Impacts of Climate Change on Coastal Aquifers

M. Elfleet
Caledonian Environment Centre, Glasgow Caledonian University,
Glasgow, Scotland, UK

Abstract

The development potential of coastal areas of semi-arid regions is restricted in various ways, not least of which is the limited availability of fresh water. Increased pressure on water resources emerges when the hydrological cycle includes processes such as evaporation and precipitation that are predicted to shift with climate change.

This paper presents a case study that uses a 2Dimensional-1Layer flow and solute model to investigate the possible impacts of climate change on saline intrusion in a coastal upper aquifer in Tripoli, Libya. In this example the impacts were evaluated by incorporating the estimated infiltration inputs within the model. This has been done on the basis of infiltration changes by ±20%. , examining the effects of changes in the seasonality of rainfall were also tested. The most noticeable and consistent result of the climate change impact simulations is the increase in the aquifer drawdown by 40%. However, in scenario in which infiltration was projected to increase by 20%, there was indication of slower drawdown by about 3%. Hence, changes in the seasonality of rainfall predicated to have no effect on aquifer drawdown.

Introduction

The Jefara 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 populations. Increased use of the Upper aquifer below the Jefara Plain for multi purposes has led to severe depletion and deterioration in groundwater quality. With groundwater records suggesting that groundwater levels have fallen from 5m to 70m below the ground surface. The significance rise in salinity in the immediate vicinity of the coast of the aquifer is evidence that saline intrusion is occurring along the northern coast (El-Fleet M. and Baird J). Moreover the Tripoli groundwater resources and water supply management will become more difficult with climate change. Climate change will increase the risk and unpredictability of aquifer system behaviour. Extreme events will occur more often and high temperatures will speed up the flow of water back to the atmosphere, disrupting the water balance.

As a result of the above, although less demand has been placed on the Upper aquifer any changes arising from climate change may worsen the long-term repercussions on Tripoli Upper aquifer. To address this issue, model simulations are made to assess the possible climate change impacts on Tripoli Upper aquifer by:

I. Incorporating the estimated infiltration inputs within the model. This has been done on the basis of infiltration changes by ±20%. ,
II. examining the effects of changes in the seasonality of rainfall
III. Sea level rise impact.

This paper summarises the simulation predications to assess whether there are additional stresses acting on Tripoli aquifer.

CLIMATE CHANGE PROJECTIONS

The uncertainties in climate change impacts on water resources, droughts and floods arise for various reasons, such as different scenarios of economic development, greenhouse gas emissions, climate modelling and hydrological modelling. Despite these uncertainties, some robust results showed increases in globally averaged mean water vapour, evaporation and precipitation over the 21st century.

Precipitation

Hydrological and climate models suggest that precipitation generally increases in the areas of regional tropical precipitation and at high latitudes, with general decreases in the sub-tropics. Increases in precipitation at high latitudes in both the winter and summer seasons are highly consistent across models. Precipitation increases over the tropical oceans and in some of the monsoon regimes, There are widespread decreases in mid-latitude summer precipitation, except for increases in eastern Asia. Decreases in precipitation over many sub-tropical areas– particularly in some regions such as the tropical Central American—Caribbean and the Mediterranean. Increases in annual precipitation exceeding 20% occur in most high latitudes, as well as in eastern Africa, the northern part of central Asia and the equatorial Pacific Ocean. Substantial decreases of up to 20% occur in the Mediterranean and Caribbean regions and on the sub-tropical western coasts of each continent.

Sea Level

There are uncertainties in the estimates of the contributions to the long-term sea-level change. Global mean sea level has been rising and there is *high confidence* that the rate of rise has increased between the mid-19th and the mid-20th centuries. The average rate was 1.7 ± 0.5 mm/ yr for the 20th century, 1.8 ± 0.5 mm/yr for 1961–2003, and 3.1 ± 0.7 mm/yr for 1993–2003. The latest IPCC assessments indicate that the world's average temperature would increase somewhere between and 1.4 and 5.7 degrees Centigrade and the sea level would rise between10–90 cm by the year 2100 (IPCC, 2007).

Impacts on Coastal Regions

Climate change can affect the timing and volume of freshwater runoff. Modelling scenarios by Milly et al. (2005) concluded that climate change during the next 50–100 years will increase discharges to coastal waters in the Arctic, in northern Argentina and southern Brazil, parts of the Indian sub-continent and China, while reduced discharges to coastal waters are suggested in southern Argentina and Chile, western Australia, western and southern Africa, and in the Mediterranean Basin.

Hydrogeology and Resource Demand for Tripoli

The principal aquifer Figure1 used by the population in the Jefara 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.

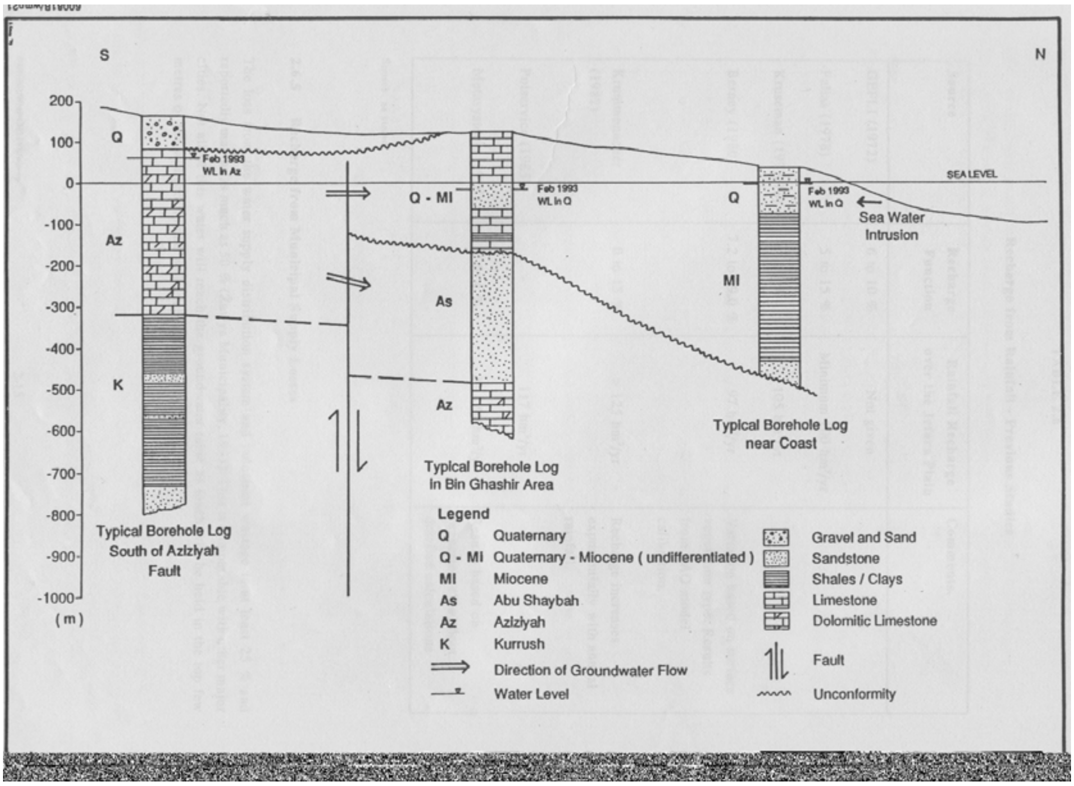

Figure 1 Schematic Cross Section (based on Krummenacher, 1982)

Climate - Mediterranean climate (hot dry summer – mild, occasionally rainy winter).

Rainfall - The rainfall in the study area is seasonal; Figure 5.1 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.

Upper Aquifer System - In Tripoli area, groundwater occurs under unconfined conditions. 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.

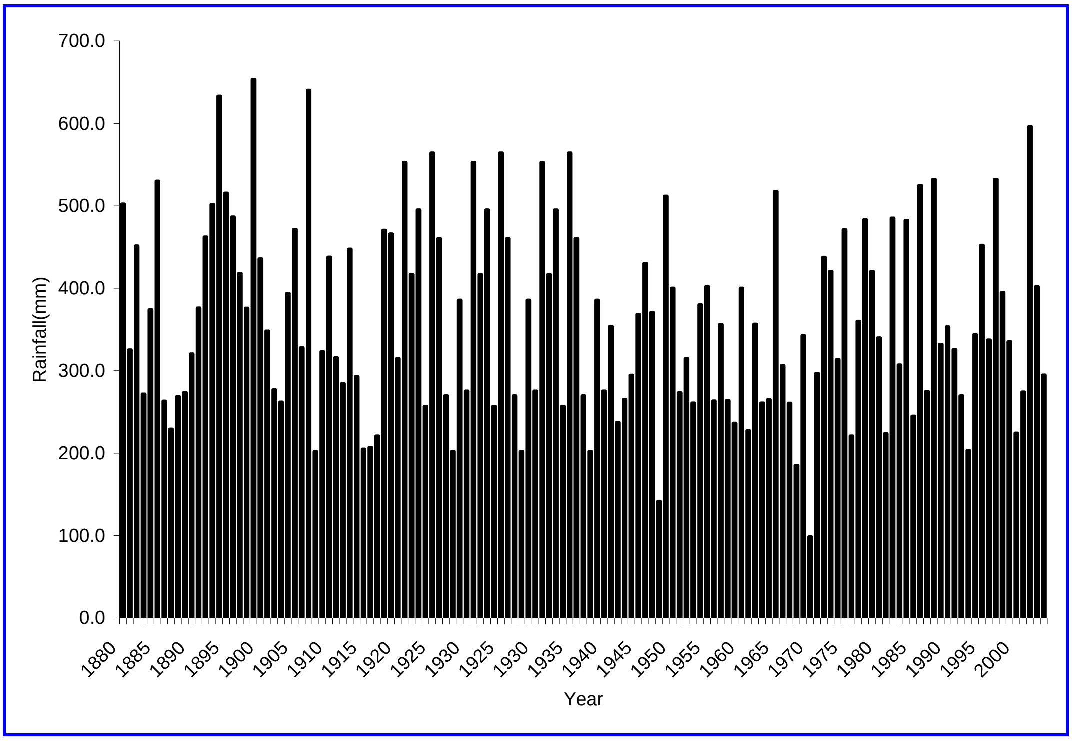

Figure 2 Tripoli-rainfall between 1879 and 2007.

Recharge - An important aspect of the groundwater modelling process is the identification of the mechanisms of recharge and discharge within the system. Data rainfall for Tripoli is readily available as can be seen from Figure 5.2 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. It is difficult therefore to estimate the actual recharge that takes place. A further complication is that municipal wastewater supply system leakage and also irrigation water finds their way into the aquifer system - in effect acting as recharge.

Several studies (Gefli, 1972; Kruseman, 1977; Pencol, 1978) have attempted to quantify the amount of recharge. Their findings concluded that 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

Mm3/year. As described in chapter 2 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-Mad River Project (GMMR).

Table 1 Demand/Supply for Tripoli

Year	*Total demand (Mm3/yr)*	*Total Abstracted from Upper aquifer (Mm3/yr)*	*Total Recharge (returned plus)rainfall (Mm3/yr)*	*net loss from upper aquifer (Mm3/y)*
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**

Modelling and Simulation Scenarios-Tripoli 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 undoubtedly 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 to focus on a 2 dimensional model (in plan view), which would provide some initial insight into understanding the behaviour of the aquifer as a consequence of saline intrusion.

The modelling approach has been developed to understand the behaviour of the Tripoli Upper Aquifer as a consequence of over abstraction and the possible impacts of climate change.

The model utilises 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. The model also uses a forward time, spatially centred, explicit finite difference scheme to describe the hydraulic equations which describe the flow processes in the aquifer. it also uses Gauss-Seidel iterative method to improve the performance of the model.

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 model has 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 model has been calibrated and validated as part of the development process.

Description of the Simulation

The purpose of the simulations is to apply the flow and solute model to to assess the possible climate change impacts on Tripoli Upper aquifer. The modelled scenarios were made - all assume the Tripoli population will continue to rise at 1-3% from 1996 onwards (National Consultant Bureau and Mott MacDonald, 1994). The scenarios assume abstraction for both municipal and agricultural supplies at 2000 levels as shown in Table1, 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). Simulation parameters used are summarised in Table 2.

Table 2 Simulation Parameters

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

Simulation Results

Impacts of Climate Change on Tripoli Aquifer Recharge

As with most aquifers, coastal aquifers such as the Tripoli Upper aquifer are recharged primarily by precipitation. Assessment on the recharge response to climate change in the area under investigation is carried out based on the scenarios of infiltration changes by ± 20%. Figure 5.6 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%.

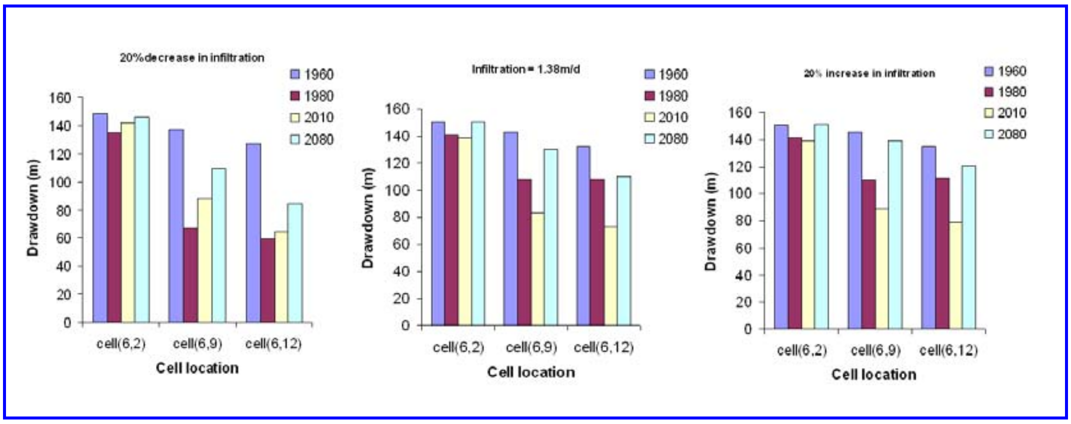

Figure 3 the possible impacts of infiltration changes by ± 20% on the aquifer drawdown

Sea Level Rise Simulation

The sea level rise simulation carried out using an average of the mean rise of 22 cm and 44cm, the simulation results show that an increase of 2.7% drawdown is likely however, with 44 cm rise of sea level would lead to a drawdown of 4.4% as shown in Figure 4.

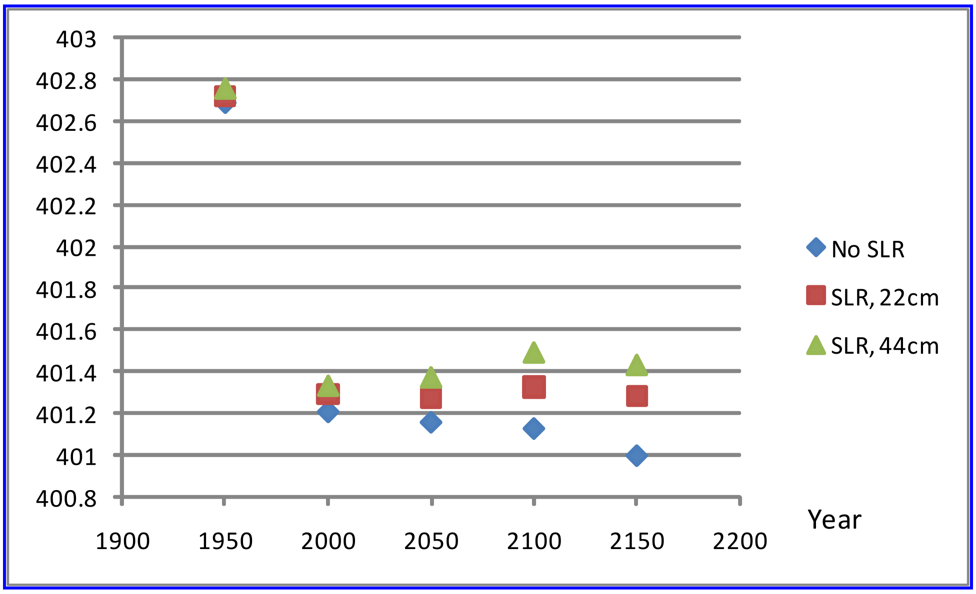

Figure 4 the possible impact of the sea level rise on Tripoli Upper aquifer

The Effect of Seasonal Infiltration on the Aquifer Behavior

In the scenario test discussed above the recharge was assumed constant, though the rainfall in Tripoli as indicated is seasonal. To examine the effects of changes in the seasonality of rainfall, a simulation of seasonal infiltration was run using the same parameters presented in Table 2. As the simulation timestep is about 120 days (four months) so that the annual infiltration rate can be divided into three four months intervals. The model result is shown in Figure 5. The infiltrations seasonal variation has no effect on the aquifer drawn as the average drawdown for every three time steps equals the head drawdown calculated by the constant infiltration scenario.

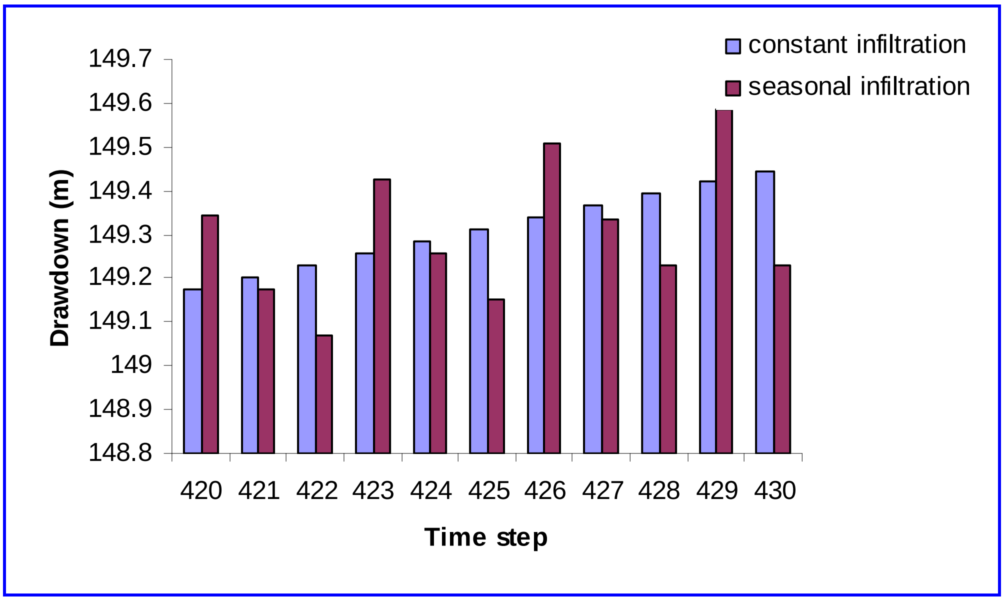

Figure 5 Seasonal infiltration and constant infiltration comparison

Conclusion

Simulations with the change in the mean annual rainfall by ± 20% as impacts of climate change have indicated that the decrease of the mean annual rainfall will fast 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. Changes in the seasonality of rainfall did not affect water drawdown, while the mean sea level rise by 44cm may increase the drawdown by about 2.72%.

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.

Field data needed to be properly evaluated and monitored. The hydrological data will remain an important part of groundwater resources assessment in more detail. Therefore, subsequent research should focus on improved estimates of the climate related parameters particularly precipitation and evaporation and the water balance components. This is an area that deserves further investigations.

This work does not explicitly consider the seasonal abstraction and recharge, Statistical and mathematical models can be always an approximate description of reality, and the treatment of uncertainty is a basic issue in all hydrologic modelling and climate change research.

References

Elfleet M. and Baird J. (2002) “Long-term Management of Coastal Aquifers” WaRMAR, Kuwait

FAO. (1979). “Jefara plain water management project. Seawater intrusion study” field report.

Gefli. (1972). “Soil and water resources survey for hydro-agricultural development, western zone” water resources survey. Report, GWA-Lib.

Hanasaki N, Kanae N., Oki T., Masuda K., Motoya K., Shirakawa N., Shen Y., and Tanaka K. “n integrated model for the assessment of global water resources – Part 1: Model description and input meteorological forcing”Hydrol. Earth Syst. Sci., 12, 1007–1025, 2008

Krummenacher. R. (1982). “Jefara plain water management plan project” UTFN9182, Lib-005.

IPCC: The Climate Change 2001: Synthesis report, Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, 398 pp., 2001.

IPCC: Fourth assessment report climate change 2007, Paris, http: //www.ipcc.ch/, 2007.

McBean, E. and Motiee, H. (2008). “Assessment of impact of climate change on water resources: a long term analysis of the Great Lakes of North America”, Hydrol. Earth Syst. Sci., 12, 239–255 M and, 2008

National Consultant Bureau and Mot McDonald (1994). “Final Water Management Plan” Volume I: main report.