Artificial recharge enhancement to prevent seawater intrusion in the coastal aquifer of Korba-Mida (Tunisia)

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Abstract: In recent decades the groundwater overexploitation and unabated use has led to severe environmental problems such as resource depletion, land subsidence and seawater intrusion in coastal areas. Globally, climate change is expected to impact on rainfall intensity and duration, causing more intense extreme events, *i.e.* river floods, rainstorms and droughts (EEA, 2007; IPCC, 2008). Additionally, the growing imbalance between water supply and water demand, exacerbated by climate change, population growth and urbanization, requires more efficient water resources management (EEA, 2009). To mitigate these adverse impacts and to protect this valuable resource, rational and integrated groundwater management practices and policies, as well as robust modelling and analysis tools have been developed in Tunisia. The Korba-Mida aquifer, one of the most productive in Tunisia, is heavily suffering from water scarcity and salinization due to seawater intrusion. It is an important tourist, industrial, and above all agricultural area. This paper describes the measured positive influence of the on-going artificial recharge (AR) experiments in the surrounding groundwater quantity and quality. The data was collected during the period before and during artificial recharge (2007 to 2012) by using several probes located in the surrounding piezometers and wells, at different depths.

Keywords: Artificial recharge, saltwater intrusion, water reuse, Korba-Mida aquifer.

Introduction

In Tunisia, the coastal aquifer of the Cap-Bon peninsula located in a semi-arid climate is one of the first studied examples of groundwater depletion, seawater intrusion and salinization. Since the sixties, large quantities of water have been collected from the agricultural and the industrial sectors resulting in a spatiotemporal evolution with dramatic piezometric drawdown and degradation of groundwater quality mainly due to seawater intrusion. The economy of the region depends to a large extent on the availability of water of adequate quality for crop irrigation, and therefore the marine intrusion and salinization of this water could endanger the economic future of this coastal area (Gaaloul, 2011; Ennabli, 1980).

From 1962 to 2008, the piezometry of the Plio-Quaternary aquifer of Korba-Mida region has registered an alarming reduction and a high increase in water salinity due to its over-exploitation (Gaaloul *et al*., 2008). This means that the hydraulic gradients were reversed mainly towards the central part of the aquifer leading to an acceleration of seawater intrusion. Before initiation of artificial recharge (December 2008), all the piezometric levels were below the sea level over the entire study area.

As a result of water deficit, groundwater artificial recharge in Tunisia is part of the integrated management of water resources since the seventies (Gaaloul *et al*., 2012a). In 1986 the first pilot project was built with a groundwater artificial recharge experimental station in Nabeul Oued Souhil (irrigation efficiency) using treated wastewater. In 2008, a new aquifer recharge pilot site was established in the region of Korba-Mida to recharge the aquifer with domestic treated wastewater of the Korba treatment plant and help controlling seawater intrusion (Figure 1).

Material and Methods

The east coast aquifer of the Cap Bon Peninsula, which lies 100 km east of Tunis, extends for about 45 km and underlies an area of approximately 475 km² (Figure 1). The region has a semi-arid climate characterized by an average annual rainfall of 480 mm with temporal irregularities. The climatic deficit covers a period of about 10 months.

The Korba-Mida aquifer is made up mainly of marine sediments deposited in the Dakhla syncline north of Korba city (Gaaloul *et al.*, 2012a). The study area is bounded to the north by Wadi Lebna, to the south by Wadi Sidi Othmen, to the west by the elevated mountains consisting of Mio-Pliocene sequences, and to the east by the Mediterranean Sea. It is underlain mainly by Pliocene formations and Quaternary marine platforms: (i) the Middle Miocene is the base of the system and is not exposed except some relics North West of the study area. (ii) Marine Pliocene sediments transgress unconformably the Miocene and outcrop North West of Taffeloun and (iii) Quaternary deposits in the study site contain upper Pleistocene and Holocene deposits. It can reach 150 m in the Taffeloun area (Gaaloul *et al.*, 2012a).

The artificial recharge site (Figure 1) is located in Korba-Mida aquifer which consists mainly of marine sediments deposited in the Dakhla syncline north of Korba city (Gaaloul *et al*., 2012a). It was selected on the basis of its lithologic character, hydrologic situation, and a favourable geohydrologic environment. The soils in recharge site of Korba-Mida present 80% sandy, 15% loamy and 5% clay and their texture ranges from sand to sandy loam. The gross hydrologic characteristic is relatively uniform through the area. The transmissivity ranges from $4x10^{-3}$ to $6x10^{3}$ m²/s. 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 (Leitão *et al.*, 2013).

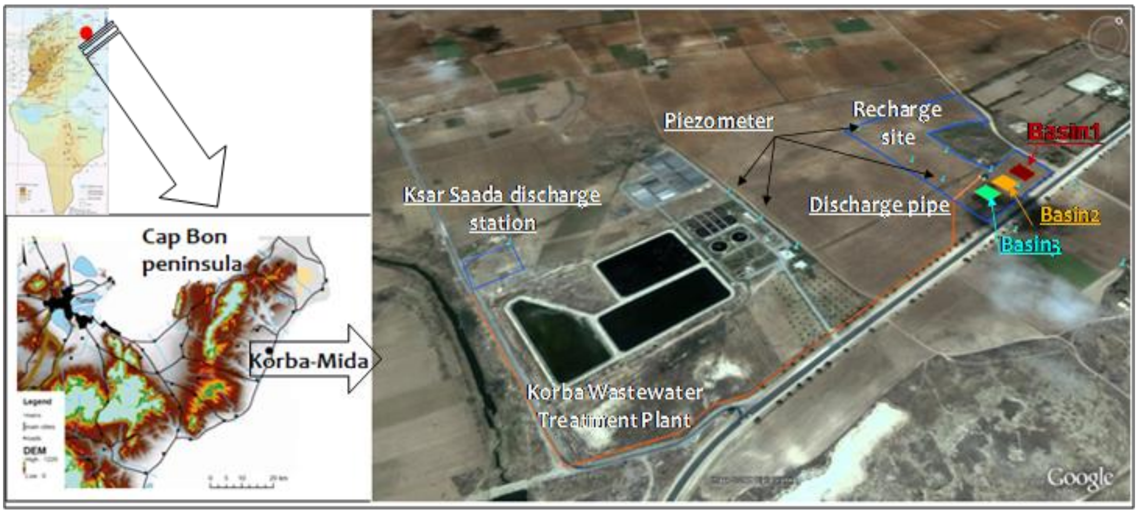

Figure 1 Location map of the Korba – Mida site in the Cap Bon Peninsula

Concerning the water balance, rainwater infiltration and irrigation recharge are estimated at around 18 Mm^3/year (Gaaloul *et al*., 2012b), direct infiltration from *wadis* and dams reaches nearly 8 Mm^3/year. Pumped abstraction of the groundwater by 2008 was estimated at 50 Mm^3 (Ennabli, 1980; Gaaloul *et al*., 2012b) which is twice the total recharge.

The Korba-Mida artificial recharge site contains three infiltration basins, of which two function simultaneously. In order to provide a hydraulic barrier against seawater intrusion, treated wastewater is infiltrated through ponds and undergoes soil aquifer treatment to improve its quality. The wastewater treatment plant receives both urban wastewater and industrial wastewater from some 50 factories, mainly tomato or fish processing plants, also slaughterhouses, and steel and tissue washing plants. The plant treatment consists on pre-treatment, secondary treatment by an oxidation channel process, and tertiary treatments performed with maturation ponds.

The control network consists of 16 piezometers located at different depths in the site recharge station. Since the start of the recharge site, in December 2008, several measurements were made in the piezometers including physical and chemical parameters (pH, electric conductivity, temperature and nitrates) measured *in situ* and *on site* in a monthly basis frequency, mainly ensured by INRGREF-Tunis, to examine the impact of this recharge in the aquifer. The anions and cations were analysed using the DX100 and DX120 Ion Chromatograph. The analyses of SO_4^{2-} were undertaken by a gravimetric method, those of HCO_3^-, Cl^-, and Ca^{2+} by the titrimetry method, and Mg^{2+} and Na^+ were analysed by spectrometry of atomic adsorption (SAA).

The data sets used in this study were provided mainly by National Institute of Research in Rural Engineering of Water and Forestry (INRGREF-Tunis) and the local groundwater management authority (CRDA Nabeul). For control and management purposes a monitoring network was set up in 2008 (before recharge) and today (after recharge) to record field data at regular intervals of one month. Hydrogeological, geophysical, and chemical measurements are taken regularly at the observation wells and collected into a geothematic database.

Results and Conclusions

Situation without artificial recharge (2008)

The historical evolution of the piezometric levels has been realized on the period between 1962 and 2008. Analysis and interpretation of the piezometric observation between 1962 and 1977 allows highlighting a lowering of the hydraulic heads below sea level and an estimation of the annual drawdown of 2 m. Several factors were at work between 1962 and 1977: increased pumping times combined with damming river Chiba in 1963. Thus, the Chiba dam caused a decrease of the groundwater table downstream due to the reduction of the recharge by its effluents (Gaaloul *et al.*, 2008).

The groundwater abstraction has increased during the 1980s, especially near the coast where Chiba dam was under construction, and its evolution from 1996 to 2008 is characterized by shallow depths and the apparition of a concentric depression of 5-10 m below sea level in particular in Diar El Hojjej area and in the coastal zone. The presence of shallow depth piezometric level within the coastal area is favourable to the seawater intrusion by reversing the hydraulic gradients (Gaaloul *et al.*, 2003).

The piezometric map built in 2008 shows piezometric depressions with negative piezometric levels on the order of - 20 m, intense and continuous withdrawal mainly for agricultural and industrial purposes. These have not only modified the previous hydrodynamic setting but also led to the seawater intrusion into the aquifer.

From 1962 to 2008, the piezometry of the Plio-Quaternary aquifer of Korba-Mida region has registered an alarming reduction and a high increase in water salinity due to its over-exploitation (Gaaloul *et al.*, 2008). This means that the hydraulic gradients were reversed mainly towards the central part of the aquifer leading to an acceleration of seawater intrusion. Before initiation of artificial recharge (December 2008), all the piezometric levels were below the sea level, over the entire study area and vary between zero from the Korba wastewater treatment plant to -7 m at the left site of the Ennajar Wadi which is a depression area.

In order to identify the origin of the salinization and the interaction between fresh and saltwater, about 19 water samples have been taken in this area mainly from large wells; a limited number were taken from piezometers.

The groundwater quality in coastal aquifer of Cap-Bon is recognized to be largely influenced by the interaction between the sea and the bordering aquifer systems. This interaction can result in salinization of fresh water bodies. Therefore the main mechanism for salinization is hydrodynamically driven; also physical and chemical processes within the aquifer will alter groundwater composition. In terms of quality, groundwater showed gradually increasing salinity between 1963 and 2008, and after building dams (Chiba, M'Laabi and Lebna). Between 1963 and 1997, the increasing mineralization was observed mainly in coastal and western parts of the aquifer between Diarr el Hojjaj and Tafelloun. Salinity of the water increased from 2 g/L to more than 6 g/L especially in the depression of Diarr El Hojjaj where the concentration reached 8 g/L. Several factors were at work: damming river Chiba in 1963, M'Laabi in 1964 and Lebna in 1986 combined with increased pumping times. Indeed, building dam constitutes a major factor of increasing mineralization by affecting the groundwater table downstream due to a reduction of recharge by its effluents. The interpretation of the spatial salinity highlights a continuous growth of the salinity (>10 g/L) especially in Diarr El Hojjaj and Tafelloun area. Thus, a strong connection between the increase in salt contamination and the lowering of piezometric levels in Korba aquifer, which can be ascribed to groundwater overdraft and/or a natural decrease in groundwater recharge, has been recognized in this coastal aquifer. The return flow from the inner irrigated coastal areas and/or chemical compounds of the fertilizers and pesticides used in agriculture are also not negligible factors playing roles in the increasing of salt concentration in groundwater (Kouzana *et al.*, 2009). Based on the hydrogeological and hydrodynamical information, the mathematical simulation will help to understand the behaviour of Korba system and to improve management policies of the local groundwater resources. The salinity of groundwater in wells and piezometers in 2008, varied from 1 to 12 g/L.

The nitrate concentration of the used to recharge the Korba Mida aquifer is about 4.5 mg/L. Initially and before the recharge, more than 85% of the area shows high nitrate concentrations, exceeding 50 mg/L, which is the trigger value set by the European Groundwater Directive (EC, 2006) for groundwater good chemical status. The most polluted area was identified in the Western side of the study area where nitrate contents exceed 100 mg/L and reach values as high as 350 mg/L.

Situation after four years with artificial recharge (2009 to 2012)

The monthly volume of water injected into the artificial recharge basins has ranged from 6,000 m^3 (December 2008) to 37,653 m^3 (July 2010) with a total of about 1.5 Mm^3 of treated wastewater injected between December 2008 and December 2012.

Figure 2 shows the great variation obtained during the forty months of injection in three basins and the depth of water table resulting. It is remarkable to notice that for the first couple of basins (B1 and B3), the groundwater table fluctuations are very similar, and that in the third basin (B2), the effect of injection is stronger. Water levels at the Basin 1 and basin 3 have increased about 1 m. On the other hand the water table in basin 2, has increased about 2 m. Water levels also increased to a lesser extent at other locations within the study area during December 2008 to December 2012, caused either by artificial recharge or increased infiltration associated with above-average precipitation during this period. Figure 3 shows the local effect of the piezometric rise due to the artificial recharge process, being the natural flow direction towards SW.

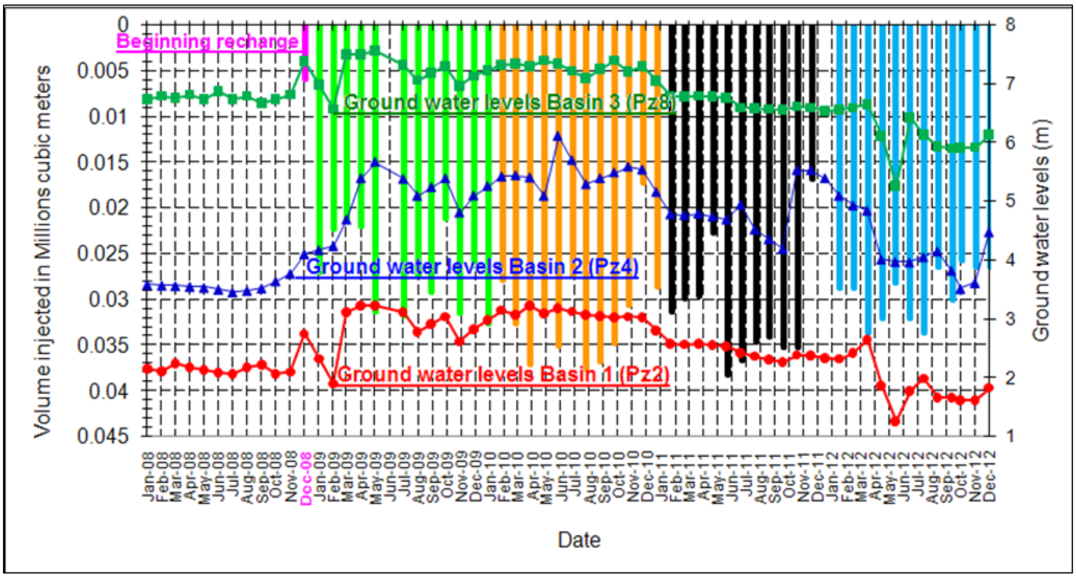

Figure 2 Evolution of the groundwater piezometric levels and the volume of wastewater injected in the three basins of the Korba-Mida recharge site (December 2008 – December 2012)

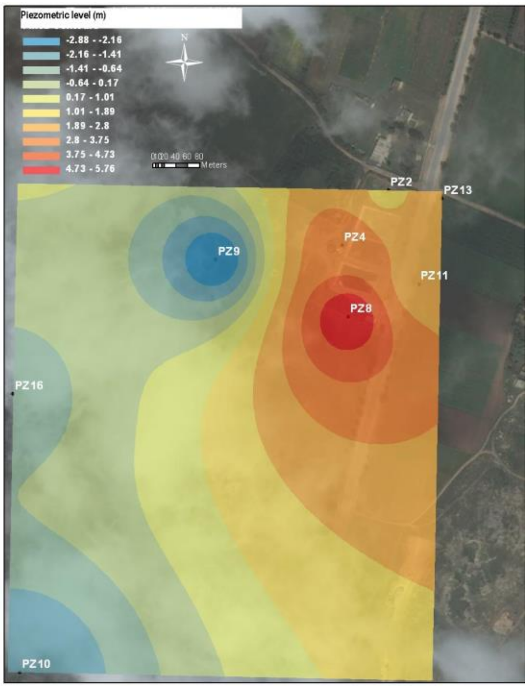

Figure 3 Piezometric contour lines registered during the artificial recharge (Leitão *et al*., 2013)

In September 2011, the cumulated volume of wastewater treated injected was about one Million cubic meters. The hydrograph of water levels at the piezometer 2, 4 and 8 are characteristic of water levels near the three basins 1, 2 and 3 respectively at the recharge site (Figure 2). The hydrograph shows that water levels in basins 1 and 3 declined during December 2008 to February 2009.

In agreement with the observed values, and considering the volume of water injected in each basin, the flow rate/piezometric uplift relation seems to stay more or less constant, which indicates no evidence of possible clogging until now.

From a quantitative point of view, and accordingly to the results of a mathematical model developed by Terceiro *et al*. (2010), the recharge rate at each basin should be duplicated to 3000 m^3/d to avoid piezometric levels below zero.

From the water quality point of view, the comparison of the groundwater quality before (2008) and after four years of artificial recharge (2012), resulting from the mixing of groundwater and infiltrated treated wastewater, showed the effectiveness of the project to cure high salinity which exceeded 1.5 g/L (cf. Figure 4).

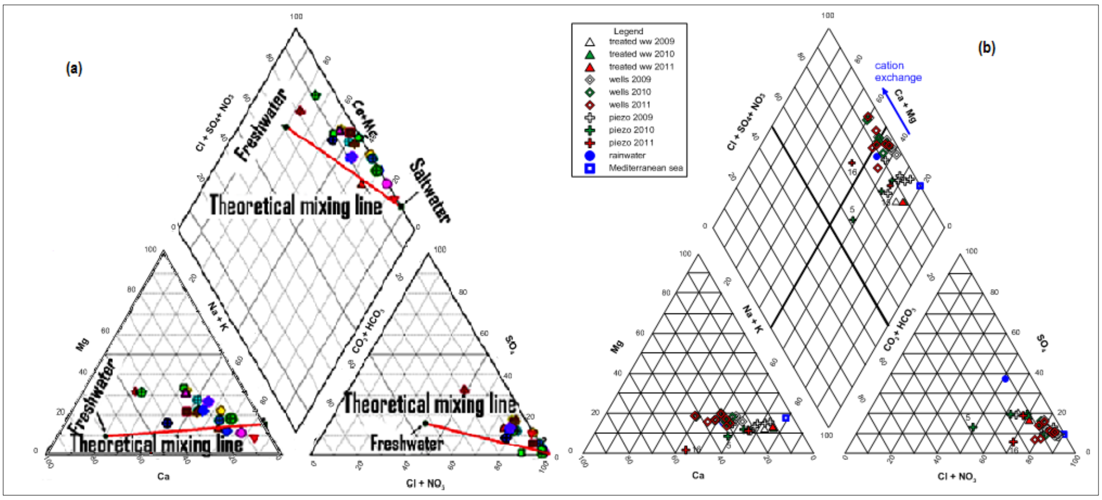

Figure 4 Water sampling analytical results plotted in the Piper Diagram (a) before recharge 2008, (b) after recharge 2009, 2010 and 2011

Generally speaking, the major element concentrations illustrate a strong variability of the water quality collected for this study in temporal and spatial terms. In wells, conductivity varied between 5,200 and 10,000 µS/cm. The highest conductivity was nonetheless recorded in piezometers 11 and 2 in 2009 (more than 12,000 µS/cm). Some samples had a notable low mineralization: (1) the 2010 Piez 5 sample (EC of 502 µS/cm); (2) the 2011 Piez 16 sample (EC of 1044 µS/cm). All pH were neutral, Piez 16 sample showing the most acid pH of the area (6.59). All major elements data are plotted in a Piper diagram representing the ion proportions (Figure 4b).

After four years of recharge with this treated wastewater, there is a displacement in the nitrate contaminated area. The low nitrate concentration spot in the central area of the study region has disappeared and show now a higher nitrate concentration whereas the south-western area show new spots of low nitrate levels. There is also a slight improvement of the quality regarding nitrate near the recharge site.

However the return flow from the inner irrigated coastal areas and/or chemical compounds of the fertilizers and pesticides used in agriculture are also not negligible factors playing roles in the increasing of salt concentration in groundwater (Kouzana *et al*., 2009). Also the impact of the artificial recharge in water quality is limited due to the treated wastewater quality, which still needs to be greatly improved before recharge to prevent the groundwater quality degradation. The dynamics of the studied system was evidenced by the spatial and temporal variability of chemical elements content, revealing the complexity of the groundwater contamination as a result of salinization and anthropogenic activities. The system is highly vulnerable and permanently disturbed by the different temporal dynamics of continuous processes such as cation exchange, and by threshold processes linked to oxido-reductive conditions which are enhanced by the intrusion of treated wastewaters.

Conclusions

Management of artificial recharge of groundwater has been an integrated management tool for increasing water resources in Tunisia, since the seventies (Gaaloul et al., 2012a).

This paper presents the results of the impact of an artificial recharge experiment in the region of Korba-Mida, which aimed at increasing aquifer recharge and controlling seawater intrusion.

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. In fact, the comparison of the quality of the groundwater before (2008) and after four years of recharge (2012), resulting from the mixing of groundwater and infiltrated treated wastewater, showed the effectiveness of the project to cure high salinity which exceeded 1.5 g/L. The site thus played the role of a hydraulic barrier to mitigate the problem of marine intrusion and to limit its geographical extension.

The impact of the artificial recharge is limited as a refresher when considering its brackish facies. Wastewater treatments need to be greatly improved before recharge to prevent degradation of groundwater quality. The dynamics of the studied system was pointed out by the spatial and temporal variability of element contents, revealing the complexity of the groundwater contamination by salinization and anthropogenic activities. The system is highly vulnerable and permanently disturbed by the different temporal dynamics of continuous processes such as cation exchange, and by threshold processes linked to oxido-reductive conditions which are enhanced by the intrusion of treated wastewaters.

Acknowledgements

The authors would like to thank H. Chaeib from DGRE, and M. Rekaya and F. Jellasi from the Regional Commissariat for Agricultural Development (CRDA) of Nabeul. The scientific work was carried out by the INRGREF-Tunis in cooperation with National Laboratory for Civil Engineering of Lisbon (LNEC, Portugal).

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