Global NEST Journal, Vol. 7, No 2, pp 197-203, 2005

MODELING THE SALTWATER INTRUSION PHENOMENON IN COASTAL AQUIFERS - A CASE STUDY IN THE INDUSTRIAL ZONE OF HERAKLEIO IN CRETE

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Selected from papers presented in 9th *International Conference on Environmental Science and Technology (9CEST2005)*
1-3 September 2005, Rhodes island, Greece

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ABSTRACT

Salinity is a common problem in Greek islands, especially, during the summer period when the saltwater intrusion becomes more severe due to extensive over pumping. In the past few years, the industrial zone of the City of Herakleio in Crete appears to have an increasing water demand as result of the continuous industrial development. The water demand is mainly cover from groundwater resources. The karstic nature of the geological formations beneath the industrial zone has a great impact in the overall hydro-geological characterization of the aquifer. Also the expansion of the saltwater front into the aquifer is hard to be determined due to the presence of innumerable cracks, which act as closed conduits of saltwater and the density variation between the saltwater and the fresh water.

The main objectives of this study were to map the geology and the salinity zone in the area based on geophysical measurements. The industrial zone lies on a karstified limestone with several faults that need to be delineated. Mapping of the area revealed also specific places that were recommended for observation wells. In the future, these wells are planned to be used as injection wells for the restoration of the aquifer. Another objective of this study was to propose different management scenarios to inhibit the saltwater intrusion front further inland. In this paper, scenarios that suggest artificial recharge of fresh water are presented in order to raise the groundwater level and to create a groundwater flow towards the sea.

KEYWORDS: Saltwater intrusion phenomenon, water quality, groundwater simulation model, geophysical measurements, artificial recharge.

INTRODUCTION

In early 1900, Ghyben [1] and Herzberg [2] were the firsts that examined the nature of the saltwater-freshwater interface in coastal aquifers under natural conditions. In the sharp interface approach, saltwater and freshwater are treated as two immiscible fluids Assuming hydrostatic conditions, the weight of a unit column of fresh water (h_f) (extending from the water table to the interface) was balanced by a unit column of saltwater (ξ) (from the sea level to the interface) they were able to calculate the interface between the fresh and the salt water as follows [3] (Figure 1):

$$\xi = \frac{\rho_f}{\rho_s - \rho_f} h_f \approx 40 h_f \qquad (1)$$

where,

- ξ: the interface located below the sea level (m),
- h_f: the hydraulic head of the fresh water above the sea level (m),
- ρ_f : the density of fresh water (gr cm^{-3}),
- ρ_s: the density of the saltwater water (gr cm^{-3}).

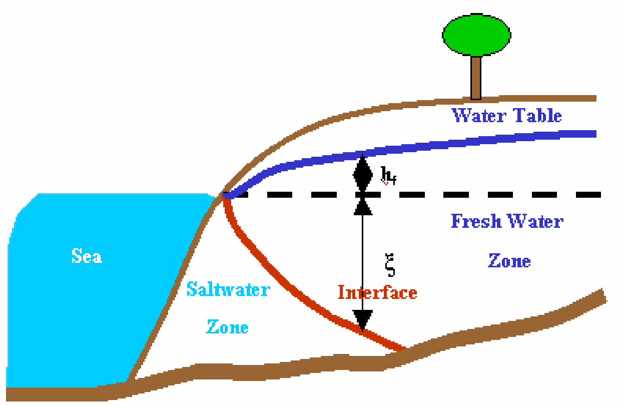

Figure 1. Saltwater - Freshwater sharp interface

Herny [4], Pinder and Cooper [5] were among the firsts that tried to model the density-dependent miscible saltwater-freshwater systems. According to this approach, the mixing zone between saltwater and freshwater is significant due to the diffusion phenomenon that occurs between the two miscible fluids with different densities (Figure 2).

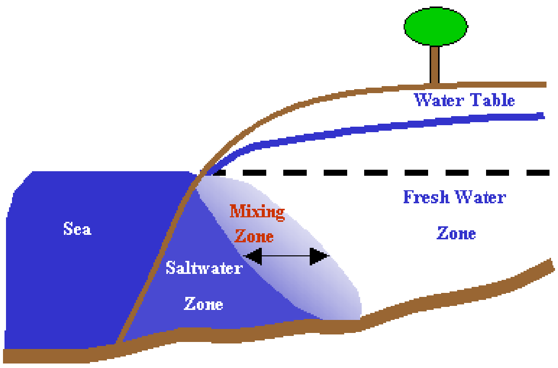

Figure 2. Density-dependent miscible saltwater-freshwater system

DESCRIPTION OF THE STUDY AREA

The area of interest is the industrial zone of the city of Herakleio in Crete. The industrial zone is located on a coastal aquifer where the saltwater intrusion phenomenon appears to be the major contamination problem and immediate action should be taken in order to control the problem. The north boundary of the site is the coastline while the area is extended about 4500m to the south. Geophysical measurements were taken in the industrial zone in order to characterize the geology of the area. The main geologic formations present in the area of interest are primarly marly limestones, neogenic marl formations, karstified limestone of Tripolis zone and alluvial deposits (Figure 3). Data obtained from existing wells located in the industrial zone confirm that saltwater has intruded into the aquifer beneath the industrial zone.

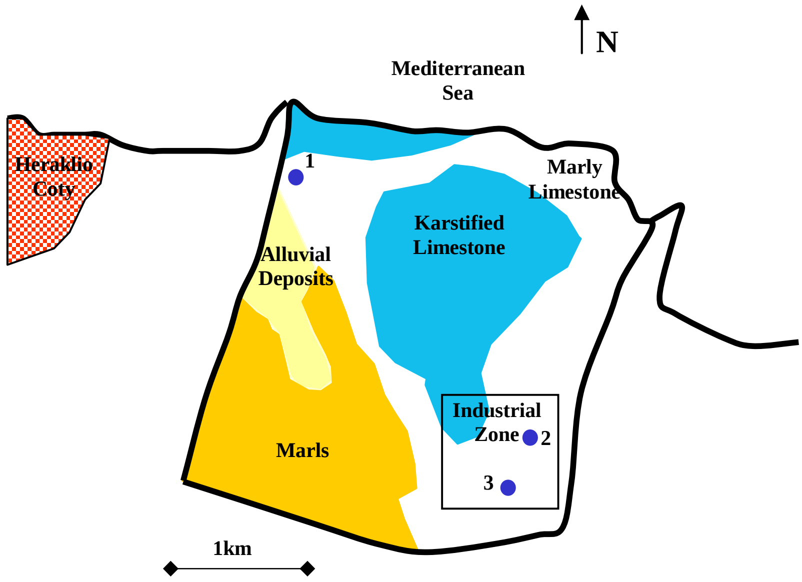

Figure 3. Geological map and domain outline of the study area

The geological and hydrogeological characterization of the aquifer was obtained from the analysis of geophysical tomographies that were performed in the industrial zone. With the use of geophysical methods such as geolectrical tomographies, hydrogeologists and engineers are able to infer conclusions related to the geological structure of an aquifer, the degree of water saturation and the quality of groundwater. The tomographies measured electrical resistivity with a penetration depth between 100m to 130m. The major conclusions drawn from the three geo-electrical tomographies performed in the area of interest are summarized as follows:

- Reduced values of electrical resistivity are observed at areas where geological faults are present.
- Significant reduction in electrical resistivity values is also obsreved at depth close to the mean sea level that is explained as saltwater intrusion into the aquifer.
- The increased values of electical resistivity observed along the tomography represent more consolidated limestones.
- A lateral change in the electrical resistivity values between 100Ωm-700Ωm reveals area of marly limestone.
- High values of electrical resistivity (>1300Ωm) are observed at area where karstified limestones occur.

The above conclusions are coming in accordance with information and data obtained from geological maps and observation wells. A representative geo-electrical tomography from the area of study is shown in Figure 4.

MODELING OF THE SALINITY ZONE

For the purposes of this paper, a 3-D finite element-finite difference groundwater flow simulation model based on the Princeton Transport Code (PTC) [6] and ArgusOne Interface [7] was developed. The extension of the saltwater front along the coastal zone is calculated only hydraulically because the present model does not consider diffusion due to different density values between salt and fresh water

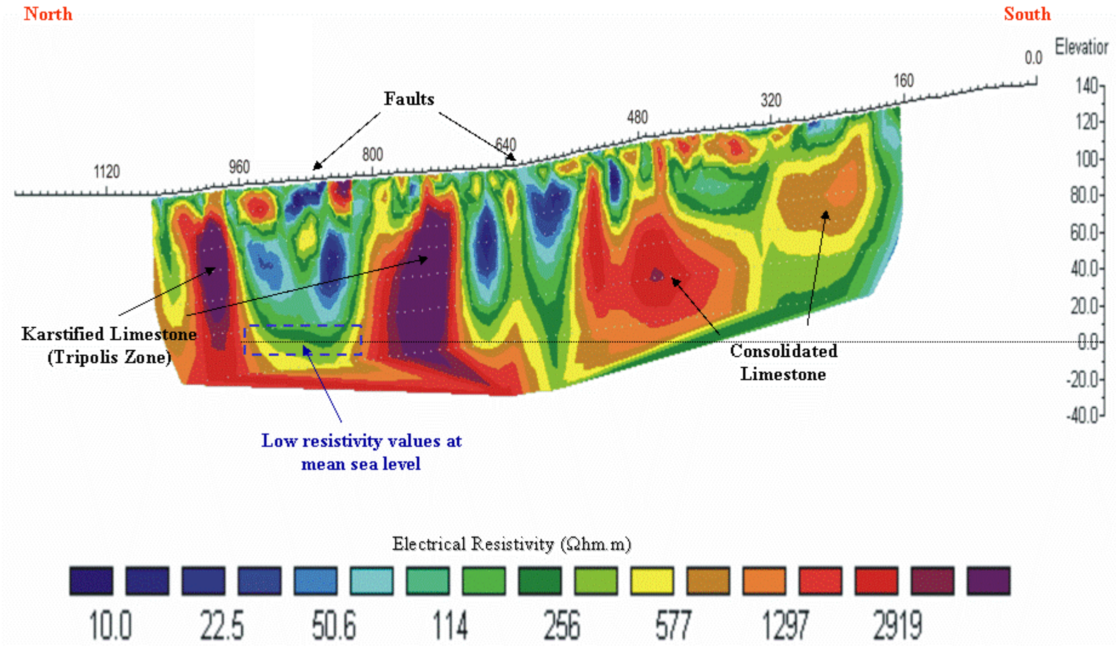

Figure 4. Representative geo-electrical tomography

The field site is characterized as an unconfined aquifer, with a total thickness of 30m along the coastline that goes up to 110m in the mainland. The aquifer is composed of two layers where the bottom layer is 25m thick and contains primarly marly and Tripolis limestones. The thickness of the top layer varies from 5m thick at the coastline up to 110m in the mainland containing also alluvial deposits at locations close to the sea, marly and Tripolis limestone. A two-layer vertical discretization was chosen in order to accurately represent the variation of hydraulic conductivity [8]. The area of interest has been discretized into 1042 nodes and 1961 triangular elements.

During the calibration of the simulation model no-pumping rates were considered since no pumping takes place at the present time. Based on field measurements at the existing well locations, low values of hydraulic heads are expected at the coastline and at the area where well 2 is located (Figure 5). On the contrary, evidence from well 3 (Figure 5) verifies high hydraulic heads at the south boundary of the area indicating that the main penetration of saltwater takes place through the east boundary of the area, which coincides with a fault that ends up at the sea. The high hydraulic heads in the south are attributed to a flow of fresh water coming from the outside of the modeled area. If the geological fault along the east boundary of the modeled area is not considered in the analysis the hydraulic head field is completely different. The saltwater intrusion front was estimated between 800m from the coastal line and up to 2000m in areas where alluvial deposits and perpendicular to the coastal line geological faults are present (Figure 5).

PROPOSED MANAGEMENT SCENARIOS

The location of the sharp interface changes over time depending on the distribution of the hydrostatic pressures of the system, which results to a water movement that in some cases is towards the sea and in some others towards the inland. It is obvious that there is not movement of the interface if the aquifer system is in equilibrium. Pumping affects this equilibrium especially in the case where the pumping wells are located in the mixing zone. Under normal conditions the direction of the groundwater flow is towards the sea. Overpumping is the main reason of the inversion of the groundwater flow from the sea towards the inland that results to the saltwater intrusion into the aquifers.

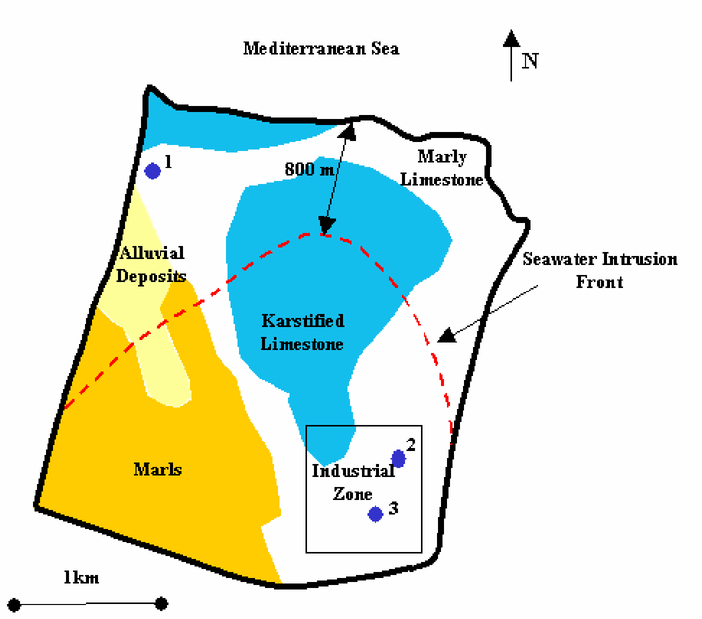

Figure 5. Simulated saltwater intrusion front

The artificial recharge of fresh water into the aquifer was selected in the proposed management scenarios. The objective is to raise the groundwater level and maintain this by a continuous injection such that a hydraulic gradient towards the sea will be created that will insure a groundwater flow towards the sea. Using a groundwater simulator the salinity zone is determined and alternative recharge scenarios were examined. Representative scenarios of recharge were presented in this paper using different injection well locations and different injection rates. In all the proposed scenarios the injected water will be received from the effluent of the Waste Water Treatment Plant of the Industrial zone after tertiary treatment.

Scenario 1

In the first scenario (Scenario 1), two injection wells, with injection rate of $40m^3\ h^{-1}$ each, were placed in the region between the industrial zone and the coastline. The management period was selected to be 3 years. The response of the physical system for this scenario is shown in Figure 6. The resulting hydraulic head distribution shows that over the three-year period of injection the saltwater intrusion front remains away from the industrial zone during the winter period but not during the summer period.

Scenario 2

The first scenario was not adequate to protect the groundwater quality beneath the industrial zone during the summer season. For this reason, a second scenario with more injection wells along the coastal zone was proposed in order to minimize the saltwater water intrusion. The proposed scenario required the activation of 4 injection wells, at $40m^3\ h^{-1}$ injection rate at each well (Figure 7). The physical system appears to have similar performance as in the first scenario. During the summer season the injection of fresh water at locations along the coastal line was not able to inhibit the saltwater intrusion front outside the industrial zone.

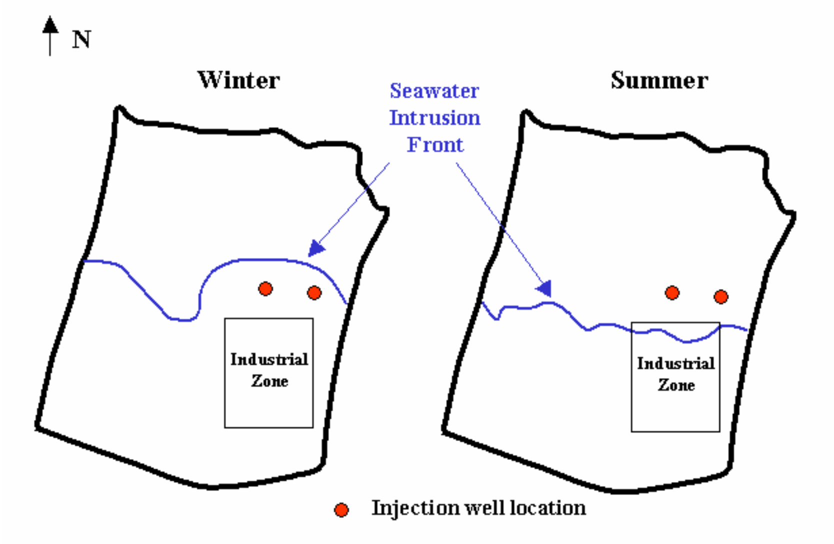

Figure 6. Recharge Scenario 1: Two injection wells with injection rate of 40m^3 h^{-1} each

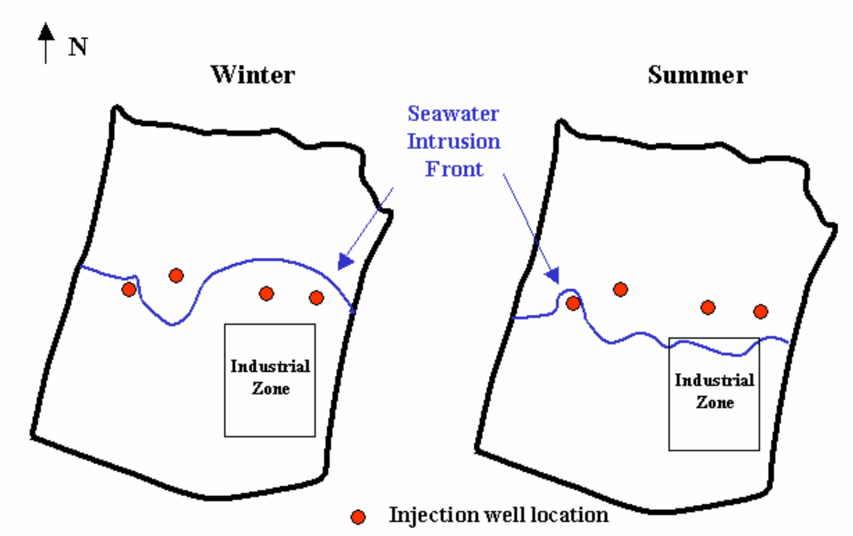

Figure 7. Recharge Scenario 2: Four injection wells with injection rate of 40m^3 h^{-1} each

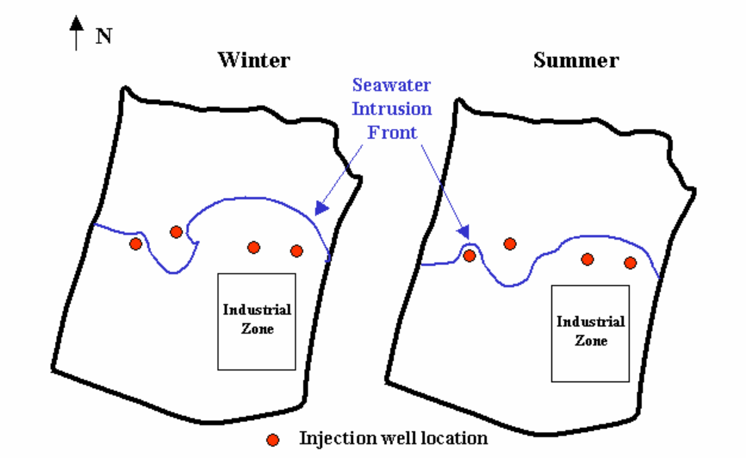

Figure 8. Recharge Scenario 3: Four injection wells with injection rate of 80m^3 h^{-1} each

Scenario 3

In the third scenario, an increase of the injection rate from $40m^3/h$ to $80m^3/h$ for each injection well was applied (Figure 8). The performance of the third scenario is adequate since with the implementation of this injection strategy the saltwater intrusion front was inhibited from the industrial zone keeping the groundwater supplies there in satisfactory levels during the entire calendar year.

CONCLUSIONS

The saltwater intrusion front in coastal aquifers is very hard to be estimated especially in areas with complex hydrogeology as the one of the field site presented in the paper. For these reasons, in-situ geophysical measurements were obtained in order to identify the geology of the aquifer and the impact of the faults in the groundwater flow. Saltwater intrusion appears to take place along the coastline and the east fault of the area, which coincides with the east border of the model. The interface between the fresh and the saltwater is about 1000-2000m away from the coast, revealing a quite big salinity area. The presence of the fault along the east boundary of the modeled area, perpendicular to the coastal line, operates as a closed conduit and results to a main entrance of saltwater into the aquifer. However, the seawater front is not spreading towards the south due to fresh water that flows from the opposite direction. The fault that is mapped from the geophysical measurements seems to take in this fresh water and prevent it from moving north.

The saltwater intrusion problem is a long-term phenomenon that requires long-term remediation. The third management scenario, among the ones that were presented in this paper, was very promising since the obtained results for a three-year remediation period have shown significant improvement of the saltwater intrusion front.

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