# Groundwater Resource/Modelling Saline Water Intrusion Into Coastal Aquifers

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## Summary

In coastal regions, where groundwater is the principal source of fresh water, the problem of over-abstraction can lead to particular problems – where the groundwater level effectively falls below that of the sea level leads to the potential intrusion of saline water into the aquifer, resulting in abstracted water being contaminated by salt water and therefore unfit for human consumption.

The physical processes of fluid flow and dispersion which occurs in such aquifers is complex and subject to the relative geological strata in which the flows occur, the relative densities of the fresh and saline water, the rate of rainfall recharge back into the aquifer and the extent to which continuous abstraction occurs. The problem is indeed complex and unique to each aquifer system.

In order to develop and understand the impact of strategies for the sustainable exploitation of available water resources near coastal areas, a means of predicting the response of the aquifer to the different demands placed on it is needed. Good management requires the ability to forecast the aquifer's response to planned abstraction operations.

The most obvious approach is to develop a computer based simulation tool which attempt to encapsulate the fundamental equations which govern the flow of water in the aquifer.

This paper summaries the development and application of new computer model to Tripoli coastal aquifer. The long-term simulation results indicate that excessive discharge can trigger a contamination problem in the aquifer. It is clear from the model that once an aquifer is contaminated it would be very difficult to recover.

Simulations with the change in the mean annual rainfall by $\pm$ 20% as impacts of climate change have indicated that the decrease of the mean annual rainfall will negatively affect the drawdown of aquifer water level while the increase in the mean annual rainfall will slow the drawdown marginally and help to speed up the aquifer recovery.

## Introduction

As with most aquifers, coastal aquifers such as the Tripoli aquifer are recharged primarily by precipitation. Under natural conditions, aquifer recharge is in equilibrium with groundwater discharge. Consequently, the interface/or the zone of diffusion maintains a position of relative stability, moving slightly landward or seaward in response to varying climatic conditions. When groundwater is pumped from coastal aquifers, freshwater that would normally discharge to the sea is intercepted, disturbing the natural equilibrium. This causes the interface/the zone of diffusion to migrate landward and/or locally upward.

Groundwater drawn into pumping wells can become increasingly saline. Over time, the water can become unfit for consumption. This is especially true for wells located near to the shoreline.

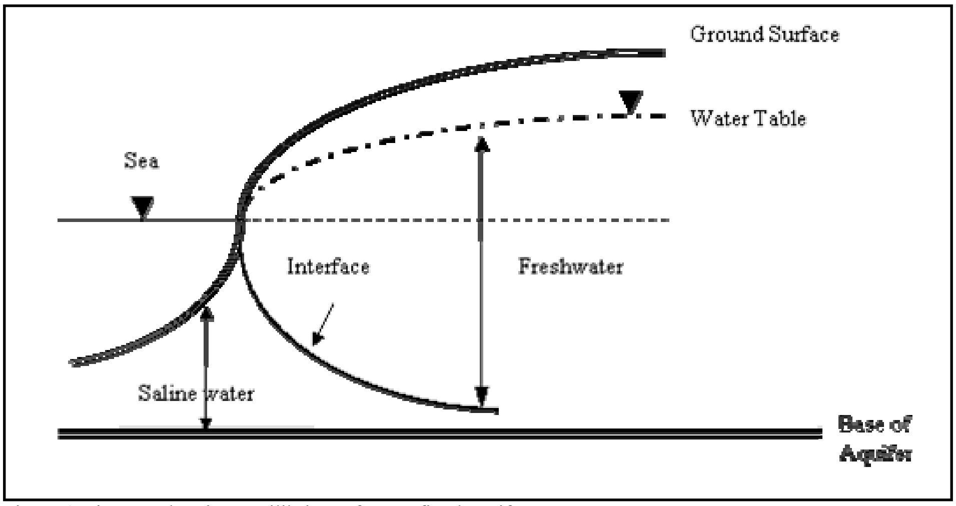

Figure 1 Diagram showing equilibrium of unconfined aquifer

From Figure 1 it can be seen that the freshwater exists like a 'lens' within the aquifer. The distance that the freshwater lens extends above sea level is an approximate indication of how deep it extends below sea level. For each metre a freshwater lens extends above sea level, it theoretically extends 40 metres below sea level. This called the Ghypen-Herzberg relation after the two European scientists discovered it over a century ago Reilly and Goodman (1985). It occurs because of the difference in density between freshwater and the saline water. This relation assumes the hydrologic system is at equilibrium, which is not often, in practice, the case.

The movement of the groundwater flow/saline interface – the zone where freshwater meets the saline water - is critical to understanding the saline intrusion process. The process is a 3 dimensional complex process. However, considering the relatively shallow depth of the aquifer (150m) and the distance inshore where saline intrusion is known to have an effect (5-10km) it was considered appropriate for the first part of the research described in this work to focus on a 2 dimensional model (in plan view), with a single horizontal layer, which would provide some initial insight into understanding the behaviour of the aquifer as a consequence of saline intrusion.

This model was further developed to a two layered two dimensional model which could accurately represent the behaviour of the saline interface.

## Hydrogeology and Resource Demand for Tripoli

Tripoli is part of Jeffara plain as shown in Figure 2. This plain and its vicinity has been the subject of geological and hydrogeological investigations (Gefli, 1972; Pencol, 1978; FAO, 1979; Krummenacher, 1982; NCB-MM, 1994).

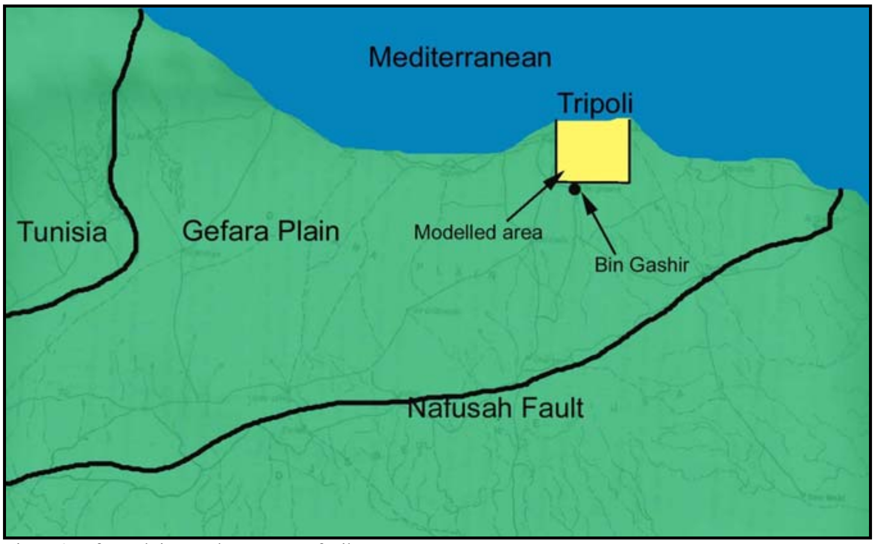

Figure2 Jefara Plain-north western of Libya

**Climate** - Mediterranean climate (hot dry summer – mild, occasionally rainy winter).
**Rainfall** - The rainfall in the study area is seasonal; Figure 3 shows Tripoli rainfall for the period 1879-2004 according to the Libyan Metrological Office, the records show that Tripoli receives an annual average of 370mm.

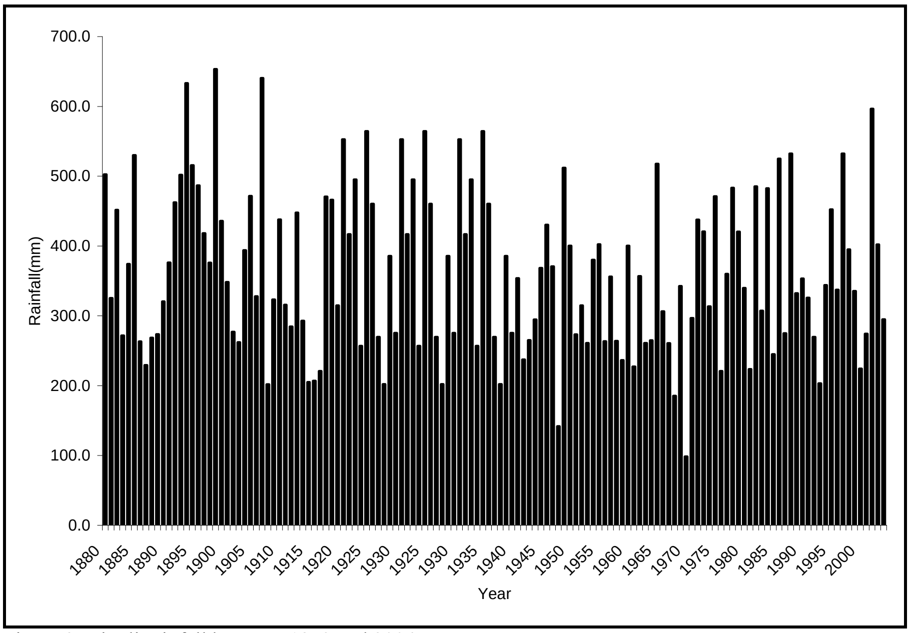

Figure 3 Tripoli rainfall between 1879 and 2004.

**Upper Aquifer System** - Groundwater occurs under unconfined conditions in the Tripoli area,. This aquifer is known to be of Quaternary-Miocene Pliocene origin. It is in general, about 100-150 meters thick (Gefli, 1972; Krummenacher, 1982). The aquifer formation consists mainly of fine material, mostly silt and sand with gravel bands. The formation is often topped with a hard calcareous crust. Groundwater flows from south to north across the aquifer, supplying abstraction wells and to the sea.

**Recharge** - Data rainfall for Tripoli is readily available as can be seen from Figure 2 is typically 350-400mm per annum. However, given the climate and soil conditions of the region a significant proportion is lost to evaporation and evapotranspiration, approximately 10% of mean annual rainfall contributes to the recharge of the Upper Aquifer in an average year. The data available shows that the mean annual direct recharge has been assumed to be taken as 36.9 mm at 95% of the water balance area (Pencol, 1978). This amounts to a total inflow (recharge + groundwater inflow from supply system, waste water and irrigation) of 17.4 $Mm^3$/year. The total recharge included the returned water from irrigation and water supply leakage.

**Historical abstractions** - The abstraction of groundwater has grown dramatically in the last four decades. Estimates by Vlachos gave an annual domestic supply extraction of 12 $Mm^3$ in 1960 and 24 $Mm^3$ in 1970 (Pencol, 1978). The municipality abstraction for 1980 was 69 $Mm^3$ and 73 $Mm^3$ in 1990. By September 1996 the amount of water abstracted from the aquifer for municipal supplies was significantly reduced as a consequence of the commissioning and operation of the Great Man-Made River Project (GMMR). Figure 4 illustrates the abstraction estimation for the period 1930-2010, this estimation was collected from internal reports of water section of Municipality of Tripoli and by personal contacts.

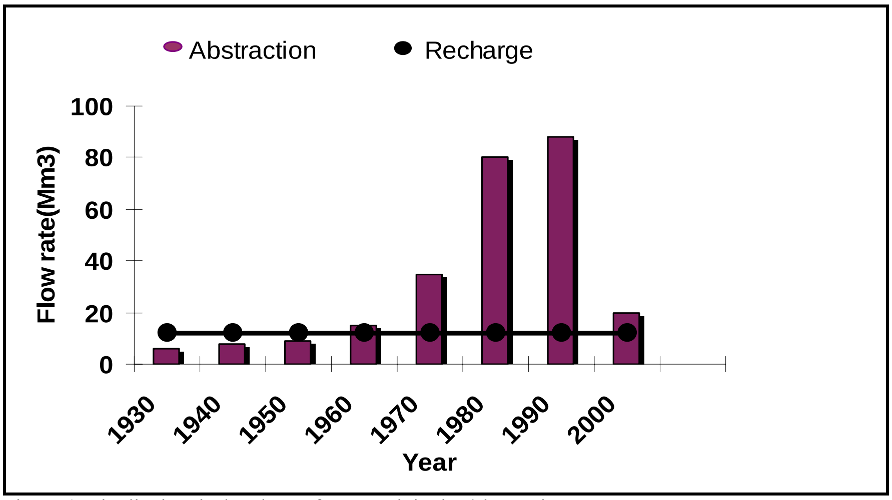


Figure 4 Tripoli Historical recharge from precipitation/abstraction

### Water Demands; Previous, Recent and Future

Groundwater is used extensively in Tripoli area for both domestic supply and agricultural irrigation. Most of this demand has been met until recently by the Upper aquifer, although some abstraction from lower aquifers now takes place. Demand has dramatically increased over the past forty years and is expected to continue with the population growth and development in many sectors. However, the abstraction has been significantly reduced after September 1996 due to the GMMR project. As this new supply is made available, less demand has been placed on the Upper aquifer. Table 1 summaries water balance for the study area.

Table 1 Demand/Supply Balance for Tripoli Aquifer

| Year | Total demand ($Mm^3/yr$) | Total Abstracted from Upper aquifer ($Mm^3/yr$) | Total Recharge (returned plus)rainfall ($Mm^3/yr$) | net loss from upper aquifer ($Mm^3/yr$) |
|---|---|---|---|---|
| 1930 | 6 | 6 | 11.4 | -5.4 |
| 1960 | 25 | 15 | 14.5 | 0.5 |
| 1980 | 140 | 94 | 33.8 | 60.2 |
| 1990 | 150 | 94 | 35.5 | 58.5 |
| 2000 | 155 | 21.9 | 36.3 | -14.4 |
| 2010 | 180 | 31.4 | 40.5 | -9.1 |

The table points to a positive recharge aquifer from 2000, as a consequence of the GMMR project. However, demand for water will continue to rise. Generally, about 45 per cent of water demand is for domestic supply, and given the current sewerage infrastructure for Tripoli, it is estimated that 25% of this water is returned to the aquifer via leakage and effluent seepage. The other 55% of demand is for irrigation, with 10% considered to be lost to the aquifer (FAO, 1979; Krummenacher, 1982).

## Modelling Methodology

In summary two new models have been developed to understand the behaviour of the Tripoli Upper Aquifer as a consequence of different abstraction regimes on the saline intrusion process.

Both models utilise a grid system (in plan view) which allow variable grid spacing in the areas closest to the coast where the impact of saline intrusion is more severe. Both models also use a forward time, spatially centred, explicit finite difference scheme to describe the hydraulic equations which describe the flow processes in the aquifer. They also use Gauss-Seidel iterative method to improve the performance of the models.

The one layered model also utilises an explicit finite difference method with upwind differencing to improve stability when predicting the behaviour of a solute (in this case salt water) in the flow/dispersion equations.

The two layered model does not use a solute equation approach. Rather it treats the saline water as a separate but variable layer underneath the freshwater layer (hence two layered), and utilising the govern flow equations and the density ratios of the top and bottom layers to determine the movement of the saline interface, based on the Ghypen-Herzberg relationship.

Both models have been written in Visual Basic (Version 6) and can be run in most personal computers. Another unique feature of the model is that it has been written for application to any unconfined aquifer near the coasts. The Tripoli situation is uniquely described by two data files which contain all the geologic/ hydrogeologic and simulation control parameters. The model could equally be applied to other regions.

The models have been calibrated and validated as part of the development process.

## Simulation of the aquifer response to abstraction

A regular grid with 16 by 23 rows and columns and uniform nodal spacing of 1000 m was used to represent 294 square kilometres of area as shown below.

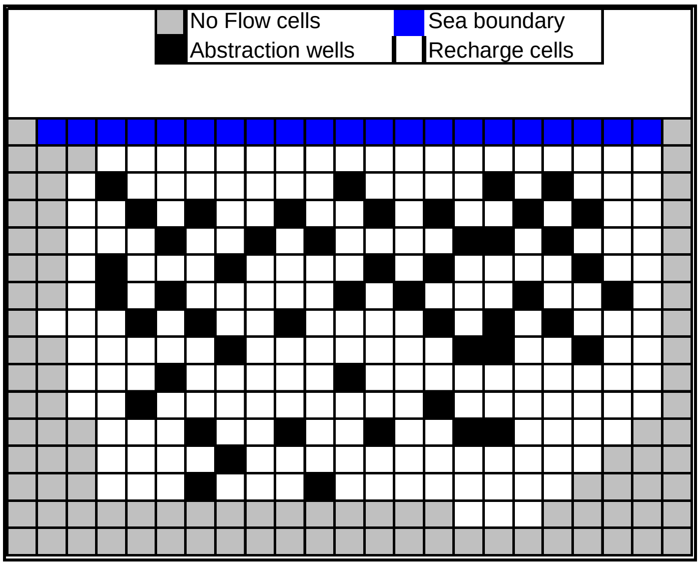


Figure 5. Finite difference discretisation of the modelled area.

### Boundary conditions

The boundary conditions used in this model are based on a regional iso-piezometric map presented by Flogel 1977, the boundaries configuration are:

- The eastern and western boundaries were defined as no-flow boundaries, because these boundaries are parallel to the general groundwater flow direction. The southern boundary of the area was defined as no-flow boundary. There are similar communities to the east and west of the modelled area. Groundwater abstraction is expected to be similar in these communities.
- The northern boundary was defined by the sea level (topography minus aquifer thickness), which was regarded as constant. A constant-head boundary condition was applied to this bound.

### Simulation parameters

Data collected from hydro-geological studies carried out in Libya during the past were reviewed and used in this study. The representation of the aquifer properties is given in table 2. A sensitivity analysis has also been carried out in the model using different values for the parameters chosen.

Table 2 Values of parameters used in the simulation

| Parameter | Value |
|---|---|
| Aquifer thickness | 150m |
| Hydraulic conductivity ( $k$ ) | 1.35m/d |
| Infiltration | 0.00012m/d |
| Initial head | 500m |
| Storativity | 0.1 |
| Longitudinal dispersivity | 25 |
| Transverse dispersivity | 1 |
| Porosity (n) | 0.3 |

## Description of Simulations

Three modelled scenarios were made to investigate a long term over abstraction impacts on Tripoli - all assume the Tripoli population will continue to rise at 1-3% from 1996 onwards (National Consultant Bureau and Mott MacDonald, 1994). The three scenarios were:

**Scenario 1 (Max Abstraction)** - Abstraction continues for both municipal and agricultural supplies at early 1990 levels, based on the principal supply of water coming from the Upper Aquifer but supported by some lower aquifer supplies (Ain Zara and Swani well fields).

**Scenario 2 (Reduced GMMR impact) -** Abstraction for municipal supplies is substantially reduced in 1996 as a result of the GMMR project meeting domestic demands by supplying 91Mm3/yr. Under this condition, demand from the aquifer is assumed to drop by the equivalent amount while losses to the aquifer were maintained at 25% of the total water demand.

**Scenario 3 (Max GMMR Use)** - Extends the GMMR capacity yet further to 116m3/yr ceasing the demand on the Upper Aquifer, while maintaining the replenishment levels (as described for Scenario 2).

Each simulation starts in 1930 when demand on the aquifer was considered to be less than total recharge, giving the model the opportunity to 'warm up' to represent groundwater levels rather the simplified and initialised water table at 5m below the ground surface. This early start therefore allows the model to establish steady state conditions within the modelled aquifer before the abstraction rate is significantly increased.

Figure 4 shows the predicted head level for three scenarios at a cell 2km from the coast, indicating that continued abstraction at 1990 rates will continue to lead to substantial reductions in groundwater levels. Beyond 1990, scenario 1 shows the water table continuing to fall – indeed beyond 2000 the model becomes unstable, despite the controlling effect of an aquifer depth varying transmissivity has on reducing flow to the abstraction cells. This demonstrates the unsustainable conditions of abstraction in the absence of the GMMR source. Reduced abstraction in Scenario 2 and Scenario 3 leads to steady recovery of groundwater levels until around 2020.

However, with respect to saline contamination of groundwater, Figure 4 indicates that close to the coastline even after 2080, the groundwater in the coastal area remains saline, with some recovery being shown for Scenario 3 by 2050.

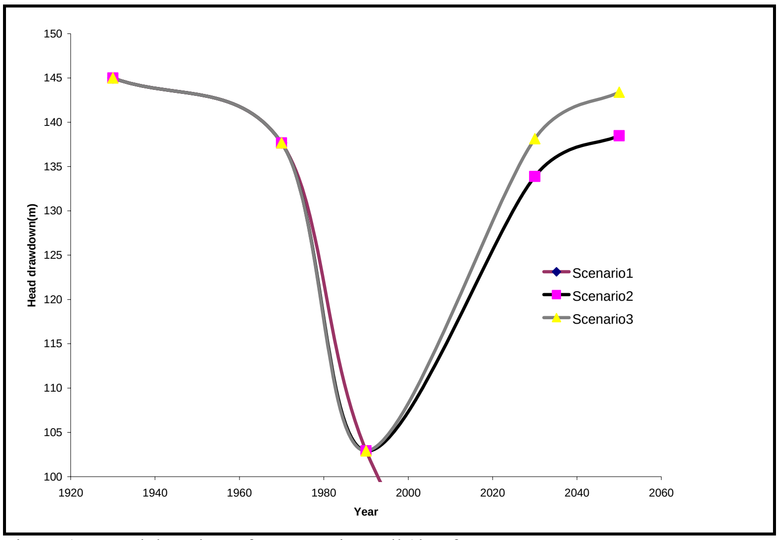


Figure 4 Head drawdown for a pumping cell 2km from coast

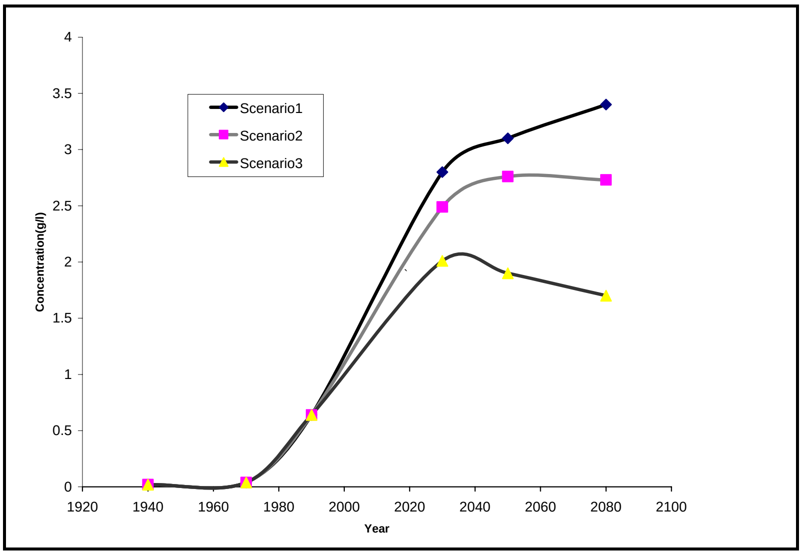


Figure 5 Concentration profile for pumping cell 2km from coast.

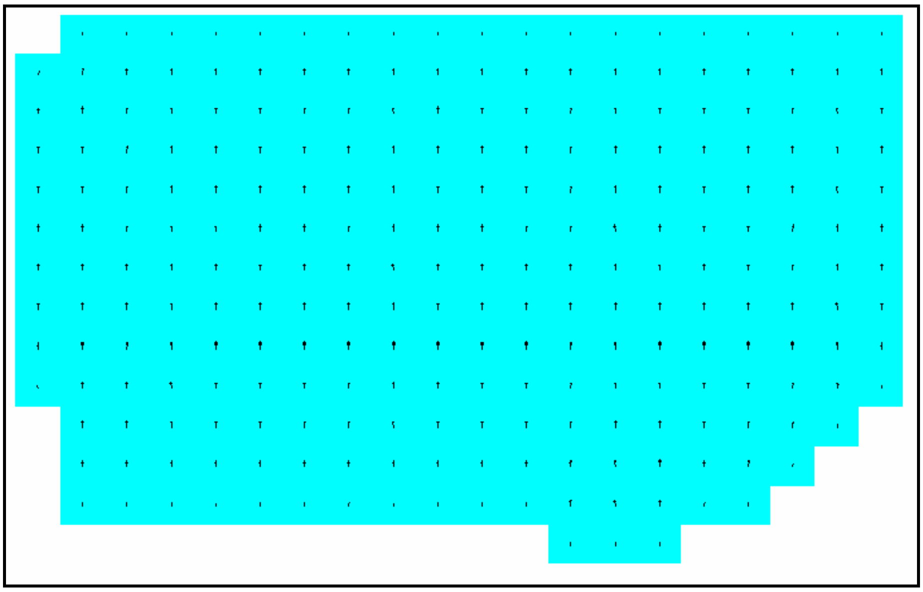

Figure 6 Velocity vectors profile 1930 – All Scenarios

Figure 6 shows the velocities in the modelled area at the start of simulation showing a general direction of groundwater from the south to the north. Figure 7 shows the effect of abstraction on the modelled flow. Increasingly more of the groundwater movement is directed towards the points of abstraction in the model.

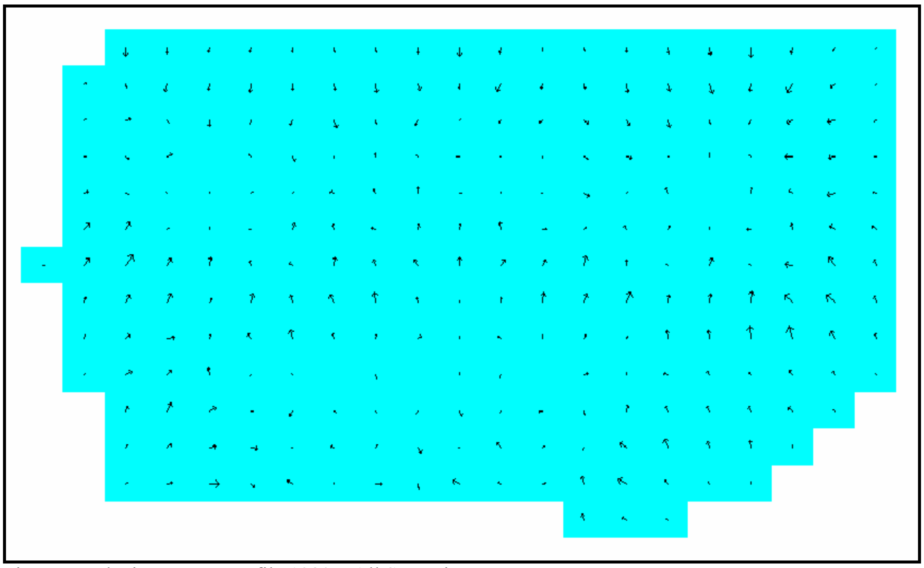

Figure 7 Velocity vectors profile 1980 – All Scenarios

It is important to remember that the cells to the extreme east, west and south are not included in the calculation procures and therefore are not changed from the initial simulation start conditions – they should therefore be ignored.

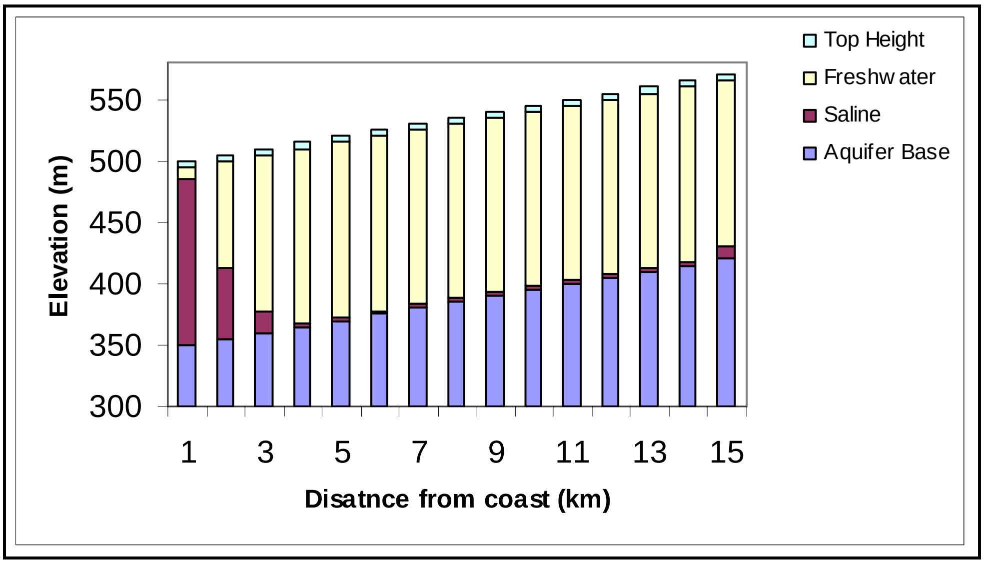


Figure 8 Aquifer Simulations Year-1930; this represents the initial conditions for the three scenarios_1, 2 and 3.

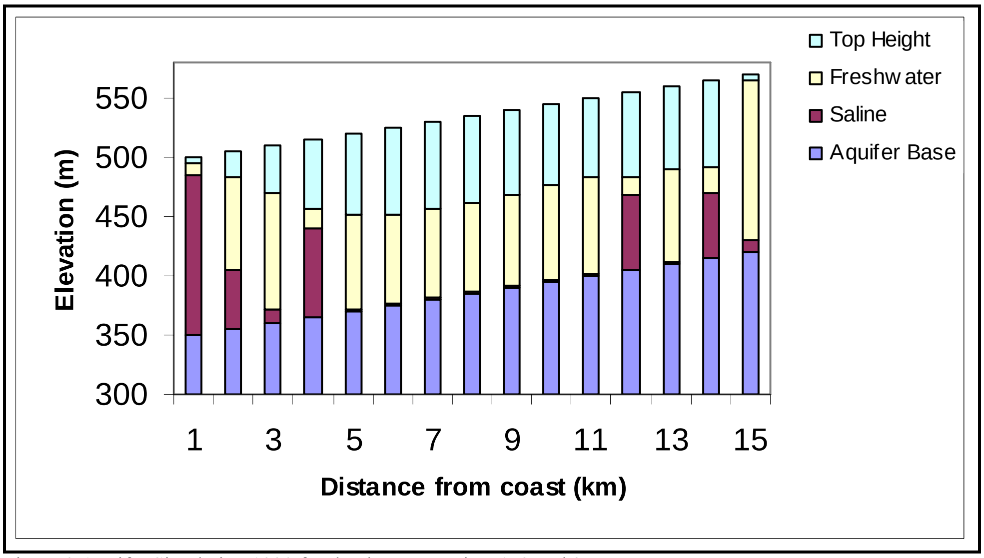


Figure 9 Aquifer Simulation 1990 for the three scenarios_1, 2 and 3

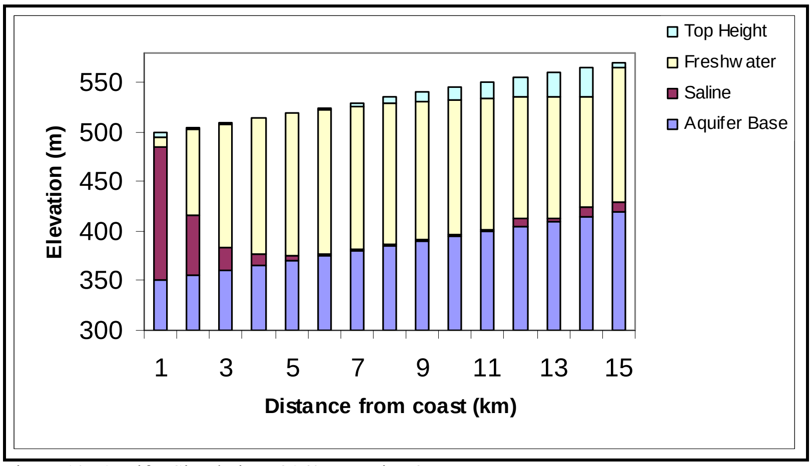


Figure 10 Aquifer Simulations 2160 scenario _3

## Impacts of climate change on Tripoli aquifer recharge

Climate change as a consequence of carbon dioxide emission is widely accepted as real phenomenon which will also bring change to local climates. Some studies have suggested that North Africa will become drier (UNEP, 2001). The impact can be reproduced in the model by altering the infiltration rates. This has been done on the basis of infiltration changes by ±20%. Figure 11 shows that the scenario in which rainfall projected to decrease by 20%, the aquifer drawdown increased by about 40%. However, in scenario in which infiltration was projected to increase by 20%, there was indication of slower drawdown by about 3%. The reduction is more critical on the model and therefore an initial indication would suggest that climate change will have an important negative impact on the ability of the aquifer to recover from over-abstraction.

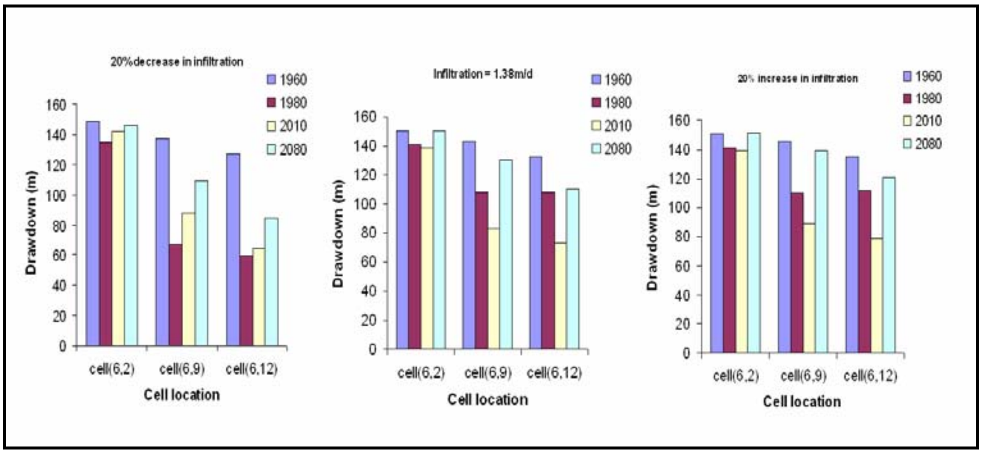


Figure 11 the impacts of infiltration changes by ± 20% on the aquifer drawdown

## Discussion of the results

The model has demonstrated the effects of excessive abstraction on the aquifer and illustrated the potential impact and recovery as a consequence of different management scenarios for the aquifer Figures 8,9,10. The model has illustrated what has been observed in previous studies. In reality however, groundwater problems, particularly those which involve saline intrusion, are three-dimensional in nature, mainly because of density effects. However, since the depth of the Tripoli Upper Aquifer is small in relation to its horizontal dimensions and for the available data collected from previous studies, two-dimensional finite difference computer program was developed to analyse groundwater flow and solute-transport for groundwater basin without the inclusion of density effects. The physical parameters, initial heads, and boundary conditions were defined on the basis of available data.

The long-term simulation results indicate that excessive discharge can trigger a contamination problem in the aquifer. It is clear from the model that once an aquifer is contaminated it would be very difficult to recover.

The model is valid to approximate the behaviour of the aquifer and provide a tool for prediction and quantification of impacts due to groundwater extraction.

Changes in the seasonality of rainfall did not affect water drawdown to any great extent.

Simulations with the change in the mean annual rainfall by $\pm 20\%$ as impacts of climate change have indicated that the decrease of the mean annual rainfall will negatively affect the drawdown of aquifer water level while the increase in the mean annual rainfall will slow the drawdown marginally and help to speed up the aquifer recovery. However, the ability to predict climate change impacts on groundwater resource is lacking of good predications of future climate and a lack of fundamental understanding of many of the effects of climate variability on the hydrological characteristics of groundwater resource.

## Conclusions

Utilising the modelling techniques developed during the course of this study can be effective tool for decision support to Tripoli groundwater resources and water supply management. In the light of the simulation predictions, it is clear that Tripoli Upper Aquifer is sensitive to the abstraction/recharging regime applied and the careful estimation of model parameters. The aquifer water levels are dramatically changing in response to abstractions particularly in the pumping cells and the neighbour's cells. These changes can produce significant rise in salinity. Over-abstracted aquifer recovery in terms of quality would take many decades.

Simulations with the change in the mean annual rainfall by $\pm 20\%$ as impacts of climate change have indicated that the decrease of the mean annual rainfall will increase the drawdown of aquifer water level while the increase in the mean annual rainfall will slow the drawdown marginally and help to speed up the aquifer recovery. Rainfall in the region is expected to decrease as a consequence of climate change. However, the ability to predict climate change impacts on groundwater resource is lacking of good predications of future climate and a lack of fundamental understanding of many of the effects of climate variability on the hydrological characteristics of groundwater resource.

Various strategies may be employed to retard saline water movement:

- Maintaining sufficient head of freshwater near the interface
- Control run-off of storm water
- A redesign of well fields.

## References

**Bear J, Cheng A., Sorek S., Quazar D., Herrera I. 1999.** "Seawater Intrusion in Coastal Aquifers Concepts, Methods and Practices", Kluwer Academic Publishers.

**Essaid, H.I. 1990.** The Computer Model SHARP, a Quasi-Three-Dimensional Finite-Difference Model to Simulate Freshwater and Saltwater Flow in Layered Coastal Aquifer Systems, U. S. Geol. Survey Water-Res. Inv. Rept. 90-4130.

**FAO. 1979.** "Jefara plain water management project. Seawater intrusion study" field report.

**Frind, E.O. 1982.** "Simulation of long-term transient density-dependent transport in groundwater" Adv. Water res., 5, 73-88.

**Gefli. 1972.** "Soil and water resources survey for hydro-agricultural development, western zone" water resources survey. Report, GWA-Lib.

**Glover, R.E. 1959,** "The pattern of freshwater flow in a coastal aquifer," J. Geophys. Res., 64(4), 457-459.

**Krummenacher. R. 1982.** "Jefara plain water management plan project" UTFN9182, Lib-005.

**National Consultant Bureau and Mot McDonald. 1994.** "Final Water Management Plan" Volume I: main report.

**Pencol Engineering consultants. 1978.**Tripoli water master plan. Technical Report.

**Reilly T. E. and Goodman A. S. 1985.** "Quantitative analysis of saltwater-freshwater relationships in groundwater systems- a historical perspective" J.

**UNESCO .1977.** "World Distribution of Arid Regions" UNESCO, Paris.

**UNEP; WHO, Climate Change . 2001.** "Impacts, Adaptation, and Vulnerability" Contribution of Working Group Π, Report of the Intergovernmental Panel on Climate Change

**World Resources. 1992-1993.** "Discussing global withdrawals of freshwater by various industries" supra note 1, at 161-162.