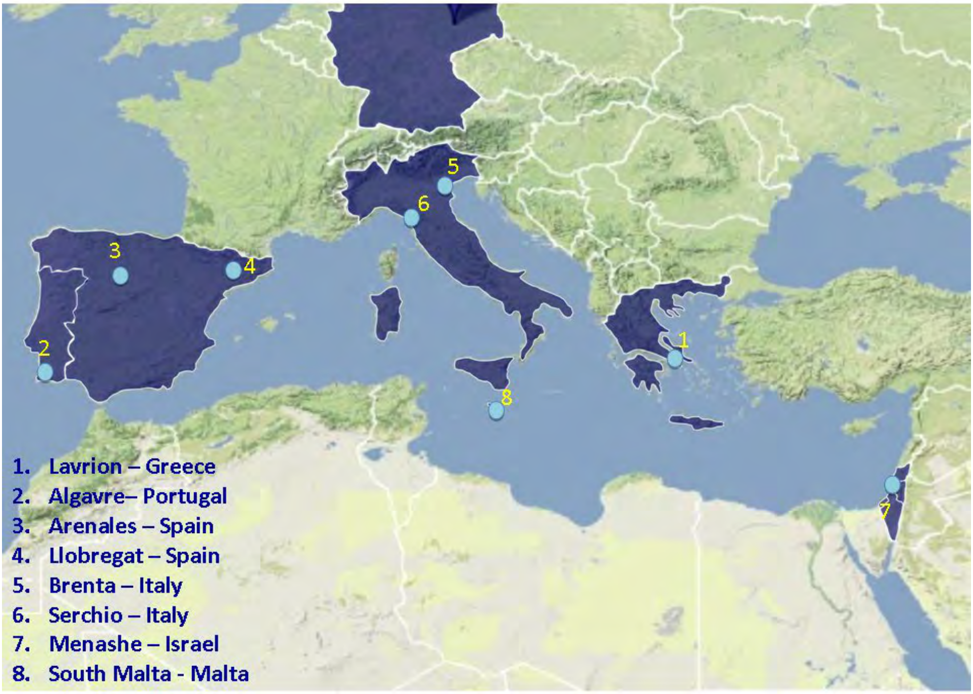
- Replenishing of over-exploited aquifers (Lavrion, Arenales, Llobregat, Brenta)
- Combating sea-water intrusion (Lavrion, Malta South)
- Increasing the ecological and chemical status of aquifers (Campina de Faro, Llobregat, Brenta)
- Soil-Aquifer Treatment (SAT) (Lavrion, Arenales)
- Seasonal storage and aquifer storage recovery of surplus fresh waters (Menashe)

Different recharge techniques:

- Infiltration basins (Lavrion, Campina de Faro, Arenales, Llobregat, Menashe)
- Forested infiltration area (Brenta)
- River bank filtration (Serchio)
- Wells (Campina de Faro, Malta South)
- Others (artificial wetlands, ditches, drainage pipes) (Arenales)

Different recharge water sources:

- Surface waters (Campina de Faro, Arenales, Brenta, Serchio)
- Treated effluents (Lavrion, Arenales, Malta South)
- Desalinated water (Menashe)



Location of MARSOL DEMO sites

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Technological & Cultural Park, Lavrion, Greece

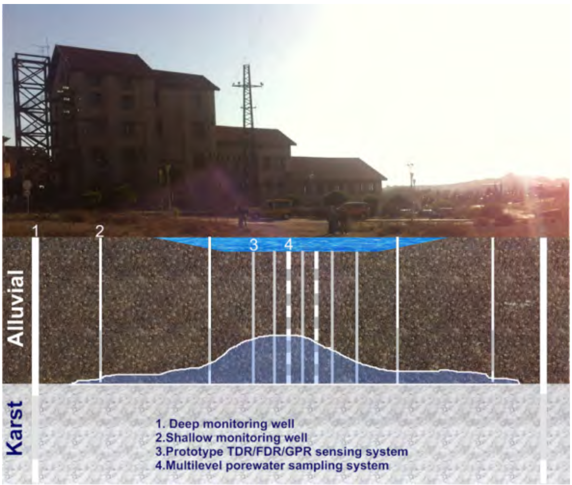
Lavrion Technological & Cultural Park (LTCP) of the National Technical University of Athens is located at the coastal area of Lavrion (Attica), within the wider area of Athens. The case study combines all typical Mediterranean water problems and hydrogeological settings (i.e. seawater intrusion, water scarcity, karst aquifers, extensive irrigation etc.) and MAR application is envisaged to combat all those. The pilot site involves the employment of infiltration basins at experimental scale, which are using waters of impaired quality as a recharge source, hence acting as a Soil-Aquifer-Treatment (SAT) system. The LTCP site is used as a reference experimental site to develop, adapt, integrate and demonstrate new technological developments that can provide:

- High resolution monitoring of MAR related hydrologic processes
- Subsurface investigation and characterization through the application advanced in situ technologies
- Reliable acquisition and transfer of environmental data
- A web-based portal application for reliable data storage and management

Lavrion Technological & Cultural Park, Lavrion, Greece

To realize the above:

- The basins are equipped with new prototype Time & Frequency Domain Reflectometry technologies that are developed, adapted and integrated during MARSOL; providing continuous monitoring of the infiltrating recharge-water.
- Radar-based systems such as Continuous Wave and Ground Penetrating Image Radars have been developed to monitoring relative changes of the groundwater in the unsaturated and saturated zone respectively.
- A research platform for model supported near surface characterization has been employed, that combines non-invasive surface geophysical measurements and minimum invasive Direct Push in-situ profiling technology, providing extensive multi-scale data sets.
- A wireless ad-hoc sensor network for adaptive process oriented environmental monitoring (including an open platform to connect sensors and actuators) is developed and installed, that is used for the realization of real-time hydrological/climate data-transfer during artificial recharge within the pilot area.
- A web-based data platform has been developed to provide long-term statistical series of specific hydrologic variables for the analysis of the MAR experimental facility in LTCP.



Conceptualization of the monitoring instrumentation of the LTCP experimental basin

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Direct Push for enhanced site characterization

High resolution information about the subsurface structure, especially about hydraulic conductivity (*K*) and its distribution in space is essential for understanding and predicting groundwater flow and transport processes. This is particularly true for sedimentary deposits with a high degree of heterogeneity and complex sedimentary architecture. In many cases, traditional tests, e.g. calculation of *K* based on grain size distribution or pumping tests, fail to provide required accuracy, spatial resolution or efficiency under these conditions. Against this background, Direct Push profiling technology has been developed over the last decades and has become a reliable and, in many cases, advantageous alternative for high resolution site characterization of sedimentary deposits. Thereby, Direct Push refers to a technology that uses hollow steel rods that are hammered and/or pushed into the subsurface.

By attaching sensor probes at the end of the rod string, continuous in-situ vertical high resolution profiling of various deposit specific characteristics can be performed. Alternatively, Direct Push can be used to rapidly install permanent or temporary groundwater monitoring wells or to retrieve minimally disturbed soil samples. For hydrogeological site investigations, geophysical, hydrogeological and geotechnical Direct Push profiling tools can be used. Among the variety of available Direct Push applications, tools that were frequently applied in the course of the MARSOL project include Direct Push electrical conductivity profiling (EC), Direct Push Injection Logging (DPIL), and Direct Push Slug Testing. In the following, a brief overview of theses specific tools is provided.

Direct Push profiling

Electrical conductivity logging is an efficient tool for very rapidly gaining high resolution vertical profiles of the distribution of soil electrical conductivity in the subsurface. Therefore, as the EC probe is advanced into the subsurface an electrical current is applied and the current and resulting voltage are measured. Based on this information, groundwater confining clay rich layers within the subsurface can be rapidly inferred, as an increase in the electrical conductivity under non-saline conditions often corresponds to an increase of clay material content in the soil.

DPIL was used to distinguish between layers of different hydraulic properties. This tool is used semi-continuously, i.e. measurements are taken at discrete depth intervals (e.g. every 0.5 m). During the measurement water is injected into the soil through a screen at the tip of the probe while the injection rate and line pressure is recorded. Relative hydraulic conductivity, a proxy closely correlated to *K*, is derived as function of flow rate, injection pressure, and different system parameters. DP electrical conductivity and injection logging in-situ profiling results are available at real-time during the measurement progress. This allows on-site decision making, e.g. exact delineation of aquifer confining layers prior to well installation, ensuring an optimized well design.

EC probe (top) and DPIL probe (bottom)

To derive absolute *K* values in specific depths or specific units that were identified using EC logging or DPIL, Direct Push Slug Testing was used. Therefore, temporary groundwater monitoring wells were installed and pneumatic slug testing performed. Thereby, the well is pressurized until the head in the well has adjusted to a predefined pressure value. In a second step, this excess pressure is instantaneously released, leading to a near instantaneous change in head. Head recovery is recorded with a pressure transducer and can be analyzed using specific models. By pulling up the rod string of the temporary ground water monitoring wells, multilevel slug testing can be performed at different depths. The combination of different DP tools has proven to be a very reliable approach for the efficient high resolution vertical hydraulic characterization of the different MARSOL test sites.

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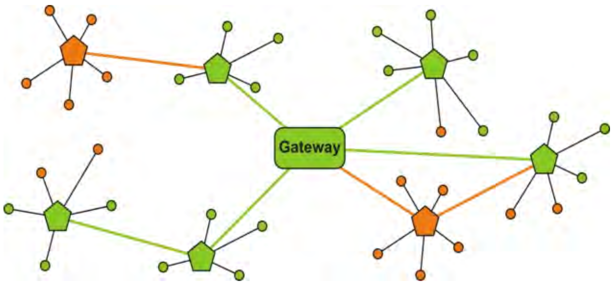
Wireless Sensor Networks

For an adequate characterization of ecosystems it is necessary to detect individual processes with suitable monitoring strategies and methods. Due to the natural complexity of all environmental compartments, single point or temporally and spatially fixed measurements are mostly insufficient for an appropriate representation.

The application of wireless sensor networks for soil, plant, and atmosphere sensing offers significant benefits, due to the simple adjustment of the sensor distribution, the sensor types and the sample rate to the local test conditions. This can be essential for the monitoring of heterogeneous and dynamic environmental systems and processes. Additionally, since there is no need of external power supply and data cable the sensor nodes ensures a minimal invasive behavior. Hence, the application of wireless sensor networks provides an innovative tool for efficient and multi-parametric environmental monitoring over large study areas. To improve the investigation of nature processes by implement other measurement methods the sensor network can be easily adapt by new sensor nodes.

Weather station in Lavrion park



Ad hoc sensor network (schematic)

Multispectral and soil moisture sensor node

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MARSOL Database Management System

The MARSOL web based data platform was designed to provide long-term statistical series of specific hydrologic variables for the analysis of the MAR facilities which will be used to derive efficient prevention, mitigation and adaptation strategies.
The portal application brings the data together which are collected from the individual sensors. It serves as a database node to provide scientists and decision makers with reliable and well accessible data and data products.
In particular, the collected data from the different pilots in MARSOL are stored in a database carefully designed for the purposes of each pilot. In addition, a graphical user interface was designed offering interaction with the user and visualizing the results.

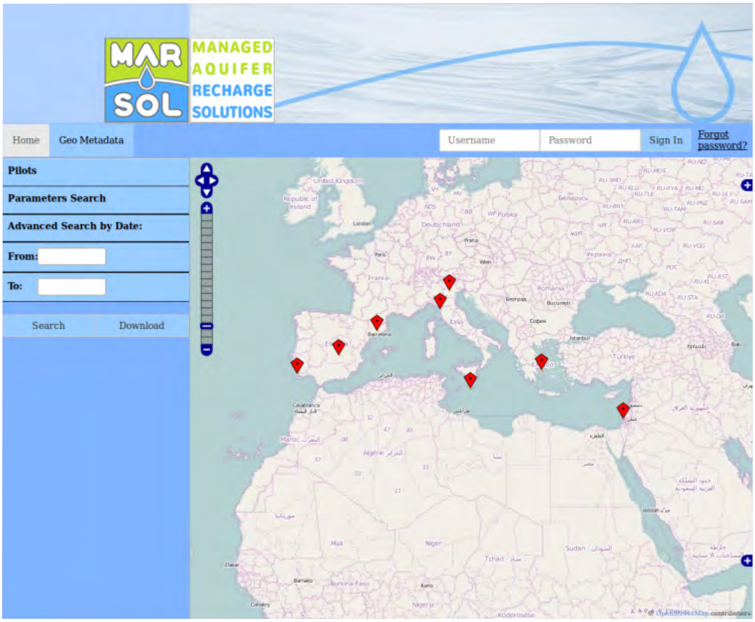

Image of MARSOL web platform (link: marsol.iccs.gr)

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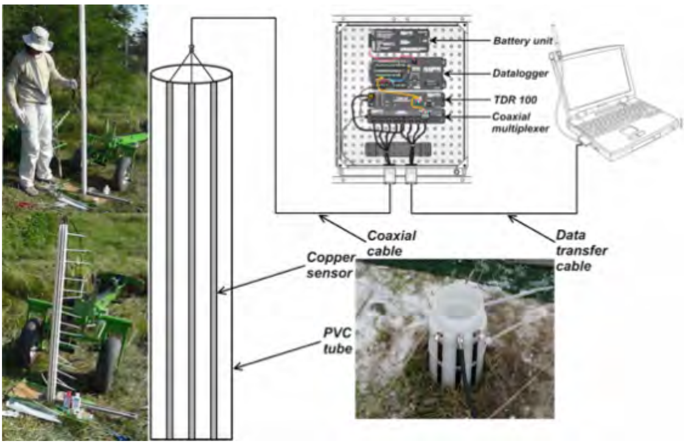
The wide application of electromagnetic methods (EM) - such as Time and Frequency Domain Reflectometry- in the collection of water content data have allowed the unsaturated zone to be included quantitatively in numerous hydrological processes. The basis for these advances in EM methods was the development of improved understanding of microwave interaction in soil as applied to the measurement of water content.

Time Domain Reflectometry:
TDR estimates the bulk dielectric permittivity, ε_b, of the soil mixture (soil matrix, soil water and air) by measuring the propagation time of an EM pulse, generated by a pulse generator and containing a broad range of different measurement frequencies. The technique involves the installation of vertically inserted long waveguides, that cover significant part of the unsaturated zone, offering continuous monitoring of the infiltrating water front during infiltration. The measured waveform is analyzed by using an inverse modeling approach, resulting in an apparent relative dielectric permittivity profile of the surrounding medium along the TDR sensor length. The derived dielectric profile is then converted into volumetric soil water content profile along the sensor applying Topp-formula (universal empirical equation which describes volumetric water content as a function of dielectric permittivity).
Additionally, tailored software was developed that provides optimized management and compression of the TDR waveforms.



Conceptualization of the TDR development

Frequency Domain Measurements:

High frequency measurements like time and frequency domain are important parts in monitoring concepts of managed aquifers. Also with frequency domain (FD) methods issues like water saturation level and infiltration process can be investigated.

Therefore similar wave-guides are vertically installed in the unsaturated zone and excited with electromagnetic waves. By capturing and evaluating the waves, detailed properties of surrounding materials can be determined.

Frequency Domain Measurement Technologies are based on swept continuous waves sent and received by a vector network analyzer (VNA). They show potentially higher data precision and measurable distance. Additionally more information about the soil frequency spectrum can be gained from the improved inversion algorithm. Due to the measurement from two sides of the sensor rode more information of the soil under test are available. This leads to the higher data precision and the improved inversion. Furthermore the sophisticated calibration methods of the VNAs make it possible to remove unwanted influences and disturbances.

Preparation of FD-sensor rode with cables for two side measurements

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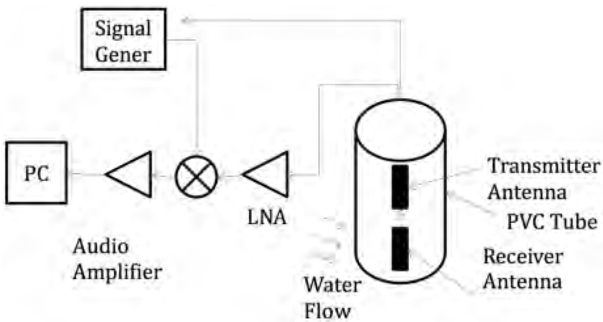
Radar Based Sensing Technologies

During MARSOL, a set of radar based sensing technologies has been developed to complement the monitoring of MAR related hydrologic processes in the subsurface. More specifically, the aforementioned technologies regard the development of a Continuous Wave and a Ground Penetrating Image Radar.

CW Doppler Radar:

The proposed measurement principle is based on the Doppler component of backscattered radiation using continuous wave (CW) radar. The transmitter and receiver antennas are placed inside the TDR sensing probes, while the frequency of 800MHz is selected as a comprise to have a good propagation within the subsurface, keeping attenuation low while have measurable Doppler shift.

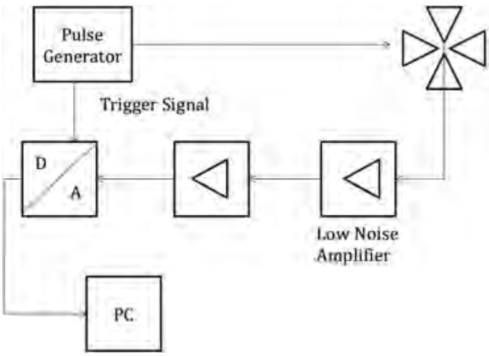


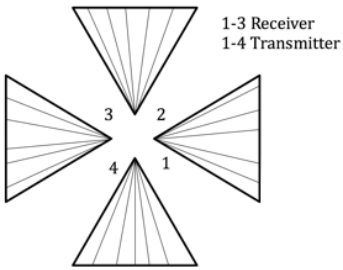
Operation principle and block diagram of the Continuous Wave (CW) Radar

Image of the Continuous Wave Radar

Ground Penetrating Image Radar:

The Ground Penetrating Image Radar (GPIR) system is developed of two antennas of bow-tie being orthogonal to each other in order to achieve a good isolation between the pulsed transmitter and receiver. The use of two orthogonal polarizations is expected to improve the detection of water table changes in the saturated zone. A pulse of 50V amplitude and duration of 10 sec is transmitted by one bow-tie dipole while the reception of signals is done by some antenna being orthogonal to the transmit antenna. The receiver consists of a chain of a low noise amplifier to drive directly an Analog to Digital Converter operating with a sample rate of 150 MS/sec. The trigger signal is received from the transmitted pulse and is shared in a temporary memory, while later the received signals are being averaged to a number 100-1000 to improve the signal to noise ratio. The data processing consists basically of implementing a sensitivity time control and presentation of reflection coefficient versus time delay-depth.





Operation principle and block diagram of the Ground Penetrating Radar (top)

Image of the Ground Penetrating Radar (bottom)

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WP Investigation and Monitoring Techniques

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