Numerical Modeling of Saltwater Intrusion in the Rmel-Oulad Ogbane Coastal Aquifer (Larache, Morocco) in the Climate Change and Sea-Level Rise Context (2040)

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Published in Water, Volume 13, Issue 16, 2167, 33p. Web Link: https://doi.org/10.3390/w13162167

Introduction

Water resources in Morocco are recognized to be upon the most important water resources suffering from:

- **Scarcity due to arid and semi-arid conditions,**
- **Aggravated by global climatic changes occurring worldwide.**

More than 9.5 million people are living in the coastal cities of Morocco and this number is steadily growing. Indeed, in 2015 more than 50% of total population is living in the coastal zone, with an increasing proportion of rural population due to poverty and rural exodus. This situation makes **more pressure on many coastal aquifers** leading to salinization in the coastal fringe in some catchments in Morocco.

Fig. 1: Location map of Rmel-O. Ogbane area.

The Rmel-O. Ogbane aquifers (Fig.1) are:

- Located in North-West part of Morocco
- Well known for their role in industrial, economic and social development.

The average of rain decline from 1121 mm/y in 1963 to 508 mm/y in 2014, this is due to the impacts of Climate Change (CC) and causes the recurrent droughts and decreases in recharge, which directly affect groundwater level.

This is coupled with heavy abstraction rates, that is used for industrial and drinking water supply for rural and urban areas, and irrigation.

This situation has led to :

- Major **decline in the groundwater levels** ;
- Cause a **deficit water balance** of the aquifer ;
- **Degradation of the freshwater quality** by seawater intrusion on the coast and the coastal plain of the study area (303 km^2).

Africa is the least responsible continent of the CC, but the most vulnerable to its effects; and hence Morocco belongs to the most important physical water resources scarcity area in the world, due to arid and semi-arid conditions as shown in Fig. 2.

According to the seasonal variation using 12-month moving average, the **monthly values of rainfall** in the Loukkos basin indicate a **decrease** over the last five decades after the most important intensity during the 1960's. The variation shows a clear seasonal irregularity (Fig. 3).

Moreover, the monthly average values of the **temperature** in the Loukkos basin indicate an **increase** during the last three decades since the 1976's (Fig. 4). Hence, the impact of CC in the Loukkos basin in north-western of Morocco causes the recurrent droughts and **decreases in recharge** (Fig. 5) directly affect the **groundwater level**.

Fig. 2: Areas of physical and economic water scarcity in the world.

Fig. 3: Monthly variation of precipitation (1963 – 2014) in Larache station at Loukkos basin.

Fig. 4: Monthly variation of temperature (1977 – 2000) in Larache station at Loukkos basin.

Fig.5: Monthly variation of natural recharge of Rmel-O. Ogbane aquifer calculated by Thornthwaite method (1948).

Methodology

The water resources managers need tools that can assist them as to the making decisions regarding the actions, management of water resources and planning. Currently, these decision supports are provided with effective technical tools such as **Geographic Information Systems (GIS)**, **Geostatistical Models** and **Mathematical Models.**

From the data of **drilling** and **geophysical studies**, we modeled the aquifer using a **3D Geoscientific Information Systems (3D SIGS)**. Finally all of these outputs have been exploited and processed to:

- Update the aquifer water balance of 1961/1962,
- Design of a conceptual model and
- Development of a mathematical flow model in steady state and transient flow and transport of pollutants, including seawater intrusion of Rmel-O. Ogbane aquifers using the MODFLOW/SEAWAT code.

GIS & 3D Model

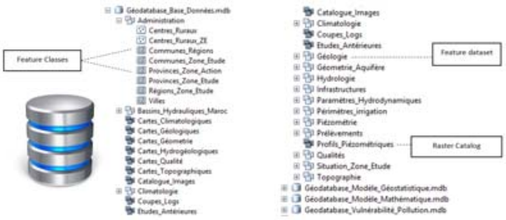


Fig. 6: Geodatabase Structure of the database.

- A **Hydrogeological Geodatabase** has been designed based on data collected from various organizations and studies which describes the:
  - Surface water
  - Groundwater resources (geology, piezometry, geometry).
- The **geostatistical model**, the **simulation results** from the mathematical model and the **pollution vulnerability** of the study area have been, then, integrated into a Hydrogeological Geodatabase (Fig. 6).

- **Database, water balance** and **hydrogeological modelling** play a crucial role and we had much to gain in incorporating these modelling results in a **GIS** by developing a **Visual BASIC application ('MONAROO' extension)** (Fig.7) for this case study.
- This package facilitates and helps the user to **manipulate this product** in order to:
  - Complete input data,
  - Exploit the output results
  - Understand how the modeling steps.

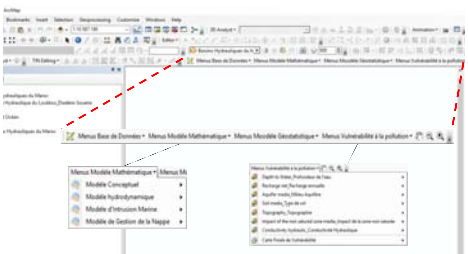
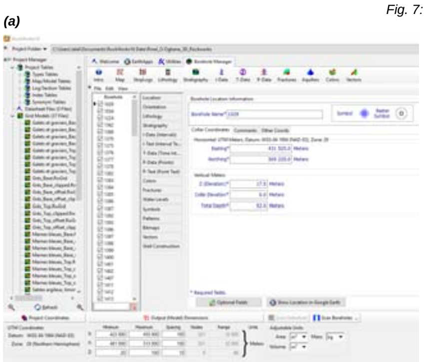


Fig. 7: Display of the 'MONAROO Toolbar'.

(a)



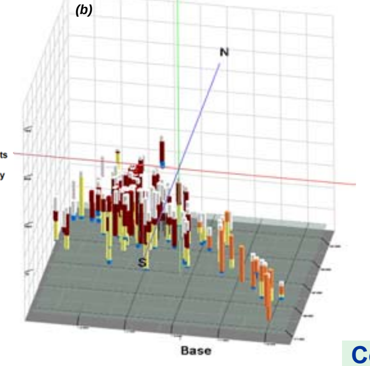
The **reservoir** is composed of :

- Moghrebien shelly sandstones, which are surmounted in the Rmel area by Quaternary sands and red silts more or less marly (Fig. 8).
- They evolve laterally in pebbles and sandy silt in Oulad-Ogbane area.

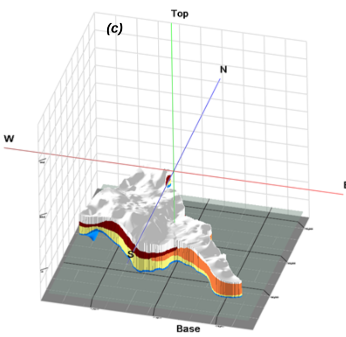
Its **thickness** is between 0.1 and 146 m.

The isopach map of intermediate layer, containing **clayey sand** and **sandy clay**, constitute semi-permeable screen, in some areas of the groundwater, that insulate hydrogeologically the two aquifers (upper and lower).

(b)



(c)



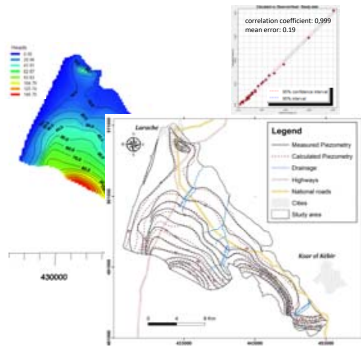
Stratigraphy

- Sands Marls and Silts
- Sands clayely, loamy
- Pebbles and gravel
- Sandstone
- Blue marl

Fig. 8: 3D hydrogeological structure of ROOCA: (a) borehole manager method for stratigraphic succession visualization; (b) location of 127 full boreholes; (c) creating a stratigraphic model.

Hydrodynamic & SEAWATER Intrusion Model

Fig. 9 : Comparison of observed and simulated piezometries of Rmel-O. Ogbane groundwater level for the year 1961/1962.



A **three-dimensional numerical groundwater flow** model, calibrated under:

- Steady state (Fig.9)
- Transient state resolving Equation (1) for a period from 1963 to 2016,

It was developed by means of the Visual Modflow based on MODFLOW/SEAWAT code.

Figure 10 shows the evolution of volumes (intruded SWI, pumping, and recharge) in the indicated period.

The model predicts also the drawdown and the hydraulic head in the aquifer system for the period ranging from 2016 to 2040 under **three different groundwater management scenarios** and gives the water balance within time.

Eq. (1)

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)\pm W=S_s*\frac{\partial h}{\partial t}$$

- The GW balance between 1962 and 2016 indicates that the aquifer had a **decrease in aquifer recharge** associated with **over-pumping** occurring between **1980** and **1990**. As a result, **seawater moved inland** in **1982** and **1991** (Figure 10).
- It also demonstrates that a decrease in recharge and over-pumping, especially in 1998, 2004, 2011, and 2015, increased SWI, though **less pronounced** than the intrusion of seawater in 1982 and 1991.
- The SWI entered the first region west of the **ONEE pumping wells**. The aquifer is contaminated in the NW coastal plain, where the toe extends some 0.5 km inland.
- The contamination of the aquifer is limited beyond these areas.

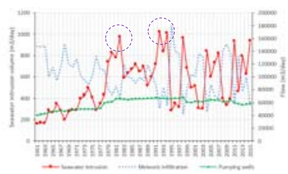
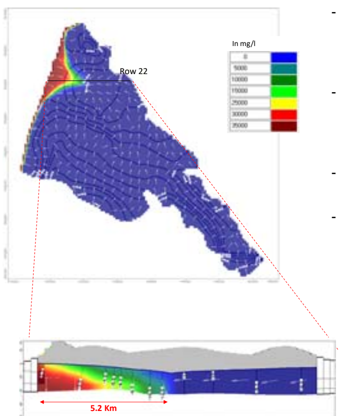


Figure 10. Evolution of volumes (intruded SWI, pumping, and recharge).



- The **coupled flow** and **transport code** (SEAWAT) resolving Equation (2) was applied to study **seawater intrusion in the Rmel-O. Ogbane** coastal aquifer in both qualitative and quantitative aspects,
- The simulation results under RCP 4.5 (pessimist scenario) show that the maximum extent (about 5.2 km) of SWI would increase in 2040 in the northwestern sector of the study area.
- The water quality would be most affected in the **ONEE pumping area**, which is directly adjacent to the seashore.
- The **GW abstraction** associated with **CC** is the primary driver of **SWI in the study area**. Furthermore, the **reduction in recharge** and the **rise in sea level** caused by **CC** exacerbate **saltwater intrusion** into the aquifers, reducing the fresh GW resources.

Eq. (2)

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right)-\frac{\partial}{\partial x_i}(V_iC)-\frac{q_sC_s}{\theta}+\sum_{k=1}^{N}R_k$$

Fig. 11: Calculated piezometry and salinity: (a) plan view of salinity simulated in 2040 for layer 3; (b) transversal section of simulated salinity (based on RCP 4.5 scenario and SLR projection).

Conclusion

The primary impact of this SWI would be unnecessary over-pumping that would deplete renewable water resources. However, this situation can be improved by the use of :

- Surface water for irrigation (provided from the neighboring dam reservoir),
- Desalination plant project for DWS,
- Artificial recharge of the aquifer.

GW recharge with recycled water would be also an effective and feasible way to address the rapid GW depletion and saltwater intrusion in the study area. This would greatly increase the GW production in the coastal sectors of the aquifer and would protect freshwater from SWI. Such long-term results and findings will help the local decision-makers and all relevant stakeholders to **better plan, manage, and improve the fresh GW resources** for the aquifer.

Acknowledgements: The authors express their gratitude to the Moroccan Ministry of Water for providing data to conduct this research. This study is a part of the contractual project between EMI, DRPE, and ABHL (2011-2016).