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The effectiveness of artificial recharge by treated wastewater in combating seawater intrusion – The case study of Korba-El Mida aquifer (Cape Bon, Tunisia)

Amira Mekni and Abderrazek Souissi

Water Science and Technology Laboratory,
National Agronomy Institute of Tunis,
University of Carthage, Tunisia

ABSTRACT: The Korba aquifer on the North-Eastern of Cape Bon (Tunisia) has suffered from an overexploitation since the 1960s. This overexploitation has caused a seawater intrusion and a degradation of groundwater quality. Therefore, as part of planning and development of water resources in Tunisia, artificial recharge by treated wastewater was installed in the north of Korba treatment plant since December 2008. The process could act as a barrier for seawater intrusion hydraulic barrier to combat saltwater intrusion and to maintain the quality of groundwater.

After 4 years, piezometric maps established from 18 piezometers and 25 observation wells measured showed a progressive increase in piezometric level locally between 2008 and 2012. The increase of piezometric level exceeds 1.5 m per year in some regions, especially around the recharge site. The salinity distribution in 2012 revealed a decrease in groundwater salinity around the recharge area and in the northwest. In addition, stability in a 1 km-wide band parallel to the sea through recharge site was showed. However, in the northwest of the recharge site, high salinity was observed and reaching 7.5 g/l in some wells. The spatial variability of groundwater quality illustrates the complexity of the aquifer contamination by salinization and anthropic activities.

KEYWORDS: Korba aquifer, seawater intrusion, artificial recharge, piezometric level, salinity, anthropic activities.

1 INTRODUCTION

Water stress is a major problem of countries concerned by water scarcity for multiple reasons. In fact, the water demands have increased during the last decades due to rapid urbanization, agricultural activities and the growth of the population. In an arid or semi-arid context, the intensive extraction groundwater from coastal aquifers reduced freshwater outflow to the sea and created local water aquifer depression, causing seawater intrusion [1]. A large proportion of the Mediterranean coastline was reported to be affected by seawater intrusion [2], [3], [4], [5]. In many parts of the country, groundwater development has already reached a critical stage. The coastal aquifer of the Cape Bon peninsula in the North East of Tunisia, is a typical case of groundwater depletion due to the large quantities of water abstracted by the agriculture and industrial sectors since the 1960s [6], [7], [8], [9]. Additionally, the use of various fertilizers has damaged qualitatively and quantitatively the groundwater resources [10]. Therefore, managed aquifer recharge using treated wastewater has the potential to provide new and low cost source of water, especially to prevent the seawater intrusion by creating freshwater barriers and reducing groundwater salinity in agricultural areas. This technique has shown positive and very encouraging results in many countries throughout the world. In Tunisia, it is part of the integrated management of water resources since the seventies [11].

In December 2008, a pilot site was established in the region of Korba to recharge the aquifer with treated wastewater from Korba treatment plant. The present article, aims to investigate the effect of artificial recharge on the groundwater quality during 4 years since its implementation. Water levels, salinity, Ph and Conductivity and are the principal parameters measured to characterize the spatial and temporal evolution of groundwater after recharge experiment.

2 SITE DESCRIPTION

2.1 GEOGRAPHIC, GEOLOGICAL AND HYDROGELOGIC CONTEXT

The Korba-El Mida aquifer is located in the North-Eastern Cape-Bon peninsula of Tunisia and administratively belongs to Nabeul governorate (Fig. 1a). The study area is the central part of the oriental coastal plain of the Cap Bon (average 470 Km²). The aquifer is delimited in the South by wadi Sidi Othmen, in the North by wadi Lebna, in the west by Jebel Abderrahmane and in the East by the Mediterranean Sea (Fig. 1b). The study area is characterized by a semi-arid Mediterranean climate with an average temperature of 19 °C; a relative humidity varies between 71 % and 81% and a mean evapotranspiration of 1100 mm. The rainfall is characterized by strong variability with an annual average precipitation of 420 mm/year [12]. The majority of rainfall comes between November and March, the period of highest groundwater levels.

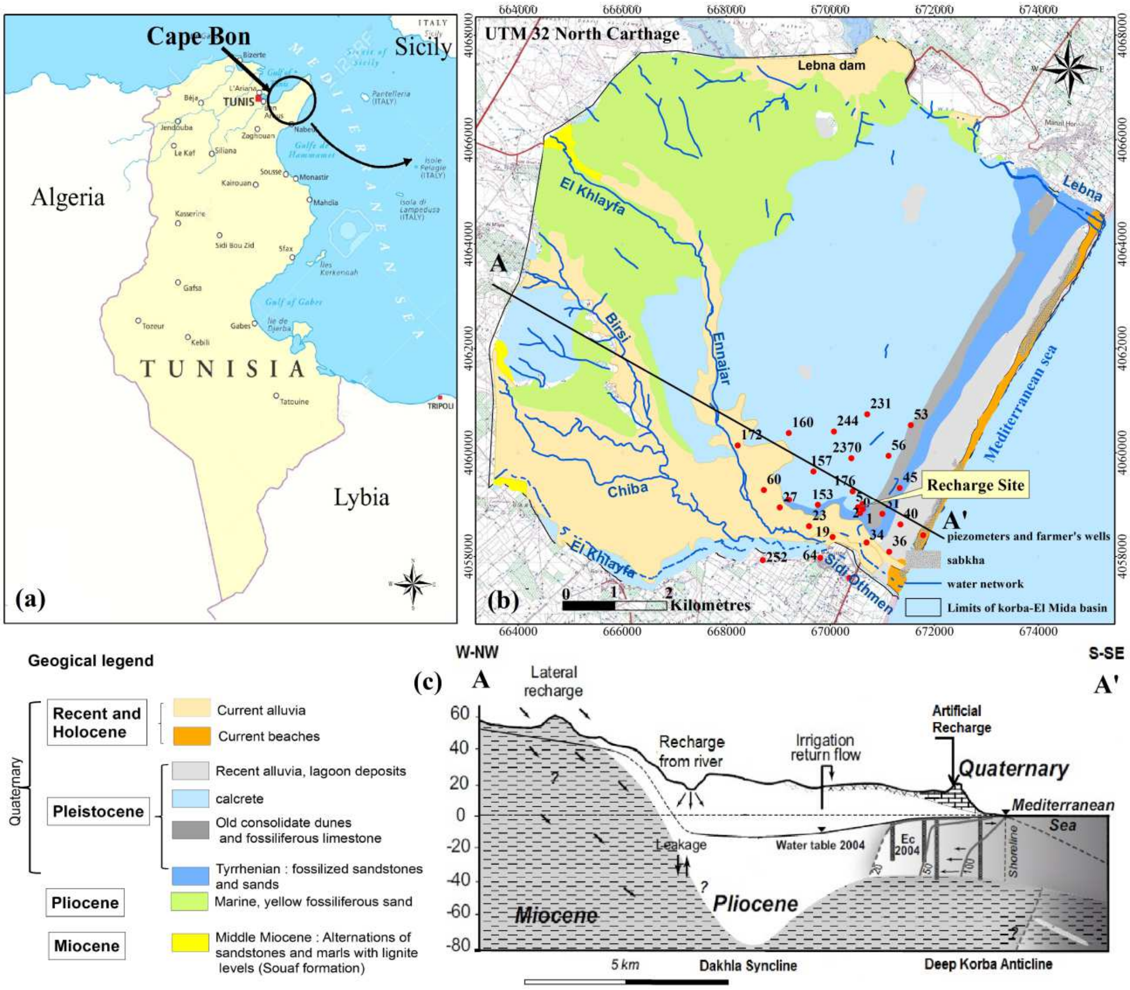

Fig. 1. (a) Location Map (b) Geological settings of Study Area with sampling points on control piezometers and farmers' wells (c) Simplified geological cross-section

The Korba-El Mida aquifer system is constituted by three main geological units: marine Quaternary, Pliocene and Middle Miocene ages (Fig 1b) such as described by [6] and [13]. The Middle Miocene relates to detrital deposits mainly from deltaic bodies known as the Belgia formation. The Pliocene deposited presents the main aquifer, was formed by marine deposit in the Dakhla synclinal north of Korba city [8]. Quaternary deposits are composed of two units: upper Pleistocene and Holocene deposits. These deposits forms nowadays coastal consolidated dunes built by wind following marine regression [14]. The old consolidated dunes cover the Tyrrhenian deposits [15]. The Tyrrhenian formations forming approximately a 1.2 km width band parallel to the coast all along the domain [8]. It is made of arenitic limestones overlying conglomeratic units [16] with a total thickness ranging between 10 to 50 m [17] . The encrusted limestone extends over significant distances. They are very rich in calcite, silica, sometimes in gypsum and alumina and frequently colored by iron salts. Finally, the late Holocene deposits are formed by recent alluvia of Oued Chiba, by sebkhas deposits and current dunes and beaches [1].

The aquifer can be divided in two hydrogeological units: the deeper Miocene and the Plio-Quaternary units. The Miocene marls of the Souaf formation constitute an impermeable substratum and contain a brackish water with a salinity of 3 to 4 g/L [11]. The Plio-Quaternary aquifer is constituted by two formations, the deeper Pliocene and the upper Quaternary. This aquifer is very productive, especially in Korba plain, with a transmissivity of 10^{-2} to 10^{-4} m^2/s and 60 m of average thickness. Piezometers and shallow wells typically intersect the two horizons. Its depth varies between 20 to 50 m.

Previous studies have contributed to the understanding of the coastal plain of the Cap Bon [6], [7]. The water table is: recharge by infiltration of precipitation estimated to be less than 10%. Additional recharge from wadis and topographic depressions is also expected [8]. Other sources of recharge are irrigation return flow and lateral recharge by leakage from the underlying Miocene sandstones [8]. The most important output of this aquifer is the groundwater abstraction for irrigation.

2.2 PRESSURE ON GROUNDWATER RESOURCES IN THE REGION

The Korba plain is an important agricultural region involving several irrigated areas, especially, it is the main producer of tomato and peppers in Tunisia (3000 ha cultivated area to each: 22% of the national production and 35% of the regional production [18]. Also, this region is characterized for being one of the first providers, in winter, of fresh vegetables (the first in Cap Bon regional production level) and fruits without forgetting strawberries production which is experiencing remarkable growth (8000 tons quantity produced: 85% of the national production).

The exploitation of the Korba aquifer began in the 60’s mainly for irrigation purposes, and reached 43 Mm^3/year in the 80’s. Since then, the exploitation rates oscillate around 50 Mm^3/year[8]. Indeed, the local water management authority identified more than 9000 active wells in a region covering around 400 km^2 [8]. Most of the wells located in very small farms are traditionally dug, shallow, and equipped with oil or electrical motor pumps. Besides, the study area is discussed in the north and south by industries, but with low density. Thus, their influence on the tablecloth is of less importance compared to other sources of pollution.

According to the qualitative analysis, groundwater depletion is on the one hand caused by limited recharge and on the other by the overexploitation (abstractions exceeding natural replenishment) of aquifers. Overexploitation can be attributed to illegal borehole drilling, mostly by farmers for irrigation purposes, and to the lack of control over the operation of private boreholes. In addition, the technical capacity of farmers in the region is very limited. Therefore, the adoption of water intensive cropping patterns and the restriction to apply water saving techniques exacerbates the problem. Furthermore, three types of fertilizers are used: organic, mineral and mixed. Their massive use in the Korba area has disturbed the local ecosystem and increased pest resistance, which results to, even more, extensive pesticide use [19].

3 MATERIAL AND METHODS

3.1 EVOLUTION OF KORBA GROUNDWATER DURING THE LAST FIFTY YEARS

Hydrodynamic and quality data have been collected through a network, set up since the sixties by the local groundwater management authority: Regional Office of Agriculture Development (CRDA Nabeul) and the General Direction of Water Resources (DGRE) at the Ministry of Agriculture, Water and Fisheries Resources.

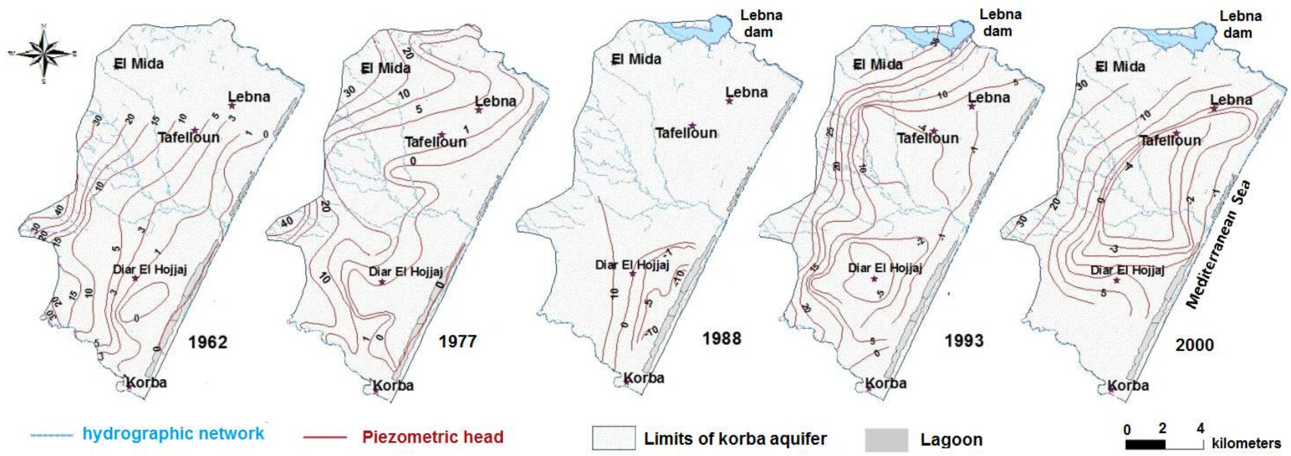

Fig. 2. Piezometric evolution of the Korba aquifer: 1962 and 1977 from Ennabli (1980); 1988 from Ochi (1988); 1993 from Rekaya (1993) and 2000 from CRDA Nabeul (2004) (Chiba and Lebna dams built respectively in 1963 and 1986)

Piezometric map in 1962 [6] shows a zero curve which appeared for the first time at Diar El Hajej (Figure 2). At this moment, water flow has a west-east direction with a positive hydraulic heads. After that, the construction of Chiba dam in 1963 caused a decrease of water table downstream and the progress of the zero curves in the continent to Tafelloun in 1970. In addition, the growth of groundwater abstraction during 80s and the irregularity of precipitation caused a negative pezometric level (10 m below sea) near the sea in 1988 at Diar El Hojaj. Years later, two critical depressions (5 m below sea) are appeared in 1993 at Diar El Hojaj and Tafelloun regions. This means that, the hydraulic gradients were reversed mainly toward the central part of the aquifer leading to an acceleration of the seawater intrusion. Consequently, hundreds of wells were salinized and then abandoned in spite of the action of the authorities. This situation is ameliorated in 2000 at Diar El Hojaj and Tafellou regions. Indeed, the artificial recharge of aquifer from dams or the Mejerda Cape Bon canal by direct infiltration of surface water started in 1999 but never exceeded 1 Mm^3/year [20] and the stabilization of the exploitation are the origins of this positive effect. As opposed to that, the migration of pumping to northward caused another critical depression in the Lebna and Chott Zouhour regions about 2 m below sea level from 2004 to 2008.

Obviously, the salinity distribution from several studies [21], [22], [23], [24] is correlated with the piezometric evolution. Indeed, the salinity was average 2 g/l in 1962 at Diar El Hojaj and reached 7 g/l in 1996 (Figure 3)**.**

The Korba aquifer has undergone overexploitation since the 60's, leading to the reversal of hydraulic gradient and saline intrusion. The water quality of groundwater is often degraded by different processes: salt water intrusion, diffuse pollution, intensive agricultural activities in semi-arid or arid contexts and anthropic activities.

Multidisciplinary approaches have been used to study the sea water intrusion. The most recent studies combined geophysical and chemical tracers [1], [25], [26].

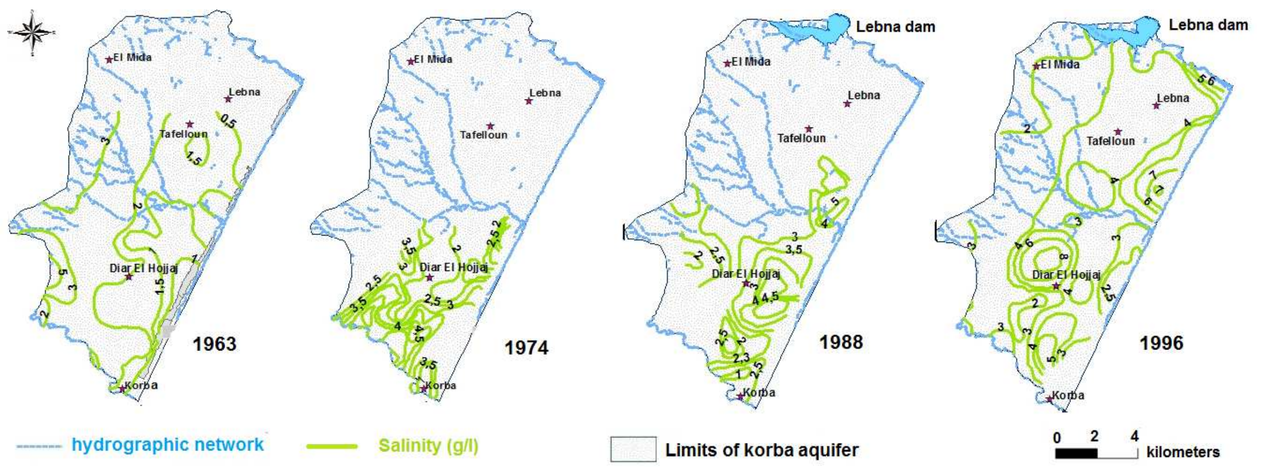

Fig. 3. Salinity evolution of the Korba aquifer: 1963 from Daniel and Chabot (1963); 1974 and 1988 from Ochi (1988); 1996 from Jemaii (1998), (Chiba and Lebna dams built respectively in 1963 and 1986)

The authors quantified the invasion of seawater inland, reaching 1.5 km south of wadi Chiba 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) lay in the Northern coastal aquifer but the most concentrated (22 g/L) was in the North of Korba. Salinity was more pronounced along the coast, resulting in a high number of abandoned shallow wells.

3.2 MANAGED AQUIFER USING THE ARTIFICIAL RECHARGE

Reuse of wastewater combined with artificial recharge offers alternate solutions in many countries in the frame of integrated water resources management to increase the sustainable yield of the aquifer. Indeed, if the aquifer is unconfined and surface soils are permeable, artificial recharge can be achieved via infiltration facilities on the surface. Percolation through the unsaturated zone can filter and disinfect wastewater and adsorb contaminants [27]. In 2008, Tunisian water management authorities (General Direction of Water Resources) has established integrated water resources planning based on a managed an artificial recharge site by treated wastewater in order to provide a hydraulic barrier against seawater intrusion.

The korba-El Mida artificial recharge site is located about 300 m north of the Korba treatment plant, distant to 1.5 Km from the coast and lies 15 m/NGT above sea level (Figure 4). Two infiltration basins on 3 functioned simultaneously and were fed by average 1500 m^3/day. The treatment plant received both urban and industrial wastewaters coming from around 50 factories mainly of tomatoes or fish transformation, slaughterhouses, steel and tissue washing. The treatment process consists of pre-treatment, secondary then tertiary treatments performed with maturation ponds. This process allows the reduction of the organic content without artificial ventilation or mixing [28]. The treated wastewater is infiltrated through ponds and undergoes soil aquifer treatment to improve its quality.

Fig. 4. Satellite image obtained from Google Earth showing the treatment plant and the recharge site, Picture during the filling of infiltration basins with TWW in recharge site and one of control piezometer

3.3 MONITORING OF RECHARGE STRUCTURES

Basic water quality parameters such as specific conductance can be measured in the recharge basin and in water derived from the wells to estimate the percentage of artificially recharged water that is being recovered [29].

Since the start of recharge (December 2008), measurements in situ of pH, electrical conductivity, temperature and piezometer levels were measured with the team of the General Direction of Water Resources. Groundwater was sampled from 18 piezometric and 25 observation wells. The average sampling depth was 15 m.

The treated wastewater is characterized by a slightly alkaline Ph, conductivity varied between 5.2 and 9.8 mS/cm. A significant concentrations of Cl (33, 68 and 78 mmol/L, respectively) and Na (34, 70, 75 mmol/l, respectively) were measured during 3 years (2009, 2010, 2011) by Cary et al [30] . The wastewater had high concentrations of Ca (3.7–5.7 mmol/l), K (1–1.6 mmol/l), SO4 (5.2–9 mmol/l). The major elements showed no notable differences with those determined by El Ayni in 2008 [28]. A yearly evolution can be expected depending on the different water uses and also on climatic variations

4 RESULTS AND DISCUSSION

4.1 PIEZOMETRIC EVOLUTION OF KORBA-EL MIDA AQUIFER AFTER ARTIFICIAL RECHARGE

To study piezometric evolution of korba aquifer after the artificial recharge, piezometric maps generated by kriging interpolation method using GIS of piezometers and wells observations data were drawn during the rainy season. In fact, groundwater abstraction during the dry season represents an inconvenience to draw piezometric maps [31].

Fig. 5 displays the evolution of piezometric level in the Korba-El Mida aquifer from 2009 to 2012 at the rainy season. This map shows a multidirectional flow. A visual comparison shows three general piezometric behavior types:

(1) An increase in piezometric level was registered in the majority of piezometers located in the recharge site and wells near the site especially in NW site. The water level at the site registered in 2008 before the recharge was 2 m bellow sea attaint an average 2 m at the end of rainy season on 2012 that means 1m/year. The maximum of increase during these four years registered in 23 well was 0.6 m/year. The higher elevations of the aquifer around recharge site, the flow direction and how they diverge radially are explained by the recharge effect.

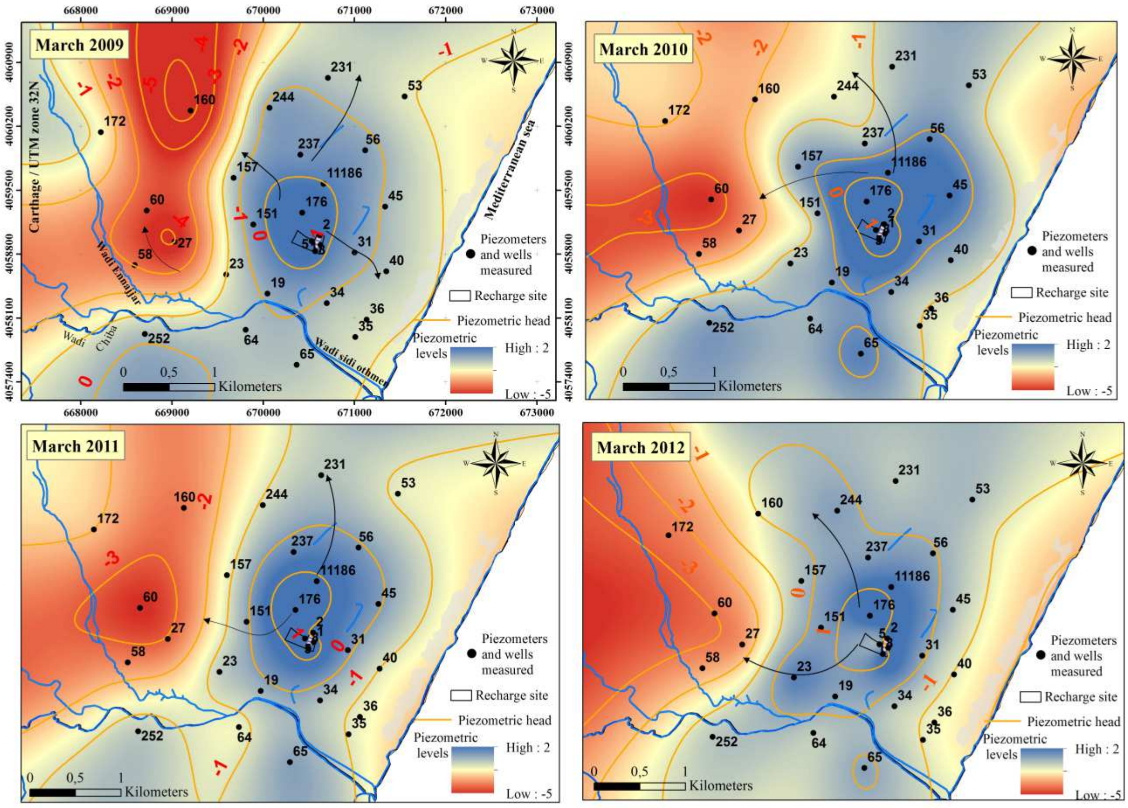

Fig. 5. Evolution of the piezometric level after artificial recharge in Korba-El Mida aquifer during rainy season (2009-2012)

(2) Piezometric level, continue to decrease in two zones. The first one, is in the northwest of the recharge site (after the zero contourline, Fig 5) revealed by translation of the piezometric depression with values which reached - 7 m in the northwest direction. It is due to excessive groundwater abstraction from wells. The second one is the band near the sea of extent 1 km parallel to the coastline, exactly how the piezometric level at 40 well passed from -0.3 m below sea in March 2009 to reach -1.15 m below sea in 2012. Although, during the survey effected, the owner of this one confirmed practically that he didn't use this well more than five years (not exceed 10 l/day). The piezometric decrease in this zone can be explained by the presence of geological barrier (Tyrrhenian, Quaternary) that is in parallel to the coastline. It is formed by sandstone

(3) Near the recharge site and by its northwest, a stable piezometric level was showed in parallel to the coast during this period (2009-2012). The zero contourline were translated in the direction of the piezometric depression from the recharge site to the northwest and a decrease of hydraulic gradient was presented. All this argument pronounces the existence of an

hydraulic barrier that can resist against the intrusion of seawater and stop the marine intrusion subsequently. The interaction between aquifer and river is inexistent.

Table 1. Annual Rainfall and treated wastewater volume

	Rainfall (mm)	Treated wastewater (m^3)
2008/2009	460,6	235 717
2009/2010	349,9	374 774
2010/2011	420,2	367 462
2011/2012	508,5	330 858
2012/2013	484,6	314 575

4.2 GROUNDWATER QUALITY ON OF KORBA-EL MIDA AQUIFER AFTER ARTIFICIAL RECHARGE

Apparently, the salinity distribution in the Korba-El Mida aquifer after the artificial recharge is correlated with the piezometric head evolution. The pH measured is around 7.00, the majority of samples are alkaline. The high groundwater salinity observed before the recharge in the study area varies between 4 g/L and 12 g/l [24]. The salinity maps in highest groundwater levels during 2009-2012 showed a general decrease varying from 1 g/L to 3 g/L surrounding the recharge site except some areas, especially in the northwest.

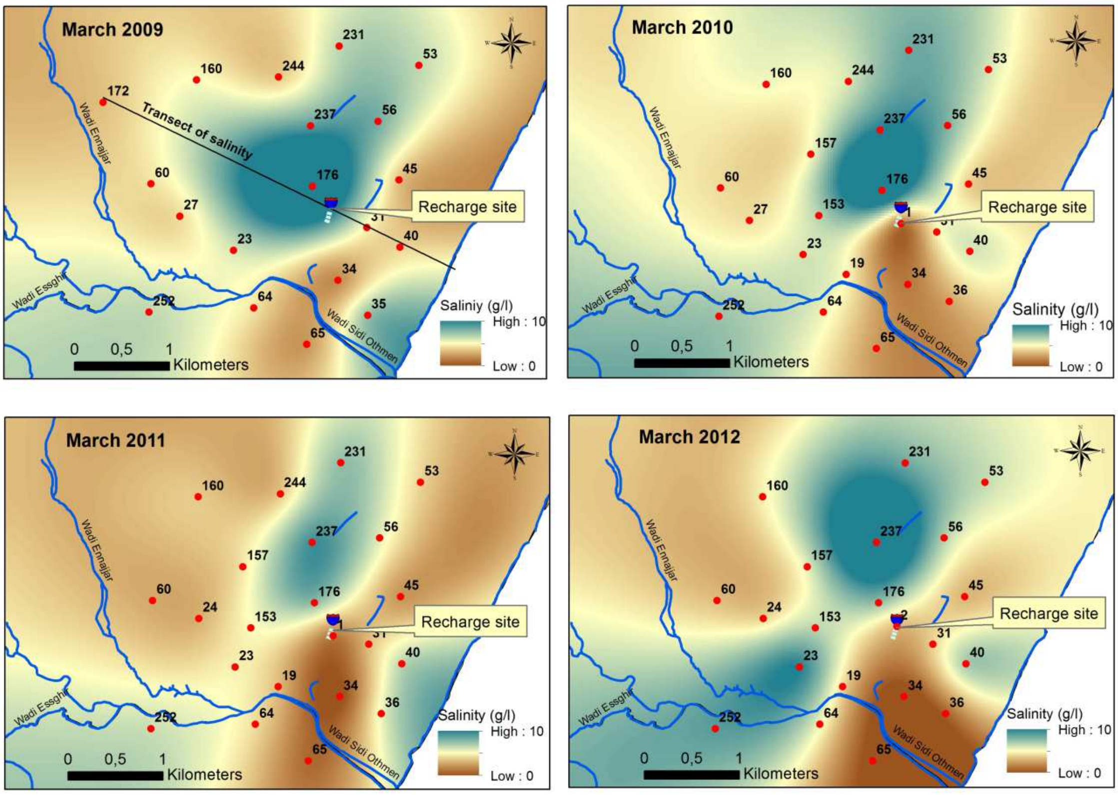

Fig. 6. Evolution of Salinity distribution after artificial recharge in Korba-El Mida aquifer during rainy season (2009-2012)

Opposed of the flow direction, the salinity values decreased from west to east direction. In March 2009, the high values of salinity were observed in the recharge site and on the wells in proximity to the northwest area. One year after, in March 2010 the contaminated area was smaller than the situation in March 2009 and starts to translate to the northwest direction. The salinity distribution maps in March 2011 and 2012 showed amelioration and stability again in a 1 km wide band in parallel to the coastline and through the recharge site. This confirmed the appearance of a hydraulic barrier concludes from piezometric maps.

In order to more clearly delineate this evolution, transect of 4 km perpendicular to the coastline and through the recharge site was traced to carry out the field measurements. These profiles confirmed the three behavior categories of salinity behavior:

(1) First zone: 1.5 Km from the recharge site to the Northwest direction which continues an insignificant increase in salinity between the situation before and after charging, mainly due to the irrigation water return from farms surround the recharge site. In fact, the farmers in this region do not have access to freshwater; they have no other choice than use this salty and polluted groundwater to irrigate their crops particularly in summer dry season when no rainfall occurs [28].

(2) Second zone: about 2 km-wide band via the recharge site and parallel to the coastline, high salinity show in piezometers in recharge site were passed during March 2009, March 2010, March 2011 and March 2012 respectively 11.2 g/l, 8.4 g/l, 6.7 g/l and 5.4 g/l explained essentially by the direct effect of recharge.

(3) Third zone: from the recharge site to the coastline direction, inversely to the situation in the second zone, groundwater qualities continue to deteriorate deduced by the continual increase of salinity due to marine intrusion. The majority of wells (80%) located in this band: 1 Km parallel of the sea, are abandoned the irrigation from wells during the last five years according to the investigation realized with farms on 2010. The groundwater uses in this region doesn't exceed 8 l/day, but the salinity of groundwater was continuing to increase.

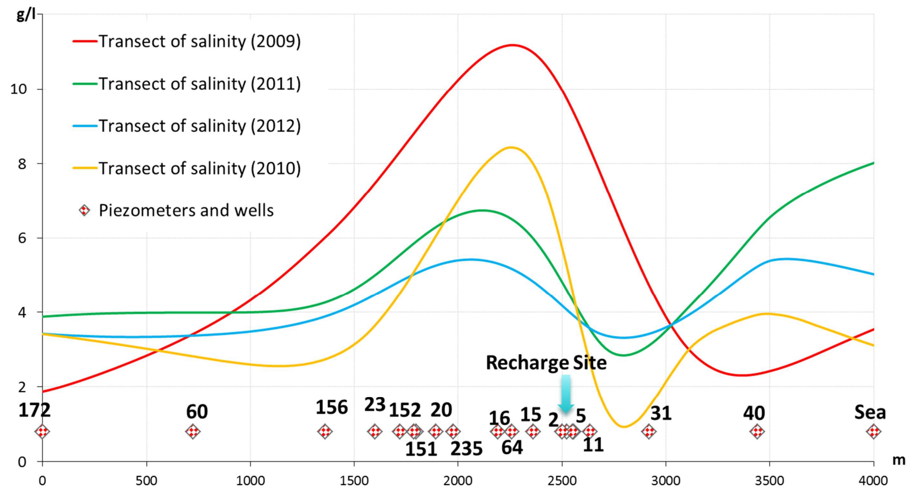

Fig. 7. Transect of salinity in Korba-El Mida aquifer during rainy season (2009-2012)

Further, recent works complete this study by adding additional approach: chemical tracers [32], Bornes isotopes [33] and confirmed these results. The mixing of treated wastewater was estimated at a maximum of 30 % with groundwater and seemed very local. According to fluxes directions, artificial recharge could clearly not influence some wells composition. The impact of artificial recharge seemed thus very limited in terms of quality: recharge waters were salted and poorly contribute to refresh the system [33]. Ultimately, the degradation of irrigated soils and crops diversity, currently limited by salt tolerance, will not improve. Moreover, B isotopes showed that artificial recharge seemed to influence some piezometers at vicinity but had low impact, if any, on close farmers' wells [30].

Based on the previous findings, an improvement of the treatment efficiency as well as the implementation of a regular monitoring approach of TWW before the recharge is crucial to avoid adverse health effects and to guarantee the safety of groundwater quality [34].

4.3 Suitability of Artificial Recharge at the Recharge Site

In September 2011, two data loggers were installed in the piezometer N°1 (distant 15 m of recharge basins) and N°6 (150 m of recharge basins) in the recharge site to record six instantaneous parameters such as water level and salinity.

The pump station was stopped due to a problem during 45 days from 16/11/2011 to 31/12/2011. During this period, the injection of wastewater in recharge basins was deactivated.

Piezometric fluctuations and salinity during this period are illustrated in figure 8. Water levels fluctuate between -16.1 m and -16.05 m before stopping the injection of treated wastewater. A remarkable decrease in piezometric level was recorded after 8 days in PZ1 and was registered about 0.15 m during 45 days.

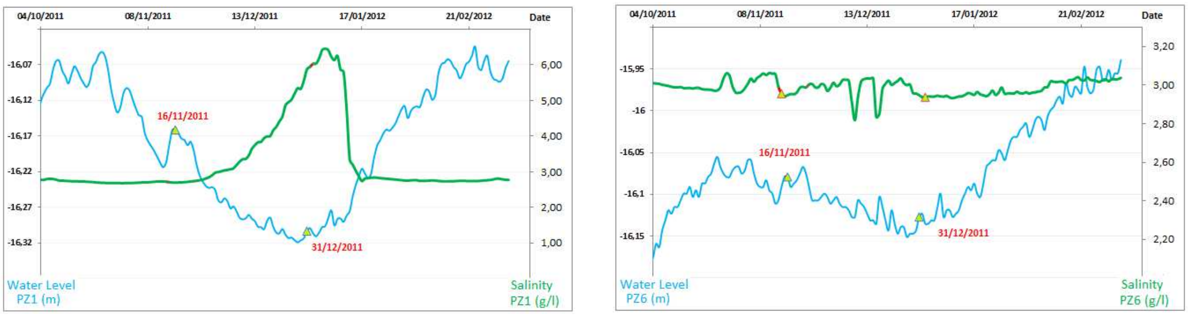

Fig. 8. Piezometric level and Salinity Evolution at PZ1 and PZ6

As compared to PZ1, changes were less important in PZ6, a little decrease in piezometric level of 0.05 m that means 1.1 mm/day was exposed. Water levels in PZ1 return to his normal level after activating the recharge but in PZ6 water level continue to increase. This piezometric increase showed in PZ 6 was mainly caused by the natural recharge with meteoric water. In this way, natural recharge has more importance than artificial recharge in PZ 6 (150 m to recharge basin), is opposed to PZ1 (near recharge basin) influenced directly by wastewater recharge of the aquifer. This means that, vertical recharge is more significant than lateral one.

Opposing to water level variation, the salinity started to increase since 26/11/2011, just after 10 days of the inactive injection of wastewater and was passed from 2.78 g/l to 6.42 g/l after 40 days in piezometer PZ1, whereas salinity fluctuation in PZ6 doesn't revealed a considerable variation.

5 CONCLUSION

The monitoring of water quality evolution of the Korba aquifer during 4 years of recharging operations using infiltration basins showed the effectiveness of the project. In fact, the piezometric study showed a notable increase of piezometric level and was exceeding 1 m in some area surrounding the recharge site, undoubtedly, due to the effect of recharge by wastewater. At the northwest of recharge site, existing depression before the recharge is spatially and temporally translated gradually to the northwest of the continent. Additionally, in terms of quality, salinity at the recharge site mostly decreases from 10 g/l in 2004 to 2-3 g/l in 2012 near recharge site. The site also played the role of a hydraulic barrier to mitigate the problem of marine intrusion and to limit its geographical expansion. But, this impact is limited and less pronounced beyond the site due to the relatively low volume of recharge or the heavy exploitation.

Aquifer recharge is still at the experimental stage, and results are encouraging. But, the system is highly vulnerable by the different process such as the excessive abstraction from wells in the northwest of recharge site and the seawater intrusion in the southwest. A better knowledge of the aquifer hydrogeology and hydrodynamics, coupled to a detailed geological-hydrogeological model is in progress to better foresee this qualitative and quantitative evolution.

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