The MARSOL project has received funding from the European Union’s Seventh Framework Programme for Research, Technological Development and Demonstration under grant agreement no 619120.

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**MARSOL**

**Demonstrating Managed Aquifer Recharge as a Solution to Water Scarcity and Drought**

**MAR to combat seawater intrusion and to apply SAT in alluvial and karstified aquifers, Lavrion, Greece**

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<td>Version Date</td>
<td>30.11.2016</td>
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Contents

Executive Summary ........................................................................................................................................ 7

1. Overview .................................................................................................................................................. 8

2. General Setting of the Study Area ........................................................................................................ 9

3. Geological Setting of the Study Area .................................................................................................. 11

4. Hydrometeorology ............................................................................................................................. 13

5. Hydrogeological Conditions ............................................................................................................... 14

6. Direct Push Vibro-Coring Activities .................................................................................................. 24

7. Geophysical Investigations ................................................................................................................ 30

8. Hydrochemical conditions in the aquifer system of Lavrion .............................................................. 32

9. Development and application of a multi-criteria decision support system for a MAR-SAT location in Attica ......................................................................................................................... 37

10. Development of an experimental Soil-Aquifer Treatment (SAT) system and an accompanying monitoring system in the Lavrion Technological and Cultural Park (LTCP) ........................................... 38

   10.1. General description of the activities within the Technological Park ............................................ 38

   10.2. Complementary adjustment and integration of the monitoring systems (TDR & FDR) .............. 39

   10.3. Geophysical and direct-push investigation for the optimal location of the experimental SAT basin ................................................................................................................................................. 40

   10.4. Construction and operation of an experimental-scale SAT basin at the Lavrion Technological and Cultural Park (LTCP) ........................................................................................................... 42

   10.5. Wireless Sensor Network .......................................................................................................... 48

   10.6. Web-based data management Platform ...................................................................................... 50

11. GW Modeling and upscale of SAT facilities for the coastal aquifer of Lavrion .................................. 53

   11.1. Groundwater flow model setup .................................................................................................. 53

   11.2. Upscale of MAR-SAT and modelling under different scenarios .................................................. 57

12. Dissemination and training activities ................................................................................................. 62

   12.1. Introduction .................................................................................................................................... 62

   12.2. Training of young scientists and engineers .............................................................................. 62

   12.3. Lavrion Workshop, 16-18 March 2016 .................................................................................... 64

   12.4. Other dissemination activities .................................................................................................... 68

13. Conclusions ............................................................................................................................................ 69

14. References ............................................................................................................................................ 70
List of Figures

Figure 1: Research activities scheme that was performed during WP3 of the MARSOL project ......................................................... 8
Figure 2: Geographical location of the study area ................................................................. 9
Figure 3: Land use of map of the study area (based on CORINE 2012). .............................. 10
Figure 4: Geological map of the study area (IGME 2003, 2007, with modifications) ........... 11
Figure 5: Mean annual precipitation in Lavrion during the period 1970-2015 ........................ 13
Figure 6: Areas where the boundaries of the hydrogeological basin where defined in the southern (a) and northern (b) part of the study area ................................................................. 14
Figure 7: Monitoring wells network in the study area .......................................................... 15
Figure 8: Piezometric conditions of the alluvial aquifer in May 2014 ................................. 15
Figure 9: Piezometric conditions of the alluvial aquifer in August 2014 ............................ 16
Figure 10: Piezometric conditions of the alluvial aquifer in October 2014 .......................... 16
Figure 11: Piezometric conditions of the alluvial aquifer in January 2015 .......................... 17
Figure 12: Piezometric conditions of the alluvial aquifer in May 2015 ............................... 17
Figure 13: Piezometric conditions of the alluvial aquifer in January 2016 .......................... 18
Figure 14: Piezometric conditions of the alluvial aquifer in April 2016 ............................. 18
Figure 15: Piezometric conditions of the alluvial aquifer in June 2016 .............................. 19
Figure 16: Piezometric conditions of the alluvial aquifer in September 2016 ..................... 19
Figure 17: Flow diagram with the inflows and outflows of the karstic aquifer ....................... 20
Figure 18: Hydraulic head fluctuations at drill into the karstic aquifer (point K1) ................. 20
Figure 19: Results of the pumping test analysis along with the final values .......................... 21
Figure 20: Response to pumping measured in a piezometer. The shape of the response curve is due to water being flushed from fractures that become hydraulically connected after pumping ........................................................................................................ 22
Figure 21: Comparison of the hydraulic heads in the karstic (D8) and the alluvial (MSW11) aquifers .............................................................................................................................. 23
Figure 22: Locations of direct-push activities in the alluvial aquifer of Lavrion .................... 24
Figure 23: Direct-push activities in the alluvial aquifer of Lavrion: (a) installation of multi-level piezometers and (b) electrical conductivity logging ................................................................. 24
Figure 24: Results from electrical conductivity logging through direct-push activities ......... 27
Figure 25: Results from electrical conductivity logging through direct-push activities ........ 28
Figure 26: Results from electrical conductivity logging through direct-push activities ........ 28
Figure 27: Results from electrical conductivity logging through direct-push activities ........ 29
Figure 28: Results from electrical conductivity logging through direct-push activities ........ 29
Figure 29: Location of the ERT and IP profiles that were performed during the MARSOL project. ........................................................................................................................................................................ 30

Figure 30: ERT profiles that were performed during the MARSOL project (TR1-TR8) (all units in x/y axes are in meters). ........................................................................................................................................................................................................................................ 31

Figure 31: Monitoring network for the qualitative measurements of the coastal hydrosystem of Lavrion........................................................................................................................................................................ 32

Figure 32: Chloride concentrations distribution in the groundwater prior the irrigation period of 2014 (April 2014). ........................................................................................................................................................................................................................................ 33

Figure 33: Chloride concentrations distribution in the groundwater prior the irrigation period of 2015 (May 2014). ........................................................................................................................................................................................................................................ 33

Figure 34: Chloride concentrations distribution in the groundwater prior the irrigation period of 2016........................................................................................................................................................................................................................................ 34

Figure 35: Piper diagram regarding the groundwater samples taken prior to the irrigation period of 2014. ........................................................................................................................................................................................................................................ 35

Figure 36: Piper diagram regarding the groundwater samples taken prior to the irrigation period of 2015. ........................................................................................................................................................................................................................................ 35

Figure 37: Piper diagram regarding the groundwater samples taken prior to the irrigation period of 2016. ........................................................................................................................................................................................................................................ 36

Figure 38: Isotopic signatures of the GW samples based on the aquifer type and period of sampling. ........................................................................................................................................................................................................................................ 36

Figure 39: Isotopic signatures of the GW samples based on different sources ........................................................................................................................................................................................................................................ 36

Figure 40: Final suitability map (Tsagaratos et al., 2013). ........................................................................................................................................................................................................................................ 37

Figure 41: Research activities scheme for the experimental-scale SAT system at the Lavrion site. ........................................................................................................................................................................................................................................ 38

Figure 42: Development of soil column experiments for the integration of the TDR and FDR systems that were developed during the completion of WP11........................................................................................................................................................................................................................................ 39

Figure 43: Optimal location of the experimental-scale SAT basin on the premises of Lavrion Technological and Cultural Park (LTCP), location of geophysical profiles. ........................................................................................................................................................................................................................................ 40

Figure 44: Optimal location of the experimental-scale SAT basin on the premises of the Lavrion Technological and Cultural Park (LTCP), results of resistivity measurements. ........................................................................................................................................................................................................................................ 41

Figure 45: Optimal location of the experimental scale SAT basin on the premises of the Lavrion Technological and Cultural Park (LTCP), results of non-invasive geophysical investigations. ........................................................................................................................................................................................................................................ 41

Figure 46: Direct-push equipment at the location of the experimental-scale SAT basin on the premises of the Lavrion Technological and Cultural Park (LTCP)........................................................................................................................................................................................................................................ 42

Figure 47: Construction of an experimental-scale SAT system at the Lavrion Technological and Cultural Park (LTCP), equipped with TDR and FDR probes and accompanied with multi-level pore water sampling equipment. ........................................................................................................................................................................................................................................ 43

Figure 48: Quality of untreated wastewater quality during 2014, in the Wastewater Treatment Plant of Metamorfosis, EYDAP. ........................................................................................................................................................................................................................................ 44

Figure 49: Quality of treated wastewater quality during 2014, in the Wastewater Treatment Plant of Metamorfosis, EYDAP. ........................................................................................................................................................................................................................................ 44
Figure 50: Quality of untreated wastewater quality during 2015, in the Wastewater Treatment Plant of Metamorfosis, EYDAP ............................................................................................................................................................................ 44

Figure 51: Quality of treated wastewater quality during 2015, in the Wastewater Treatment Plant of Metamorfosis, EYDAP ............................................................................................................................................................................ 44

Figure 52: Pore water samplers installation using percussion drilling equipment for extra mobility and flexibility. ........................................................................................................................................................................................................ 45

Figure 53: Multi-level pore water samplers installed in the experimental-scale SAT basin of MARSOL ............................................................................................................................................................................ 45

Figure 54: Infiltration experiments at the experimental SAT basin at the Lavrion Technological Park........................................................................................................................................................................................................ 46

Figure 55: Example for TDR probing electromagnetic signals during wetting processes in the unsaturated zone. ........................................................................................................................................................................................................ 47

Figure 56: Example for TDR probing electromagnetic signals during drying processes in the unsaturated zone. ........................................................................................................................................................................................................ 47

Figure 57: Integrated monitoring system that was installed in the Lavrion experimental SAT basin. ........................................................................................................................................................................................................ 48

Figure 58: Sensor network node (open view) for weather station. ........................................................................................................................................................................................................ 49

Figure 59: Implementation of the weather station into the wireless sensor network. Rain sensor (left side) and wireless network node (white case) with other meteorological sensors (right side). ........................................................................................................................................................................................................ 49

Figure 60: Implementation of the water-level station into the wireless sensor network. Well with sensor inside (right side) and secured network node (left side)......................................................................................................................................................................................................... 50

Figure 61: Web-based platform connected with the installed sensing equipment that is installed in the Lavrion aquifer system. ........................................................................................................................................................................................................ 51

Figure 62: Precipitation value from rain sensor in the metrological station (yellow line) and water pressure value from water level sensor in station G3TGE (blue line). ........................................................................................................................................................................................................ 52

Figure 63: Wind-direction (blue) and wind-velocity (green) from sensors in the metrological station........................................................................................................................................................................................................ 52

Figure 64: Successiveness of the Lavrion integrated model. ........................................................................................................................................................................................................ 53

Figure 65: Spatial distribution of boundary conditions in the alluvial aquifer layer ........................................................................................................................................................................................................ 55

Figure 66: Spatial distribution of boundary conditions in the karstic aquifer layer ........................................................................................................................................................................................................ 56

Figure 67: Model domain and boundary conditions of the alluvial groundwater model. ........................................................................................................................................................................................................ 56

Figure 68: Pathlines for the karst formation ........................................................................................................................................................................................................ 57

Figure 69: Location of proposed full-scale MAR-SAT system and WWTP of Lavrion. ........................................................................................................................................................................................................ 58

Figure 70: Quality of untreated wastewater during 2016, in the Wastewater Treatment Plant of Lavrion (Municipality of Lavrion). ........................................................................................................................................................................................................ 59

Figure 71: Quality of treated wastewater during 2016, in the Wastewater Treatment Plant of Lavrion (Municipality of Lavrion). ........................................................................................................................................................................................................ 59

Figure 72: General layout of the proposed full-scale MAR/SAT system of Lavrion. ........................................................................................................................................................................................................ 59

Figure 73: Model run results for artificial recharge of 800,000 m³/yr ........................................................................................................................................................................................................ 60

Figure 74: Model run results for artificial recharge of 1,000,000 m³/yr. ........................................................................................................................................................................................................ 61
Figure 75: Model run results for artificial recharge of 1,500,000 m³/yr ............................................ 61
Figure 76: Undergraduate students of the National Technical University of Athens, during field excursion at the Lavrion wadi estuary. ........................................................................... 63
Figure 77: Postgraduate students of the National Technical University of Athens, during field excursion at Lavrion Technological and Cultural Park (LTCP). ............................................. 63
Figure 78: Postgraduate students of Technical University of Darmstadt, Germany, during field excursion at Lavrion Technological and Cultural Park (LTCP). ............................................. 64
Figure 79: MARSOL Workshop on Monitoring and Investigations Technologies, March 16-18, Lavrion, Greece .................................................................................................................. 65
Figure 80: MARSOL Workshop on Monitoring and Investigations Technologies, March 16-18, Lavrion, Greece .................................................................................................................. 65
Figure 81: MARSOL Lavrion Workshop dissemination material. ....................................................... 66
Figure 82: MARSOL Workshop WP11 dissemination material in the form of leaflet (distributed during the workshop). ............................................................................................... 66
Figure 83: MARSOL Workshop technologies demonstration............................................................. 67
Figure 84: MARSOL Workshop field visit to the Psyttaleia Wastewater Treatment Plant of EYDAP. ................................................................................................................................. 67
Figure 85: Homepage of the Lavrion Hydro-Environmental Observatory - LEO (www.leo.ntua.gr). ................................................................................................................................. 68

List of Tables

Table 1: Overview of the geoprobe hydraulic tests that were performed in Lavrion during the MARSOL project. .................................................................................................................. 27
Table 2: Overview of connected stations in Lavrion Technological Park ..................................................... 48
Table 3: Values used by the NWT solver, in MODFLOW-NWT ................................................................... 53
Table 4: Values and relative parameters used in the model ........................................................................ 55
Executive Summary

Work Package 3 of the MARSOL Project refers to the demonstration activities that took place during the project’s duration at the Lavrion pilot site, Greece. The site comprises typical water resources environmental – seawater intrusion, coastal alluvial and karstic aquifer environments, submarine groundwater discharge – and managerial – water scarcity, security of water supply, wastewater reuse – issues and challenges. Due to its limited size, the Lavrion site was envisaged to serve as a coastal experimental hydrosystem for demonstrating new monitoring technologies and techniques, with the contribution of local (EPEM, ICCS, EYDAP) and other (UFZ, TUDa) MARSOL partners. The Lavrion Technological and Cultural Park (LTCP) of the National Technical University of Athens (NTUA) was used as a major supporting infrastructure for the installation of the new developments within MARSOL's Work Package 11.

The work that has been carried out during the implementation of the project includes a series of research activities such as: (i) site investigation with advanced techniques and equipment (e.g. vibro-coring geoporobe activities, floating geophysics etc); (ii) novel monitoring techniques for different hydrologic zones (e.g. installation and operation of prototype Time Domain and Frequency Domain sensing systems); (iii) novel wireless data transmission for data acquisition (e.g. ad-hoc sensor networks); (iv) new modelling concepts for coastal aquifer systems simulation; and (v) hydro-geological investigation (e.g. campaign-based measurements, groundwater sampling etc).

Additionally, the Lavrion demonstration site is continuously used for training activities of young scientists and engineers (e.g. semester field excursions of under-graduate and post-graduate students of NTUA; annual field excursions of Master students of TUDa etc.), while in March 2016, the LTCP infrastructure hosted the MARSOL Workshop on Monitoring and Investigation Technologies.

During the implementation of the project, pilot-size Soil-Aquifer Treatment systems were constructed on the premises of LTCP that were equipped with the monitoring systems developed in the frame of Work Package 11 and recharged by treated wastewater delivered by the Athens Water Supply and Sewerage Company (EYDAP).
1. Overview

Lavrion Technological and Cultural Park 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 (i.e. seawater intrusion, water scarcity, intensive irrigation needs etc.) and MAR application is envisaged to combat all those. The site offers a typical hydrogeological setting for a Mediterranean coastal aquifer system (containing both alluvial and karstified aquifer layers), supporting both irrigation as well as water supply demands of the area. The entire aquifer system suffers from: (i) water shortage resulting from both anthropogenic activities (overexploitation) and natural conditions (low precipitation records), as well as (ii) contamination due to the intrusion of seawater.

The demonstration 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. This system is equipped by new technological developments – that are developed in MARSOL – which provide continuous monitoring of the infiltrating groundwater through all hydrologic zones (surface, unsaturated and saturated zone). This will be achieved through the adaptation and installation of an integrated system of prototype sensors installed on‐site offering a continuous monitoring and evaluation of the performance of the SAT system.

The main monitoring system for the unsaturated zone involves the use of Time Domain Reflectometry (TDR) and Frequency Domain Reflectometry (FDR) technology, through the use of prototype probes that are installed vertically in the unsaturated zone, underneath the experimental‐scale SAT facility. Additionally, the aquifer system within the vicinity of the SAT system is monitored continuously – through a series of monitoring wells that target the saturated zones of both the alluvial and the karst aquifer – while the data are transferred on real time basis through a tailored – developed during MARSOL – wireless sensor network.

The following figure (Fig. 1) shows the generalized concept of the research activities that were performed during the completion of WP3.
2. General Setting of the Study Area

Lavrion is located in the southeast coastal zone of Attica (Greece), within the area of Lavreotiki. The region of Lavreotiki was first mined for silver and lead at the late Neolithic period (4200 - 3100 B.C.) while mining and metallurgical activities ceased after classical times for hundreds of years, until 1865 when an Italian-French company founded a metallurgical factory, utilizing the ancient slags. In 1873 silver and lead exploitation restarted for a short period by “The French Company of Lavrion Mines” and the Hellenic state, until the early years of 20th century. The study site (Fig. 2) covers an area of approximately 20 km², characterized by typical Mediterranean climate conditions with dry and hot summer periods.

Figure 2: Geographical location of the study area.

Figure 3 shows the land use characteristics of the study area, illustrating the fact that rural activities are dominant in the area of Lavreotiki.
Figure 3: Land use of map of the study area (based on CORINE 2012).
3. Geological Setting of the Study Area

The geological structure of the wider Lavrio area has been an area of research for many decades, due to the fact that the ore deposits present in the area were of great importance and mining activities have been active even since the classical times (Kakavogiannis, 2005). Despite these efforts, a final widely accepted theory on the geological evolution of the Lavrio area is not made, with the researchers having conflicting views on important aspects of the topic. Ongoing study of the area is taking into account these opposite views (e.g. Scheffer et al., 2015 and references therein), but this is outside the scope of the present study. Here the nomenclature used in many of the studies (Marinos and Petrascheck, 1956; Stamatis et al., 2001; Skarpelis, 2007; Baziotis, 2008; Skarpelis et al., 2008; Baziotis et al., 2009; Lati et al., 2009; Baziotis and Mposkos, 2011; Berger et al., 2013; Lati et al., 2013) is utilized, while the structure is based on these references and the geological maps published by the Institute of Geological and Mineral Exploration (IGME, 2003, 2007, Figure 4), and on field observations that took place during the MARSOL-related field work.

![Figure 4: Geological map of the study area (IGME 2003, 2007, with modifications).](image)

The Lower Tectonic Unit (LTU, also found in the literature as the Kamariza Unit) in Lavrio is represented by three layers. At the bottom, the Lower Marble formation is a 400 m thick sequence of marble (IGME, 2003), mainly present at the western part of the area. Above is a thick sequence of schists, named either Kaisariani or Kamariza schists in the literature. On the top of the LTU there is
the Upper Marble formation which is a highly karstified and at the same time mylonitized marble. For
the LTU there is also the theory that there is just one marble formation that is above the Kaisariani
schists and that the folding patterns and/or normal faulting are responsible for having the marble
below and above the schists (Avdis, 1991; Photiades and Carras, 2001; Baziotis, 2008).

The Upper Tectonic Unit (UTU) consists of phengite-chlorite-epidote schists that are mainly meta-
pelites and metasandstones forming blueschists and greenschists (Baziotis et al., 2009) with some
marble intercalations. Some small metabasalt bodies are also present in the UTU (Baziotis et al.,
2009). Locally, above the UTU, limestone remnants of Upper Jurassic age are found, with this forma-
tion being assigned to the non-metamorphic (Photiades and Carras, 2001; Scheffer et al., 2015) Sub-
Pelagonian Tectonic Unit.

On the top of the stratigraphic column, recent alluvial deposits are covering both the LTU and UTU.
The alluvial deposits are of Quaternary age and are consisted mainly from silty material. Close and
into the riverbanks the material becomes coarser. The thickness of the formation varies from a few
meters up to around 20 m in the central part of the valley.

An igneous intrusion is also present in the area. The intrusion is in the LTU and it is a granodiorite,
with the intrusion time being approximately 15 - 9 Ma (Skarpelis et al., 2008; Baziotis, 2008). Main
minerals are quartz, plagioclase, K-feldspar and biotite, while minerals like zircon and apatite are also
present (Voudouris et al., 2008). Dykes also originate from the intrusive body, placed approximately
4 km below the surface (Tsokas et al., 1998), and are spread throughout the area. This intrusion is
the source of the Pb-Zn-Ag rich ore deposits in the area. The metalliferous minerals are pyrite,
sphalerite, galena, and tetrahedrite-tennantite (the two latter Ag rich), but other sulphuric salts (e.g.
pyrargite, lillianite) are present (Voudouris et al., 2008; Skarpelis and Argyraki, 2009). The ore is
found in skarn, veins or skarn-free carbonite replacement (Voudouris et al., 2008). The age of the
intrusion is 8.34 ± 0.2 Ma (Liati et al., 2009).

The contact between the LTU and UTU and its nature is one of the key features that there is a big
controversy between scientists. The contact is undoubtedly tectonic, but the debate on its kinetics is
still going on. Some researchers support that the contact is a thrust fault while the majority
interprets the contact as a thrust fault that has evolved to a low angle extensional detachment fault
under the present tectonic regime in the Aegean (Scheffer et al., 2015 and references therein). Other
normal faults are also present in UTU and not in the LTU (IGME, 2003, 2007; Scheffer et al., 2015).
4. Hydrometeorology

The climate of Lavrio can be characterized as semi-arid. Meteorological data taken from the Lavrio Port Meteorological Station (LPMT, managed by the National Observatory of Athens, data available since 01/10/2008 in daily time steps) show that the mean annual temperature is 19.06 °C, but it can be highly variable throughout the year (from 38.7 °C in August to 1.4 °C in February). The mean annual precipitation is 394.22 mm (years 2009 - 2015), but the variation is high also for this parameter (257.2 mm for the year 2010, 496.2 mm for the year 2015, Figure 5).

![Figure 5: Mean annual precipitation in Lavrio during the period 1970-2015.](image)

The distribution of precipitation in the hydrological year is uneven, with the vast majority of rain falling during the winter months and summer months having a precipitation height close to zero most of the times. A figure reverse to the one for precipitation would represent the evapotranspiration, with the highest values being in the summer, when the water availability is lower and the demand higher, a fact that is the general trend for other parts of the country too (Paparrizos et al., 2014). The dominant wind direction is Northern and the wind speed can have values up to 40 km/h (Center for Renewable Energy Sources and Saving, 2001, assessed at geodata.gov.gr in 23/10/2015, wind map), becoming an additional factor enhancing potential evapotranspiration (Allen et al., 1998).

The climate of the whole Attica region can securely be characterized as semi-arid, as mentioned numerous times in the literature (e.g., Bajocco et al., 2012; Kargas et al., 2012; Moussoulis et al., 2015; Nastos et al., 2013). This is a major attribute affecting the water resources management strategies that need to be implemented in the area.
5. Hydrogeological Conditions

In the area there are two aquifer systems developed in the different geological formations. The aquifers, apart from different flow regimes, show discrepancies regarding qualitative data and water table response throughout the hydrological year.

The first aquifer is developed in the Quaternary alluvial deposits, where an aquifer of granular nature is formed. In this aquifer the groundwater flows eastwards and, essentially, discharges to the Thoricos gulf. The thickness of the formation varies across the valley, with the thickest part being in the middle (up to 20 meters). Towards the edges the thickness decreases and is essentially becomes zero were the geological boundary is. Abstraction from this aquifer takes place in the warmer period of the year (between April and September), in principal from dug wells, with the water abstracted used entirely for small scale irrigation activities.

The area characterized as agricultural area is close to 5.2 km² (CORINE, 2012) but a more detailed study on the water needs for agriculture given by Panou (2015) shows that approximately 1.05 km² are irrigated in the whole municipality area (that actually covers an area larger than that of the Thoricos basin), with the water demand being 1172127 m³/year, a part of which returns to the aquifer as recharge. The aquifer is subjected to seawater intrusion, especially closer to the coast, as shown from the hydrochemical parameters.

![Figure 6: Areas where the boundaries of the hydrogeological basin where defined in the southern (a) and northern (b) part of the study area.](image)

During MARSOL, a network of monitoring wells has been established, in order to provide measurements for the piezometric conditions of the alluvial and the karstic aquifer. Figure 7 shows the spatial distribution of the network in question, which is composed of both private and recently installed monitoring piezometers.

Figures 8 to 16 show the piezometric conditions of the alluvial aquifer for two periods of the hydrological year (wet and dry). The general discharge axis in both cases is NW-SE, towards the coast. The shape of the contours suggests that there is some lateral inflow coming from the karstic aquifer in the southern margin of the alluvial, while in the northern margin the case is the opposite, with the alluvial aquifer discharging to the karstic one.
Figure 7: Monitoring wells network in the study area.

Figure 8: Piezometric conditions of the alluvial aquifer in May 2014.
Figure 9: Piezometric conditions of the alluvial aquifer in August 2014.

Figure 10: Piezometric conditions of the alluvial aquifer in October 2014.
Figure 11: Piezometric conditions of the alluvial aquifer in January 2015.

Figure 12: Piezometric conditions of the alluvial aquifer in May 2015.
Figure 13: Piezometric conditions of the alluvial aquifer in January 2016.

Figure 14: Piezometric conditions of the alluvial aquifer in April 2016.
Figure 15: Piezometric conditions of the alluvial aquifer in June 2016.

Figure 16: Piezometric conditions of the alluvial aquifer in September 2016.
Based on the above piezometric observations, the following flow diagram (Fig. 17) regarding the inflows and outflows and the interactions between the karstic and the alluvial aquifer was developed.

![Flow diagram with the inflows and outflows of the karstic aquifer.](chart)

*Figure 17: Flow diagram with the inflows and outflows of the karstic aquifer.*

The second aquifer formed is of karstic nature. It is developed in the Upper Marble formation (LTU) and, in the past, it was the main source of drinking water supply for the city of Lavrio. Water supply from this aquifer stopped due to the deterioration of the water quality, bring an effect of the seawater intrusion taking place. A major outsource of this aquifer is the submarine springs, with the discharge being spread along the north side of the Thoricos bay. Although mainly submarine, these discharges have also some coastal occurrences, one of which was found to have been discharging even in the end of the dry period (end of August). The thickness of the formations varies but in Lavrio the minimum considered thickness ~ 50 meters, as show at drill cores from previous studies (NTUA, 2000) but also by the depth of the doline located south of the Agios Konstantinos town (Chaos, depth 55 meters at its deepest point). Fig. 18 shows the hydraulic head fluctuations (daily average) for one of the drills placed in the karstic aquifer (point K1 placed in the LTCP) in comparison with the precipitation recorded in the Lavrio port meteorological station that is approximately 1.5 km away.

![Hydraulic head fluctuations at drill into the karstic aquifer (point K1).](chart)

*Figure 18: Hydraulic head fluctuations at drill into the karstic aquifer (point K1).*
The response of the aquifer seems to be relatively irregular. The aquifer is responding rapidly to rain events that exceed a value of approximately 40 mm/day, while smaller rain events have to accumulate in order to have some significant response. The time needed can vary between 2 and 10 days. Measurements of the water temperature for the same period of time did not show considerable variation, with a mean value of 21.7 °C for the winter period (first) and 22.3 °C for the summer period (second), making temperature an unsuitable parameter for tracing rain events that notably contribute to groundwater recharge.

An estimate about the hydraulic properties of that aquifer was possible since raw pumping test data from a previous study (NTUA, 2000) have been acquired and re-evaluated (Fig. 19). For the interpretation of the data the AQTESOLV 4.5 PROFESSIONAL software (HydroSOLVE Inc.) was used. The method used for the analysis was the one suggested by Barker (1988), since it was found to be the most appropriate for the aquifer under investigation. Nevertheless, the solutions varied, with the fracture hydraulic conductivity ranging between 30 - 310 m/day and the matrix hydraulic conductivity ranging between 1.2×10⁻⁵ - 0.46 m/day. Additionally, the storage coefficient for the fractures was estimated to vary between 2.29×10⁻⁷ - 7.598×10⁻⁵ and the matrix specific storativity between 1.8×10⁻⁴ - 0.058 m⁻¹. An interesting result that occurred is that during pumping there was some water entering suddenly in the piezometers. This is depicted in Fig. 20, where it is shown that while some drawdown was occurring in the piezometer, the water table was recovering suddenly due to some water entering the system. A possible explanation of this is that there is some water that is inert at steady state conditions and it becomes mobile when there is some drawdown in the system producing hydraulic head difference. This water is initially stored in fractures or small cavities in the karstified aquifer. This is an important attribute of the aquifer and gives a better understanding on the mechanisms that dominate the movement on groundwater, especially in such a karstified environment.

![Figure 19: Results of the pumping test analysis along with the final values.](image-url)
Figure 20: Response to pumping measured in a piezometer. The shape of the response curve is due to water being flushed from fractures that become hydraulically connected after pumping.

Another feature of the aquifer is that there are apparently many fractures that become hydraulically connected when there is abstraction, the result being that water that was previously inert enters the system as shown in Fig. 20.

The two aquifers described above, along with the main stream in the area, are in tight hydraulic connection. Between the aquifers the general case is that the karstic aquifer contributes to the granular one. This is more pronounced in the southern part of the alluvial valley. On the contrary, in the northern part of the valley this regime is more complex. This is a result of the stream being involved, so that the piezometric maps do not give a clear picture of the hydraulic connections at that particular point. A possible solution to this would be to use stable isotopes to define the source of the water. This was unfortunately not applicable in this study because water samples from the streams were not taken (due to the stream being dry) but also because the isotopic signatures for each aquifer were not so distinct from each other (see section that follows). The understanding of this flow regime and, basically, of the individual hydraulic connections becomes more problematic if the affection from seawater intrusion is accounted. Of course, in that case, the isotopic signature of the seawater, along with the large electrical conductivity values, should be indicative of such an effect. In Fig. 21, the comparison of the hydraulic heads between two nearby points that are in different aquifers (D8 in the karstic and MSW11 in the alluvial, distance between them ~ 48 m) shows that, at least for the dry period of the hydrological year, the hydraulic head is higher in the alluvial aquifer than in the karstic one, meaning the water is flowing from the alluvial aquifer to the karstic aquifer. This is something that is also shown in the piezometric map of the alluvial aquifer. The difference between the two points is relatively stable for the whole monitoring time (~ 0.34 m), while their response to the major rain events is consistent.
It is worth mentioning that shallow wells were also found in the Kaisariani schists formation. The wells were placed in high altitudes and they were all dry. At times were the mining activity was active those wells were had a double role, on one had to store water that was brought there with other means (animals mostly) but also to take advantage how much water the upper weathered part of the schists could supply at times of high precipitation. Nevertheless, this formation is considered to be the impermeable bottom of the two aquifers due to its poor hydraulic properties and large average thickness.
6. Direct Push Vibro-Coring Activities

During the aquifer characterization research in MARSOL, the need to use invasive vibro-coring technologies was realized in order to define the thickness as well as the hydraulic characteristics of the unconsolidated formations of the study area. Additionally, geoprobing activities were focused to the installation of a network of monitoring piezometers within the study area. The following figures show the geoprobing machinery that was used for the field investigations of the Lavrion aquifer system as well as the locations of the aforementioned activities.

Figure 22: Locations of direct-push activities in the alluvial aquifer of Lavrion.

Figure 23: Direct-push activities in the alluvial aquifer of Lavrion: (a) installation of multi-level piezometers and (b) electrical conductivity logging.
The geoprobing activities can be summarized as follows:

**MSW 02**

GWM well cluster installation:
- 1” well with filter screen 0-2.0 m bgs
- 1” well with filter screen 3.0-5.0 m bgs
- 1” well with filter screen 7.0-10.0 m bgs
- 1” well with filter screen 10.0-15.0 m bgs

**MSW 05**

EC to 18.71 m bgs
GWM 1” well installation with filter screen 18.9-8.9 m bgs

**MSW 06**

EC to 8.67 m bgs
GWM 1” well installation with filter screen 9.2-4.2 m bgs

**MSW 08**

EC to 8.81 m bgs
GWM cluster installation:
- 2” well with filter screen 0-11.0 m bgs
- 1” well with filter screen 6.0-5.0 m bgs
- 1” well with filter screen 10.0-9.0 m bgs
DPIL to 11.0 m bgs
DPST in 6.0-5.0 m bgs
Soil sampling to 9.5 m bgs

**MSW 09**

EC to 18.88 m bgs
GWM cluster installation:
- 2” well with filter screen 0-19.0 m bgs
- 1” well with filter screen 14.0-15.0 m bgs
- 1” well with filter screen 10.0-9.0 m bgs
- 1” well with filter screen 4.0-5.0 m bgs
DPIL to 19.5 m bgs
DPST in:
- 4.0-5.0 m bgs
- 10.0-9.0 m bgs
- 14.0-15.0 m bgs
MSW 10
EC to 3.12 m bgs
Soil sampling to 1.0 m bgs

MSW 11
EC to 9.05 m bgs
GWM 1” installation with filter screen 5.55-8.55 m bgs
Soil sampling to 8.3 m bgs

MSW 14
EC to 18.44 m bgs
GWM cluster installation:
- 1” well with filter screen 11.2-21.2 m bgs
- 1” well with filter screen 0-2.0 m bgs
- 1” well with filter screen 3.0-5.0 m bgs
- 1” well with filter screen 7.0-10.0 m bgs
- 1” well with filter screen 10.0-15.0 m bgs
DPIL to 20.5 m bgs
DPST in 11.2-21.2 m bgs

MSW 15
EC to 9.03 m bgs
GWM 1” well installation with filter screen 12.2-6.2 m bgs

MSW 16
EC to 8.69 m bgs
GWM 1” well installation with filter screen 2.0-9.0 m bgs

MSW 17
EC to 3.95 m bgs

MSW 18
EC to 9.40 m bgs
GWM 1” installation with filter screen 10.0-17.0 m bgs

Explanation:

MSW: investigation point.
EC: direct push vertical high-resolution electrical conductivity profiling.
GWM: ground water monitoring well.
DPIL: direct push injection logging; profiling of vertical distribution of relative DPIL hydraulic conductivity, a parameter closely correlated to K. Measurements performed every 50cm depth.
DPST: Pneumatic slug testing performed in DP installed small diameter wells.
The results of the hydraulic tests during the geoprobe activities are shown in Table 1, and the results of the EC loggings are summarized in Figures 24 - 28.

Table 1: Overview of the geoprobe hydraulic tests that were performed in Lavrion during the MARSOL project.

<table>
<thead>
<tr>
<th>MSW_9</th>
<th>MSW_8</th>
<th>MSW_14</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DPST screen [m b.g.s.]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.00 - 5.00</td>
<td>9.00 - 10.00</td>
<td>14.00 - 15.00</td>
</tr>
<tr>
<td><strong>K [m/s] unconfined average</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.96E-04</td>
<td>9.76E-04</td>
<td>8.60E-06</td>
</tr>
<tr>
<td><strong>K [m/s] unconfined standard deviation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.19E-04</td>
<td>6.29E-05</td>
<td>5.74E-07</td>
</tr>
<tr>
<td><strong>well development [l]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30.00</td>
<td>35.00</td>
<td>50.00</td>
</tr>
<tr>
<td><strong>number of slugtests</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18.00</td>
<td>9.00</td>
<td>6.00</td>
</tr>
</tbody>
</table>

Figure 24: Results from electrical conductivity logging through direct-push activities.
Figure 25: Results from electrical conductivity logging through direct-push activities.

Figure 26: Results from electrical conductivity logging through direct-push activities.
Figure 27: Results from electrical conductivity logging through direct-push activities.

Figure 28: Results from electrical conductivity logging through direct-push activities.
7. Geophysical Investigations

The need to characterize the subsurface setting of the alluvial and karstic aquifer of Lavrion dictated the realization of a series of geophysical investigations that aimed at: (i) defining the vertical boundaries of the aquifer layer successions, and (ii) providing a topographic map of the submarine extent of the karstic aquifer.

ERT (electrical resistivity tomography) and IP (induced polarization) profiles with 175 m length (50 m investigation depth) and pole-dipole electrode array were positioned in such a way to follow the salinization front entering to the valley from the sea shore. Also, 5 m electrode distance was used with the current and potential electrodes separated in parallel lines (in order to avoid polarization effects, Dahlin and Leroux, 2012). Figure 29 shows the locations of the ERT and IP profiles within the study area of Lavrion.

![Figure 29: Location of the ERT and IP profiles that were performed during the MARSOL project.](image)

All resistivity sections show that in even in depths of 40 m we have conductive media implying salinization as a dominant phenomenon (Fig 30). The chargeability sections give additional information regarding the conductive media with the higher values implying higher clayey character. This clayey presence near the sea is in depths of 30 m going to 20 m as we enter the valley but they vanish in northern areas.
Figure 30: ERT profiles that were performed during the MARSOL project (TR1-TR8) (all units in x/y axes are in meters).
8. Hydrochemical conditions in the aquifer system of Lavrion

During the completion of WP3, a set of private and monitoring wells was used to develop a monitoring network of both the alluvial and the karst aquifer of Lavrion. During the completion of the project, a series of chemical analyses were performed, that aimed at measuring the major ion composition of the groundwater samples, as well as heavy metals and stable isotopic signatures. The monitoring network that was used for the purpose of the investigation is shown in the following figure (Fig. 31).

![Monitoring network for the qualitative measurements of the coastal hydrosystem of Lavrion.](image)

In Lavrion, seawater intrusion is taking place in both the aforementioned aquifer systems, deteriorating their water quality, as depicted in the following figures. The distribution of chloride ions coming from seawater show that the effect is as expected larger during the dry period of time. In the winter time, the chloride concentrations are smaller but still considerably high, but the fact that January 2015 is in the middle of the wet period and more precipitation events are expected (in that specific case, during the period February to April there was a total of 166.2 mm of precipitation) has to be taken into account. Furthermore, the effect of pumping during the dry period is expected to have some impact on the results of May 2015, due to the enhancement of the effect of seawater intrusion.

The following figures show the distribution of the chloride ions in both the alluvial and the karst aquifer of the study area, from selected sampling periods and measurements (Figs. 32 - 34).
Figure 32: Chloride concentrations distribution in the groundwater prior the irrigation period of 2014 (April 2014).

Figure 33: Chloride concentrations distribution in the groundwater prior the irrigation period of 2015 (May 2014).
The following Piper diagrams are complementary to the spatial distribution of chlorides in the coastal aquifer of Lavrion (Figs. 35 - 37). The groundwater of the area of investigation is mainly contaminated by high concentrations of chloride ions as well as sulphate ions; the latter due to the mining activities that were taking place in the past.

Samples for analyzing the stable isotopic composition ($\delta^{18}O$ and $\delta^2H$) were also taken. The following figures (Figs. 38 - 39) show that samples taken from open wells appear to have varying isotopic signatures, while from the other sources the range of values is smaller. At the same time, the isotopic compositions of the samples appear to be very close to the meteoric water lines that are relevant to the area of interest (Gat and Carmi, 1970; Matiatos, 2010), suggesting that recharge occurs rapidly in the system. This could be justified also by the fact that the water table in the alluvial aquifer is not very deep, while in the karstic aquifer that movement of groundwater is considerably prompt. Furthermore, there are some differences in the values of the open wells and piezometers in the alluvial aquifer, with the values from the piezometers being, in general, more depleted. In overall, water coming from different sources does not appear to differ largely considering the isotopic composition, giving a more mixed signal rather than a distinct one for each source.

Figure 34: Chloride concentrations distribution in the groundwater prior the irrigation period of 2016.
Figure 35: Piper diagram regarding the groundwater samples taken prior to the irrigation period of 2014.

Figure 36: Piper diagram regarding the groundwater samples taken prior to the irrigation period of 2015.
Figure 37: Piper diagram regarding the groundwater samples taken prior to the irrigation period of 2016.

Figure 38: Isotopic signatures of the GW samples based on the aquifer type and period of sampling.

Figure 39: Isotopic signatures of the GW samples based on different sources.
9. Development and application of a multi-criteria decision support system for a MAR-SAT location in Attica

The process of site selection for the installation of a MAR facility is of paramount importance for the feasibility and effectiveness of the project itself, especially when the facility will include the use of waters of impaired quality as a recharge source. The complexity in which the spatial problem results, may require processing at a level that exceeds a decision maker’s cognitive ability. The role of Geographical Information System (GIS) and Multi Criteria Decision Analysis (MCDA) techniques is to support the decision maker in achieving greater effectiveness and efficiency of decision making while solving spatial decision problems. The development of a multi-criteria Decision Support System (DSS) that integrates within a dynamic platform the main groundwater engineering parameters associated with MAR applications together with the general geographical features which determine the effectiveness of such a project has been described for the Attica region, where the Lavrion area is located, by Tsangaratos et al. (2013). The final product of this study has been the set-up of a composite suitability map of the study area (Fig. 40). Major criteria for this were: hydrolithological setting, unsaturated zone thickness, slope inclination, and economic aspects related to the proximity of the WWTP with the potential SAT locations and the difference of elevation between the suitable area and the WWTP. The map is classified into 3 classes: good, fair, and bad. Since most of the study area involves mountainous zones and highly urbanized areas, the spatial distribution of locations preferable for SAT facilities are quite limited for the study area.

The outcomes of this investigation were used for the sampling of soil cores that were used in the soil column experiments described in details in Deliverable D14.4 "Column Experiments Results - MAR Column Experiments with Soils from MARSOL Demonstration Sites in Greece and Israel" (WP14).

Figure 40: Final suitability map (Tsangaratos et al., 2013).
10. Development of an experimental Soil-Aquifer Treatment (SAT) system and an accompanying monitoring system in the Lavrion Technological and Cultural Park (LTCP)

10.1. General description of the activities within the Technological Park

The activities that took place in the area of the Technological Park, refer to: (i) complementary adjustments of the monitoring system in terms of probe installations and signal calibration; (iii) geophysical investigation for the optimum location of the SAT basin; (iii) construction of experimental-scale SAT system and installation of probes – through drilling activities – and monitoring piezometers in the vicinity of the infiltration basin; (iv) installations of a wireless sensor network for the data acquisition of the installed monitoring equipment; (v) operation of the web-based platform for the management of the generated data in the Technological Park area (including other monitoring systems from different MARSOL sites).

The activities scheme that refers to the realization of the above is illustrated in Fig. 41.

Figure 41: Research activities scheme for the experimental-scale SAT system at the Lavrion site.
10.2. **Complementary adjustment and integration of the monitoring systems (TDR & FDR)**

For the purpose of monitoring systems integration, partners from ICCS and UFZ decided to develop and operate a series of soil column experiments that would contain both the TDR and FDR systems. The above aims at counter-calibrating the electromagnetic signals that are generated during the wetting process of the experimental SAT system. The following figure illustrates the construction and the soil column activities (Fig. 42), accompanied by relevant photographic material.

The above were considered necessary in order to maximise the potential for successful monitoring of the infiltration basin through the entire unsaturated zone thickness. Results are reported in the framework of work package WP11.

![Figure 42: Development of soil column experiments for the integration of the TDR and FDR systems that were developed during the completion of WP11.]
10.3. Geophysical and direct-push investigation for the optimal location of the experimental SAT basin

Prior the construction of the experimental-scale infiltration basin, a set of subsurface characterization methods was applied, in order to select the optimal location within the premises of the Lavrion Technological and Cultural Park (LTCP). Methods involved were (i) non-invasive geophysical investigations, and (ii) direct-push drillings using geoprobe machinery.

The results of the geophysical investigations that were performed prior the geoprobe drillings dictated the optimal location of the SAT basin as shown in the following figures (Figs. 43 - 45).

The selection investigation was complemented with direct-push drillings in order to finalise the decision for the selection of the experimental scale SAT basin, based on the application of direct-push vibro-coring technology (Fig. 46).

Figure 43: Optimal location of the experimental-scale SAT basin on the premises of Lavrion Technological and Cultural Park (LTCP), location of geophysical profiles.
Figure 44: Optimal location of the experimental-scale SAT basin on the premises of the Lavrion Technological and Cultural Park (LTCP), results of resistivity measurements.

Figure 45: Optimal location of the experimental scale SAT basin on the premises of the Lavrion Technological and Cultural Park (LTCP), results of non-invasive geophysical investigations.
10.4. Construction and operation of an experimental-scale SAT basin at the Lavrion Technological and Cultural Park (LTCP)

The experimental-scale SAT basin on the premises of the Lavrion Technological and Cultural Park (LTCP) was constructed (Fig. 47) after the completion of the research stages that were described in sections 10.1-10.3. The construction involved the excavation of two identical infiltration ponds, with dimensions 3 x 5 x 0.5 m.

The system was receiving treated wastewater from the Wastewater Treatment Plant of Metamorfosis (operated by MARSOL partner EYDAP) that has the characteristics depicted in Figs. 48 - 51.

During the installations of the pore water samplers, the need to shift to a more mobile and flexible direct-push methodology was identified. Therefore the Eijkelkamp percussion drilling set for heterogeneous soils with gasoline-powered percussion hammer (Cobra TT, standard equipment for drilling to depths down to 5 meter) was employed as shown Fig. 52. The multi-level pore water samplers installed in the basin are shown in Fig. 53. The operational basin is shown in Fig. 54.
Figure 47: Construction of an experimental-scale SAT system at the Lavrion Technological and Cultural Park (LTCP), equipped with TDR and FDR probes and accompanied with multi-level pore water sampling equipment.
Figure 48: Quality of untreated wastewater quality during 2014, in the Wastewater Treatment Plant of Metamorfosis, EYDAP.

Figure 49: Quality of treated wastewater quality during 2014, in the Wastewater Treatment Plant of Metamorfosis, EYDAP.

Figure 50: Quality of untreated wastewater quality during 2015, in the Wastewater Treatment Plant of Metamorfosis, EYDAP.

Figure 51: Quality of treated wastewater quality during 2015, in the Wastewater Treatment Plant of Metamorfosis, EYDAP.
Figure 52: Pore water samplers installation using percussion drilling equipment for extra mobility and flexibility.

Figure 53: Multi-level pore water samplers installed in the experimental-scale SAT basin of MARSOL.
The TDR probing system that was developed and integrated during WP3 and WP11 of the MARSOL project was used to measure and monitor the hydrologic processes in the unsaturated zone during wetting and drying cycles. Figures 55 - 56 show some example wetting and drying acquired electromagnetic signals from the TDR probing systems.

The installed monitoring module that provides real-time continuous measurements of the SAT basin in Lavron is composed of an integrated system of low cost energy efficient components such as: (i) processing mainboard, (ii) micro-controller, (iii) D/C converter, (iv) RF switch; and (v) TDR pulse generator (Fig. 57). The system is connected through co-axial cables with the installed probes within the SAT basins.
Figure 55: Example for TDR probing electromagnetic signals during wetting processes in the unsaturated zone.

Figure 56: Example for TDR probing electromagnetic signals during drying processes in the unsaturated zone.
10.5. Wireless Sensor Network

A wireless sensor network (WSN) was developed in the frame of WP11 and – documented through Deliverable D11.3 – was installed in the Technological Park in Lavrion. Table 2 gives an overview of the connected stations with their corresponding meteorological sensors of the WSN at the site.

Table 2: Overview of connected stations in Lavrion Technological Park.

<table>
<thead>
<tr>
<th>Station</th>
<th>Position North, East</th>
<th>Physical unit</th>
<th>Sensor Name</th>
<th>Output value</th>
<th>Measurement range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ground Water Well G4TGE</strong></td>
<td>37.723402, 24.050300</td>
<td>Water level</td>
<td>CTE9000CS (First Sensor)</td>
<td>4-20 mA</td>
<td>0-2000 mbar</td>
</tr>
<tr>
<td><strong>Ground Water Well G3TGE</strong></td>
<td>37.722872, 24.047422</td>
<td>Water level</td>
<td>CTE9000CS (First Sensor)</td>
<td>4-20 mA</td>
<td>0-2000 mbar</td>
</tr>
<tr>
<td><strong>Meteorological Station WEATHER STATION</strong></td>
<td>37.723096, 24.049117</td>
<td>Wind velocity</td>
<td>WE550 (Global Water)</td>
<td>4-20 mA</td>
<td>0-50 m/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wind direction</td>
<td>WE570 (Global Water)</td>
<td>4-20 mA</td>
<td>0-352 °N</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Humidity</td>
<td>WE600 (Global Water)</td>
<td>4-20 mA</td>
<td>0-100% rH</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temperature</td>
<td>WE700 (Global Water)</td>
<td>4-20 mA</td>
<td>-50-50 °C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solar radiation</td>
<td>---</td>
<td>4-20 mA</td>
<td>n.a.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Barometric</td>
<td>WE100 (Global Water)</td>
<td>4-20 mA</td>
<td>800-1100 mbar</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rain</td>
<td>52202 (R.M. Young)</td>
<td>pulse</td>
<td>0.1 mm res.</td>
</tr>
</tbody>
</table>

For the demonstration of using a wireless sensor network in Lavrion the nodes were developed to overcome the strong weather influences and the possibility that somebody can steal the equipment.
For protection only cases with minimum IP66 are relevant to get a proper safety against the dusty environment and heavy rain events. All in- and outputs are sealed with O-rings and the case is protected against incoming humidity as a result of pressure differences with an equalization valve (Fig. 58). Additionally, these both components of the network node are placed in a secured lockable box. The following pictures show the implementation for two different stations (Figs. 59 - 60).

**Figure 58: Sensor network node (open view) for weather station.**

**Figure 59: Implementation of the weather station into the wireless sensor network. Rain sensor (left side) and wireless network node (white case) with other meteorological sensors (right side).**
Figure 60: Implementation of the water-level station into the wireless sensor network. Well with sensor inside (right side) and secured network node (left side).

The sensor nodes were programmed with a measurement interval of 15 minutes. This is a good compromise between observations of inert meteorological processes and acceptable power consumption. The timestamp for the measurement is passed directly on the node and is synchronized by the clock from the network stream. In case of errors during the runtime of the network the data is saved directly on the node. Therefore there is a removable 8 MBit flash memory on board. The data is also saved periodically on the flash card (8 GByte) in the base station.

For future implementations the sensor nodes are well prepared for connecting additionally sensors with analogue and digital sensor interfaces. This supports the adaptive measurement process which results of the outcome of the first observations. New implementations require only some adjustments in the mechanical part and later in the acquisition in the database.

10.6. Web-based data management Platform

After successful recording and preprocessing of the environmental measurements in the wireless sensor network, the data is transmitted via the base station to a data platform for storage and further treatment.

The MARSOL web-based data platform (Fig. 61) 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 together the data collected from the individual sensors and therefore, it will serve 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. The platform interface, the offered functionalities and usage instructions etc. are described in detail in deliverable D11.3 "Wireless Sensor Network and Web-based Data Platform". The server of the platform is installed at the Lavrion Technological Park and is currently under operation.

![Figure 61: Web-based platform connected with the installed sensing equipment that is installed in the Lavrion aquifer system.](image)

The following diagrams show example data series from two stations (Fig. 62). The measurement figures are taken directly from the management platform. In the first pair the measured precipitation is confronted against the pressure from the water level sensor. As a first result the increase of water in the groundwater well correlates with strong rainfall events. Also the daily fluctuation of the water level is clearly visible.

The second dataset shows example data from the wind direction and wind velocity sensors at the weather station (Fig. 63).
Figure 62: Precipitation value from rain sensor in the metrological station (yellow line) and water pressure value from water level sensor in station G3TGE (blue line).

Figure 63: Wind-direction (blue) and wind-velocity (green) from sensors in the metrological station.
11. GW Modeling and upscale of SAT facilities for the coastal aquifer of Lavrion

11.1. Groundwater flow model setup

The following section provides some basic information about the most recent model that is used for the parameter estimation and sensitivity analysis. For simulation purposes, the MODFLOW-NWT is used; with the NWT solver having the values specified in Table 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head change criteria (HEADTOL)</td>
<td>0.001 m</td>
</tr>
<tr>
<td>Flux criteria (FLUXTOL)</td>
<td>0.1 m³/day</td>
</tr>
<tr>
<td>Maximum iterations (MAXITEROUT)</td>
<td>1000</td>
</tr>
<tr>
<td>Matrix solver (LINMETH)</td>
<td>Chi MD</td>
</tr>
<tr>
<td>Model complexity (OPTIONS)</td>
<td>Complex</td>
</tr>
</tbody>
</table>

Table 3: Values used by the NWT solver, in MODFLOW-NWT.

The units used through the model are meters for length and days for time, while the grid size is 50 × 50 m. There are 28 stress periods in the model. The first one is a steady-state stress period to make the model stable at the beginning. The rest are transient, with daily time step. Each stress period represents a month in the simulated period of time (January 2014 - March 2016).

There are 3 layers in the model (top to bottom): the Alluvial, the Karst and the Schist (Fig. 64). In the Alluvial and Karst layers unconfined aquifers are formed. For that reason they are both simulated as convertible layers in the model. The Schist is the base of the model and is simulated as confined.

Figure 64: Successiveness of the Lavrion integrated model.
For the model top, a Digital Elevation Model (DEM) of the study area is used. The initial DEM has 5 × 5 m cells, but it was re-sampled in order to make the 50 × 50 m raster used as model top. The thickness of the Alluvium is taken from the depth at which the Geoprobe drilled. The Karst is 50 m thick (taken from the drill cores in the LTCP and reports from the Chaos doline). This nonetheless is the minimum thickness expected. The schist has a thickness of 50 m (although geological maps mention up to 200 m). Since this layer is just the base of the aquifer with very poor hydraulic properties this is considered to be a valid approach.

As for the hydraulic parameters that are used in the model, these are the following:

- Different hydraulic conductivity is assigned in each model layer. The starting values used are the following; Alluvial 5 m/day, Karst 40 m/day and Schist 0.0001 m/day.
- There is no horizontal hydraulic anisotropy used. The vertical hydraulic conductivities are by default 10% of the horizontal ones.
- For the specific storativity of the layers the default value of 0.00001 m³ is used.
- Specific yield values are additionally assigned to the layers that are simulated as being convertible. The starting values used are 0.1 for Alluvium and 0.08 for Karst.

The model top (surface) is used for the initial heads of the simulation.

The boundary conditions (BC) used in the model are the following:

- Upstream weighting (UPW): This package is used to define the parameters of the model. It is used because it is used by MODFLOW-NWT.
- Time variant specified head (CHD): This BC is assigned at the coastal area of the model. The starting and ending heads are both 0 m throughout the whole simulation. The BC is assigned both in the Alluvial and Karst formations.
- Stream flow routing (SFR): The main stream coming from the north is simulated with that BC. The stream is divided in seven segments (previously used in PRMS). The values used in that BC are the following:
- Gage (GAGE): Used for printing the flow values from SFR.
- Well (WEL): Used for adding recharge to the aquifers. That BC is used instead of the Recharge (RCH) package because this was also compatible with GSFLOW. For the Karst aquifer, 30 % of the precipitation is used as recharge (data taken from the Lavrio meteorological station that is owned by the National Observatory of Athens). For the Alluvial aquifer 15 % of the precipitation is used. This BC is also used for applying pumping to the Alluvial aquifer during the dry period of the year.
- Head observation (HOB): This BC is used for importing the head observations in the model.
**Table 4: Values and relative parameters used in the model.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reach length (RCHLEN)</td>
<td>Object length</td>
<td></td>
</tr>
<tr>
<td>Streambed top (STRTOP)</td>
<td>(Model top + Alluvium bottom)/2</td>
<td></td>
</tr>
<tr>
<td>Stream slope (SLOPE)</td>
<td>0.017 m/m</td>
<td>Slope of 1°</td>
</tr>
<tr>
<td>Streambed thickness (STRTHICK)</td>
<td>1 m</td>
<td>Maximum estimate</td>
</tr>
<tr>
<td>Streambed Kv (STRHC1)</td>
<td>0.00001 m/day</td>
<td>Estimate</td>
</tr>
<tr>
<td>Stage calculation (ICALC)</td>
<td>Rectangular channel</td>
<td>Better approximation in our case</td>
</tr>
<tr>
<td>Stream width (WIDTH)</td>
<td>5 m</td>
<td></td>
</tr>
<tr>
<td>Channel roughness (ROUGHCH)</td>
<td>0.03</td>
<td>Literature</td>
</tr>
</tbody>
</table>

The following figures (Figs. 65 - 66) show the boundary conditions for each aquifer layer, alluvial and karst. The model of the karst aquifer system in Lavrion was developed using MODFLOW along with new packages that are specific for fractured aquifers. GIS-based data for topography/geology and model domain, climate as well as pumping test data were used as input.

![Figure 65: Spatial distribution of boundary conditions in the alluvial aquifer layer.](image)
Figure 66: Spatial distribution of boundary conditions in the karstic aquifer layer.

Figure 67: Model domain and boundary conditions of the alluvial groundwater model.
11.2. Upscale of MAR-SAT and modelling under different scenarios

During MARSOL, a Soil-Aquifer Treatment (SAT) infiltration basin was constructed and operated in the premises of the Lavrion Technological Park of the National Technical University of Athens. However, due to the experimental scale of the aforementioned basins – combined with lack of a continuous connection with a recharge water source – the operation of the SAT system was not enough in order to combat seawater intrusion in the entire aquifer hydrosystem of Lavrion area. Due to the above, one of the main goals of the modeling part of this WP was to prove through different and/or alternative scenarios that the full-scale application of SAT facilities within the alluvial aquifer of Lavrion, could be seen as a sound engineered method that would tackle the problems of water scarcity and seawater intrusion.

Nowadays, the population of the entire Lavrion Municipality needs approximately 7.8 MCM of water for domestic use, and 0.2 MCM for livestock and 1.2 MCM for irrigation purposes, respectively. Household and livestock water is provided by the Municipal Company of Water Supply and Sewage System of Lavrion. Irrigation water is withdrawn from the aquifer and the pumping cost is covered by the farmers. From the total cropland area of 296 ha about 102 ha are irrigated. The situation with respect to groundwater is expected to worsen as demand increases and capacity decreases owing to seawater intrusion, decreasing precipitation trends due to climate change, etc.

For the realization of the above, an assessment exercise was performed, in order to describe a continuous full-scale MAR-SAT in the alluvial aquifer of Lavrion that will be connected with the local...
Wastewater Treatment Plant of the Municipality of Lavrion. The locations of the proposed full-scale MAR-SAT facility as well as of the WWTP of Lavrion are shown in Fig 69.

![Map of Lavrion WWTP and MAR-SAT facility](image)

**Figure 69: Location of proposed full-scale MAR-SAT system and WWTP of Lavrion.**

The WWTP of Lavrion was constructed in 1995, and at present it receives the municipal sewage of a population of approximately 12,000 people. The wastewater undergoes secondary treatment (nitrogen removal, disinfection through chlorination and further treatment with sand filtration). The qualitative characteristics of the untreated and treated wastewater are shown in the following figures, for 2016 (Figs. 70 - 71).

Proposal #1 is to construct a SAT system that will be used to artificially recharge the alluvial aquifer, to mitigate seawater intrusion. The proposed SAT system will consist of six infiltration ponds arranged in two series, as shown in Fig. 72.

The site of the proposed MAR facility has been selected considering the geological and hydrological features of the area (e.g., geological boundaries, hydraulic boundaries, storage capacity, porosity, hydraulic conductivity, depth of the water table etc.), and the distance from the source of recharge water (i.e. the Lavrion WWTP) that will affect the capital and operating transportation costs.

The simulation period of the model is one year; while three different model runs were conducted, each one having a different infiltrated volume of treated wastewater. The hydraulic heads in the end of the simulation period were subtracted by the model top (i.e. surface elevation) to get the thickness of the unsaturated zone. The results are shown in the following maps (Figs. 73 - 75).
In all three runs the model responded well by means that the cells of the alluvial aquifer layer were not flooded. The water infiltrated was taken out of the model through the CHD boundary, which is in the southeastern end of the aquifer, as expected. Besides the ability of that aquifer to host that volume of water, it is worth mentioning that at the 1.5 M m$^3$ scenario the thickness of the unsaturated zone become very small close to the sea (0.287 m), adding a risk of flooding if that amount of water is expected to be infiltrated, especially under the perspective of a wet hydrological year or
other factors that could affect locally the water balance (e.g. sea level fluctuations) or cause structural instabilities in the aquifers resulting in other side effects (e.g. liquefaction).

In addition, approximately 20 piezometers (including multi-level screens within the coastal zone) will be required for monitoring the performance of infiltration basins. Monitoring equipment should be installed at the basin facilities, as well as at aquifer scale, in order to achieve qualitative and quantitative auditing.

Limiting factors for the SAT system are the following:

- On the side of supply, the secondary effluent from the Lavrion WWTP equals 766500 m³/yr
- On the side of infiltration capacity, the potential of the six proposed infiltration basins if constantly supplied of water is estimated at 1.2 MCM/yr
- On the side of the capacity of the aquifer (using the most recent water level measurements, September 2016) and a Sy of 0.1, the volume of the unsaturated zone is calculated to be 406823 m³

![Figure 73: Model run results for artificial recharge of 800,000 m³/yr.](image)
Figure 74: Model run results for artificial recharge of 1,000,000 m³/yr.

Figure 75: Model run results for artificial recharge of 1,500,000 m³/yr.
12. Dissemination and training activities

12.1. Introduction

The dissemination and training activities during the implementation of WP3 are classified into three distinct levels: (i) the training of young scientists and engineers, (ii) the Lavrion Workshop, and (iii) other dissemination activities.

12.2. Training of young scientists and engineers

Training of young scientists and engineers is considered one of the most important dissemination activities in MARSOL WP3. During the completion of the project, and specifically during the different stages of progress (i.e. preliminary hydrogeological assessment, geological mapping, groundwater wells inventory, geophysical investigation, drilling activities, infiltration tests, construction and operation of SAT facilities, monitoring of hydrologic processes etc.) different series of field excursions took place from several European academic and research institutes. More specifically, a number of undergraduate and postgraduate students from different academic programs such as the ones that follow:

- Undergraduate Academic Course in Environmental Hydrogeology at the National Technical University of Athens (NTUA), Greece, for the Undergraduate Program of Mining and Metallurgical Engineering.
- Undergraduate Academic Course in Applied Hydrogeology at the National Technical University of Athens (NTUA), Greece, for the Undergraduate Program of Mining and Metallurgical Engineering.
- Undergraduate Academic Course in Science and Technology of Geothermal Fields at the National Technical University of Athens (NTUA), Greece, for the Undergraduate Program of Mining and Metallurgical Engineering.
- Postgraduate Academic Course in Groundwater Salinisation, at the Technical University of Darmstadt, Germany, Postgraduate Programme on "Tropical Hydrogeology and Environmental Engineering" (TropHEE), Department of Material- and Geosciences of the Technical University of Darmstadt.
- Postgraduate Academic Course in Advanced Hydrogeology at the National Technical University of Athens (NTUA), for the Interdepartmental Program of Postgraduate Studies (IPPS) in Water Resources Science and Technology (WRST).
- Postgraduate Academic Course in Groundwater Exploitation Works, Management and Protection of Aquifers at the National Technical University of Athens (NTUA), for the Interdepartmental Program of Postgraduate Studies (IPPS) in Water Resources Science and Technology (WRST).

The aforementioned events were repeated in every academic semester, and included visits at the Technological Park of Lavrion, the aquifer system of Lavrion and also several of the facilities of the Athens Water and Wastewater Company (EYDAP), as shown in the following figures.
Figure 76: Undergraduate students of the National Technical University of Athens, during field excursion at the Lavrion wadi estuary.

Figure 77: Postgraduate students of the National Technical University of Athens, during field excursion at Lavrion Technological and Cultural Park (LTCP).
12.3. Lavrion Workshop, 16-18 March 2016

During the implementation of the MARSOL Project, a scientific workshop took place at the premises of the Lavrion Technological and Cultural Park (LTCP) of the National Technical University of Athens. The topic of the workshop was focused on investigation and monitoring technologies during hydrological studies, while the presentation topics covered a wide range of approaches: sensor development; data acquisition, transfer, management and storage; monitoring strategies and analytical techniques for measurements of environmental parameters.

The target groups of the Lavrion Workshop covered a wide range of water professionals, such as: hydraulic engineers; electrical engineers; hydrogeologists; postgraduate and undergraduate students of hydrogeology, water science and technology; academic and research staff; private professionals that work in the field of water management; water authorities; water utilities.

During the workshop, a poster session was also organized in order to promote the investigation and monitoring technologies that are applied in all MARSOL demonstration sites.

As the MARSOL Lavrion Workshop was dedicated to investigation and monitoring technologies, aiming to disseminate and promote the technological advancements that were developed during MARSOL project, the concept of a mixed "presentations and on-site demonstrations" was applied. Each workshop day included: (i) presentations session, (ii) on-site demonstration session, and (iii) open discussion session. The on-site demonstration sessions included field visits and activities within the Technological Park facilities that promoted the monitoring and investigation technologies which were developed during MARSOL such as: (i) wireless sensor networks, (ii) TDR & FDR probing.
systems, (iii) integrated monitoring schemes for MAR infiltration basins, and (iv) direct-push and geoprobeing technologies. For the purposes of the Workshop, special dissemination material was prepared, that describes in details all the technological advancements that were developed through MARSOL project.

Figure 79: MARSOL Workshop on Monitoring and Investigations Technologies, March 16-18, Lavrion, Greece.

Figure 80: MARSOL Workshop on Monitoring and Investigations Technologies, March 16-18, Lavrion, Greece.
Figure 81: MARSOL Lavrion Workshop dissemination material.

Figure 82: MARSOL Workshop WP11 dissemination material in the form of leaflet (distributed during the workshop).
The MARSOL Lavrion Workshop also included a site visit at the the Psyttalia Wastewater Treatment Plant (WWTP) of EYDAP, a unique project located on a small limestone island of Athens. The wastewater treatment in Psyttalia includes pre-treatment, primary and secondary treatment with advanced biological nitrogen removal, sludge treatment and cogeneration of electrical and thermal energy. The Psyttalia WWT capacity is 5,600,000 p.e., being one of the largest WWTPs in Europe and worldwide. The average supply of incoming wastewater is the range of 730,000 m³ per day.
12.4. Other dissemination activities

This section includes the conventional dissemination activities that took place during MARSOL project and are related to the tasks of WP3 (in combination with the tasks of WP11 and WP2). The aforementioned activities involved the dissemination of the scientific outcomes of the project, at different levels of dissemination such as: (i) national and international scientific fora, conferences, workshops, events, (ii) national and international peer reviewed scientific journals, (iii) other types of MARSOL promotion activities. All the above are included in the dissemination reports of the project; however the initiative of developing a communication platform that will go beyond the life-time of the MARSOL project was conceptualized during the implementation of WP3. Therefore, the "Lavrion hydro-Environmental Observatory - LEO" was established by the Laboratory of Engineering Geology & Hydrogeology (School of Mining & Metallurgical Engineering, National Technical University of Athens), which is a platform of dissemination and communication of the scientific activities that are taking place in the area of Lavrion. The LEO platform is online since 2014, providing information on the MARSOL WP3 and relevant multi-disciplinary scientific activities. The site also serves as an online data repository that provides real-time data with respect to hydro-environmental (among others) parameters of the Lavrion coastal hydrosystem.

![Figure 85: Homepage of the Lavrion Hydro-Environmental Observatory - LEO (www.leo.ntua.gr).](image)

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13. Conclusions

The MARSOL demonstration site of Lavrion was primarily used as a reference site to develop, construct, test and install new technologies that target to monitor relevant processes within all hydrologic zones (surface, unsaturated and saturated) at a Managed Aquifer Recharge facility. Since the case study of the Lavrion hydrosystem is a coastal one that also suffers from seawater intrusion, MAR application is considered as a groundwater engineering technique that will remedy this certain type of problem in the local alluvial aquifer system.

After the implementation of the project, the Lavrion demonstration site proved that it successfully served its original purpose, by means of providing a physical hydro-environmental field laboratory for hosting different types of monitoring technologies and subsurface investigation techniques. The MARSOL infrastructure that was installed during the project is considered a working field platform of NTUA which still serves the purposes of demonstration for academic and other target groups. The MARSOL Lavrion site is selected by the Organizing Committee of the 11th International Hydrogeological Conference of Greece, organized by the Greek Chapter of the International Association of Hydrogeologists during 4-6 October 2017, as the official site for the Conference Excursion.

The Lavrion demonstration site was partially designed in order to be used by MARSOL partner EYDAP as an experimental site, before the implementation of a full-scale wastewater re-use master-plan of the company, utilizing the majority of the wastewater treatment plants in different locations within the Attica Region, Greece. The experience gained from the MARSOL project enabled the company to comprehend the potential for wastewater reuse and application of Managed Aquifer Recharge within the region of Attica, at sites with characteristics similar to the Lavrion site. One of the targets of the MARSOL concept, i.e. to prove that SAT can effectively combat seawater intrusion in coastal aquifers, was not effectively illustrated due to the limited size of the experimental-scale pilot SAT basins. However, tailored site investigation and modelling activities during the implementation of Work Package 3 have proved that the installation of SAT basins at selected locations within the alluvial aquifer of Lavrion can effectively combat seawater intrusion and also water scarcity in the local coastal hydrosystem.

The experience gained – such as limitations, drawbacks, advantages etc. – from the implementation of the field activities in Work Package 3 were also used for the partial completion of Deliverables 11.1 to 11.4.
14. References


Kakavogiannis, E., 2005. Metals worked and forgiven; the organizing and exploitation of ore deposits at Lavreotiki from the Athenian democracy, Ministry of Culture (in Greek).


