



# Assessing the efficiency of a coastal Managed Aquifer Recharge (MAR) system in Cyprus

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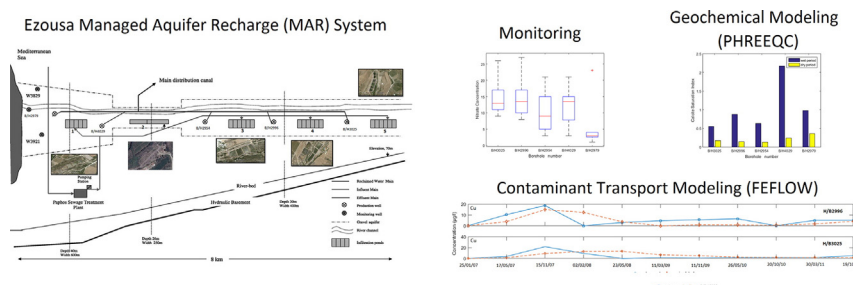
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## HIGHLIGHTS

- MAR system operation prohibit nitrogen attenuation processes.
- Total Phosphorous is strongly absorbed and attenuated into the aquifer matrix in contrast to Nitrate that is mainly diluted.
- Inverse modeling shows a low mixing ration of reclaimed with the native groundwater in specific infiltration ponds.
- Copper deteriorate the MAR water quality originated by the parent material dissolution.
- Inverse modeling and simulation of groundwater flow and contaminant transport validated the weak mixing in MAR operation.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Managed Aquifer Recharge (MAR) is becoming an attractive water management option, with more than 223 sites operating in European countries. The quality of the produced water, available for drinking or irrigation processes is strongly depended on the aquifer's hydrogeochemical characteristics and on the MAR system design and operation. The objective of this project is the assessment of the operation efficiency of a MAR system in Cyprus. The coupling of alternative methodologies is used such as water quality monitoring, micro-scale sediment sorption experiments, simulation of groundwater flow and phosphate and copper transport in the subsurface using the FEFLOW model and evaluation of the observed change in the chemical composition of water due to mixing using the geochemical model PHREEQC. The above methodology is tested in the Ezousa MAR project in Cyprus, where treated effluent from the Paphos Waste Water Treatment Plant, is recharged into the aquifer through five sets of artificial ponds along the riverbed. Additionally, groundwater is pumped for irrigation purposes from wells located nearby. A slight attenuation of nutrients is observed, whereas copper in groundwater is overcoming the EPA standards. The FEFLOW simulations reveal no effective mixing in some intermediate infiltration ponds, which is validated by the inverse modeling simulation of the PHREEQC model. Based on the results, better control of the infiltration capacity of some of the ponds and increased travel times are some suggestions that could improve the efficiency of the system.

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## 1. Introduction

One of the main focus areas introduced by the Integrated Water Resources Management (IWRM) is wastewater reuse to achieve environmental sustainability (Lazarova et al., 2001). The number of water reclamation and reuse projects in Europe and around the world has increased considerably in the last few decades (Chidambaram et al., 2012; Dillon et al., 2010; Teijon et al., 2010). Managed Aquifer Recharge (MAR) is becoming an increasingly attractive water management option for the replenishment of depleting aquifers, especially in arid and semi-arid regions with limited surface water supplies. More than 224 currently active Managed Aquifer Recharge (MAR) projects in 23 European countries exist (Sprenger et al., 2017) providing significant volumes of water for drinking (several sites in Hungary, Slovakia, the Netherlands, Germany, Finland, Poland, Switzerland and France) and irrigation purposes. The type of MAR design applicable in each region depends on site-specific conditions. Direct injection in predefined aquifer depths, water infiltration ponds, river bank filtration (RBF) and farms flooding are the most common recharge processes used in MAR systems.

MAR systems have been applied to coastal aquifers to hinder seawater intrusion and provide drinking water standards, such as the MAR project at the coastal aquifer of Barcelona (Spain) (Teijon et al., 2010) or the recharge of freshwater lenses in water-scarce islands (Hejazian et al., 2017). The main advantages of MAR technology are (a) natural filtration and attenuation of contaminants; (b) high recharge rates for small surface areas; and (c) protection from contamination, evaporation losses and algae blooms. In each case, several limitations may exist such as (a) high operational costs, (b) unreliable water quality and quantity controlled by the degradation rate of pollutants, natural reactions with the porous media and clogging phenomena, (c) low infiltration rates, and (d) water losses due to mixing with brackish groundwater. For example, when MAR was combined with the distributed stormwater collection (DSC) in California to overcome groundwater overdraft (Beganskas and Fisher, 2017) even though the technology was successful in storing significant water volumes used later in a drought year, the fine sediment load, transported via runoff, reduced the soil infiltration capacity and the overall method performance (Beganskas and Fisher, 2017). Another example is the natural RBF system in Berlin (Germany). In some of the RBF sections strong mixing of freshwater with wastewater was observed (15–30% in Lake Tegel) and the ability of the system to eliminate dissolved organic carbon (DOC) was strongly depended on water travel time and redox conditions (Grünheid et al., 2005). High energy and monitoring costs are often encountered in the application of MAR systems. Based on prediction management scenarios, the profitability of the MAR system in the Boquerón aquifer in Hellín (Albacete, Spain) would be achieved only if future irrigation demand remains stable or slightly decreases (10%) (Rupérez-Moreno et al., 2017).

The technical feasibility of MAR systems depends not only on quantitative terms but mostly on the quality of water these systems provide. MAR water contains many residual contaminants, strongly dependent on reclaimed water quality, residence time and aquifer geochemical conditions that may have adverse effects on human health if used for drinking purposes. For example, the wastewater used for recharging the aquifer at Depurbaix facility in Barcelona, Spain resulted in documented attenuation of heavy metals such as Cd, Hg, Ni, Pb (specifically Ni concentration was decreased from 28.2 mg/L of a tertiary treatment effluent down to 12.1 mg/L) (Teijon et al., 2010). In contrast, some other pollutants were not attenuated significantly. For instance Diuron (a widely used pesticide), with an influent content of 30.7 ng/L, was still detected in the groundwater in a range of about 0.34–110.9 ng/L.

Monitoring of MAR systems coupled with groundwater transport simulation and the understanding of geochemical processes could improve the system design parameters according to the desired objectives. For example the PHREEQC model has been used to gain more insight into the aquifer geochemistry during MAR storage and recovery (Gaus

et al., 2002; Kuster et al., 2010) or the natural attenuation technology of acid groundwater plumes underneath uranium mill tailing ponds (Zhu et al., 2001). Specifically, in coastal aquifers it has been used to simulate the sea water intrusion front (Han et al., 2011; Petalas and Lambrakis, 2006).

Groundwater flow and contaminant transport models can be linked with geochemical models in order to determine a variety of parameters such as: the direction and rate of groundwater flow, the chemical nature of groundwater, the concentrations of contaminants, their soil-water phase interactions and their potential for transformation during transport (Backnäs and van den Dool, 2011). The most commonly used models for simulating groundwater flow and transport are: MODFLOW, MIKE SHE, PTC and FEFLOW. MODFLOW is a finite difference groundwater flow simulation model that has been coupled with other models and now includes capabilities to simulate coupled groundwater/surface-water systems, solute transport, variable-density flow, aquifer-system compaction and land subsidence among others. The MIKE SHE modeling system is a fully integrated modeling framework for simulating all land phases of the hydrological cycle and contaminant transport (Graham and Butts, 2005). PTC is a groundwater flow and contaminant transport simulator that combines finite elements and finite differences methods in order to generate a three-dimensional mathematical model (Babu et al., 1997). FEFLOW is a groundwater modeling software that enables multi-species reactive transport via a reaction kinetics editor and linkage of the surface water component through an interface manager (Kolditz et al., 1998). In recent years studies have combined groundwater flow and transport models with geochemical models. Specifically, PHREEQC was combined with MIKE SHE (Backnäs and van den Dool, 2011), MODFLOW (Dhiman and Keshari, 2006; Machado et al., 2007; Prommer et al., 2002) and recently with FEFLOW (DeSouza, 2012).

Over the course of the last decade, there have been a few documented studies of simulated MAR field applications involving modeling using either geochemical or groundwater flow and transport models or a combination of both. In terms of geochemical modeling, PHREEQC was used to perform a reactive transport modeling study of a sandy aquifer in Herten, Netherlands where a storage and recovery (ASR) trial was conducted (Antonioni et al., 2013). Geochemical models were also used in order to gain an understanding of the geochemical evolution of groundwater at the Great Plains (Dakota) aquifer system (Gosselin et al., 2001).

In terms of groundwater flow and transport models, a simulation-optimization methodology based on MODFLOW was employed by Eusuff and Lansey (2004) in order to find the optimal management policy of an artificial recharge facility considering water quality changes. In another case study, a groundwater flow and transport modeling study was performed utilizing data derived from the initial aquifer flushing by injection of stormwater into the central recovery wells at an Aquifer Storage Transfer and Recovery site in Salisbury, South Australia (Kremer et al., 2008). Flow and transport modeling techniques were used to investigate the site suitability for the construction of a MAR system at Northern Gaza coastal aquifer (Rahman et al., 2013). MODFLOW in combination with other techniques was used to determine the human health risk from water recovered from a MAR system in Perth, Western Australia (Toze et al., 2010). Probabilistic modeling was applied for evaluating nitrogen, phosphorus and organic carbon removal efficiency of an aquifer storage and recovery (ASR) project in an anoxic carbonate aquifer at Bolivar, near Adelaide, South Australia (Vanderzalm et al., 2013). A conceptual biogeochemical model for reclaimed water was developed to simulate pretreated, nutrient-rich reclaimed water injected into a limestone aquifer at the Bolivar trial site near Adelaide, South Australia (Greskowiak et al., 2005). The model was then incorporated into an existing reactive multicomponent transport model. Also, a combination of a groundwater flow and a reactive transport model was used to describe the temporal and spatial evolution of the redox zonation in

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