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EXECUTIVE SUMMARY

Deliverable 11.1 is the first deliverable of the MARSOL project’s Work Package 11: Investigation and Monitoring Techniques, considered as a scientific product of Task 11.1: Investigation and Monitoring Strategies.

Main tasks of this work package are the evaluation of state-of-the-art and innovative monitoring strategies at MAR sites and the further development of specific sensor and IT technologies. The results, including experience based on the investigation and monitoring approaches at the project’s eight demonstration sites, will be compiled and integrated into a guideline document on appropriate investigation and monitoring strategies at MAR facilities. More specifically, Task 11.1 (Investigation and monitoring strategies) is associated with a thorough literature review on investigation and monitoring strategies that can be applied at MAR sites and their performance evaluation that will form the scientific basis for the development of a best-practice guideline for the selection of appropriate investigation and monitoring strategies and systems for MAR facilities (Task 11.5, Deliverable 11.4: Best Practice Guidelines).

This deliverable serves as a wide literature review that provides a detailed description of the engineering approaches that may be applied in order to effectively investigate and monitor the challenging hydrologic processes within MAR systems.
1. INTRODUCTION

1.1. General

Artificial recharge systems are engineered systems where surface water is put on or in the ground for infiltration and subsequent movement to aquifers to augment groundwater resources (Bouwer, 2002). In general terms, artificial recharge systems can be categorized into the following, based on the hydrologic zone that they target:

- Surface Infiltration
- Vadose Zone Infiltration
- Injection Wells
- Conjunctive systems

Bouwer (1999) summarizes the key factors that refer to the optimal design and management of Managed Aquifer Recharge facilities, and include: site selection criteria, maintenance of high recharge rates, sufficient hydrogeological conditions to ensure adequate hydraulic connection between the MAR facility and the underlying aquifer body, and finally optimized groundwater control for recovery. In order to optimize the performance of an artificial recharge system, numerous investigation methods accompanied by sophisticated monitoring approaches and techniques should be applied that will ensure comprehensive understanding of the relevant processes within the surface, unsaturated or saturated hydrologic zone.

1.2. Investigation Strategies for MAR Facilities

Investigation is the first and foremost step in setting up any MAR sites. Proper investigation data enables one to take decision in designing and monitoring the site which ensures the sustainability of the project itself avoiding any unwanted circumstances. Normally, the sites at new locations require rigorous study with higher costs.

In general, the investigation process in MAR includes the following aspects:

i. Assessment of water demand

ii. Hydrological and hydrogeological assessment of the area

iii. Geological assessment of the area

iv. Design and risk assessment
1.2.1. Assessment of water demand and availability

In a first step, the rational for the implementation of a MAR facility has to be elaborated. This should include an evaluation of the quality and the long term availability of the recharge water source, and an estimate on the water demand of potential end users of the infiltrated water (i.e. public water supply, agriculture, industry), or estimates on water demand for specific target applications, respectively (i.e. flood mitigation, aquifer restoration, prevention of sea-water intrusion). To warrant long term benefit of the MAR system, future projections for both, water demand and water availability are required, i.e. demographic development or climate scenarios.

1.2.2. Hydrological and hydrogeological assessment of the area

Related to the assessment of water demand and availability, the target water volumes for the MAR system have to be defined. For infiltration and storage, (i) availability of space for infiltration facilities is required and (ii) a suitable aquifer, which should have an adequate permeability, sufficient storage capacity, and either retain water for later recovery at the site of infiltration, or allow water to move for recovery downgradient of the infiltration site. Site characterization and investigation typically relies on a thorough review of available data, and on hydrological, hydrogeological, and geophysical methods.

1.2.3. Geological assessment of the area

Besides the proper assessment of the immediate vicinity of the MAR site, the geological boundary conditions in the surrounding area have to be evaluated. Especially the presence of karst systems and major fault zones as well as the probability of geo hazards (i.e. earth quake, floods, tsunamis) have to be considered.

1.2.4. Design & Risk assessment

Design of a MAR site and the mandatory infrastructure should warrant full functionality and stable operation without relevant environmental impact at the site and its periphery. The risk assessment usually addresses health risks and environmental risks, which is especially applied in cases where Managed Aquifer Recharge is associated with the use of reclaimed waste water as a recharge source (Dillon, 2005; Dillon, 2009; Dillon et al., 2008; Page et al., 2010).

1.3. Monitoring Strategies for MAR Facilities

The demonstration sites of the MARSOL project cover a wide range of MAR methods and technologies, such as: (i) Recharge basins - Menashe (Israel), Arenales, Segovia, and Valladolid (Spain), Lavrion (Greece); (ii) River bank filtration - Serchio (Italy), (iii) River infiltration basins - Llobregat (Spain), Algarve (Portugal); (iv) Infiltration trenches - Brenta (Italy), Arenales, Segovia, and Valladolid(Spain); and (v) Injection wells - South Malta (Malta), Arenales, Segovia, and Valladolid (Spain).
Figure 1 summarizes the investigation and monitoring techniques that are currently applied at the demonstration sites of the MARSOL project, which in turn can serve as a blueprint for other Managed Aquifer Recharge facilities worldwide.

![Figure 1](image.png)

*Figure 1. Main strategies that are mandatory for sufficient investigation of MAR methods.*

Based on the backbone of the ongoing investigation and monitoring strategies of the MAR demonstration sites of the MARSOL project, this document describes in detail a wide range of technologies that include:

- **Surface geophysical methods**: non-invasive exploration technologies that measure the physical, electrical or geochemical properties of the aquifer matrix or groundwater (ground-penetrating radar, electromagnetics, resistivity, seismic refraction and reflection).

- **Vadose zone monitoring**: monitoring of storage, infiltration rates, pore water extraction and quality.

- **Direct push technologies**: vibro-coring technologies that can offer high resolution subsurface investigation, logging and geophysical tools, pore water or groundwater probing and undisturbed deep soil sampling.

- **Groundwater monitoring schemes**: optimum groundwater monitoring schemes that are necessary for the supervision and optimization of MAR facilities inspection, monitoring systems design criteria, sampling and analytical protocols.

Depending on the MAR type, the phase of the MAR project, the original reasons for the implementation of the MAR system, etc., various strategies and technical solutions for monitoring can be applied. Each particular MAR system may require a specific approach to monitoring. Generally, monitoring should always be in line with the complexity and risk of the proposed MAR...
scheme. It should have a clear objective that the monitoring has to achieve and should warrant safe and sustainable site operation. Therefore it should be integrated within the risk assessment and management processes of the site.

For example, if the source-water is highly variable in quality and quantity, grab samples may give less valuable information compared to integrated measurements like passive sampling. In such a case, mean concentrations are more relevant for potentially resulting water quality changes in the aquifer. To select proper monitoring methods and strategies is therefore of high importance for successful site operation.

Table 1 shows the main types of monitoring according to the Australian Guidelines for Water Recycling.

**Table 1. Types of monitoring strategies (Kazner, 2012).**

<table>
<thead>
<tr>
<th>Type of Monitoring</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Baseline Monitoring</td>
<td>This provides the maximum risk assessment which defines the state of the system before Managed Aquifer Recharge starts.</td>
</tr>
<tr>
<td>2 Validation Monitoring</td>
<td>This is important when there is reliance on the treatment capacity of the aquifer. Quantifies treatment efficiencies of any treatment step; pre-treatment, post-treatment, as well as detection of water quality degradation (such as Arsenic release, or disinfection by-products); It includes: (a) monitoring surrogate parameters (b) the use of piezometers</td>
</tr>
<tr>
<td>4 Verification Monitoring</td>
<td>It is compulsory for all actively operating projects, for regulatory agencies, checking whether the MAR system is functioning as expected or not along with other MAR components.</td>
</tr>
</tbody>
</table>
Various methods for monitoring have been developed and are used in various MAR sites throughout the world. With a proper monitoring strategy, one can assess the efficiency of the system and sort out and solve the problems in the system as quickly as possible, and with this potentially prolonging the life of the MAR system.

Keeping the seven components of MAR into considerations, the key factors in the design and proper management of a MAR site in order to implement it successfully are (Bouwer, 2002):

1. Site and system selection
2. Maintenance of adequate infiltration rates
3. Hydraulic conductivity between the recharge system and the aquifer (no clay layers in the unsaturated zone)
4. Groundwater control for effective water recovery
5. Prevention of undue groundwater rises in recharge area

To meet the target of optimized and consistent performance of a Managed Aquifer Recharge system, various investigation methods followed by sophisticated monitoring approaches and techniques should be practiced. This provides an insight into the suitable method according to the hydrological zone (surface, unsaturated or saturated).
2. SURFACE GEOPHYSICAL METHODS

This minimally invasive set of methods includes various technologies that investigate hydro-geologic conditions in the subsurface. Geophysical methods are typically fast and generate a large data set for interpretation. A vast and continuous collection of data along a traverse line can be acquired with this method, however this also has its limitations. Therefore, careful selection of the most appropriate method as per the requirement of the MAR project site conditions is a crucial step.

The advantages of opting for these methods are that they are non-invasive or minimally invasive compared to other methods, enables in-situ measurement of the physical, electrical or geochemical properties of the aquifer matrix or groundwater within the saturated or unsaturated zone.

Generally, accuracy depends on the contrast between the aquifer body and its background. The higher the contrast better is the resolution. Similarly, the size of the aquifer body is equally important. If the aquifer body is not large enough, detection is also not possible. Before selecting any particular method or a set of methods, the objective of the project must be clear and the detailed information about the site condition is important.

The most widely applied hydro-geo-physical methods also incorporated at the present MARSOL sites are as follows:

- Ground-Penetrating Radar (GPR)
- Electromagnetics and resistivity
- Seismic refraction and seismic reflection
- Micro gravity
- Magnetometer

2.1. Ground-Penetrating Radar

GPR is the study of the sub-surface using high-frequency (polarized) electromagnetic waves, from 10 MHz to 1 GHz. A transmitter unit emits the electromagnetic energy into the ground hitting the aquifer components with different dielectric constants or electrical conductivity that may be indicator of natural hydrogeological conditions such as bedding, cementation, moisture, fractures, void, clay content etc. which emits different signals (reflected, scattered, or refracted) to the receiver.

Guidelines for environmental site characterization by GPR are available in ASTM Standard D 6432 (ASTM, 2004a). According to Benson (2006), the water table can be detected in coarse-grained

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1 Not used in MARSOL
materials but not in fine-grained sediments with a large capillary fringe. An interface between two rock or soil layers show a clear profile in GPR when they have sufficient contrast in their electric properties (Cassiani et al., 2010; Rust et al., 2011; Benson and Glaccum, 1979; Benson et al., 1982; Benson and Scaife, 1987).

Typically, GPR penetrates in soil and rock in the range of 5 m and 10 m, respectively, whereas for silts and clays, penetration is limited to less than 1-2 m. According to Benson (2006), radar penetration is generally better in coarse, dry, sandy, or massive rock. The results will be poorer in wet, fine grained, clayey (conductive) soils; meanwhile the data can be obtained also from saturated material if the specific conductance of the pore fluid is sufficiently low.

The application of GPR has following advantages over other hydro-geo-physical methods:

- High data resolution
- Large site coverage
- Flexibility in field measurements

### 2.2. Electromagnetic (EM) and Resistivity Methods

According to Werban et al. (2014), Benson et al. (1982), McNeil (1982), and Telford et al. (1982), principally, the EM and the resistivity methods are similar as they both measure the same parameter but in different ways, equally applicable for the assessment of the natural hydro-geologic conditions.

Natural variation in subsurface conductivity (or resistivity) are generally due to factors like changes in basic soil or rock types, thickness of soil and rock layers, moisture content, and depth to water table; localized deposits of natural organics, clay, sand, gravel, or salt-rich zones, along with structural units like faults, fractures, domes, or voids, etc.

The correlation between the groundwater chemistry data and results using electrical methods to map inorganics from landfills has been as good as 0.96 at the 95% confidence level, as per Benson et al. (1985). This implies that the electrical methods can be a means of direct mapping of the extent of possible contaminants within a soil-aquifer-treatment facility, also obtaining the flow direction and estimating the concentration gradients, where it would also measure time series to obtain data on plume dynamics (Benson et al., 1988; Cassidy et al., 2001) and thus provide vital information for modelling groundwater flow.

### 2.3. Electromagnetics

The electromagnetic method is widely applied in aquifer mapping, estimating volume extent and internal structure of the aquifers, mapping the infiltration of the unsaturated zone, and contamination of the groundwater. The most commonly practiced EM instrumentations are: (i) Frequency-domain systems (continuous energy radiation from the transmitter); and (ii) Time-domain systems (measurement of induced current vs. time). These frequency-domain and time-domain systems both
induce currents into the ground by EM induction (McNeil, 1982). Guidelines on the use of time-domain and frequency-domain EM conductivity are given in ASTM Standards D 6820 (ASTM, 2004b) and D 6639 (ASTM, 2004c) respectively.

Following are the major characteristics and advantages of the electromagnetic method:

- Less time-consuming
- Profiling also offers the lateral variation in conductivity
- Frequency-domain EM instruments may provide data from depth of 0.5 m to 60 m
- The vertical resolution of the frequency domain EM sounding is relatively poor because measurements are made at only a few depths
- Time domain transient EM systems can generate detailed sounding data to depths of 45 m to ≥ 300 m.

2.4. Resistivity

As with EM measurements, electrical resistivity measurements are a function of the type of soil or rock, its porosity, and the conductivity of the fluids that fill the pore spaces (Benson, 2006). The method may be used in many of the same applications as the EM method (Griffith and King, 1969; Mooney, 1980; Benson et al., 1982; Telford et al., 1982). ASTM Standard D 6431 (ASTM, 2004d) provides guidance on the use of the DC resistivity method for environmental site characterization.

Similar to the EM measurements, the resistivity can be applied for profiling or sounding, where profiling helps mapping the lateral changes in sub-surface electrical properties to a given depth and is suitable for the delineation of the hydro-geologic anomalies and mapping of the contaminant plumes as in the case of SAT facilities in groundwater artificial recharge.

According to Benson (2006), the considerable space required by the array during survey is one drawback of resistivity sounding. For example, in a Wenner Array sounding (with four electrodes equally spaced) might require that the spacing between the electrodes be as much as three or four times the depth of interest, and therefore, a sounding to a depth of 30 m could require array length of about 275 m to 365 m. In most sites, this much space might not be available; if available, it has to pass through many disturbances which act as noise.

2.5. Seismics (Reflection & Refraction)

The seismic method builds on the propagation of low-frequency waves through the earth layers to estimate the properties of the sub-surface. The method’s advantages can be seen in its high accuracy, high resolution, and greater penetration depth. The basic principle is the recording of the time interval for the waves to travel from the sources to a series of geophones, predisposed along a straight line directed towards the source, as seismic waves travel with different speed through
differing aquifer component like lithological strata, depth of water table, fracturing, faulting, and buried bedrock channels (Benson, 2006). Detailed information on seismic refraction and reflection can be found in ASTM standards D7128 and D6439, respectively.

The technique to assess the sub-surface condition under water (e.g. river or lake) is called continuous seismic profiling.

i) Seismic Refraction: If the survey aims on investigating shallow aquifers, seismic refraction is the suitable method (Griffith and King, 1969; Benson et al., 1982; Telford et al., 1982; Haeni, 1986). One benefit of refraction over reflection is that it comes with the lesser noise so that data interpretation is easier. With application of more energy, survey of more depth is possible, with up to 3-4 different layers of soil and rock can be normally determined, if a sufficient velocity difference or contrast exists between adjacent layers. For environmental site characterization, guidelines are available in ASTM Standard D 5777 (ASTM, 2004e).

ii) Seismic Reflection: Seismic reflection is similar to seismic refraction, but the study of deeper aquifers is possible with lesser energy than by refraction ranging from 3 m to 30 m. Seismic frequency for shallow aquifer studies should be relatively high (150 to 600 Hz). Additional information on seismic reflection can be found in ASTM D7128-05.

2.6. Applications in MAR engineering

If the target of the artificial recharge is the unsaturated zone, many of the available surface methods can be applied to make measurements about the bottommost and sub-bottom area (ASTM, 2004c; ASTM, 2004d; Haaken et al., 2012; Maliva et al., 2009; Maliva et al., 2014). However, the effectiveness of the method in determining the performance of the geo-purification process in a Soil-Aquifer Treatment (SAT) project is questionable.

According to Olhoeft (1986), direct detection of the contaminant level in the infiltrating water can be done by electrical methods, including ground-penetrating radar and complete resistivity measurements afterwards. Similarly, if the contamination level is significantly high, they can be detected by electrical methods and radar. The higher the specific conductance of the pore fluids, the easier it is to map the plume. Benson (2006) reports that inorganic plumes have a very low specific conductance, or dispersed organic compounds are encountered which are beyond the range of detection by electrical methods.

The vertical sounding is possible with both the resistivity and EM. The limited penetration depth to about 60 m of the frequency domain EM method provides a less resolution than the resistivity method because the measurement is possible only for few depths. The depths to which resistivity sounding data can be obtained are virtually unlimited. Depth of approximately 50 m or more than 300 m is easily accessible.
In order to monitor the changes in the properties with time and during remediation, during the SAT process, both the electrical measurements (EM and resistivity) along with radar can be used (Olhoeft, 1986). After the assessment of the spatial extension of the contamination by surface geo-physical method, continuous borehole logging can be used to evaluate changes in the properties of the aquifer vertically like vertical hydraulic conductivity of the soil and rock, as well as distribution of the contaminants. Vertical attributes like distribution and concentrations of various parameters of the water being infiltrated can vary drastically which had direct impact on the test results obtained from a monitoring well.

The unsaturated zone is an interlinking zone between a human-influenced surface water source and the water table or the aquifer system underlying. The most common objectives of monitoring the unsaturated zone are:

- To determine the fluid saturation (water, air and non-aqueous phase)
- Assessing the mobility of the fluid (infiltration rates, unsaturated hydraulic conductivity, or relative permeability)
- Sampling the inter-particle fluids present

As various parameters like moisture content, pressure, hydraulic conductivity are inter-related, usually one of the variables is measured and used as a surrogate or estimate of the others (Ballestero et al., 2006).
3. MONITORING IN THE VADOSE ZONE

The vadose zone is considered as the most critical zone that plays the role of an interface between a surface Managed Aquifer Recharge facility and the underlying groundwater body of the aquifer. In this sense, the unsaturated zone governs most of the conditions that are responsible for the performance of the MAR facility, from a quantitative (e.g. infiltration rates, mechanical clogging etc.) or qualitative (e.g. geo-purification processes) point of view. This section describes the significance of the most critical factors that are needed to be considered when it comes to monitoring of the vadose zone such as: monitoring of storage, monitoring of infiltration rates, and monitoring of water quality.

3.1. Monitoring of Storage

In order to monitor the water storage in the unsaturated zone, the measurement of physical properties like bulk density, total thickness, porosity, water content, and soil moisture content versus tension relationship is necessary. The measurement of the tension and water content can be done using tensiometers, electrical resistance blocks, thermocouple psychrometers, gamma-ray attenuation, or nuclear magnetic resonance.

3.1.1. Tensiometers

Tensiometers measure the soil matrix potential (pressure), where a water continuum is created to the unsaturated zone, from where pressure can be measured anywhere within the continuum. It consists of a glass or plastic tube with a porous ceramic cup, attached to a pressure sensor via a tube filled with water. The porous cup is located in the unsaturated zone where the information on the pressure (matrix potential, or suction) is extracted. The most reliable data are obtained by purging the tensiometer and allowing it to equilibrate before recording the measurements. Stannard (1990) presents a number of designs, along with their advantages and disadvantages.

3.1.2. Electromagnetic methods (EM)

Topp (2003) mentions that one of the key factors that enable the quantitative inclusion of the hydrological processes within the unsaturated zone is the wide application of electromagnetic methods that target to water content measurements. EM methods and more specifically their application in the investigation of the unsaturated hydrological zone (and the contained water within the soil matrix through the unsaturated column), mainly include time domain reflectometry (TDR), ground penetrating radar (GPR), capacitance and active microwave remote sensing. Topp and Ferre (2002) provide a detailed update of methods for soil analysis and they included five EM techniques where new developments have occurred.

3.1.2.1. Time Domain Reflectometry

Time-domain reflectometry (TDR) is a complex electronic technology originally used primarily for testing high-speed communication cables (Topp et al., 2003). Stacheder et al. (2009) are defining TDR
measurements as an “estimation of the bulk dielectric permittivity, \( \varepsilon_r \) of the soil mixture (soil matrix, soil water and air) by measuring the propagation time of an EM pulse, generated by a pulse generator and containing a broad range of different measurement frequencies”. TDR technology is in principle a geophysical technique (Stacheder et al., 2009) based on the relation between the permittivity of soil and its volumetric water content. TDR has been developed and widely used in water studies as an indirect geophysical technique (ASTM, 2004e) which is based on the relation between the dielectric permittivity of soil and its volumetric water content and therefore capable of estimating the water content contained within the soil matrix, with Hoekstra and Delaney (1974) and Topp et al. (1980) being the pioneers in the field. Whalley (1993) also quotes that the use of TDR for measuring soil water content was originally proposed by Davis and Chudobiak (1975), Davis and Annan (1977) and Topp et al. (1980), although the potential of a balanced two-wire transmission line for probing the soil had already been recognized by Kirkschether (1960). Most usual shape of TDR probe is that of two or three parallel metallic rods of limited length. However, single rod probes have also been recorded in literature such as the prototype of Oswald et al. (2004), who investigated a TDR probe that employs only one single metallic rod for measuring volumetric water content based on the concept of a Sommerfeld wire; and the work of Nussberger et al. (2005) who inserted a single rod into the ground that acts as a line for transmitting a fast rise voltage step launched by the TDR instrument, with the interference of a coaxial cable which connects the TDR instrument with the probe. The TDR pulse travels until the end of the transmission line (end of the probe) and it is reflected back, received from the TDR, where the signal is analysed. The velocity, at which the pulse is propagated from the TDR instrument to the end of the probe and back, is related to the dielectric permittivity of the medium. The relative permittivity of air is 1, while those for common minerals in soils and rocks lie in the range 4.5 to 10 (Keller, 1989; Robinson and Friedman, 2003), while water has a permittivity of 78.5 at 25 °C (Robinson et al., 2003). The aforementioned constitutes the basis on which the application of TDR technology lies to determine the water content of a soil medium, i.e. the relation between the bulk dielectric permittivity of the soil and its water content.

According to Evett et al. (2005), TDR technology aims to the accurate acquisition of soil water content from the surface to well below the root zone, and this, in order to determine the crop water use, water use efficiency, irrigation efficiency, and the hydraulic characteristics of soils.

According to Topp (2003), TDR is and will be used to validate ground penetrating radar (GPR) findings, making it natural for these two techniques to be used in complementary ways to define appropriate scales of measurement for calibration and use of hydrological models. Huisman et al. (2003) focused on the potential of measuring the temporal development and spatial variation of volumetric water content using Ground Penetrating Radar (GPR) and Time Domain Reflectometry. They compared GPR and TDR variograms and the results showed a high accuracy and reproducibility for GPR measurements of the spatial and temporal development of soil water contents under, e.g. irrigation activity.
3.1.2.2. Electrical Resistance Blocks

Electrical resistance blocks are a minimally invasive, inexpensive method which is used to measure either moisture content or soil-water pressure, consisting of two-metal plates imbedded in a porous material, typically gypsum, nylon, or fibreglass, generally used in scheduled irrigation. Wires are attached to the plates which measure the electrical resistance in between.

According to Ballester and al. (2006), following are the main advantages of electrical resistance blocks:

- Very suitable for the general use of soil-water relation
- Inexpensive
- Determines both suction or moisture content
- Minimum maintenance
- Temperature sensitivity (in-situ) time-consuming calibration

Likewise the major disadvantages are:

- Temperature sensitivity (in-situ)
- Time-consuming calibration
- Slow response times
- The independent effects of salinity on electrical resistance
- Inaccuracy of measurements of high water content (or low soil-water pressure).

The upper limit of the suction for tensiometers is 0.8 mpa, which is generally why they are used only for suction in excess of 0.8 atm. Additionally, gypsum is dissolved in the long-run which might be a problem in certain period of time.

3.1.3. Thermocouple psychrometers

Thermocouple psychrometers measure the water potential and its components by determining the vapour pressure in a sealed atmosphere in equilibrium with sample containing liquid water.

A thermocouple in the chamber above the sample determines the vapour pressure in the atmosphere and thus in the sample (Boyer, 1995). No continuous liquid is needed which makes the method more versatile than others requiring the liquid continuity. The sample is enclosed in a small, air-tight chamber and allowed to equilibrate.
Soil-water pressure is determined based on relationship between soil-water pressure and relative humidity in the soil (Brown and Van Haveren, 1972). The instrument should be calibrated before the field installation.

Despite psychrometers prove to be the best monitoring choice in dry soil conditions, the method has following disadvantages:

- Very sensitive to temperature fluctuations
- Expensive
- Complex

3.1.4. Gamma-Ray Attenuation

Gamma ray attenuation can be an indicator of variation in the lithology of the target aquifer, indirectly used to measure the moisture content by non-invasively determining the soil density (Dierke and Werban, 2013). According to Ballestero et al. (2006), the attenuation of the gamma rays (usually from caesium) passing through a soil column depends on the density of the soil column i.e. if the soil density remains constant (i.e. the soil is non-swelling). A soil containing clay minerals has the potential to swell when the water content is increased.

This method requires 2 parallel access holes, one for the source and other for detector. The accurate determination of the location of the wetting front can be measured up to 2 cm, both vertically and horizontally.

Following are the major disadvantages of this methodology:

- Expensive
- Difficult to use
- Careful operation and handling of the radioactive source is required
- Instrument calibration is sensitive to changes in bulk density
- The availability of vertical boreholes is a must, if the site cannot provide vertical borehole, no gamma ray attenuation study is possible

3.2. Monitoring of infiltration rates

In the unsaturated zone, monitoring the infiltration rates is important to estimate the downward fluid movement during the wetting cycle of a MAR process, especially at infiltration basins. Infiltration rates are affected by many factors such as soil texture and structure (including soil layers), initial moisture content, entrapped air and pressure within, also the water salinity. Field methods for
measuring the unsaturated hydraulic conductivity are described in detail in ASTM Standard D 5126 (ASTM, 2004f).

Typically, infiltrometers are used to measure the infiltration rates, either single ring or the double ring. The basic principle is maintaining a constant head in the inner and the outer ring within the infiltrometer. The double-ring infiltrometer are more reliable than the single ring ones due to minimal lateral flow and simplicity in calculation of the saturated hydraulic conductivity. ASTM Standard D 3385 (ASTM, 2004g) encloses the detailed description of the method.

3.3. Monitoring Water Quality in the Unsaturated Zone

As the unsaturated zone plays a key role during MAR, being a path of water flow, it is important that detailed spatial and temporal changes in water quality are measured and monitored. This quality monitoring is even more important if the input water is of lower quality like treated sewage (Abiye et al., 2009; Alidina et al., 2014a; Alidina et al., 2014b; Asano et al., 2007; Bekele et al., 2011; Bekele et al., 2013; Bekele et al., 2015; Betancourt et al., 2014; Drewes, 2009; Dutta et al., 2014; Greskowiak et al., 2005). Proper monitoring of the unsaturated zone can prevent many unwanted results like possible contamination and detection of contaminant movement during the SAT (Henzler et al., 2014; Hochstrat et al., 2010; Kim et al., 2015; Li et al., 2006; Li et al., 2013; Maeng et al., 2001; McFarlane et al., 2009; Ollivier et al., 2013; Su et al., 2013; Toze et al., 2010). It acts as an early warning system, where we can take corrective action before the contamination spreads throughout the aquifer being recharged.

A detailed discussion on the chemical reactions affecting the contaminant migration in the unsaturated zone is presented in Wilson (1980), whereas, Ballestero et al. (2006) explain the following three main types of methods available for monitoring water quality in the unsaturated zone:

- Direct soil water sampling
- Direct measurement of pore water from soil cores
- Indirect methods, including measurements of electrical and thermal properties

3.3.1. Electrical Properties Measurements

Electrical conductivity is the conductance of the soil along with its soil solution. The data acquired from the field measurement of electrical conductivity (EC) and resistivity is the clear indicator of the soil characteristics like soil salinity. It is also a tool to map the contaminant plumes. Likewise, electrical resistivity can be measured by surface geophysical techniques or by direct-push deployed sensors, which is also possible by using electrical resistance blocks (salinity sensors) used to evaluate soil salinity. The combination of the above instrumentation installed underneath a SAT system allows remote monitoring.
3.3.2. Pore-water Sampling

Weihermüller et al. (2007) observed that new non-invasive technologies such as time domain reflectometry (TDR), electrical resistivity tomography (ERT), and groundwater penetrating radar (GPR) define new approaches for both the experimental design as well as the sampling schemes in the unsaturated zone. Wassenaar et al. (2008), in their research, comment that the $\delta^{18}$O and $\delta^D$ values of extracted pore water from saturated and unsaturated soil cores are widely used as natural tracers in several hydrologic studies. Up to present the mostly used techniques for extracting pore water from soil matrix retrieved from the saturated or unsaturated zone include the application of: centrifugation, press and/or squeezing, vacuum distillation, cryogenic micro distillation, leaching, equilibration and azeotropic distillation (Kallioras et al., 2012).

3.3.2.1. Centrifugation

Edmunds and Bath (1976) applied centrifugation as a method for porewater extraction from consolidated geological materials, for subsequent chemical analysis, where they observed that fractionation effects and small sample volumes may be related to significant analytical errors that could reach even $\pm 10\%$ in the pore water analysis. Zornberg and McCartney (2010) developed a new centrifuge permeameter with the specific objective of expediting the measurement of the hydraulic characteristics of unsaturated soils. Kinniburgh and Miles (1983) extracted interstitial water from field-moist soils and chalk by immiscible displacement with a dense, inert fluorocarbon liquid, by using a high-speed centrifuge. Their results showed that yields of interstitial water from soils at field capacity are typically 20-50% of the total water present while yields from chalk range up to 90%. Kelln et al. (2001) used hydrometric and geochemical data to examine the contribution of preferential flow to the hydrological response of a reclamation cover on saline-sodic shale mine overburden, in a cold semiarid environment. The pore water from the collected soil samples was extracted in the laboratory using high-speed centrifugation and analysed for major anions.

3.3.2.2. Mechanical Squeezing

Boettcher et al. (1997) developed a new plastic-lined high-pressure squeezing device for the extraction of soil samples with moisture contents of more than about 15%. According to the results, they concluded that enough water for major and trace element analyses was extracted, while the data did not reveal any contamination of the pore fluids from the squeezing device.

3.3.2.3. Vacuum Distillation

Allison and Hughes (1983) applied vacuum distillation, for tritium analysis, while for the stable isotopes they applied azeotropic distillation, as it was observed that no fractionation results were produced by this technique. Araguas-Araguas et al. (1995) applied vacuum distillation for extracting soil water for stable isotope analysis from three different types of soil characterized by high water content: (1) pure sand, (2) cambisol with high organic matter content, developed on calcareous sandstone under temperate climatic conditions (Austria), and (3) tropical latosol poor in organic matter, developed on sandy clay sediment (Brazil). They concluded that the method produced
accurate and reproducible results for sand, provided that more than 98% of the original soil water is extracted. Fontes et al. (1986) used stable isotope profiles in soil water in northern Sahara in order to interpret the hydrologic processes taking place within the unsaturated zone. The sampling involved alluvial and colluvial deposits down to a depth of 10 to 12m, while aliquots of the sediment (80-160 g) were vacuum-distilled at low temperature (50°C) under static conditions for about eight hours and the pore water condensed at liquid nitrogen temperature.

3.3.2.4. Cryogenic Distillation

West et al. (2006) used cryogenic vacuum distillation in order to create extraction timing curves and determine how much time is required to extract an unfractionated water sample from different types of soils samples. They concluded that the isotopic value of extracted water increased with extraction time until a certain threshold, after which the isotopic value of extracted water remained essentially constant regardless of further increases in extraction time (West et al., 2006). Heilweil et al. (2006) applied cryodistillation as a pore water extraction technique to analyse the vadose zone soil samples for $^{18}O$ and $^2H$ and investigate net infiltration and recharge to the fractured Navajo Sandstone aquifer. Figueroa-Johnson et al. (2007) undertook research to compare $^{18}O$ and Br$^-$ values of extracted suction lysimeters samples from intact soil cores with samples obtained by the direct extraction methods of centrifugation and azeotropic distillation. Ingraham and Shadel (1992) used test soils to determine the precision, accuracy and nature of two methods to extract soil water for stable isotopic analysis: azeotropic distillation using toluene, and simple heating under vacuum. In their research, Ingraham and Shadel (1992) observed a variation in the average stable isotopic compositions of the extracted and the introduced water by up to 1.4‰ in $^2H$ and 4.2‰ in $^{18}O$ with the toluene method, and by 11.0‰ in $^2H$ and 1.8‰ in $^{18}O$ for the vacuum/heat method. Walker et al. (1994) made an interlaboratory comparison of the effects of different techniques for extracting soil water on its measured $^2H$ and $^{18}O$ composition. In the comparison, four soils (sand, gypseous sand, and clay soil at high and low water contents) were prepared and distributed to 14 laboratories. The extraction techniques used included azeotropic, vacuum and microdistillation, whereas the results of revealed a large variation between laboratories in the isotopic composition of the water extracted (of up to 30‰ for 2H and 3.4‰ for 18O). The standard deviation in $^2H$ and $^{18}O$, with respect to the azeotropic distillation (using kerosene as a hydrocarbon and sandy soils for extraction) were ±1‰ and ±0.3‰ respectively. The variation increased as the water content of the soil decreased and was greater for clays than sand at comparable soil matrix suctions (Walker et al., 1994). Landon et al. (1999) used azeotropic distillation to extract soil water from suction lysimeters and wick samplers buried in the unsaturated zone of a sand and gravel aquifer for stable oxygen and hydrogen isotope analysis. Extractions from dry soil samples from the study site mixed with water of known composition indicated that the isotopic composition of the extracted water was not altered by the azeotropic distillation procedure (Landon et al., 1999; Komor and Emerson, 1994). They observed average differences for seven sets of duplicate azeotropic distillation samples were 0.06‰ for $^{18}O$ values and 1.4‰ for $^2H$ values. Sacchi et al. (2001) made a critical review of the extraction techniques available to obtain water, and solutes from argillaceous rocks, by investigating the mechanisms
involved in the extraction processes as well as the consequences on the isotopic and chemical composition of the extracted pore water. The extraction techniques applied within their research included centrifugation, squeezing, leaching, vacuum distillation, azeotropic distillation and direct equilibration. With respect to the vacuum and azeotropic distillation techniques, they mention the possibility that incomplete water extraction may be related to the salinity of the interstitial solution, via two main mechanisms: precipitation of newly formed (hydrated) phases, and water retention in the hydration sphere of the cations (Sacchi et al., 2001). In conclusion, one could argue that the main errors associated with distillation techniques (vacuum and azeotropic) are of quantitative nature, by means of incomplete extraction of the soil water. However, azeotropic distillation is proved to be the most effective pore water extraction technique, especially in cases where very low water contents are present within the soil sample. Scrimgeour (1995) quotes that although the accuracy is somewhat reduced in samples containing high levels of organic matter or very low water content; azeotropic distillation remains the “gold standard” against which other methods must be tested.

### 3.3.3. Pan Lysimeters

Pan lysimeters is an inexpensive and effective monitoring system of the infiltrating leachate underneath a SAT system, when the field conditions are favourable. In reference to Ballestero et al. (2006), pan lysimeters are free drainage samplers used to collect water samples by gravity drainage. This is used mainly at waste disposal sites below the earthen liners to enable the early detection of moisture or solute movement through the liner.
4. DIRECT PUSH TECHNOLOGIES

Detailed knowledge of preferential flow and transport paths is essential for site characterization and for a reliable planning of site operation in Managed Aquifer Recharge facilities. Dietrich and Leven (2009) present direct push technologies (also known as “cone penetration testing” or “direct drive technology”) as an alternative approach for the site investigation that refers to a growing family of tools used to obtain subsurface investigations.

With the development of new and powerful tools and sensors, this direct push technology is increasingly popular, replacing many conventional methods for the site investigations (Farrar et al., 1996). One big advantage with the direct push method is the time economy. Depth of more than 50 m can be reached for an ideal condition (like soft, unconsolidated sediments). Percussion method is applied as required when probing through sands, gravels, hard pans, high friction clays, tills, fill material and surface frost.

4.1. Logging Tools

In order to study the vertical soil profile in a site investigation, direct push technology is widely applied. The difference compared to conventional borehole logging is that it records the data directly while driving the direct push tools into the subsurface. As a result, larger sets of data can be obtained within short period of time and also in a simple way. As the direct push tools are driven into the subsurface without drilling using only the static weight of the vehicle, there is only marginal disturbance of the subsurface as well as no drill cuttings are generated. One more advantage of this method in comparison to conventional drilling is that it allows the employment of much smaller and more flexible systems. Dietrich and Leven (2009) concluded that the combined interpretation of such logging data can enable a reliable characterization of subsurface structures (s. also Schulmeister et al., 2003; Schulmeister et al., 2004; Sellwood, 2005).

4.2. Geophysical Tools

Probably, the best known geophysical direct push tool is the conductivity probe that measures the electrical conductivity while the direct push rods are driven into the subsurface (e.g. Beck et al., 2000; Schulmeister et al., 2003; Sellwood, 2005; Paasche et al., 2009; Schütze et al., 2012; Hausmann, 2014).

Dietrich and Leven (2009) report that geoelectrical probes can be additionally applied for measuring the induced polarization or spectral induced polarization, whereas special tools equipped with geophones can be used to measure seismic velocities in the vertical direction for profiling measurements (Robertson et al., 1986; Terry et al., 1996).

Nuclear logging is another type of geophysical direct push tools which either detects natural γ radiation or emits radiation (γ or neutron) and measure the response of the surrounding material (Dietrich
and Leven, 2009). This invasive measuring technique is applied – as the majority of such direct push measurements – via the insertion of hollow steel rods into the subsurface.

### 4.3. Hydroprobes

The advanced hydroprobes enable us to obtain estimates of the hydraulic conductivity "k", with the resolution and accuracy that is rarely possible by other, more conventional field investigation techniques.

One group of direct push tools employs Cone Penetration Testing (CPT) which enables surveys for estimating the soil's hydraulic conductivity, being based on the sediment classification information (Robertson et al., 1983). Butler and Dietrich (2004) reported that the simplest CPT approach is the use of empirical relationships. Other CPT probes use pore-pressure dissipation data for the determination of k values (Baligh and Levedoux, 1980; Robertson et al., 1992; Abu-Farsakh et al., 1998; Sully et al., 1999).

In the determination of volume compressibility from one of many empirical equations, there is great uncertainty when the hydraulic conductivity is estimated from this direct push method. It is possible to determine hydraulic conductivity magnitudes through a one-step method by using pore pressure magnitudes developed during advancing the CPT tools. The validity of the underlying soil or stress distribution models determines the range of application of such methods (Dietrich et al., 2003).

The estimation of hydraulic conductivity by direct push technology incorporates injection tests, too. Other essential measurements (injection pressure and rate) are done during the advancement of the rods or at particular depth. There are considerable errors in the results of injection methods, due to effects of screen clogging and the zone of compaction in the soil around the probe.

Dietrich and Leven (2009) analysed that the most reliable k estimates can be gathered from Direct Push slug tests (e.g., Hinsby et al., 1992; Henebry and Robbins, 2000; Butler et al., 2002; McCall et al., 2002) and the Direct Push permeameter (e.g., Lowry et al., 1999; Mason and Lowry, 1999; Butler and Dietrich, 2004).

### 4.4. Soil sampling tools

Soil sampling has been developed for taking undisturbed samples from unconsolidated formations. Therefore, a casing is vibrated into the ground using a variable frequency vibrator which is clamped to the outside of a sample tube. The undisturbed sample rises up inside the sample tube and is retained by a core catcher at the base of the sample tube. Then the sample is capped and identified. When the target length of the sample has been reached, the sample tube/liner is withdrawn from the formation, and the tube or a replacement returns to the hole. There are both, advantages and disadvantages to this method:
Advantages of the direct push vibro-coring:

- Possibility of undisturbed formation sampling in unconsolidated formations down to 30 m depths with minimal cross contamination of the sample
- Very rapid
- Drilling fluids not required
- Enables rapid installation of shallow monitoring systems

Disadvantages of direct push vibro-coring:

- Drilling is not possible in consolidated formations
- Progress can be easily hindered by cobbles
- Applicable only for comparatively shallow depths

4.5. Groundwater sampling tools

Dietrich and Leven (2009) report that the groundwater sampling tools which are offered by direct push technologies can basically be divided into two groups: (i) continuous tools, and (ii) tools for discrete sampling. The former consists of a screened sampler integrated with a collection port to sample at multiple depth intervals, while the latter consists of a sampling screen that is intentionally detached from the lowest rod point and is then removed to collect the sample.
5. GROUNDWATER MONITORING SCHEMES

5.1. Introduction

An optimum groundwater monitoring system within the saturated zone is of ample importance for the supervision of the managed aquifer recharge facility and its effects on the targeting aquifer layer. During the operation of a continuous MAR facility, the main processes and/or interactions, which are essential to monitor, are: (i) Hydraulic loading vs. infiltration rates; (ii) Effect of water depth on infiltration; (iii) Effects of artificial recharge on groundwater levels; (iv) Effects of groundwater levels on infiltration rates. All the above require an integrated monitoring system that would, according to Sara (2006), contain the following components:

- Three-dimensional array of monitoring points for discrete sampling, water-level measurement, and hydraulic testing

- Continuous real-time measurements of chemical parameters and hydraulic head at each monitoring point

- Sufficient number of monitoring points so that complex hydrogeologic conditions will not confound interpretation of data or prevent detection of potential releases from the facility

- Ability to immediately detect significant releases by sufficiently frequent measurements of indicator parameters

- Installation of monitoring points that are sufficiently reliable to maintain reproducibility and representativeness of ground-water sampling data
Figure 2. Flow diagram of monitoring system design (Sara, 2006).
5.2. Monitoring Scheme Design

A holistic monitoring scheme that will not only target to the MAR facility but also to the wider aquifer area of influence, depends upon various critical factors that in-turn may be used to develop standardized design criteria. Such criteria should be considered in the design of a comprehensive and effective monitoring system (Figure 3) and may be outlined as follows: (i) Monitoring network design criteria, (ii) Sampling protocol, (iii) Analytical protocol, and (iv) Data management criteria.

When a MAR project is in operation, the general zone of influence is as shown in Fig. 4. A monitoring strategy should be such that it helps assess water in all the zones of influence, both qualitatively and quantitatively.

*Figure 3. Schematic representation of Monitoring Networks Design Criteria, based on Sara (2006) and ASTM Standard D 5092 (ASTM, 2002).*

*Figure 4. Schematic diagram showing zones of influence of a MAR operation (source: Dillon et al., 2009).*
6. RECENT DEVELOPMENTS IN MONITORING & INVESTIGATION

This section includes recent developments in monitoring and investigation technologies from the year 2000 onwards. With the advancement of the technology integrated with information technology, there have been many developments in the monitoring system in a MAR system. The success of MAR is determined by the significant element of uncertainty incurred by the inherent heterogeneity of the aquifer. So, monitoring system are being developed which are able to cope with the complexity of the aquifer.

6.1. State-of-the-art in the hydro-geophysical tools

Application of a magnetic resin (MIEX) in wastewater reclamation for MAR in order to remove aromatic organic substances, nitrogen, and phosphorous has been recorded (Zhang et al., 2012). This method was further improved in combination with ozone with higher efficiency (76-84%) than the earlier one (Zhang et al., 2014a).

Direct push resistivity probes employed at the base of a MAR pond were used to measure high-resolution vertical electrical conductivity profiles, enabling a real-time estimation of the in-situ infiltration rates (Mawer et al., 2013).

Airborne electromagnetic surveys have been used in Australia as an element of an investigation to develop a conceptual hydrogeological model of the study area and for mapping and assessment of potential MAR targets (Brodie et al., 2013). The movement of saline-water interfaces can be mapped using the time series of continuous vertical electrical sounding (CVES) and generated electrical resistivity tomograms as a result of a significant resistivity contrast. Similar examples were practiced in Wadi Al Hawasinh in northern Oman, where a combination of CVES, seismic refraction surveys, and TDEM (Time Domain Electromagnetics) were used to map the position of the saline-water interface (Abdalla et al., 2010).

Sensitivity of electrical and electromagnetic methods to human/infrastructure interferences hinders their application. For this, inverse modelling is suggestible. For example, an assessment of the applications of hydrogeophysical methods for ASR was performed by Minsley et al. (2011) on a proposed system in Kuwait. A synthetic aquifer model was used to simulate the advection and dispersion of injected freshwater. Bulk resistivity values calculated from the modelled salinity distribution, which was then used to estimate DC resistivity responses. The results demonstrated that resistivity-based methods (DC resistivity and TDEM) are sensitive enough to detect the freshwater plume.

Time series of microgravity measurements were successfully used to map changes in the volume of stored water in several MAR systems in the western USA (Howle et al., 2002; Davis et al., 2008; Chapman et al., 2008). This method is most effective when used along with monitoring wells.
Microgravity and water level data can also be used to determine the specific yield of aquifers (Maliva, 2015).

The data obtained from the flowmeter logs can be used in groundwater modelling to divide an aquifer into several zones based on transmittivity, which results in improved prediction of the rate of movement and horizontal extent of recharged water (Pavelic et al., 2005).

6.2. State-of-the-art in biological indicators in monitoring

The state-of-the-art in the field of biological indicators in MAR mostly incorporates microbiology, which makes it an interdisciplinary task.

The toxicity profile of MAR water samples can be obtained by various techniques (Kočil et al., 2010), from a project deliverable of the DEMEAU project² (2015). The combined algae assay like Pseudokirchneriella Subcapitata assessing both, photosynthesis II-inhibition and effects of algae growth. Bacteria luminescence inhibition is used to evaluate acute toxicity of the samples. Also, the use of Chemical Activated LUciferase gene eXpression (CALUX)-panel to assess certain DEMEAU compounds.

A quantitative indicator of bacterial abundance in porous media (Zhang et al., 2014b) monitored changes in bacterial biomass and their growth stage by time-lapse spectral induced polarization, over the frequency range of 0.1-1 kHz.

Biofilm analyses showed the accumulation of polysaccharides and bacteria resulting in biological clogging mainly in the top-most soil layers, in a positive correlation to DOC (Page et al., 2014). Biofilm analysis was introduced as one of the approaches to avoid clogging (Page et al., 2014) of ASR in siliceous alluvium while the source water was turbid river water.

A MAR-ozone recharge hybrid uses the flow-cytometric total bacterial cell counts to monitor the water quality after treating reclaimed water, where, O₃-MAR system was more effective than MAR system alone by minimum of 10% to maximum of 30% based on EfOM, TorC & bacteria analyses (Yoon et al., 2013).

6.3. State-of-art in monitoring the hydro-geo-chemical parameters

If a MAR project focuses on water quality issues, monitoring of the hydro-geo-chemical properties is essential. The state-of-the-art in the hydro-geo-chemistry of MAR systems is in managing to control the chemical process effectively, by controlling the factors which induces changes in groundwater chemistry.

Neil et al. (2014) showed that inhibited secondary mineral precipitation in wastewater systems and dependence of Ferric ions released from iron minerals like arsenopyrite will form iron (III) hydr(oxide)

² http://demeau-fp7.eu/technology/ba
minerals, attenuating mobilized arsenic. Similar results are seen in Bell et al. (2009), CH2M Hill (2007), ASR Systems LLC (2006), and Maliva and Missimer (2012) where reduction in the DO concentrations of recharged water prevents arsenic and metals leaching in ASR systems, thus avoiding pyrite dissolution and associated arsenic releases.

Likewise, a test of minimization of Arsenic mobilization during ASR by source water degasification (Norton et al., 2012) using hydrophobic membrane and dechlorination along with addition of sodium bisulfate, resulted in a 94% reduction in arsenic release.

The absence of dissolved Ca\(^+\) and Mg\(^+\) displaces As from the sediments into solution. Increasing the dosages of common water treatment amendments including quicklime (Ca(OH)\(_2\)) and dolomitic lime (CaO.MgO) provides recharge water with higher concentrations of Ca\(^+\) and Mg\(^+\) ions and subsequently decreases the release of As during infiltration (Fakhreddine et al., 2015).

### 6.4. State-of-the-art in monitoring by tracers

The study of fluid-rock interaction is quicker and easier by using tracer methods, where a known volume of water with a known tracer concentration is poured into a well and tracks the tracer concentration by pumping the well (Clark et al., 2014; Rona et al., 2014; Sassine et al., 2015).

A practice in Berlin (Gruenheid et al., 2005) used boron (B) as a conservative intrinsic tracer to study redox potential (mV), percent bank filtrate or recharged water. Likewise, \(\delta^{18}O\) isotopes were used to calculate retention time. AOI (Adsorbable Organic Iodine) was used for long-term monitoring but it shows effects in the monitoring wells, such that proving unsuitable.

An assessment of pathogen survival potential during MAR used Rhodamine WT as tracer in the aquatic environment in-situ measurement of pH, T, redox potential, DO, EC (Sidhu and Toze, 2012).

Single-well tracer tests are proven to be the best so far, as estimation of distribution coefficient is possible (Pickens et al., 1981), the occurrence and rate of different physical & microbial reactions (Haggerty et al., 1998, Istok et al., 1997), to evaluate the longitudinal dispersivity of an aquifer to model solute transport (Pickens & Grisak, 1981; Gelhar & Collins, 1971). The best of all, single-well tracer test facilitates in-situ conditions.

Monitoring the excess air formation during bank infiltration in MAR was done by measuring neon (Ne) concentrations (Heilweil et al., 2006). The induced unconfined bank filtration site's sample generally contained excess air (up to 60% of Ne) where the highest excess air concentration (up to 81% Ne) was found at the engineered basin recharge site.
7. MARSOL Site Investigation & Monitoring

7.1. Introduction

MARSOL, a joint project with 22 partners from six EU countries (Germany, Greece, Italy, Malta, Portugal, and Spain) plus Israel, runs eight field sites in Greece, Portugal, Malta, Spain, Italy and Israel. Each of the sites uses water of various origins and qualities (like desalinated sea water, river water, and treated wastewater). MARSOL aims to demonstrate effectiveness, efficiency, and sustainability of existing MAR technologies including operation, maintenance and monitoring.

The main objectives of the project are:

1. Prove that MAR is a safe, sound and sustainable strategy to ensure water security.
2. Improve the state-of-art of MAR applications, enabling low-cost but high-efficiency solutions creating market opportunities for European industries & SMEs.
3. Facilitate and fast-track the market penetration by promoting the advantages of MAR by tailored training and dissemination programs.
4. Provide a fundamental technology to face the challenge of increasing water scarcity in southern Europe, the Mediterranean and the other regions of the world.

From the sources mentioned above, following are the sources of water at the MARSOL demonstration sites (Table 2).

Table 2. Source of water at MARSOL sites

<table>
<thead>
<tr>
<th>Site No.</th>
<th>MARSOL Demo Sites</th>
<th>Water Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Lavrion, Greece</td>
<td>Treated waste water</td>
</tr>
<tr>
<td>2.</td>
<td>Algarve, Portugal</td>
<td>River water</td>
</tr>
<tr>
<td>3.</td>
<td>Arenales, Spain</td>
<td>Multiple sources</td>
</tr>
<tr>
<td>4.</td>
<td>Llobregat, Spain</td>
<td>River water, treated wastewater</td>
</tr>
<tr>
<td>5.</td>
<td>Brenta, Italy</td>
<td>Precipitation</td>
</tr>
<tr>
<td>6.</td>
<td>Serchio, Italy</td>
<td>River water</td>
</tr>
<tr>
<td>7.</td>
<td>Menashe, Israel</td>
<td>Desalinated seawater</td>
</tr>
<tr>
<td>8.</td>
<td>South Malta, Malta</td>
<td>Treated waste water</td>
</tr>
</tbody>
</table>
From the availability of MAR techniques, MARSOL incorporates the following methods at its 8 different demonstration sites (Table 3).

### Table 3. MAR methods applied at MARSOL sites

<table>
<thead>
<tr>
<th>Site No.</th>
<th>MARSOL Demo Sites</th>
<th>MAR method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Lavrión, Greece</td>
<td>Infiltration basin &amp; SAT</td>
</tr>
<tr>
<td>2.</td>
<td>Algarve, Portugal</td>
<td>Infiltration ponds</td>
</tr>
<tr>
<td>3.</td>
<td>Arenales, Spain</td>
<td>SAT, infiltration pond, river bank infiltration, artificial wetlands, inter-dune filtration ditches, infiltration canal, open infiltration wells.</td>
</tr>
<tr>
<td>4.</td>
<td>Llobregat, Spain</td>
<td>Surface infiltration pond</td>
</tr>
<tr>
<td>5.</td>
<td>Brenta, Italy</td>
<td>ASR, furrow irrigation</td>
</tr>
<tr>
<td>6.</td>
<td>Serchio, Italy</td>
<td>River bank infiltration</td>
</tr>
<tr>
<td>7.</td>
<td>Menashe, Israel</td>
<td>Infiltration basin, ASR, seasonal storage</td>
</tr>
<tr>
<td>8.</td>
<td>South Malta, Malta</td>
<td>Coastal boreholes</td>
</tr>
</tbody>
</table>

### 7.2. Lavrión demonstration site

**MAR Technique:** Soil-Aquifer-Treatment, infiltration basins

**Main Problems:** Coastal aquifer, seawater intrusion, water scarcity

**Subsurface Investigation Activities:**

- Direct push EC Loggings ($\times$18)
- Direct push Hydraulic Tests ($\times$6)
- Direct push Monitoring piezometers ($\times$10 full screen & $\times$4 multi-level)
- Surface geophysics
- Marine geophysics

**Unsaturated zone monitoring:**

- Spatial TDR ($\times$10)
- Spatial FDR ($\times$2)
• Suction cups (×3 multi-level, 0.5 m intervals)

**Saturated Zone Monitoring:**

• CDT Divers (×2)

• Pressure Divers (×5 with real-time data transmission)

### 7.3. Algarve & Alentejo demonstration sites

**MAR Technique:** River infiltration, shallow wells

**Main Problems:** Nitrate contamination

**Subsurface Investigation Activities:**

• Surface geophysics

**Unsaturated zone monitoring:**

• Teflon cups (multi-level)

**Saturated Zone Monitoring:**

• 4 “short” piezometers in the basins (manual measurements)

• 4 piezometers in the upper aquifer unit (Upper Miocene) next to the basins

• 1 piezometer located upstream of the basins (control)

• 1 water well (not in operation) for monitoring the lower aquifer subunit (Lower Miocene)

• Dug wells scattered across territory for water quality

### 7.4. Los Arenales demonstration site

**MAR Technique:** Infiltration basins, infiltration trenches/canals, ASR

**Main Problems:** Water Scarcity

**Subsurface Investigation Activities:**

• Surface geophysics

At Los Arenales aquifer, six monitoring networks are tracked, collecting data-sets of:

**Surface Measurements:**

• Gauging stations along the MAR canals (20)
• Infiltration test stations (20)

Unsaturated zone monitoring:

• ZNS-1 at Santiuste (Santiuste basin)
  o 2 IMKO 64 humidimeters-thermometers emplaced at 0.90 and 2.10 m depth
  o -1 SDEC SR1000 tensiometer with the capsule at 120 cm depth

• ZNS-2 at Coca (Santiuste basin)
  o 2 IMKO 64 humidimeters-thermometers emplaced at 0.75 and 1.75 m depth
  o -1 SDEC SR1000 tensiometer

• ZNS-3 at Gomezserracin, Carracillo County.
  o 2 IMKO 64 humidimeters-thermometers at 0.80 and 1.80 m depth.
  o -1 Eijkelkamp T4 tensiometer.

Saturated Zone Monitoring:

• GW table evolution (54 points of water)
• GW and canals water quality (45 + 15 points)
• Clogging sampling stations (34 points)

7.5. Llobregat demonstration site

MAR Technique: Infiltration basins, SAT

Main Problems: Water scarcity, seawater intrusion

Subsurface Investigation Activities:

• Surface geophysics

Surface Measurements:

• Continuous measurements of Eh & T

Unsaturated zone monitoring:

• Continuous measurements of Eh & T

Saturated Zone Monitoring:
• Multiparametr probes (Cond, T, DO, Eh)

• Monitoring piezometers (11 multilevel)

7.6. Brenta demonstration site

MAR Technique: Infiltration trenches, infiltration basins, ASR

Main Problems: Water scarcity

Subsurface Investigation Activities:

• Surface geophysics

• Direct push soil sampling

• Direct push EC loggings

• Direct push hydraulic tests

Surface Measurements:

• Continuous measurements of Water Level

• Continuous measurements of turbidity, conductivity, redox, pH, T

 Unsaturated zone monitoring:

• Spatial TDR

Saturated Zone Monitoring:

• Water level sensors

• Monitoring piezometers

7.7. Lucca demonstration site

MAR Technique: Induced riverbank filtration

Main Problems: Water supply issues

Subsurface Investigation Activities:

• Direct push profiling (EC)

• Direct push profiling (DPIL)

Surface Measurements:
- Continuous measurements of water level (×2 weir)
- Continuous measurements of conductivity, temperature

**Saturated Zone Monitoring:**
- 6 borehole clusters were finally set in place at:
  - 12 m / 15 m / 20 m depth (15 & 20 m 2 inches)
- Continuous measurements of temperature, EC, water table level

**7.8. Menashe demonstration site**

**MAR Technique:** Infiltration basins, ASR

**Main Problems:** Water scarcity, seawater intrusion

**Subsurface Investigation Activities:**
- Surface geophysics
- Direct push soil sampling

**Surface Measurements:**
- Water levels, EC and T (cont. during MAR)
- Water quality (few times during MAR)

**Unsaturated zone monitoring:**
- WC, bulk EC and T (continuously)
- Pore water (few times during MAR)
- TDR (point measurements)
- Suction cups

**Saturated Zone Monitoring:**
- Levels, EC and T (continuously)
- Water quality (every 3 months) - CTD Divers
7.9. South Malta DEMO Site

**MAR Technique:** Injection Wells

**Main Problems:** Water scarcity, seawater intrusion

**Subsurface Investigation Activities:**

- Surface geophysics

**Saturated Zone Monitoring:**

- GW levels, EC and T (continuously)
8. CONCLUSIONS

In the MARSOL project a wide range of MAR methods and technologies are applied, that target all three hydrologic zones mentioned above, such as: (i) Recharge basins – Menashe (Israel), Arenales, Segovia, and Valladolid (Spain), Lavrion (Greece); (ii) River bank filtration – Serchio (Italy), (iii) River infiltration basins – Llobregat (Spain), Algarve (Portugal); (iv) Infiltration Trenches – Brenta (Italy), Arenales, Segovia, and Valladolid (Spain); (v) Injection wells – South Malta (Malta), Arenales, Segovia, and Valladolid (Spain). Taking advantage of the above, this document provides a synoptic review of investigation and monitoring strategies that should accompany the design and implementation of an optimised Managed Aquifer Recharge infrastructure facility including:

- Surface geophysical methods: non-invasive exploration technologies that measure the physical, electrical or geochemical properties of the aquifer matrix or groundwater (ground-penetrating radar, electromagnetics, resistivity, seismic refraction and reflection).

- Vadose zone monitoring: monitoring of storage, infiltration rates, pore water extraction and quality.

- Direct push technologies: vibro-coring technologies that can offer high resolution subsurface investigation, logging and geophysical tools, pore water or groundwater probing and undisturbed deep soil sampling.

- Groundwater monitoring schemes: optimum groundwater monitoring schemes that are necessary for the supervision and optimization of MAR facilities inspection, monitoring systems design criteria, sampling and analytical protocols.

The main findings are related to the effectiveness of different investigation and monitoring technologies, their advantages and disadvantages as well as their limitations and overlapping characteristics.
REFERENCES


51. DEMEAU: Catalogue of European MAR applications.


APPENDIX: Selected publications on Monitoring and Investigation of MAR facilities and short outline of their key content
<table>
<thead>
<tr>
<th>Paper title/ year of publication</th>
<th>Source water</th>
<th>Infiltration Method</th>
<th>Aim of MAR</th>
<th>Focus</th>
<th>Monitoring method</th>
<th>Country</th>
<th>Qualitative vs. Quantitative</th>
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<tbody>
<tr>
<td>1 E. coli and turbidity attenuation during urban stormwater recycling via Aquifer Storage and Recovery in a brackish limestone aquifer</td>
<td>Stormwater</td>
<td>ASR</td>
<td>Changes in salinity, turbidity and Escherichia Coli concentrations</td>
<td>E-coli / Turbidity</td>
<td>*</td>
<td>Australia</td>
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<td>2 Effects of effluent organic matter characteristics on the removal of bulk organic matter and selected pharmaceutically active compounds during managed aquifer recharge: Column study</td>
<td>wastewater effluent-dominated &amp; surface water</td>
<td>*</td>
<td>Removal of organic matter/ determining post-treatment method</td>
<td>Bio-polymers/ bezafibrate/ gemfibrozil/</td>
<td>Liquid Chromatography with online organic carbon detection</td>
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<tr>
<td>3 A concept for managed aquifer recharge using ASR-wells for sustainable use of groundwater resources in an alluvial coastal aquifer in Eastern India</td>
<td>Excess monsoon rain runoff</td>
<td>ASR + Canals</td>
<td>Storage of excess monsoon season runoff</td>
<td>enhancement of recharge</td>
<td>Groundwater Budget MODFLOW 11 Observation wells</td>
<td>India</td>
<td>Quantitative</td>
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<td>4 Geochemical Triggers of Arsenic Mobilization during Managed Aquifer Recharge, DOI: 10.1021/acs.est.5b01140, 2015 American Chemical Society</td>
<td>Highly purified recycled water, Secondary treated wastewater</td>
<td>Surface Recharge Basin</td>
<td>Assess &amp; minimize As mobilization</td>
<td>maintain local water quality</td>
<td>Monitoring well Core by Rota sonic vibration drilling X-ray absorption near-edge spectroscopy (XANES) to determine the oxidation state of As X-ray diffraction Isotopic analysis</td>
<td>USA</td>
<td>Qualitative</td>
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<td>No.</td>
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<td>Year</td>
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<td>Water Type</td>
<td>Fluid Sampling</td>
<td>Piezometric nests</td>
<td>Dialysis sampler (peepers) for sample collection throughout the seasons</td>
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<td>5</td>
<td>Linking denitrification and Infiltration Rates during Managed Aquifer Recharge</td>
<td>2011</td>
<td>USA</td>
<td>Pajaro River water</td>
<td>Infiltration Pond</td>
<td>Irrigation</td>
<td>Link of denitrification and Infiltration rates</td>
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<td>6</td>
<td>Reclaimed water quality during simulated ozone-managed aquifer recharge hybrid</td>
<td>2014</td>
<td>Saudi Arabia</td>
<td>reclaimed water</td>
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<td>assess the impact of hybrid approach</td>
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<td>A multi-parametric approach assessing microbial viability and organic matter characteristics during MAR</td>
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<td>assess changes in MAR behavior with microbial changes</td>
<td>AgNPs, PhACs, Organic matter</td>
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<td>8</td>
<td>Removal of bulk dissolved organic carbon (DOC) and trace organic compounds by bank infiltration and artificial recharge</td>
<td>2005</td>
<td>USA</td>
<td>Surface water influenced by the discharge of waste water treatment plant</td>
<td>Bank Filtration &amp; GW recharge</td>
<td>Public supply household</td>
<td>DOC</td>
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<td>Project</td>
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<td>Abstraction</td>
<td>Measurement</td>
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<td>9</td>
<td>River sediment and flow characteristics near a bank filtration water supply: Implications for river bed clogging</td>
<td>Canada</td>
<td>Quantitative</td>
<td>2007</td>
<td>River Water</td>
<td>Riverbank infiltration</td>
<td>Supply water to the city</td>
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<td>10</td>
<td>Quadrature conductivity: A quantitative indicator of bacterial abundance in porous media</td>
<td>USA</td>
<td>Qualitative</td>
<td>2014</td>
<td>*</td>
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<td>monitor changes in bacterial biomass and growth stage</td>
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<td>Evaluating two infiltration gallery designs for managed aquifer recharge using secondary treated wastewater</td>
<td>Australia</td>
<td>Qualitative &amp; Quantitative</td>
<td>2013</td>
<td>Secondary treated wastewater</td>
<td>Infiltration gallery</td>
<td>comparison of two aquifer types: graded gravel &amp; engineered leach drain system</td>
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<td>12</td>
<td>Assessment of pathogen survival potential during MAR with diffusion chambers</td>
<td>2012</td>
<td>USA</td>
<td>Infiltration gallery</td>
<td>The risk assessment &amp; plan mitigation of risk</td>
<td>Assessment of pathogen survival</td>
<td>Rhodamine WT used as tracer in the aquatic environment. <em>In-situ</em> measurement of pH, T, redox potential, DO, EC. A comparative microbial inactivation study was carried out in groundwater by seeding selected pathogens and indicators in laboratory microcosms and Teflon diffusion chambers (in situ) fitted with 0.010- and 0.025-lm pore-size membranes.</td>
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<td>Application of a Magnetic Resin (MIEX) in Wastewater Reclamation for MAR</td>
<td>2012</td>
<td>China</td>
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<td>removal of aromatic organic substance, Nitrogen, Phosphorous</td>
<td>6 months of continuous monitoring of aromatic organic substances; with MIEX® treatment coupled with PAC flocculation and ozonation as pre-treatment</td>
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<td>14</td>
<td>Managed Aquifer recharge of treated wastewater: Water quality changes from infiltration through the Vadose zone</td>
<td>2011</td>
<td>Australia</td>
<td>Several chemical components</td>
<td>Pharmaceuticals/total nitrogen/Carbamazepine/TOC</td>
<td>Monitoring wells, sampling and laboratory analysis.</td>
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<td>15</td>
<td>Identification of the processes affecting excess air formation during bank infiltration and MAR</td>
<td>2013</td>
<td>Surface water sources</td>
<td>Natural Bank infiltration Induced Bank infiltration</td>
<td>Phenomenon of excess air formation during bank infiltration</td>
<td>Switzerland</td>
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<td>Neon concentrations as indicator of various information</td>
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<td>&quot;Neon concentrations in excess of saturation (DNe) were used to identify excess air in the infiltrates. Neon (Ne) concentrations were analyzed at four different recharge sites in and near Berlin, where groundwater is recharged directly from surface water courses, either by near-natural bank filtration, induced bank filtration or engineered basin recharge.&quot;</td>
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<td>16</td>
<td>Impact of MAR on the chemical and isotopic composition of a karst aquifer, Wala reservoir, Jordan</td>
<td>2015</td>
<td>Storm Water</td>
<td>Karst topography</td>
<td>assess change in water quality after MAR</td>
<td>karst aquifers</td>
<td>Jordan</td>
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<td>Sources of high-chloride water and managed aquifer recharge in an alluvial aquifer in California, USA</td>
<td>2015</td>
<td>Infiltration of captured local runoff &amp; Local surface water</td>
<td>Field flooding</td>
<td>Assess seawater intrusion and impact of MAR</td>
<td>Monitoring wells for collection of chemical and isotopic data, for collection of sequential electromagnetic (EM) logs from monitoring wells, collection of flow-logs from pumped and unpumped wells, water level monitoring sequential electromagnetic logging coupled well-bore flow and depth-dependent water-quality data collection</td>
<td>USA</td>
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<td>18</td>
<td>In situ infiltration test using a reclaimed abandoned river bed: MAR in Shijiazhuang City, China</td>
<td>2013</td>
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<td>Double-ring Infiltrometer, Groundwater level variations were monitored during the in-situ test</td>
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<td>The role of organic matter in the removal of emerging trace organic chemicals during MAR</td>
<td>2009</td>
<td>USA</td>
<td>Column Experiment</td>
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<td>20</td>
<td>Quantification of pathogenic microorganisms and microbial indicators in three wastewater reclamation and MAR facilities in Europe</td>
<td>2010</td>
<td>Belgium, Spain, Italy</td>
<td>Water sampling for the analysis of water-borne pathogens and microbial</td>
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<td>21</td>
<td>Use of Treated wastewater for the managed aquifer recharge in highly populated urban centers: a case study in Addis Ababa, Ethiopia</td>
<td>2007</td>
<td>Ethiopia</td>
<td>Column Experiment, Soil test.</td>
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<td>Aquifer residence times for recycled water estimated using chemical tracers and the propagation of temperature signals at a managed aquifer recharge site in Australia</td>
<td>2014</td>
<td>Australia</td>
<td>Water sampling for chloride Bromide Tracer Test Water Temperature as a tracer Modeling</td>
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<td>23</td>
<td>A comparison of the geochemical response to different managed aquifer recharge operations for injection of urban</td>
<td>2010</td>
<td>Salisbury, Australia</td>
<td>Grab samples collection at the outlet of the wetland groundwater within the storage zone by pumping</td>
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<td>24</td>
<td>Use of static Quantitative Microbial Risk Assessment to determine pathogen risks in an unconfined carbonate aquifer for MAR</td>
<td>2009</td>
<td>Australia</td>
<td>Secondary treated wastewater, Infiltration Basins/Gallery</td>
<td>Teflon Diffusion Chambers suspended in a monitoring borehole. Monitoring the chloride concentrations. MODPATH simulations. Static QRMA</td>
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<td>Influence of intermittent infiltration of primary effluent on removal of suspended solids, bulk organic matter, nitrogen and pathogens indicators in a simulated managed aquifer recharge system</td>
<td>2014</td>
<td>Netherlands</td>
<td>Wastewater, SAT, Assessment of nitrogen, pathogens, TOC, intermittent infiltration</td>
<td>4.2 m high laboratory scale soil columns. Peristaltic Pumps.</td>
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<td>Microbial community evolution during simulated MAR in response to different biodegradable dissolved organic carbon (BDOC) concentrations</td>
<td>2013</td>
<td>Saudi Arabia</td>
<td>Surface water, reclaimed water, Microbial evolution with variation in BDOC</td>
<td>Column experiment, Spatial and temporal analysis of the sediment associated microbes. (DNA extraction, pyro sequencing), tracers KBr,</td>
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<td>Environmental monitoring of selected pesticides and other organic chemicals in Urban stormwater recycling systems using passive sampling methods</td>
<td>2014</td>
<td>Australia</td>
<td>Urban Stormwater, ASR/ASTR, Passive sampling to monitor Organic micro pollutant</td>
<td>5 different configuration of the passive samplers 1 Empore Disc (ED) with (ED1) &amp; without (ED0) diffusion-limiting membranes; polydimethylsiloxane (PDMS) samplers; semi-permeable membrane devices (SPMD); Amberlite (XAD) resins. Passive flow monitors</td>
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<td>Management of Aquifer recharge in Lebanon by removing seawater intrusion from coastal aquifers</td>
<td>2013</td>
<td>mixture of reclaimed water, groundwater, surface water</td>
<td>Injection well, feasibility study, remove seawater intrusion in Carbonate aquifers</td>
<td>Designing well-barriers</td>
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<td>Hydrodynamic and salinity evolution of groundwater during artificial recharge within semi-arid coastal aquifers: A case study of El Khairat aquifer system in Enfidha (Tunisian Sahel)</td>
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<td>The impacts of a linear wastewater reservoir on groundwater recharge and geochemical evolution in a semi-arid area of the lake Baiyangdian watershed, North China Plain</td>
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<td>Industrial Wastewater reservoir, Leakage &amp; irrigation infiltration</td>
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<td>Multi-tracers, Multi-variety analysis and geo-chemical methods, Isotope analysis by Rayleigh distillation</td>
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<td>Application of probabilistic modeling approach for evaluation of nitrogen, phosphorous and organic carbon removal efficiency during four successive cycles of aquifer storage and recovery (ASR) in an anoxic carbonate aquifer</td>
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<td>Spatial and seasonal variations of occurrences of endocrine disrupting chemicals in unconfined and confined aquifers recharged by reclaimed water: A field study along the Chaobai River, Beijing</td>
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<td>Time-lapse electrical resistivity tomography of a water infiltration test on Johannishus Esker, Sweden</td>
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<td>Artificial recharge of the phreatic aquifer in the upper Friuli plain, Italy, by a large infiltration basin</td>
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<td>* incorporate advanced borehole logging</td>
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<td>Linking water quality changes to geochemical processes occurring in a reactive soil column during treated wastewater infiltration using a large-scale pilot experiment: Insights into Mn behavior</td>
<td>2013</td>
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<td>Sealed access port for sampling Tensiometers Probes Suction porous cups Time Domain Reflectometry (TDR) probes Tracer Experiment (KBr)</td>
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<td>Biofilm analysis Column Study Batch Experiment</td>
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<td>42</td>
<td>Monitoring water infiltration for MAR using time-lapse electrical imaging: a numerical feasibility study</td>
<td>2010</td>
<td>Jordan</td>
<td>ERT, Numerical Modeling (TOUGH2) (CRMod)</td>
<td></td>
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<tr>
<td>#</td>
<td>Project Description</td>
<td>Year</td>
<td>Method</td>
<td>Parameters monitored</td>
<td>Monitoring technique</td>
<td>Qualitative/Quantitative</td>
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<td>43</td>
<td>Long-term monitoring of the Infiltration at a Managed Aquifer Site using Electrical Resistivity Probes</td>
<td>2010</td>
<td>Infiltration pond</td>
<td>* Monitor water saturation, chemistry, temperature</td>
<td>ERI Monitoring, Direct-push methods,</td>
<td>* Qualitative &amp; Quantitative</td>
<td></td>
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<tr>
<td>44</td>
<td>Monitoring Managed Aquifer Recharge with Electrical Resistivity probes</td>
<td>2014</td>
<td>* ASR</td>
<td>monitor sub-surface water quantity change</td>
<td>* Long 1D electrical resistivity probes (Monitor sub-surface response over one diversion season, benefits of integrating geophysical + standard hydrologic measurements, changes in saturation estimated from electrical resistivity models indicated large hydraulic gradients at early time and suggested the presence of highly permeable conduits and baffles between the surface and the screened interval of recovery wells</td>
<td>* Quantitative</td>
<td></td>
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<td>45</td>
<td>Recently developed (2011) direct push resistivity probes can be located in the base of a MAR pond which gives the vertical electrical conductivity profiles with inversion algorithm &amp; Auxiliary Hydrologic data</td>
<td>2011</td>
<td>Infiltration pond</td>
<td>* study the vertical profile in a pond</td>
<td>* It gives the real-time estimation of the in-situ infiltration rates from 1D electrical conductivity</td>
<td>* Quantitative &amp; Qualitative</td>
<td></td>
</tr>
<tr>
<td>ID</td>
<td>Title</td>
<td>Year</td>
<td>Techniques</td>
<td>Details</td>
<td>Site</td>
<td>Study Type</td>
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<tr>
<td>46</td>
<td>Electrical Resistivity for Characterization and Infiltration Monitoring beneath a Managed Aquifer Recharge Pond</td>
<td>2013</td>
<td>*</td>
<td>Spatial and temporal study to obtain vertical EC profiles</td>
<td>*</td>
<td>Direct-push resistivity probes can be located in the base of a MAR pond and used to obtain vertical electrical conductivity profiles with high spatial and temporal resolutions. An inversion algorithm that uses a vertical electrical conductivity profile and auxiliary hydrologic data to estimate the van Genuchten parameters and saturated hydraulic conductivity of a homogeneous unsaturated zone</td>
<td>*</td>
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<td>47</td>
<td>Multiscale Characterization of a Heterogeneous Aquifer Using an ASR Operation</td>
<td>2006</td>
<td>Brackish, Saline water</td>
<td>relation of heterogeneity and permeability,</td>
<td>*</td>
<td>Tracer testing, Modeling, Piezometer</td>
<td>Australia</td>
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<td>48</td>
<td>Time-Lapse gravity monitoring: A systematic 4D approach with application to aquifer storage and recovery</td>
<td>2008</td>
<td>Coal Mine waste water</td>
<td>monitor storage capacity and quality</td>
<td>*</td>
<td>time-lapse gravity</td>
<td>USA</td>
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<td>49</td>
<td>Use of static Quantitative Microbial Risk Assessment to determine pathogen risks in an unconfined carbonate aquifer used for Managed Aquifer Recharge</td>
<td>2010</td>
<td>Secondary Treated waste water and Urban Storm water</td>
<td>study for the design scheme in reference to residual pathogen risks</td>
<td>*</td>
<td>QMRA(Quantitative Microbial Risk Assessment)</td>
<td>Australia</td>
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<td>50</td>
<td>Risk Assessment of Aquifer Storage Transfer and Recovery with Urban Stormwater for Producing Water of a Potable Quality</td>
<td>2010</td>
<td>Stormwater</td>
<td>ASTR/ASR</td>
<td>Risk assessment for potable standards</td>
<td>*</td>
<td>Sampling and analysis of 12 hazards</td>
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<td>51</td>
<td>Water Chemistry Impacts on Arsenic Mobilization from Arsenopyrite Dissolution and Secondary Mineral Precipitation: Implications for Managed Aquifer Recharge</td>
<td>2014</td>
<td>Secondary effluent from water treatment plant</td>
<td>*</td>
<td>Study water chemistry change with Arsenopyrite dissolution</td>
<td>*</td>
<td>Sampling and laboratory analysis</td>
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<tr>
<td>52</td>
<td>The Impeller Meter for measuring aquifer permeability variations: Evaluation and comparison with other tests</td>
<td>1989</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>impeller method, tracer tests, multi-level slug test</td>
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<td>53</td>
<td>Hydrogeophysical Methods for Analyzing Aquifer Storage and Recovery Systems</td>
<td>2011</td>
<td>surface water</td>
<td>ASR</td>
<td>assess the aquifer storage capacity</td>
<td>*</td>
<td>Electrical resistivity, Seismic, TEM</td>
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<tr>
<td>54</td>
<td>Simplified Method of “Push-Pull” Test Data Analysis for Determining In-Situ Reaction Rate Coefficients</td>
<td>1998</td>
<td>Normal water</td>
<td>*</td>
<td>Assess various physical, chemical, biological reactions</td>
<td>*</td>
<td>The pulse-type injection of a prepared test solution into a single monitoring well followed by the extraction of the test solution/ground water mixture from the same well. The test solution contains a conservative tracer and one or more reactants selected to investigate a particular process.</td>
</tr>
</tbody>
</table>
An analytical method is proposed by which the effects of flow nonuniformity and variable dispersion coefficients can be evaluated for problems involving longitudinal dispersion in porous media. A boundary layer approximation is used to develop general solutions of the one-dimensional convective-dispersion equation for steady flow. Several examples are considered by using the analytical method, and the general effect of flow nonuniformity on dispersion is discussed. Comparisons of the analytical solution with numerical solutions of the exact equation indicate that the method will yield accurate results in many applications.

### Table 1: Comparison of Ground Water Replenishment with Recycled Water

<table>
<thead>
<tr>
<th>Year</th>
<th>Water Source</th>
<th>Water Quality Improvement</th>
<th>TOV Removal</th>
<th>Rating</th>
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</thead>
<tbody>
<tr>
<td>2009</td>
<td>Recycled Water</td>
<td>SAT</td>
<td>removal of TOV by SAT</td>
<td>*</td>
</tr>
</tbody>
</table>

Remark: * indicates no data