

## The development and application of groundwater models to simulate the behaviour of groundwater resources in the Tripoli Aquifer, Libya.

M El Fleet<sup>1</sup>, J Baird<sup>2</sup>

### ABSTRACT

Effective water resource management is critical in arid/semi-arid countries. Over-exploitation of existing resources, whether reservoir, river or groundwater, can lead to permanent loss and damage. A study has been undertaken for water management in Tripoli, Libya utilising 1 and 2-layered modelling techniques which have indicated groundwater resources will take many hundreds of years to recover from over-abstraction during the past thirty years as a consequence of saline intrusion.

This paper discusses the implications of over-abstraction with reference to the Tripoli situation, describing a novel 2-layer model approach to allow for salinity intrusion, considering the impact of major water strategies for the region.

### INTRODUCTION

The Gefara Plain, located in the north western part of Libya, is an important agricultural and populated coastal area, with Tripoli as the principal city with 30% of Libya's 5.6 million population. Increased use of the Upper aquifer below the Gefara Plain for both municipal and agricultural purposes has led to severe depletion of the aquifer and the region has been the subject of several studies seeking to identify the most appropriate water resources strategies for the locality. A major consideration of these strategies is the Great Man Made River project (GMMR), a major development to bring groundwater from sources in the central regions of Libya to the more densely populated coastal regions in the north.

This paper describes the development and application of a two models specially written to describe the conditions of the aquifer:

- ?? A 1 layer 2 dimensional model was used to provide some initial understanding of the aquifer under the extreme abstraction regimes encountered; and
- ?? A 2 layered 2 dimensional groundwater model to better understand the behaviour of the groundwater interface

The study considers the long-term implications for aquifer recovery following the implementation of different water management strategies in the region. Salinity/freshwater interface in the aquifer for different abstraction profiles are considered.

### GEOLOGY

The geology/hydrogeology for Northern Libya is complex. Two studies, (GEFLI, 1972 and Krummenacher, 1982), provide the most detailed accounts of the aquifer systems in the region. In summary, several East-west faults run across the northern part of the country with the Nafusa fault and escarpment dominating the southernmost part of the Gefara Plain (Figure 1). The topography of the region rises from sea level to the north to 200m above sea level, 50km to the south.

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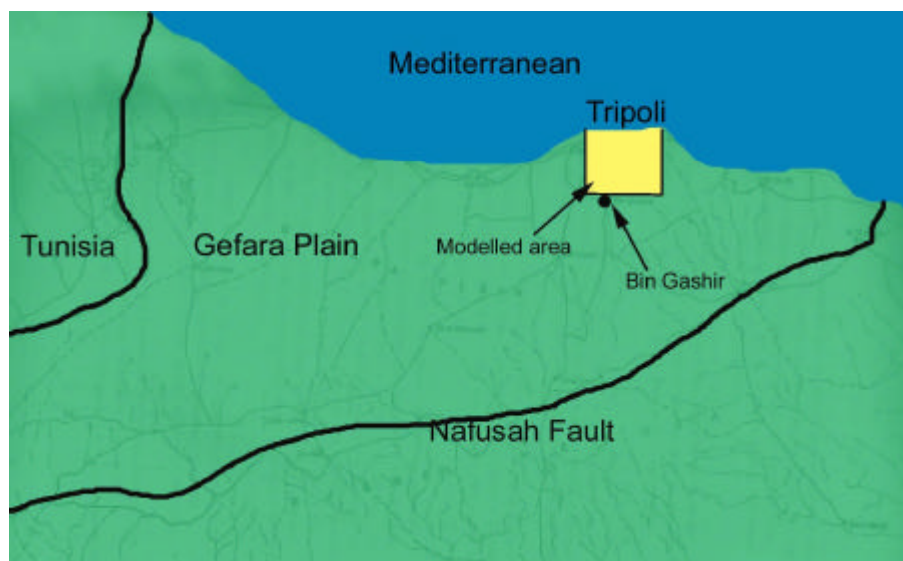
<sup>1</sup> Researcher, Department of Environmental Technology, Glasgow Caledonian University, UK

<sup>2</sup> Professor, Caledonian Shanks Centre for Waste Management, Glasgow Caledonian University, UK

The principal aquifer used by the population in the Gefara Plain and Tripoli area is an unconfined Upper Aquifer, consisting of mainly Quaternary sandstones and riverine sediments underlain by Miocene sandstone with clay lenses located near the base. The thickness of the aquifer is variable, but is typically 150m thick, lying immediately below the surface. The Groundwater level is generally between 20-60m below ground surface, making it a readily available source for economical exploitation. The deterioration in groundwater quality in the immediate vicinity of the coast in recent years, is evidence evidence that seawater intrusion is occurring along the northern coast.

#### WATER BALANCE

Managing the water balance in any aquifer system is critical to maintaining sustainable uses. This is especially true of aquifers vulnerable to seawater intrusion , such as the upper Tripoli Aquifer.



**Figure 1 Map of Area**

Average annual rainfall varies between 144mm to 595mm pa, but is typically 300-350mm per annum (pa). Much of this is lost to evaporation and evapo-transpiration, with most studies (Pencol, 1978; Krummenacher, 1982) of the region estimating the recharge function to be between 5-15% of the rainfall, depending largely on soil moisture deficit for the prevailing year. For this study 37mm (10%) of rainfall has been considered as recharge ( $10.36\text{Mm}^3/\text{yr}$ ). Recharge from seasonal river systems (or Wadis) is not considered to be significant in the Tripoli catchments, although in the wider Gefara Plain upper aquifer, some recharge is known to take place.

Water is used extensively in the Tripoli region for both domestic supply and agricultural irrigation. Most of this demand has been met until recently by the upper aquifer, although some limited abstraction from lower aquifers takes place. Demand has dramatically increased over the past 30 years and is expected to continue with population growth and agricultural development. However, the abstraction has been significantly reduced in the past three years due to the GMMR project (designed to deliver  $91\text{Mm}^3/\text{yr}$  (increasing to  $116\text{Mm}^3/\text{yr}$ ) to the coastal regions of Libya. As this

new supply is made available, less demand has been placed on the upper aquifer. Table 1 summarises the water balance for the modelled area.

Year	Total demand (Mm <sup>3</sup> /yr)	Total Abstracted from Upper aquifer (Mm <sup>3</sup> /yr)	Total Recharge (returned plus rainfall) (Mm <sup>3</sup> /yr)
1930	6	6	11.9
1960	25	15	14.5
1980	140	94	32.1
1990	150	94	33.3

Generally, about 45% of the 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). After 1996 the water demands from the aquifer has been considerably reduced because of the supplies from the GMMR project.

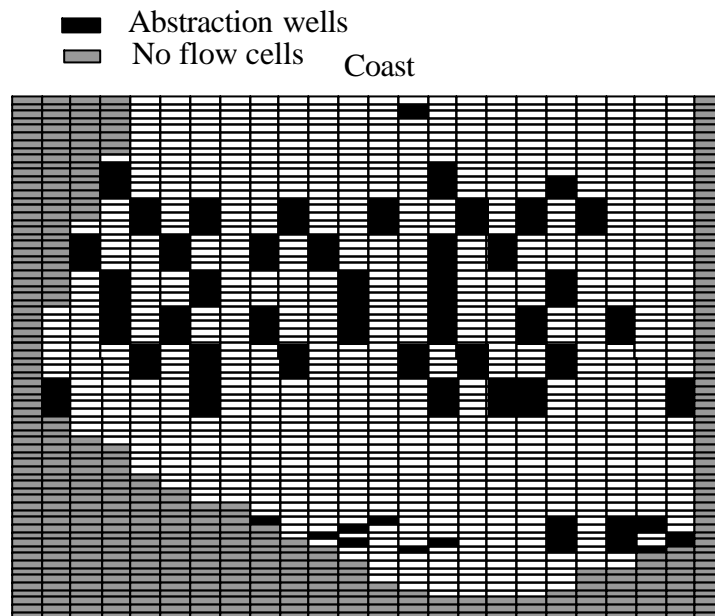
As groundwater levels dropped in the upper aquifer due to overabstraction, well depths were extended, In time those wells located within several kms of the coast encountered increasing levels of salinity. With the supply of water resources from the GMMRP and a corresponding planned reduction in abstraction from the upper aquifer this study sought to determine how long would it take for the aquifer to recover.

## 1 Layered - 2 Dimensional Model

### *Model Design and Description*

The movement of the groundwater saline interface was critical to understanding the saline intrusion process. However initially, because of the relatively shallow depth of the aquifer (150m) compared to the modelled area of 368km<sup>2</sup>, it was anticipated that a 1 layer flow model with a solute transport model would provide some useful insight and understanding to the behaviour of the intrusion process for the upper aquifer.

A generic model was developed, with a solute model utilizing calculated velocity and depth terms at the end of each timestep. A forward time (explicit), but spatially centred, finite difference scheme was used. The model utilises the Gauss-Seidal iterative method. The solute model utilized upwind differencing to improve the conservation performance of the model. The modelled area was uniquely described by the input data files which, as a consequence, allowed the testing of various grids and configurations. Cells were described by indicators ie as flow cell =0, no flow cell = 1, constant head cell= 2, abstraction cell =3. A separate data-file described the hydro- geological features of the aquifer, abstraction locations and flows and recharge levels. A variable cell size feature was also included that gave more detailed resolution in the region of the model closer to the coastal boundary. The final grid designed for the aquifer simulation was 1000m by 200m cell size with 23 columns and 80 rows as shown in Figure 2.



**Figure 2 – Grid system used for 1 layered Simulations**

*Results of 1 Layered simulation*

The purpose of the study was to examine the long-term implications for water quality in the aquifer for particular abstraction scenarios. Three modelled scenarios were made - all assume the Tripoli population will continue to rise at 1% from 1996 onwards (National Consultant Bureau and Mott MacDonald, 1994). The three scenarios were:

**Scenario 1** - 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.

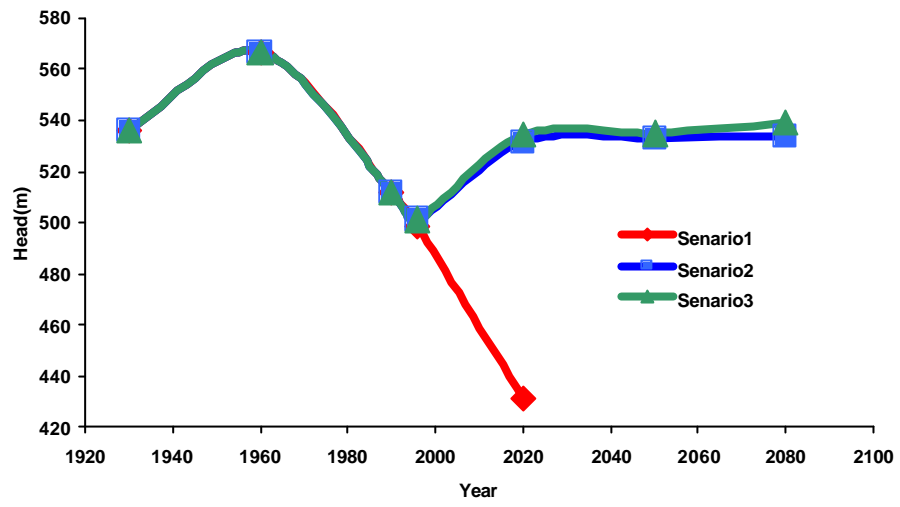
**Scenario 2** - Abstraction for municipal supplies is substantially reduced in 1996 as a result of the GMMR project meeting domestic demands by supplying 91Mm<sup>3</sup>/yr. Under this condition, demand from the aquifer is assumed to drop by the equivalent amount while losses to the aquifer were maintained at 25% of the total water demand.

**Scenario 3** - Extends the GMMR capacity yet further to 116m<sup>3</sup>/yr. Ceasing the demand on the upper aquifer, while maintaining the replenishment levels (as described for Scenario 2).

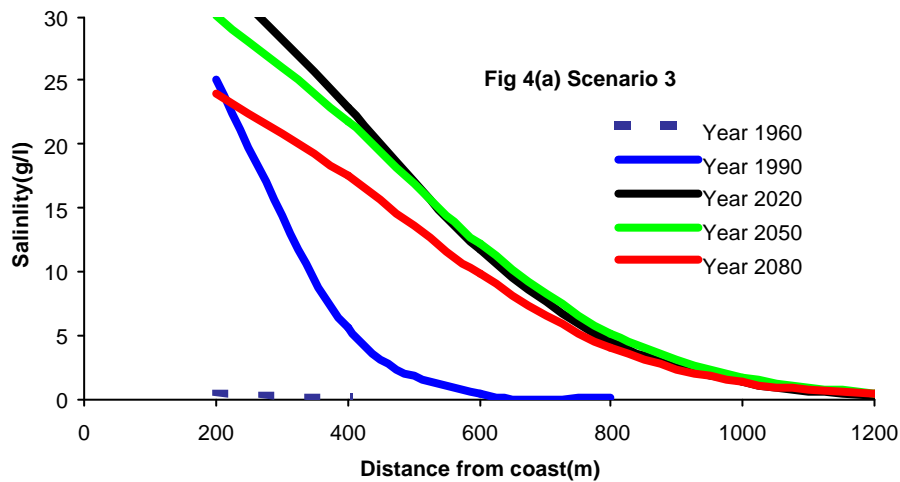
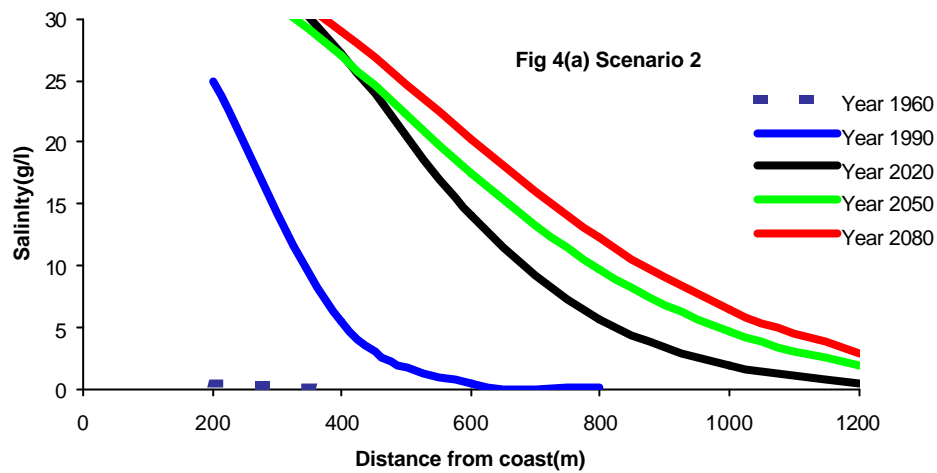
Each simulation starts in 1930 when demand on the aquifer was less than total recharge, giving the model the opportunity to 'warm up' to more representative groundwater levels than the water table at 5m below the surface as an initial start up condition.

Figure 3 shows the predicted head level for three scenarios at a cell 7km from the coast, indicating that continued abstraction at 1990 rates will continue to lead to substantial reductions in groundwater levels. Reduced abstraction lead to steady recovery of groundwater levels until around 2020. However, with respect to saline contamination of groundwater, Figures 4 (a) and (b) indicate 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 3 – Ground water level predictions**



## 2 Layered 2 Dimensional Model

### *Model Design and Description*

In order to understand the complex interaction between abstraction and the saline interface, a two layered model based on the well known Ghyben-Herzberg relationship was developed. In effect two 1-layered models with an assumed sharp interface between the freshwater and saltwater was built. The top layer simulated the movement of freshwater, driven by head differences in adjacent cells and abstraction. The bottom layer simulated the same effect of the top layer but in addition the flow regime set up by the density gradients on the bottom layer from the top layer

In effect the stepped procedure for calculation was:

- a. Calculate top layer level at start of timestep;
- b. Add top layer to bottom layer using density ratio factor to create an artificial bottom layer;

$bottomartificial(i, j) = bottomthick(i, j) \frac{?_{fresh}}{?_{salt}} + tophick(i, j)$  where bottomthick and tophick are the relative depths of flow in the top and bottom layers of the aquifer;

- c. Determine a new artificial thickness value for the bottom layer;
- d. -Subtract upper layer thickness to determine groundwater level on top layer;
- e. Update and move to new time-step.

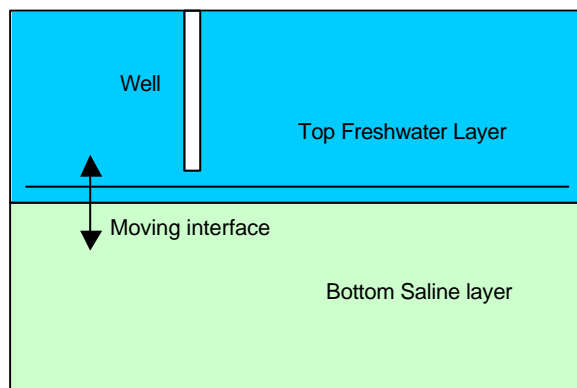
The time-step for the model was determined using normal stability criteria:

$$\Delta t \leq \frac{S}{T} \frac{?^2}{?^2 + ?^2}$$

where S is the Storativity and T is the Transmissivity.

The model was rigorously tested for stability and accuracy for grids of varying sizes, ensuring the mass balance of the top freshwater layer and the bottom saltwater layer.

As the interface between the fresh and saline layer moves vertically, some wells will begin to abstract from the bottom layer. Various models were developed based on zones of abstraction around the well pump. For the purposes of this study, at the start of each time step the model determined the position of the pumps in relation to the interface and abstracted from the appropriate aquifer as illustrated on Figure 5.



**Figure 5 Illustrative diagram of well in relation to model layers**

#### *Results of 1 Layered simulation*

The three scenarios set out previously were repeated using the 2 layered model using grid sizes of  $DX=DY=1000$ . The model simulated the period 1930 to 2080 by modelling the estimated abstraction levels from the aquifer at 20 metres below the ground. In actual fact the region has around 1000 wells all of which are located at different depths, some of which have been extended deeper over the years. The results of the simulations are presented in Figures 6 to 10.

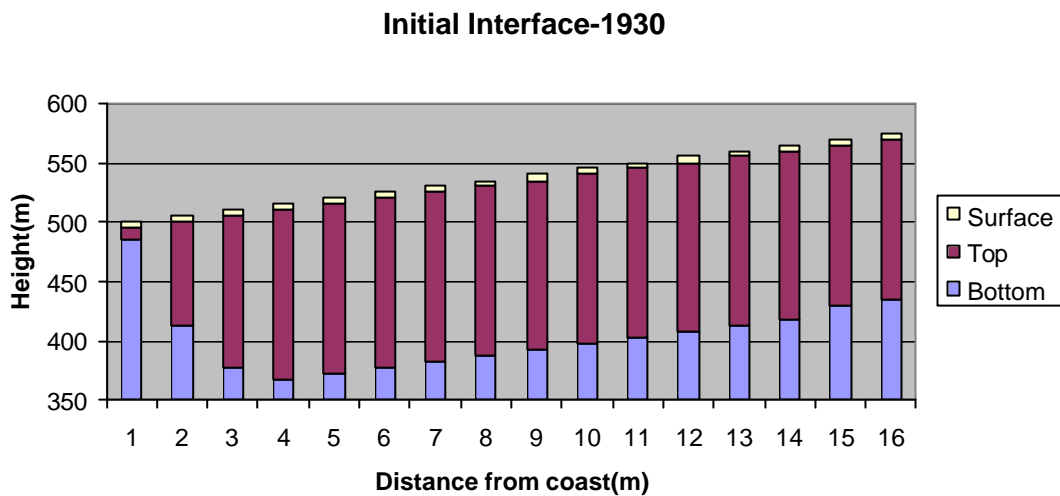
**Year 1930** - the initial freshwater, saltwater and interface distribution is shown in Figure 6 - obtained by running a simulation of an actual grid with no-abstraction using calibrated data set and allowing the interface level to settle to a steady state.

**Year 1940** – after 10 years of abstraction there is little change in the interface level – Figure 7.

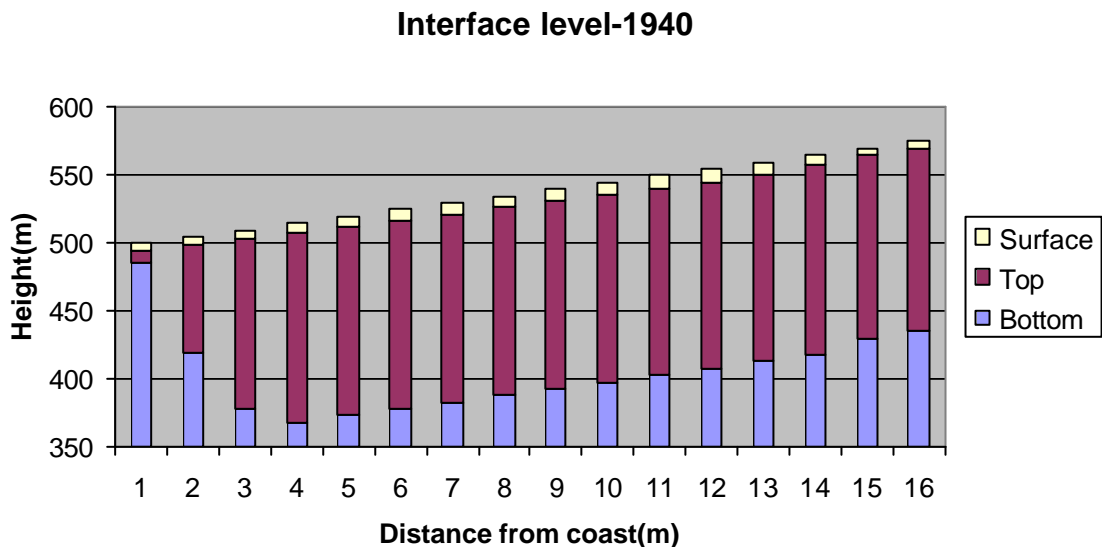
**Year 1990** - over the next 50 years abstraction significantly increases, and in 1990 when estimated abstraction exceeds the recharge by a factor of 8.5, in response to draw down of the freshwater heads, the interface position in the cells subjected to abstraction raises, suggesting upconing at these cells – Figure 8.

**Year 2040**- since 1996, the abstraction has been significantly reduced as the Great Man Made River Project provides substantial alternative supplies of water to the region and some recovery of the salinity interface is occurring – Figure 9.

**Year 2080**- at the end of the simulation period the aquifer is shown good recovery, but even after 86 years of recovery, there are residual effects in the aquifer – Figure 10.

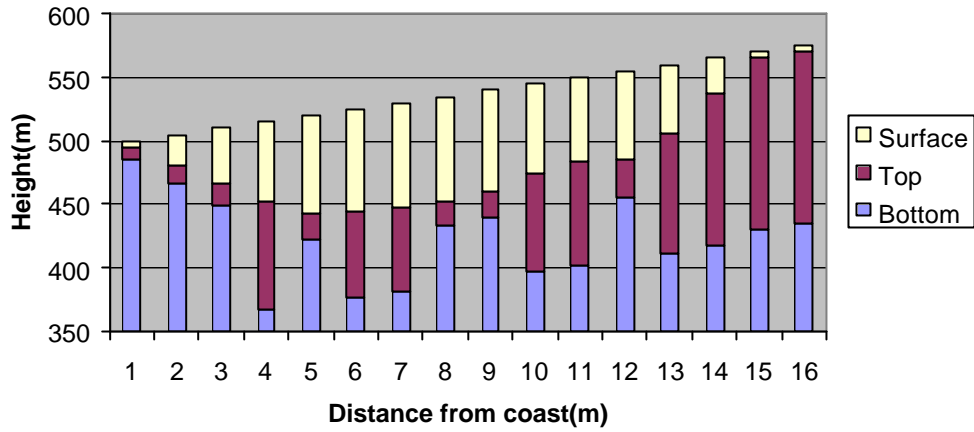


**Figure 6 Simulation at the year 1930**



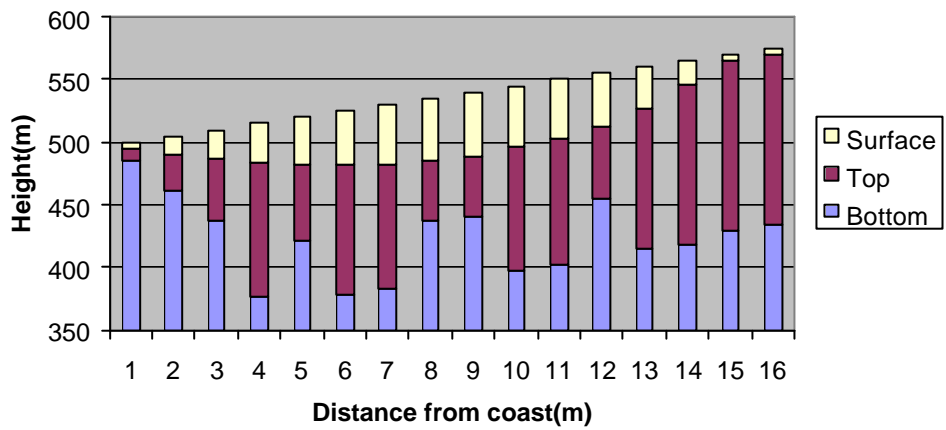
**Figure 7 Simulation at the year 1940**

**Interface position(m)-1990**



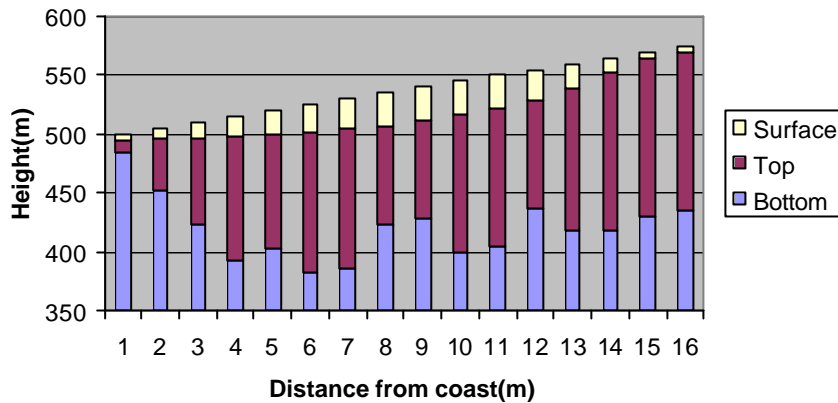
**Figure 8 Simulation at the year 1990**

**Interface position - 2040 Scenario 3**



**Figure 9 Simulation at the year 2040**

**Interface Position - 2080 Scenario 3**



**Figure 10 Simulation at the year 2080 for Scenario 3**

**Conclusions**

Coastal areas present unique problem of salinity intrusion where excessive over abstraction leads to seawater entering the fresh groundwater system in coastal towns. Saline water is not poor unacceptable for drinking purposes for agricultural use, it can accelerate through oxidation damage to pipes and pumping infrastructure.

A new 2D-2layer sharp interface model was developed and applied into a coastal aquifer in Tripoli-Libya to reproduce and predict the impact of over-abstraction for municipal and agricultural purposes.

Both the 1 layer and 2 layer models demonstrate that once severely depleted it can take many decades (if at all) for some aquifers to recover from over abstraction.

The vertical position of the salinity interface is sensitive to the extent of abstraction which takes place in a cell. The results obtained when the over-abstraction continued showed the interface moved up and the saltwater replaced the freshwater. When the abstraction has reduced or stopped, considerable time needed for the aquifer to recover to pre1930. However, GMMRP is a major investment by the country which will never meet all the demand for water, and the country must therefore look to other means of managing water resources.

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**Corresponding author**: M. Elfleet, Energy and Environmental Department, Glasgow Caledonian University, City Campus, Cowcaddens Road, Glasgow G4 0BA, UK.  
Email: M..Elfleet@gcal.ac.uk