ARTIFICIAL RECHARGE EFFECTS IN A COASTAL AQUIFER LOCATED IN THE SEMI-ARID ENVIRONMENT OF KORBA-MIDA, CAP-BON PENINSULA, TUNISIA

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ABSTRACT

The Korba-Mida aquifer, one of the most productive in Tunisia, is heavily suffering from water scarcity and salinization due to overexploitation and consequent seawater intrusion problems. The aquifer is located in an important tourist, industrial and, above all, agricultural area. As a result, the use of treated wastewater is being considered as an alternative to the use of both brackish and/or freshwater for irrigation practices. For ultimate benefit from the water management, it was proposed to fully utilize the treated wastewater directly to perform artificial recharge in the depleted aquifer, using three basins (Gaaloul *et al.*, 2012a).

This paper follows a vast number of work and publications done in the area, focusing on the description and measurement of the influence of on-going artificial recharge (AR) experiments in the surrounding groundwater quantity and quality. The data was collected during July 2012 by using several probes located in the surrounding wells at different depths. The results allowed to conclude that there is a clear increase of the piezometric level due to the recharge (1500 m^3/d), and that the AR had an overall beneficial impact in the decrease of groundwater electrical conductivity.

1. INTRODUCTION AND JUSTIFICATION

Groundwater is increasingly becoming a vital resource for living and environment. Coastal areas in several countries, mainly in those situated in the semi-arid regions (e.g. Tunisia, Morocco, Algeria, and Egypt) are characterized by groundwater systems vulnerable to salinization by seawater intrusion (e.g. Paniconi *et al.*, 2001; Gaaloul *et al.*, 2003; Kerrou, 2010; Gaaloul *et al.*, 2012b, Hsissou *et al.*, 1996; Bouchaou *et al.*, 2005, Krimissa *et al.*, 2004).

Furthermore, growing population, whether permanent or temporal like tourists, industry, agriculture and aquaculture are negatively affecting water resources due to overexploitation and inadequate soil occupation leading to groundwater resources depletion and pollution. Additionally climate change, especially in semi-arid or arid regions, and the associated increase in spatial and temporal variability of climatic phenomena, will strongly impact in groundwater quantity and quality, leading to the need of mitigation and adaptation water management measures in coastal zones.

Addressing water stress by integrated water resources management in coastal zones is often made difficult by the geological and hydrodynamics complexity, but also by the socio-economical context, conflict interests, legislation and policies. Water issues have nevertheless lead to the reconsideration of traditional aquifer management by introducing integrated water resources planning often relying on alternative water supplies, i.e. desalinization plants, Managed Aquifer Recharge (MAR), subsurface storage and subsequent utilization of treated sewage effluent through aquifer storage and recovery (ASR), possibly completed with Soil Aquifer Treatment (SAT). More advanced and consistent knowledge is still needed to improve water resources management which addresses to governance, health risks, regulation, and public perception.

Artificial recharge of groundwater in Tunisia is being part of the integrated management of water resources since the seventies. This paper addresses the benefits of AR in the quality and quantity of underlying groundwater.

2. OBJECTIVES

The objective of this paper is to present the influence of AR in the groundwater quality and quantity of Korba-Mida aquifer recharge site, in the Cap Bon peninsula.

This pilot site was established in 2008, in the region of Korba-Mida, aiming to increase the aquifer recharge and to prevent seawater intrusion. For that purpose, the aquifer recharge (1 million m^3 in 3 years, Gaaloul *et al*. 2012a) is being done with domestic treated wastewater from the Korba waste water treatment plant (WWTP), being the issue of the groundwater quality preservation a must.

3. METHODOLOGY

3.1 Geographic and climatic context

Tunisia has an arid to semi-arid climate, with an average rainfall of 500 to 800 mm per year in the northern part of the country, whereas the South only receives 100 to 200 mm. According to Gaaloul (2011) the global water resources availability is 4.8 billion m^3, 2.7 billion m^3 from surface water and 2.1 billion m^3 from groundwater resources.

The study-area is situated in Cap Bon peninsula, located at circa 100 km East of Tunis. The semiarid climate of this region (Figure 1) is characterized by an average annual rainfall of 480 mm, over an observation period of 47 years (1964-2011), with temporal irregularities like 65% of the annual rainfall being concentrated between November and March. The climatic deficit (rainfall – evapotranspiration) covers a period of about 10 months, reaching its maximum (160 mm) in July and August (Gaaloul *et al.*, 2012a). Summer is hot and dry, and winter is cold and wet. The average annual temperature varies from 17 to 19°C. The monthly evaporation is high (around 1300 mm per year), while the monthly humidity is between 68 and 76%. The dry season is pronounced thus aggravating the situation, given that the highest water demand usually coincides with the drought period.

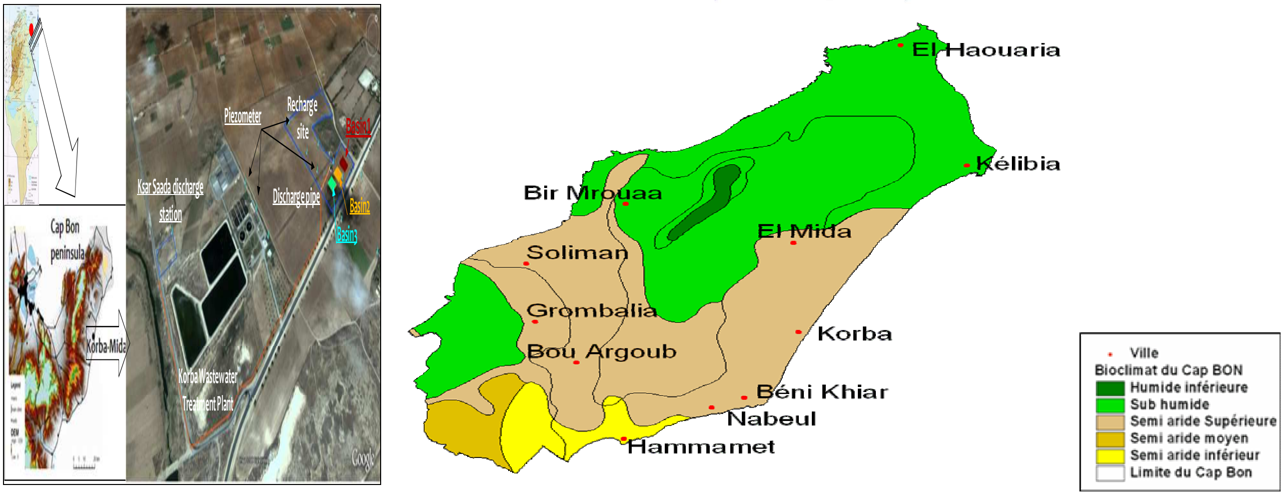
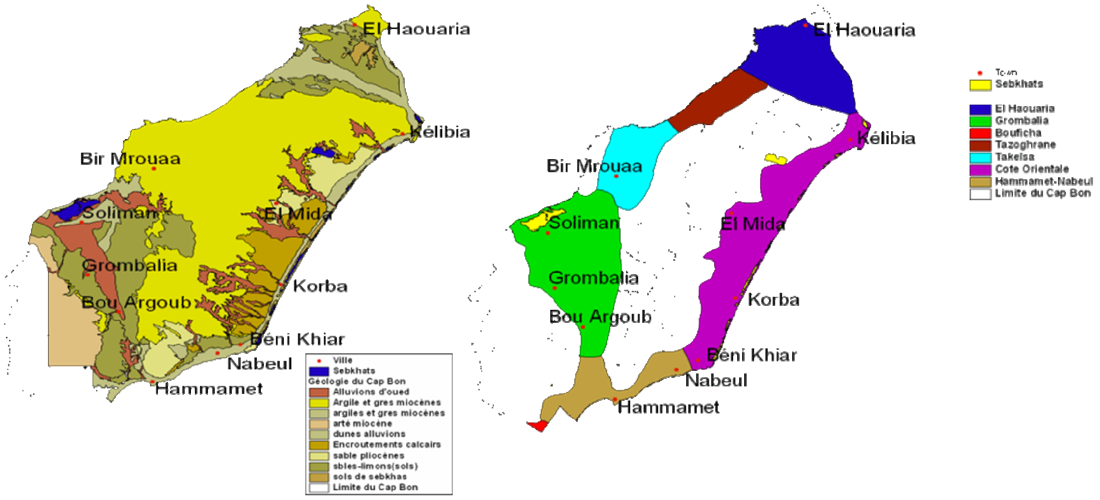


Figure 1 - Map of Cap Bon peninsula relief and climate (Gaaloul *et al.*, 2012b)

3.2 Geological characteristics

Cap Bon peninsula has seven major aquifers, the aquifer of the East Coast having an area of approximately 475 km^2 with a length of about 45 km (Figure 2). The study area is located in this last aquifer and is bounded to the south by Sidi Othmen Wadi, to the north by Lebna Wadi, to the west by Jebel Abdeerahmen and to the east by the Mediterranean Sea (Figure 3).



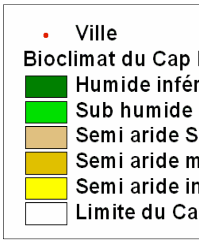


Figure 2 - Map of the geology and hydrogeology of the Cap Bon peninsula (Gaaloul *et al.*, 2012b)

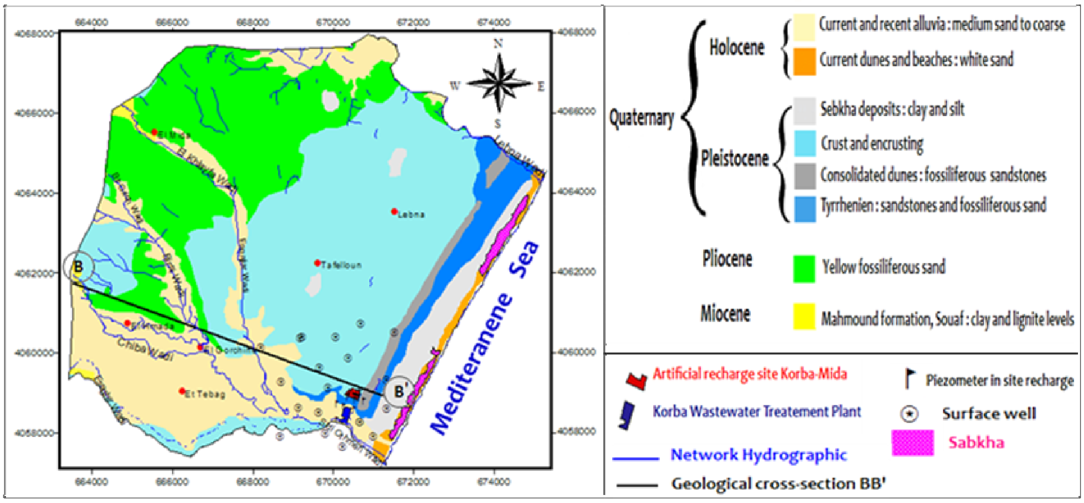


Figure 3 - Geological settings of the Korba-El Mida basin with sampling points on control piezometers and farmers' wells (Gaaloul *et al.*, 2012a)

The geological aquifer units overly (with an angular discordance) mid-Miocene marls which form the base of the system (Figure 3). This aquitard may contain lenticular sandstone and clay-sandstone bars of variable thickness and depth but often separated by thick layers of impervious marls for a total thickness of 1,200 m (Abbes and Polak, 1981). The Tyrrhenian Quaternary forms a 1.2 km wide strip parallel to the coastline all along the study area. It is made of arenitic limestones overlying conglomeratic units with a total thickness ranging between 10 to 50 m. The Korba-Mida aquifer was formed during the Pliocene by marine deposits in the Dakhla synclinal north of Korba city. The Dakhla syncline was formed during the Atlasic folding phase. It presents a north-east to south-west axis and is bounded by the Djebel Sidi Abderrahmane (640m) anticline to the west and by the deep Korba anticline to the east. The hydrogeological study of the Korba-Mida area shows that the Plio-Quaternary detrital deposits constitute a potential shallow aquifer. The marls of the Middle Miocene form the impermeable substratum of this aquifer (Ennabli, 1980) (Figure 4).

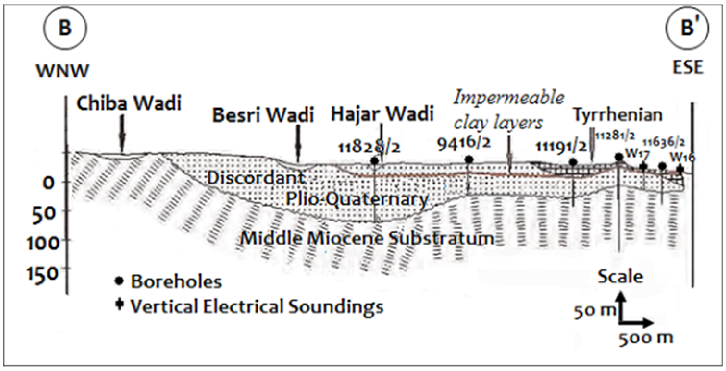


Figure 4 - Simplified geological cross-section BB' of the Korba-Mida basin (Kouzana *et al.*, 2009)

3.3 Hydrogeological settings and modelling

The Korba-Mida aquifer can be divided in two hydrogeological units: the late Miocene and the Plio-Quaternary units. The first deep unit is constituted of Miocene and Oligocene formations. The Oligocene is captured in the foothills of Jebel

Abderrahman anticline. The Plio-Quaternary, Miocene and Oligocene aquifers have the same eastern and southern limits, while in North and West, Oligocene and Miocene aquifers extends over 300 km^2 more than the Plio-Quaternary one, west of the study area. The Miocene is captured in the South. Its substratum is embodied by impermeable marls of the Souaf formation which contain a brackish water with a salinity of 3 to 4 g/L (Gaaloul *et al.*, 2012b). Younger Miocene is embodied by sand and sandstones and are actively pumped upstream of our site, from 150 to 500 m depth. The Miocene is captive and feeds the Pliocene upstream, which also feeds the Quaternary. Its natural outlet is the sea. A well of potable water supply is located in Tafelloune. The Miocene and Oligocene aquifers sink rapidly under the Pliocene in the Korba plain, down to more than 1500 m deep sometimes, favoured by a series of active faults replays (Gaaloul *et al.*, 2012b).

The second unit is the Plio-Quaternary aquifer constituted by two formations, the deeper Pliocene and the upper Quaternary, both having no distinction in terms of hydraulic. Piezometers and shallow wells typically intersect the two horizons and they are considered as one aquifer for the necessities of models. The whole depth varies between 20 to 50 m. The Miocene may be encountered at low depth in some places and according to the electric sections (Kouzana *et al.*, 2009), the Pliocene aquifer is constituted by a succession of levels saturated with freshwater and brackish water and, at the bottom, layers saturated with more or less salty water. Rain directly infiltrates in the outcrops of the Pliocene plain East of our study area.

The aquifer may be locally semi-confined due to less permeable deposits (Kerrou *et al.*, 2010) and it is the most productive of the area.

The Quaternary recharge is principally made through the incised glacis and outcrops. The topographic relief constituted by quaternary Tyrrhenian fossil dunes is favourable to retention and infiltration of surface runoff. Apart from the large rivers that have incised the dunes, the flows of streams do not cross the Tyrrhenian and directly infiltrates to groundwater. The Tyrrhenian has the highest hydraulic conductivities, ranging from 10−6 to 10−3 m/s Ennabli (1980). Ennabli (1980) proposed an average porosity of 0.12 for the whole aquifer system. The discontinuous clay lenses which may limit exchanges between the Tyrrhenian and underlying sandstones appear at the top of the salt water intrusion (Kouzana *et al.*,2009). At the North of the recharge site, a perched groundwater on a sandstone layer at an altitude of +6 to +10 m is captured by wells when possible. The aquifer is then locally vertically compartmentalized.

The main coastal sabkhas are the natural outlets of the Tyrrhenian which is no ore the case in our site where reversal of hydraulic gradient happened. The lagoon receives permanent discharges of treated wastewater and communications with the sea are occasional. Moreover, its clayed bottom limits transfer towards the groundwater and it seems to have limited exchanges with groundwater.

The Plio-Quaternary recharge is provided by direct infiltration of rainwater and surface waters in streams, and by the ascendant drainage from the deep aquifer. The recharge of the aquifer by rain infiltration is estimated to be less than 10% of the 420 mm/year average annual rainfall. This infiltration is estimated between 32 to 18 mm per year in average (Gaaloul *et al.*, 2008a)

The exploitation of the Korba-Mida aquifer began in the 60's mainly for irrigation purposes. The Korba-Mida surface plio-quaternary coastal aquifer is pumped by more than 9240 wells and over the last four decades the water table has dramatically decreased, leading to an increase of salt concentrations to peak values of 5 to 10 g/L (Gaaloul *et al.* 2012a). In 2008, groundwater abstraction by pumping is estimated at 50 Mm^3, recharge at 20 Mm^3 and irrigation return flow at 16% of the irrigation water (Ennabli, 1980; Paniconi *et al.*, 2001, Kerrou *et al.*, 2010, Gaaloul *et al.*, 2012b).

The World Bank (1996) analysis showed that the agricultural productivity levels are still increasing in the region while available water resources are already fully exploited, prospecting major water problems in the next decade. Agricultural activities are the predominant activity (horticulture, viticulture, fruit growing, grain farming and livestock) but the region also hosts food industries, textile, dairy and paper industries. These activities require significant amounts of water, supplied primarily by the plio-quaternary groundwater resources and by surface water coming from the Medjerda-Cap Bon canal, which links high rainfall areas of northern Tunisia to the region (Gaaloul, 2011).

More recent hydrogeological models showed that the situation in the central part of the Korba aquifer was critical, resulting in the exploitation of 135% of the annual recharge (Kerrou *et al.*, 2010; Gaaloul *et al.* 2008a, 2008b). The aquifer is highly vulnerable with multiple uses governed by agricultural and industrial pressures, tourism, urban and rural developments. A better rational management is needed and was notably promoted with aquifer recharge by treated wastewaters.

The equilibrium of this situation could be attained with the use of AR systems. Terceiro *et al.* (2010) have developed a mathematical model of the area to study the optimized recharge rate that could confer equilibrium between extractions and recharge, and have reached the conclusion that an artificial recharge value of 9000 m^3/d, divided by three different spots at Korba-Mida basin, would be the optimal AR value.

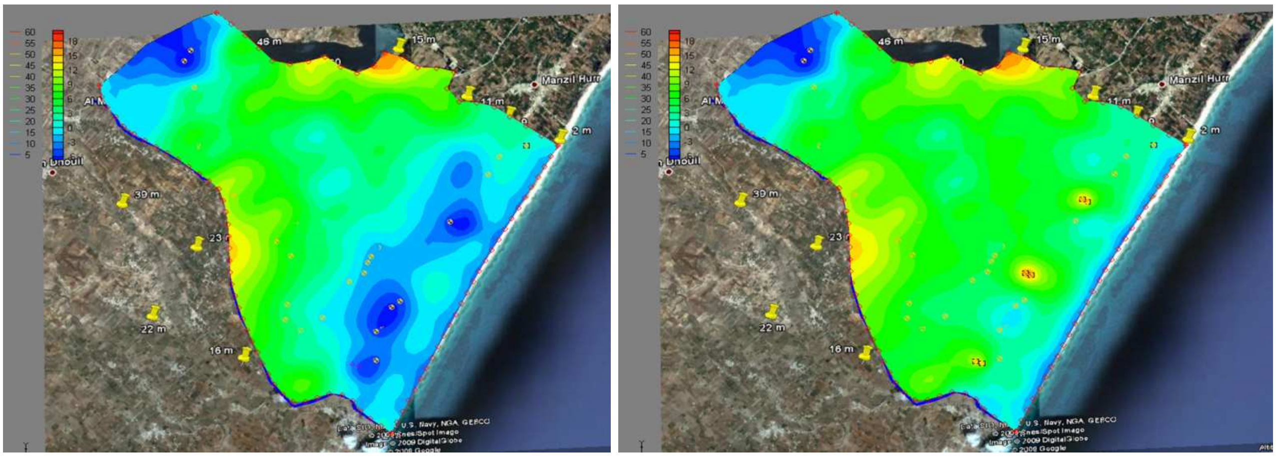


Figure 5 – Piezometric levels for the existing situation (left) and considering an optimized artificial recharge value of 9000 m^3/d (right), at three different spots at Korba-Mida basin (Terceiro *et al.*, 2010)

3.4 Geochemical context and sea water intrusion

The groundwater high salinity of the east coast has long been known. Gaaloul and Cheng (2003) have determined that the salinization in Korba has three main origins: geological, seawater and the salts irrigation concentration. Multidisciplinary approaches have been used to study the consequences of sea water intrusion in the Korba plain and to describe the evolution of the seawater intrusion. The salinity distribution in the Korba-Mida aquifer is, as expected, correlated with the piezometric evolution. The vertical salinity profiles measured in three piezometers in August 2008, before artificial recharge, allowed delineating a distribution of salt concentrations in the aquifer.

Most recent studies combined geophysical and hydrochemistry (Kouzana *et al.*, 2009). The authors quantified the invasion of seawater inland, reaching 1.5 km south of Chiba Wadi and 5 km south of Diar El Hajjej. According to the salinity maps, five salinity zones were identified, the less concentrated (2 to 4 g/L of salinity) lays in the Northern coastal aquifer and the most concentrated (22 g/L) was North of Korba. Salinity was more pronounced along the coast, resulting in a high number of abandoned shallow wells. Calculations of mixing with seawater reaches high values in some piezometers located in areas of Korba and Tafelloune, and varied from 0 to 70% reflecting the heterogeneity process of salinization (Ben Hamouda *et al.*, 2011).

Groundwater nitrate concentrations are high almost everywhere and very often exceed 100 $mgNO_3^-/L$, with a maximum of 434 $mgNO_3^-/L$ in the region of Korba. This region has a strong agricultural occupation leading to heavily nitrate contaminated waters (Gaaloul *et al.*, 2012a).

4. MATERIAL AND METHODS

4.1 Artificial recharge and treated wastewaters characteristics

The artificial recharge site is located about 100 km southwest of Tunis City and approximately 300 m north of the waste water treatment plant (WWTP) in Korba, at 1.5 km from the coast. The field site (4.46 ha) is a public property and comprehends 16 piezometers, and three injection basins. The AR concept it to use the treated wastewater that is infiltrated though ponds, undergoing soil aquifer treatment (SAT) to improve its quality, especially in terms of microbiology. This pilot project was built in to assess the suitability of the site, the chosen recharge system and the adopted techniques.

The site includes three artificial recharge basins with a depth of 1.5 m and a total infiltration area of 4500 m^2 (Figure 6). The bottom of the basins is covered with a layer of clean sand with 0.5 m thickness. The side slopes are covered with a layer of stone for protection against erosion. The setup consists of two infiltration basins functioning simultaneously and alternately with an injected daily volume varying from 533 to 886 m^3 per basin (3 to 8 hours).

The waste water supply system comprises a basin buffer tank with a capacity of 300 m^3, able to feed the basins by gravity through a 400 mm diameter pipe with an automatically controlled motorized valve. The treatment plant receives urban and industrial wastewaters coming from about 48 factories including canned tomatoes paste or fish, slaughterhouses, and fabric washing.

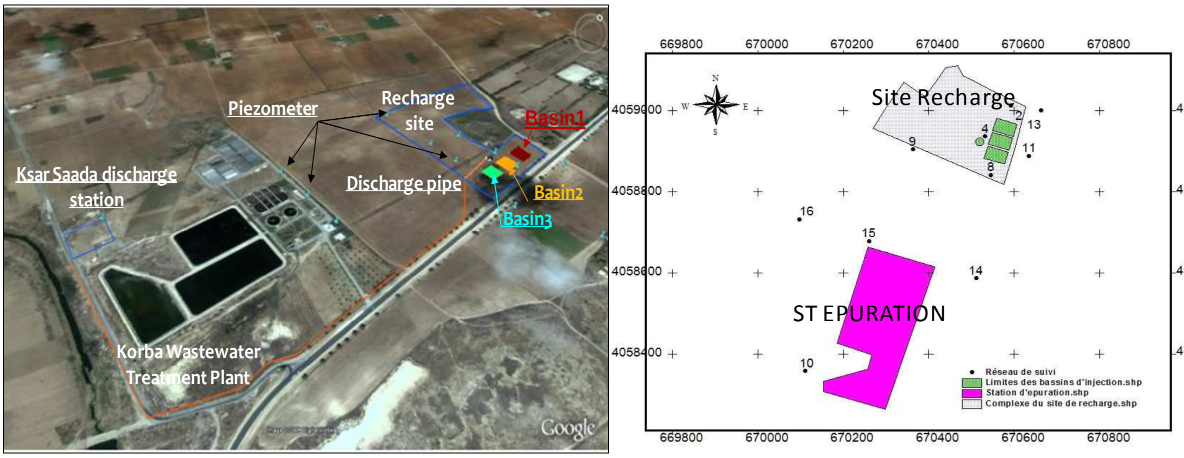


Figure 6 - Scheme of the Korba wastewater treatment plant, the Korba-Mida recharge site and the surrounding piezometers (cf. Gaaloul *et al.*, 2012a)

The site was selected on the basis of its lithologic character, hydrologic situation, and a favourable geohydrologic environment. This part of the aquifer is a typical homogenous alluvial deposits consisting of fine to medium sand with some gravel deposits. Soils in recharge site Korba-Mida presents 80% sandy, 15% loamy and 5% clay and their texture ranges from sand to sandy loam. Thus, it is expected that the vadose zone acts as transfer matrix for diverse minerals and nutrients. The gross hydrologic characteristic is relatively uniform through the area. On the selected recharge site, the transmissivity ranges from $4x10^{-3}$ to $6x10^{-3}$ m²/s. The thickness of the Korba-Mida aquifer is 20 m. The permeability of the aquifer is estimated between 1.6 $x10^{-3}$ and $2x10^{-3}$ m/s. The hydraulic gradient is varies between 0.2 to $1x10^{-3}$ m/day, and the flow velocity varies from 0.2 to 0.6 m/day. Infiltration tests at the bottom of the infiltration basin, at 1.5 m depth, gives high infiltration rates (between 5 and 60 m/day) (Gaaloul *et al.*, 2012a).

4.2 Experimental setup

Between 3rd and 7th July 2012 a continuous monitoring setup was installed in eight piezometers surrounding the AR basins, and at different depths. Its purpose was to measure the effects of the treated waste water infiltration in the groundwater quality and quantity. CTD Diver® were used as multi-parameter groundwater data-loggers to monitor electrical conductivity, water levels, and temperature.

5. RESULTS AND DISCUSSION

5.1 Quantity

Figure 7 presents the results of the piezometric levels observed during the AR experiment in the eight piezometers monitored. As expected, within the same piezometer there are no changes in the water level with depth of monitoring, since the piezometers are fully screened.

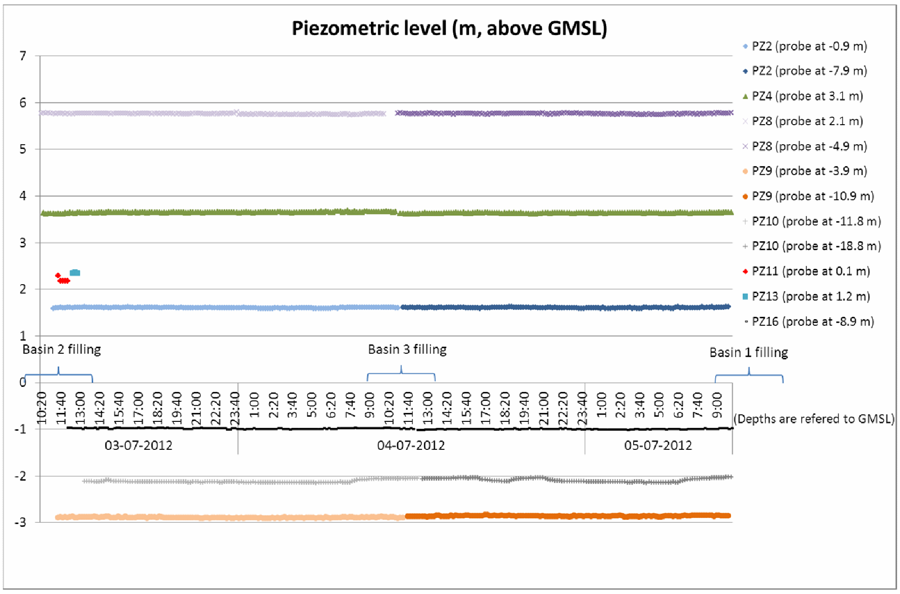


Figure 7 – Groundwater levels registered during the experiment in the piezometers surrounding the AR basins

From Figure 7 we can observe that the piezometric levels are very different from place to place, ranging from around – 3 m to almost 6 m (GMSL). Only the piezometers located around the AR basins (see Figure 6: PZ2, PZ4, PZ8, PZ11 and PZ13) have the piezometric level above 1 m, which allows concluding a clear increase of the piezometric level due to the recharge rate (aprox. 1500 m^3/d). However, the values are not reflecting strong oscillations due to changes in the basins being filled, but rather a constant value due to the continuous recharge in one of the basins.

The piezometer PZ10 is the only showing a clear oscillation in the piezometric level, which is possibly due to the influence from the river Sidi Othmen Wadi.

Figure 8 shows the local effect of the piezometric rise due to the artificial recharge process, being the natural flow direction towards SW. From a quantitative point of view, the recharge rate should be duplicated to 3000 m^3/d to avoid piezometric levels below zero (Terceiro *et al.*, 2010), as can be seen for the existing rate.

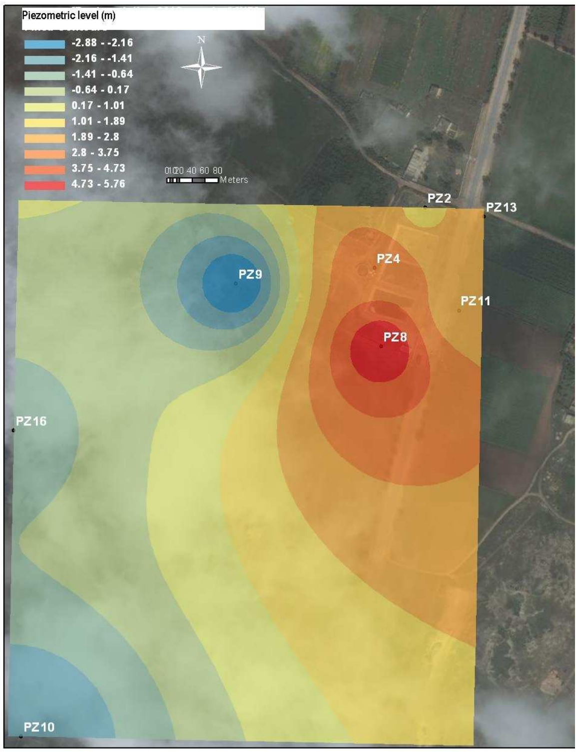


Figure 8 – Piezometric contour lines registered during the artificial recharge

5.2 Quality

To assess the AR recharge effects in the local groundwater quality, CTD divers were placed at more than one depth to check potential changes in the electrical conductivity (EC) values. Variations were observed in between piezometers and with depth, as presented in Figure 9.

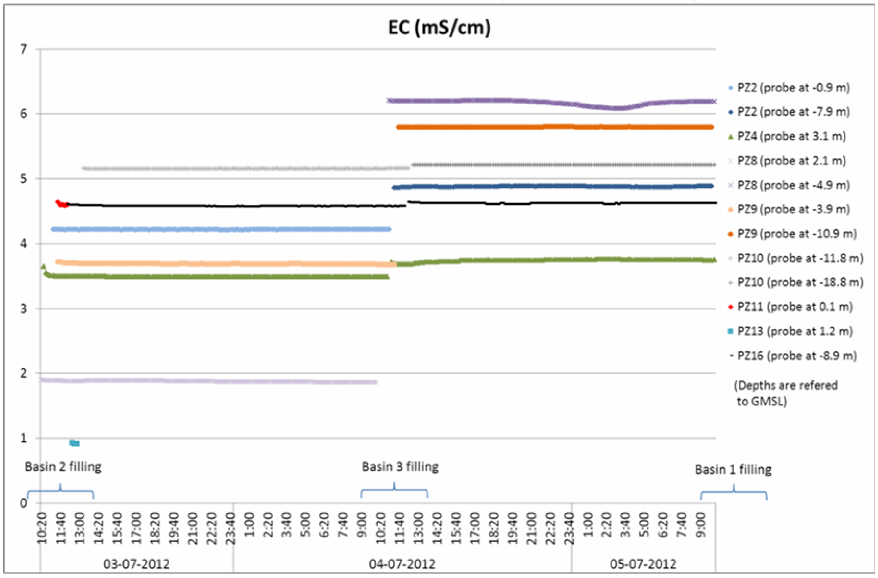


Figure 9 - Electrical conductivity values measured in several piezometers and depths during an artificial recharge period

From the piezometers where data was gathered at two different depths, it is possible to observe that only the piezometers PZ8, PZ9 and PZ2 have a clear difference in EC with depth, where the deepest probes show the higher EC. This effect is due to AR water influence (resulting in lower EC values in the top) and not marine water intrusion (resulting in higher EC values in the bottom, i.e. the same lower EC values in the top effect), an existing phenomena in the region, since the data from PZ10, the only piezometer far from the influence of the AR with data at two depths, has almost the same EC at the two depths. Therefore it is likely to conclude that the AR has a beneficial impact in the decrease of the groundwater EC. EC from the WWTP could have had values around 3 mS/cm, but this value is not constant. Note that the other piezometers located around the AR basins have no data at two levels: PZ4, PZ11, PZ13. Furthermore, considering the decrease in the values observed in PZ8 for about 8h (from around 4/7 at 22:10 and 5/7 at 6:40), we can observe that the AR had a visible impact in the decrease in EC (probe at -4.9 m) in depth, with a time delay of about 8h. Figure 10 presents the contour lines for EC in the area.

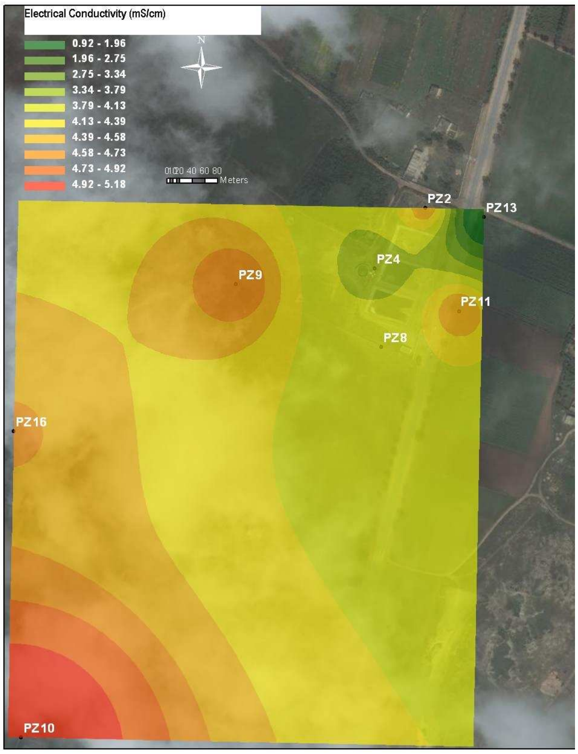


Figure 10 – Piezometric contour lines registered during the artificial recharge

6. CONCLUSIONS

The growing imbalance between water supply and water demand, exacerbated by climate change, population growth, agriculture needs and urbanization, requires more efficient water resources management. Storing water in aquifers during times of excess or with treated waste water can help address water scarcity challenges. Moreover, water quality can be improved through aquifer transport and storage, due to chemical and biological reactions. Managed Aquifer Recharge (MAR) and Aquifer Storage and Recovery (ASR) can be a key to solving water crisis by linking water reclamation, water reuse and water resources management.

This paper presents the results of the effects of an artificial recharge experiment in the surrounding groundwater quantity and quality. The results allowed concluding that there is a clear increase of the piezometric level in time due to the recharge, and that the artificial recharge process had an overall beneficial impact in the decrease of groundwater electrical conductivity. However, these values continue to be very high due to the WWTP infiltration water characteristics.

7. ACKNOWLEDGEMENTS

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