REGIONAL MODEL FOR SEAWATER INTRUSION IN THE CHAOUIA COASTAL AQUIFER (MOROCCO)

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Abstract

The Chaouia coastal aquifer is located south of the Casablanca city (Morocco), and is considered among the main sub-atlantic coastal aquifers in Morocco with an area of 1200 km^2. The only water resource available in the Chaouia plain is obtained from shallow groundwater. This favourable situation has increased irrigation by pumping, and contributed to agriculture development in this plain. But, this development of pumping has induced environmental problems, such as: over-exploitation of the aquifer with a groundwater table decrease of 0.6 m/yr; progressive dry out of some aquifer levels; salt water intrusion; degradation of the groundwater quality; and significant increase of the abandoned pumping wells. For these reasons, a mathematical model in transient conditions, based on the SEAWAT code, has been developed to study groundwater flow and salt water intrusion in this aquifer. Different management scenarios have been simulated to provide managers with a prediction tool that could help in decision making for quantitative and qualitative groundwater management of this groundwater system. The simulation results with respect to the development of water resources in this coastal aquifer showed, on one hand, that surface water is required to protect the irrigated area and to restore the abandoned exploitation, and on the other hand, the need to improve water quality in the area which is already contaminated by seawater intrusion.

Keywords. Coastal aquifer, groundwater modeling, seawater intrusion, over-pumping, Morocco.

Introduction

The coast of Morocco extends over more than 3500 km, on the Atlantic Ocean and the Mediterranean Sea. As in the rest of the world, the majority of urban and farming agglomeration activities (e.g. fishing,

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industry, harbors, agriculture and tourism) are located on the coastal areas and in the inshore plains. These intensive socioeconomic developments have led to extensive use of freshwater resources in the coastal zones, and especially groundwater resources. Groundwater has some advantages if it is compared to the surface water, because of its spatial distribution, regularity, easiness of exploitation and low cost of mobilization.

The coastal aquifers of Morocco are considered as a very important source for water supply and very essential for socioeconomic development. High rates of urbanization and increased agricultural and economic activities have required more water to be pumped from the aquifers. This pumping has continually increased the risk of seawater intrusion and the deterioration of freshwater quality of the coastal aquifers. Contamination of groundwater by seawater intrusion threatens agricultural development. In recent years, the effect of seawater intrusion is more remarkable in many coastal areas in Morocco, especially in some aquifers located on the Atlantic coast.

Currently, agricultural activity is in a critical situation because of the progressive water resources shortness and the deterioration of groundwater quality, as a result of aquifer overexploitation and of successive drought seasons.

Groundwater quality in the Chaouia aquifer is generally poor. Over-exploitation has resulted in saltwater intrusion and upconing. In some parts of the study area a slow, continuing decline in groundwater levels has been observed. Saltwater intrusion presently poses important threat to water supply, and especially with future water demand, since it is expected to increase. Hence, it is necessary to develop efficient and fast tools for predicting the response of coastal aquifers to different pumping schemes, while taking into account, as a constraint, the risk of saltwater intrusion. In practice, the spatial relationship between freshwater and saline groundwater in coastal and inland aquifers is complex, and management of the freshwater resources can be difficult. The aquifer system is rarely near equilibrium, and fresh and saline water bodies are normally separated by a transition zone as a result of chemical diffusion and mechanical mixing. Under these conditions, the response of the saline water body to pumping is difficult to predict and depends on various factors, including aquifer geometry and properties; abstraction rates and depths; recharge rate, and the distance of the pumping wells to the coastline. Efficient tools such as numerical groundwater models are required to quantify the aquifer response to these excitations. This is the case of the Chaouia coastal aquifer, where a mathematical model that considers seawater intrusion has been implemented to help managers in sustainable water resources planning and management. Hence, the objectives of this study are:

1- to analyze the phenomenon of seawater intrusion and the definition of conditions that govern the behavior of freshwater/saltwater transition zone in the coastal aquifer under different physical approaches.
2- to test management scenarios based on various economic projects, and to select the best one for the regional water resources authorities in order to implement the corresponding economic projects which improve water resources development.

To this end, a specific hydrogeological study of seawater intrusion was carried out, focusing on the hydrodynamics and hydrochemical behavior of seawater intrusion in the aquifer and to assess its impacts on freshwater resources. The variable-density SEAWAT code was used. The model output will show the occurrence of seawater intrusion and will predict its future behavior along the Chaouia coastal aquifer.

Description of the Chaouia aquifer

The Chaouia is a part of the Moroccan coastal plain located to the south-west of Morocco. Its area is about 1200 km^2 and its length is approximately 25 km along the Atlantic coast and located between the cities of Casablanca to the North and Azemmour to the South-West (Figure 1). The average mean temperature ranges from 25 °C in summer and 10 °C in winter. The climate is semi-arid, but influenced by the Atlantic Ocean. The summer is hot; especially on July and August, leading to additional pressure for groundwater abstractions to be used for irrigation. The coldest months on the year are December and January. The average annual rainfall varies from 500 mm/yr in the north at Casablanca to 300 mm/yr in the south near Azemmour. Most of the rainfall occurs in the period from October to April, the rest of the year being completely dry. The annual mean potential evapotranspiration in the study area is estimated to amount 840 mm/yr.

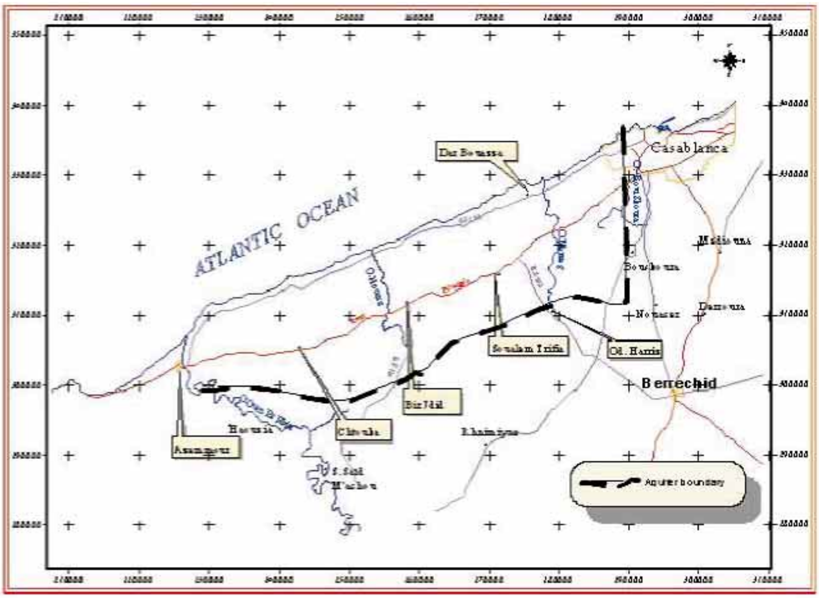


Figure 1. Location map of the Chaouia aquifer.

Paleozoic shales form the Chaouia coastal aquifer bottom. The aquifer system is formed by the following geological units:

- altered shale in the area located between Tnine Chtouka and Casablanca;
- Cenomanian marine limestone with 60 m of average thickness, mainly in the south-western zone;
- sandy dunes of about 10 m thickness at the coastal strip;

- chalky hills that mainly constitute the Quaternary deposits and cover the wadi area;
- conglomerates, alluvia and silts of small thickness, which crop out just on the banks of the wadi Oum Er Rbia.

The altered Paleozoic shale constitutes the main aquifer, extending over 90% of the total area. Towards the south-west of the area, the Paleozoic bottom rises up and allows a water divide to occur, separating groundwater circulating in the chalky horizons of the Cenomanian to the West, and groundwater flowing in the Quaternary deposits and altered shales, to the East. The Quaternary deposits generally present a maximum saturated thickness of 10 m except, in the inshore zone where they can reach up to 20 m. A simplified schema of a hydrogeological cross-section of the Chaouia aquifer system is shown in Figure 2.

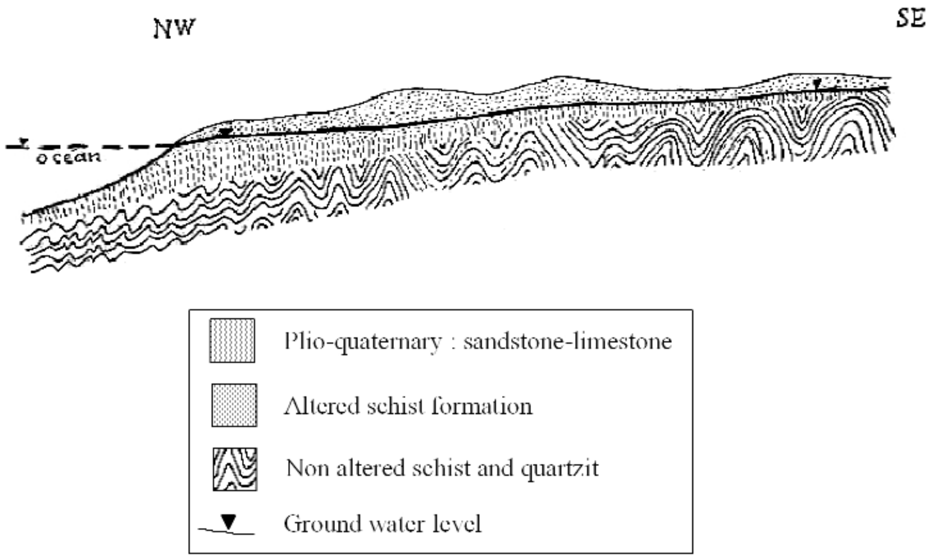


Figure 2. Schematic hydrogeological cross section of the Chaouia aquifer.

The characteristics of the groundwater system

The regional groundwater flow is mainly oriented SE-NW, discharging towards the Atlantic Ocean, except in the south-western area, where a part of the outflow discharges towards the Oum Er Rbia river. To the southwest, the hydraulic gradients range between 0.1 and 1‰. Between Tnine Chtouka and Casablanca they vary from 2 to 3‰, with lower values found towards the uphill limit of the zone, in the order of 0.5‰. This difference in the hydraulic gradient is due to variations in permeability. The depth of water table varies between 10 m along the coastline and 40 m along the south-west part in the Cenomanian marine-chalk. The comparison of the piezometric situation in 1971 and 1995 shows that the decrease of the groundwater level reached 10 m in the coastal strip and 15 m in the rest of the aquifer.

Groundwater productivity of the aquifer varies from 0.5 to 2 L/s in the coastal zone; 1 to 2 L/s in the zone between Tnine Chtouka and Casablanca and 2 to 4 L/s in the part situated between Tnine Chtouka and Azemmour.

From a hydrological point of view, the Chaouia plain is not crossed by any permanent river. Wadi Oum Er Rbias and Wadi Bousskouras, which are located respectively on the western and eastern limits of the study area, do not contribute to the replenishment of the aquifer. Hence, the major source of renewable groundwater in the aquifer is rainfall. The total rainfall recharge to the aquifer is estimated to be approximately 53 Mm^3/yr, while lateral inflows to the aquifer are estimated to amount 6.6 Mm^3/yr. Groundwater abstraction from pumping wells was estimated to be 34 Mm^3/yr, according to a field investigation carried out in 1995. This investigation has also shown that 54% of the total pumping wells used for irrigation have been abandoned, mainly due to the high salinity in the pumped groundwater, which exceeds 3 g/L. The estimated outflow towards the Atlantic Ocean was estimated to be about 41 Mm^3/yr in 1949.

The recent results of a hydrogeochemical analysis showed that groundwater salinity values are very high in some inshore sectors, exceeding 6 g/L. However, in 1971 the salinity only reached 2 g/L in these sectors, with a maximum of 4.5 g/L locally. This salinity increase in those places is due to the seawater intrusion, resulting from overpumping and conjugated with reduced recharge to the aquifer.

Modeling seawater intrusion in the Chaouia aquifer

Simulation code SEAWAT

The original SEAWAT code was written by Guo and Bennett (1998) to simulate ground water flow and salt water intrusion in coastal environments. SEAWAT uses a modified version of MODFLOW (McDonald and Harbaugh, 1988) to solve the variable density, ground water flow equation and MT3D (Zheng and Wang, 1998) to solve the solute-transport equation. The SEAWAT code uses a one-step lag between solutions of flow and transport (Langevin and Guo, 2002). This means that MT3D runs for a time step, and then MODFLOW runs for the same time step using the last concentrations obtained by MT3D, to calculate the density terms in the flow equation. For the next time step, velocities from the current MODFLOW solution are used by MT3D to solve the transport equation. For most simulations, the one-step lag does not introduce a significant error, and it can be reduced or evaluated by decreasing the length of the time step.

Model Set-up

Mesh discretization and boundary conditions

The developed model simulates transient variable density groundwater flow coupled to solute transport for a period from 1960 to 2002. This model is based on the hydrogeological description presented in the previous sections. Regular spaced finite-difference cells of 1 km x 1 km on the horizontal plane are constructed (Figure 3). Hence, the grid consists of 24 rows, 71 columns and 8 regular spaced layers on the vertical direction.

In a first step, the model developed is expected to simulate the global aquifer behavior. However, for studying local variations of the seawater intrusion a refined grid is necessary, as will be developed in the further sections.

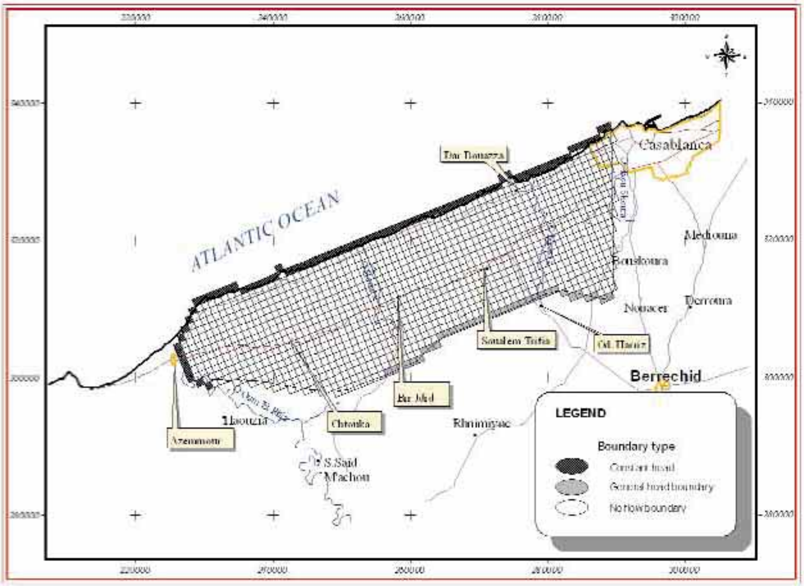


Figure 3. Finite-difference grid and boundary conditions for the Chaouia regional model.

Boundary conditions and aquifer parameters

The hydraulic parameters assigned to the model are based on those obtained from the pumping tests performed in the aquifer system. The hydraulic conductivity distribution, for tests carried out in the area, shows that values vary from $7 \cdot 10^{-4}$ m/s to $2 \cdot 10^{-6}$ m/s on the western area, with a general mean value of $2 \cdot 10^{-4}$ m/s. At the Eastern part, the average value of the hydraulic conductivity is around $6 \cdot 10^{-4}$ m/s.

Only six values of the storage coefficient are available for the Chaouia coastal aquifer. The measurements carried-out were concentrated only along the aquifer coastal part, and the measured values range from 0.13% to 7%. In the rest of the aquifer, parameters were obtained from Moroccan hydrogeological literature for similar type of soils (DRPE, 1995).

Constant head and concentrations are specified to the cells along the Atlantic coast, respectively 0.0 m and 35 kg/m^3. The head for each cell is converted to freshwater head using the specified salt concentration of 35 kg/m^3 at the center elevation of the cell. Constant head along the Oum Er Rabia river presents in layer 3, expressed by a slope of 0.1% from the sea. The concentration is assumed to be 0.0 kg/m^3. The lateral flow of groundwater upstream is represented by a general head boundary based on the groundwater level record. The aquifer bottom is a no-flux boundary, while on the top of the aquifer a recharge influx is assigned. The northern and southern west boundaries are assumed to be no-flow boundaries, due to the existence of impervious layers of schist.

Calibration and model results

First, the numerical model is established and tested against the steady state groundwater flow in 1949 (Bentayeb, 1972). During calculation, measured and calculated groundwater heads are compared, and the difference is referred to as the residual. Figure 4 shows the calibrated, simulated groundwater heads in the Chaouia aquifer for the conditions in the year 1949. The results show good agreement between calculated and measured heads, and the established freshwater-saltwater interface was far away from inland. Table 1 also shows the resulting water balance with the different components, including the discharge to the sea, which is estimated to be about 43.85 Mm^3/yr.

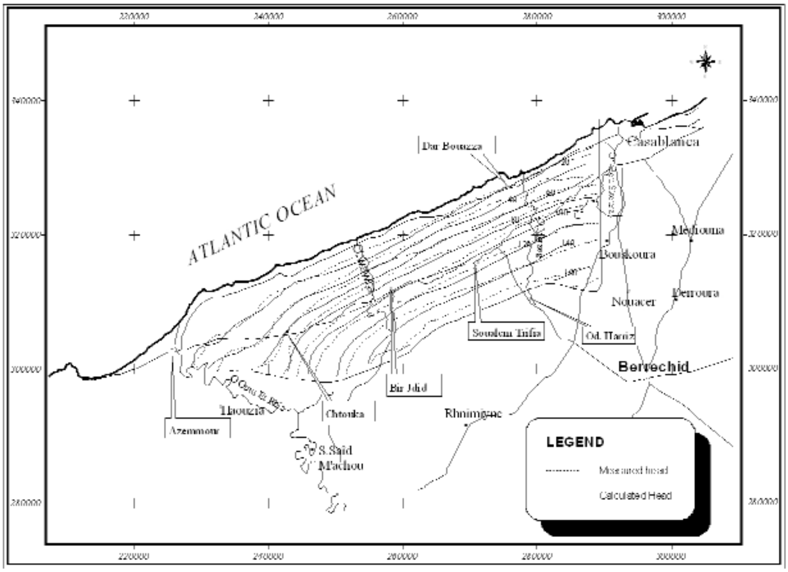


Figure 4. Calibrated and observed groundwater levels for the year 1949.

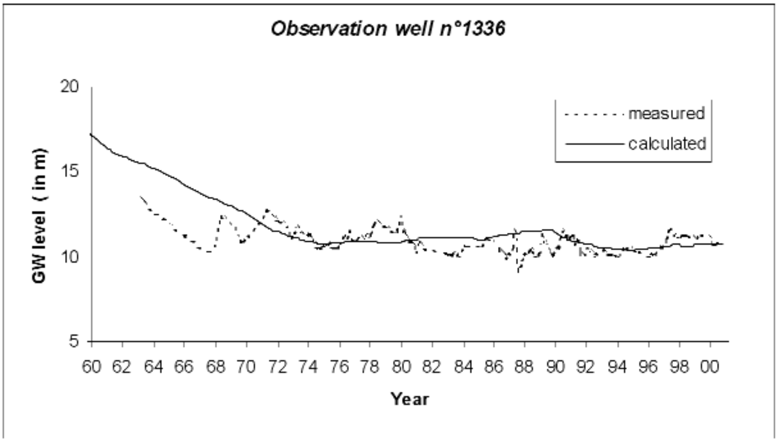
It is clear from Table 1 that the main component of the input corresponds to the recharge from precipitation, and that the ocean boundary constitutes the main outlet of the aquifer.

Table 1. Calculated mass balance in 1960 under steady state conditions.

	Water balance component	**Volumes in Mm^3 /yr**
Inflow	Recharge from precipitation	**52.67**
	Lateral flow from upstream aquifer	**6.24**
	Total	**58.91**
Outflow	Discharge to the Atlantic Ocean	**43.85**
	Discharge to the Oum Er Rbia river	**1.20**
	Evaporation	**13.34**
	Agricultural and domestic abstraction	**0.53**
	Total	**58.91**
Error %	**7 E-6**	

Transient simulations are conducted starting from the initial heads and concentration with reference to the 1960 steady state conditions, assuming that there were no changes in groundwater abstraction between 1949 and 1960. The initial salt concentration in the aquifer was assumed to be 0 kg/m^3. A transient calculation was performed for the 1960-2001 target period (41 years). The major pumping period started in1960 and was changed with lateral flows for the specified stress periods, based on field investigations and recorded data. The results of the transient calculations are prescribed in Figure 5, which shows satisfactory agreement between measured and calculated heads in different target observation wells for the considered simulation period. These transient simulations have provided answers to some of the questions raised by the decision makers and the local managers, such as:

- the date of the beginning of seawater intrusion into the aquifer and the follow up its evolution;
- identification of invaded zones by this intrusion, as well as their degree of contamination; and
- quantification of the volume of seawater intrusion, as well as the other components of the hydraulic mass balance.



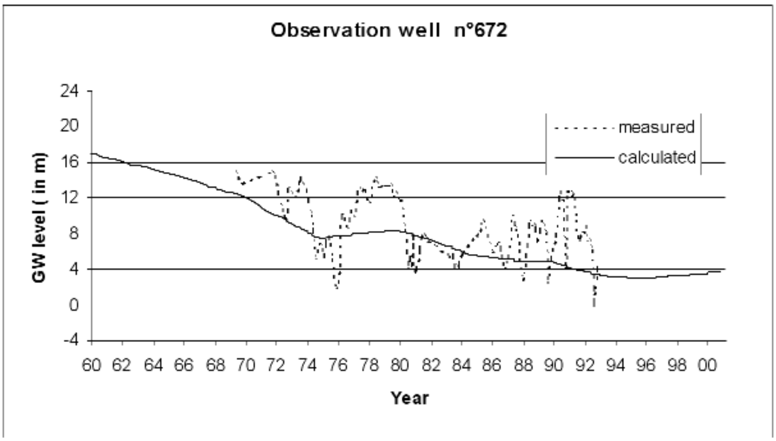


Figure 5. Calibrated and observed water level evolution.

Table 2 illustrates the results of the different water balance terms between 1965 and 2001, as obtained from the transient simulations. This table shows that intensive groundwater pumping, especially between 1965 and 1985, resulted in reduced storage in the aquifer, which reached 24 Mm^3 in 1985. As a consequence, seawater intrusion advanced inland and continued to progress until 1995. The concentration values calculated by the model identified the following invaded zones by seawater intrusion and their extent:

Table 2. Calculated mass balance for the transient simulations.

Water balance terms (Mm^3/yr)	**1965**	**1970**	**1975**	**1980**	**1985**	**1990**	**1995**	**2001**
Inflow storage variations	3,86	15,67	23,19	15,27	24,52	6,92	5,42	0,53
Seawater Intrusion	0	0	0	0	0,40	2,13	4,05	1,10
Recharge by precipitation	64,17	56,37	55,92	53,59	33,95	43,48	40,23	48,16
Lateral flow	5,86	5,53	4,56	3,72	3,08	2,81	2,67	2,37
Inflow from the Oum Er Rbia river	0	0	0	0	0	0,06	0,15	0,14
Total inflow	**73,89**	**77,57**	**83,67**	**72,58**	**61,95**	**55,40**	**52,52**	**52,30**
Outflow storage variations	0,34	0,03	0,06	0,37	0,56	8,18	3,83	4,75
Discharge to the Atlantic Ocean	41,90	34,05	23,71	23,23	13,60	10,12	8,18	10,30
Agricultural and domestic abstraction	16,36	32,79	51,93	41,71	42,43	31,12	34,65	30,62
Discharge tosprings	1,11	0,77	0,60	0,45	0,28	0,47	0,47	0,64
Evaporation	13,09	8,95	6,46	5,96	4,57	5,11	5,01	5,60
Discharge to the Oum Er Rbia river	1,08	0,98	0,92	0,87	0,50	0,40	0,37	0,38
Total outflow	**73,89**	**77,57**	**83,67**	**72,58**	**61,95**	**55,40**	**52,52**	**52,30**
Error %	-0.01	-0.003	-0.0058	-0.0089	-0.0005	-0.0073	-0.014	-0.0078

– the first zones invaded by the seawater intrusion in the earlier 1980s were located north of Azemmour. Afterwards, this invaded zone extended along the inshore line, reaching a length of about 20 km and a width of about 2 km, as shown in figures 6 and 7.
– the aquifer is strongly contaminated on the S-W coastal zone, in which the toe interface does not exceed the strip of 1 km of large. Beyond this zone, the contamination of the aquifer is limited;
– generally, the calculated concentration values exceed 10 g/L in the aquifer bottom.

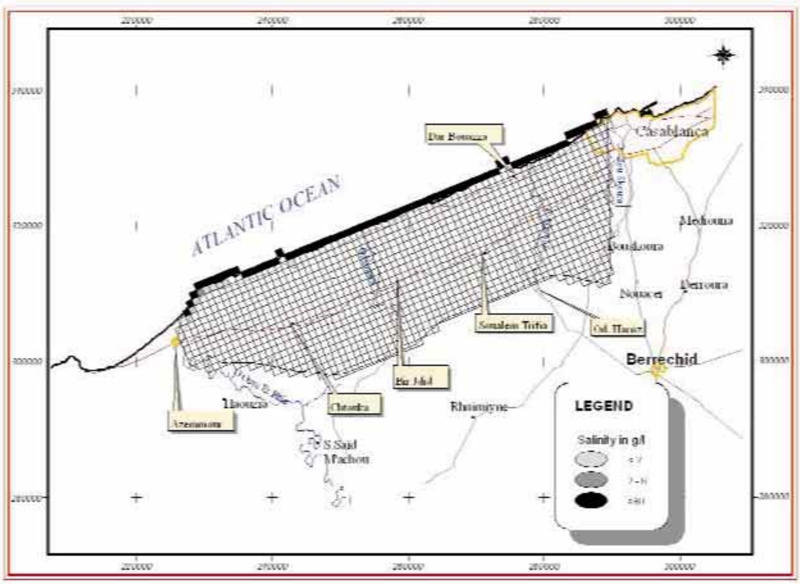


Figure 6. Simulated salinity distribution in 1985.

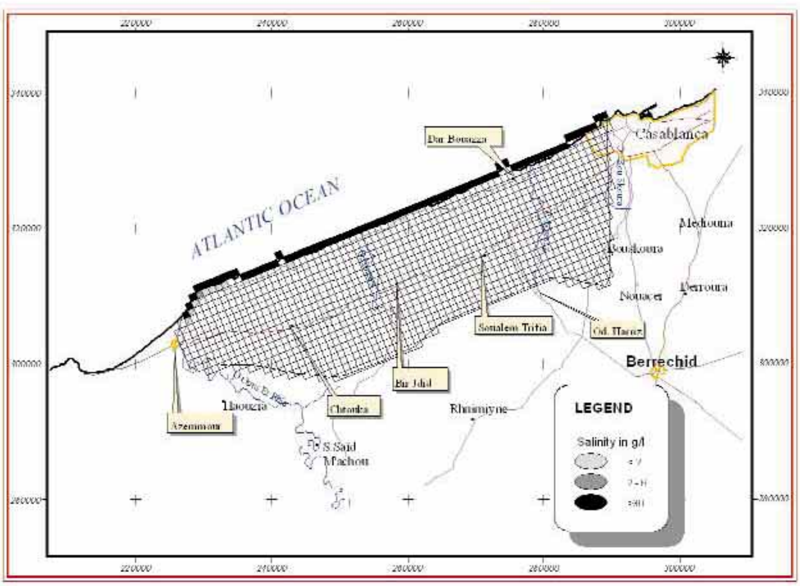


Figure 7. Simulated salinity distribution in 1995.

The relative vulnerability of the south-west part of the aquifer to seawater intrusion in comparison with the rest of the coast, is explained by the following factors:

- the relatively high hydraulic conductivity of the fissured limestone located in this sector of the coastal aquifer;

- the structure of the aquifer bottom that is deeper in this zone and reaches its maximum depth (between -60 m to -90 m) in this sector; and
- the high salt concentration of groundwater in the pumping wells in this sector.

In order to study the seawater intrusion effect on the south-western part, a model of transverse section with a refined mesh has been developed. The objective of this local model is to simulate the extent of saltwater intrusion with a finer spatial resolution in two dimensions. The model results will be of great importance for the management policy at the local level.

The mesh cells dimension is reduced to 100 m along the x-axis for the same simulation period adopted for the global model. Figure 8 illustrates the results of this transverse model in transient conditions. These results show that seawater intrusion started in 1980-85 by contaminating the aquifer up to 100 m from the coastline, and the estimated extent of the seawater intrusion wedge reaches 1300 m in 2001.

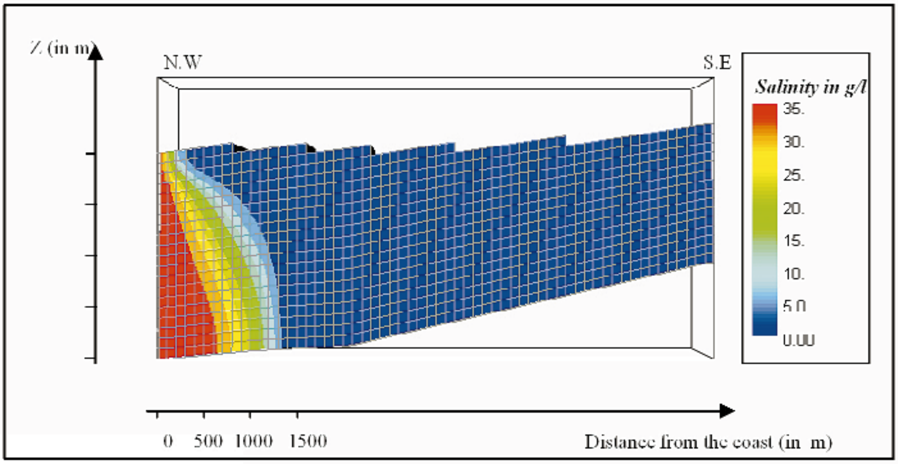


Figure 8. Result of the cross sectional simulation model in 2001.

Predicted results for a rational water management

The calibrated model can be used as a management tool for simulating the response of the aquifer, including the quantitative and qualitative aspects (variation of concentration in the Chaouia aquifer) based on proposed planning schemes by local managers.

As mentioned in previous sections, measured withdrawal of groundwater for irrigation supply, especially at the south-west sector, is the main cause of seawater intrusion into the aquifer, conjunctive decrease in groundwater withdrawal with artificial recharge is an important alternative to be considered in the future to prevent any further intrusion of saltwater inland. For this purpose, planning scenarios and schemes were designed to be used by the calibrated model for simulating the future changes in drawdown and salinity concentrations for a period of 40 years:

– The first scenario consists on the design of an irrigation project from surface water pumped from the Oum Er Rbia river. Pumping from the aquifer has to be stopped on the inshore strip to the East of Azemmour, along an area of 3 km x 20 km. A drastic reduction of withdrawal is planned when the irrigation project starts in 2005; this leads to a quasi-stabilization withdrawal of about 22 Mm^3/y, until the end of the simulation period.

– The second scenario (the worst) assumes that the irrigation project would not be achieved, and the pumping from the aquifer of about 30.5 Mm^3/y is maintained. The evolution of groundwater quality is analyzed in order to define the affected area by seawater intrusion.

In both cases, conditions of average annual rainfall, infiltration rate (normal conditions denoted as case a) and minimal annual rainfall infiltration rate about 70% of the normal infiltration rate (drought conditions, denoted as case b) are considered.

Results of the simulations

The corresponding scenario simulations are performed for a period of 40 years (2001-2040). For scenario 1a (Table 3), although the seawater intrusion volume decreases and the equilibrium is established after the year 2010 in response to the irrigation project from surface water, groundwater quality in the south-western sector would remain as of high salinity. The improvement of the water quality is a slow process, and would only be felt after the year 2020, when the width of the invaded zone by seawater intrusion would be reduced 1 km and the salinity would decrease significantly, as it is shown in Figure 9.

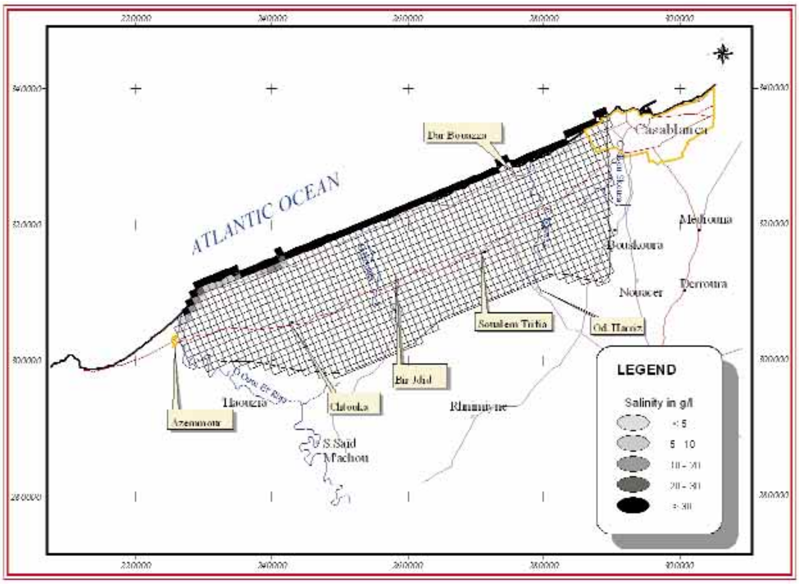


Figure 9. Results of scenario 1a in 2020.

The results also presented in Table 3 for scenario 1b shows that the volume of seawater intrusion progressively decreased until the year 2020; afterwards it continues to increase. The expected groundwater quality is not improving, as shown in Figure 10. The north-eastern sector of the coastal part would also be affected by this intrusion. The improvement in groundwater quality would remain very moderate by 2020 due to the reduced discharge towards the sea, which is 30% lower (drought conditions) compared to the discharge in the scenario 1a (normal conditions).

Table 3. Calculated volumes of seawater intrusion (in Mm^3/yr).

Year	2005	2010	2015	2020	2030	2040
Scenario 1a	1.45	0.2	0	0	0	0
Scenario 1b	2.00	0.42	0.27	0.26	0.31	0.50

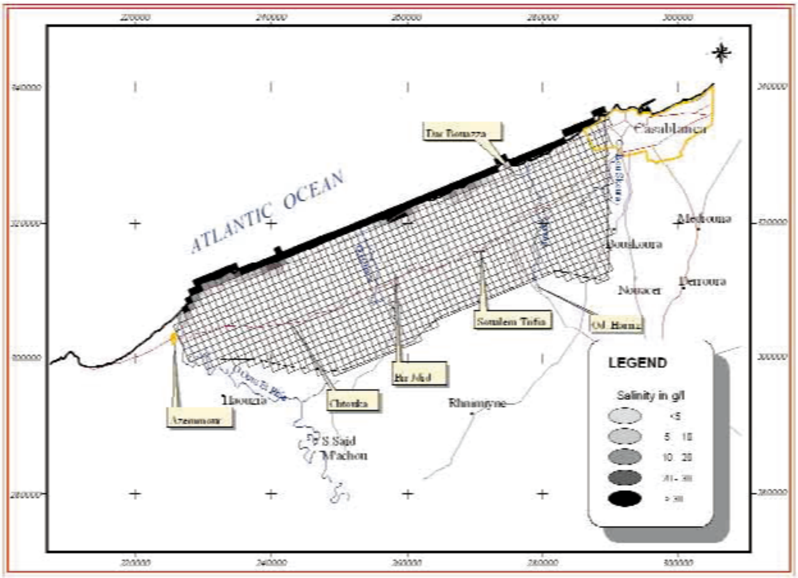


Figure 10. Results of scenario 1b in 2020.

The results of the first worst scenario 2a (Table 4) show that groundwater quality in the coastal zone is alarming, because of the important increment in salinity shown in Figure 11. Indeed, scenario 2a, with the average annual rainfall infiltration rate, leads to reach, after the year 2005, a new equilibrium condition, with a practically steady state volume of seawater intrusion (1.4 Mm^3/yr). However, the salinity in groundwater would continue to increase and would exceed 15g/L by 2020 in the deep aquifer levels.

For the second worst scenario 2b (Table 4), salinity and the volume of seawater intrusion would increase continuously and no stabilization would be established. The seawater intrusion volume would reach 3 Mm^3/yr by 2020; salinity would then exceed 20 g/L in the deepest aquifer levels. In addition, the invaded zone by the seawater intrusion would spread over 3 km and the northern sector of the coastal part would also be affected significantly by this intrusion (Figure 12).

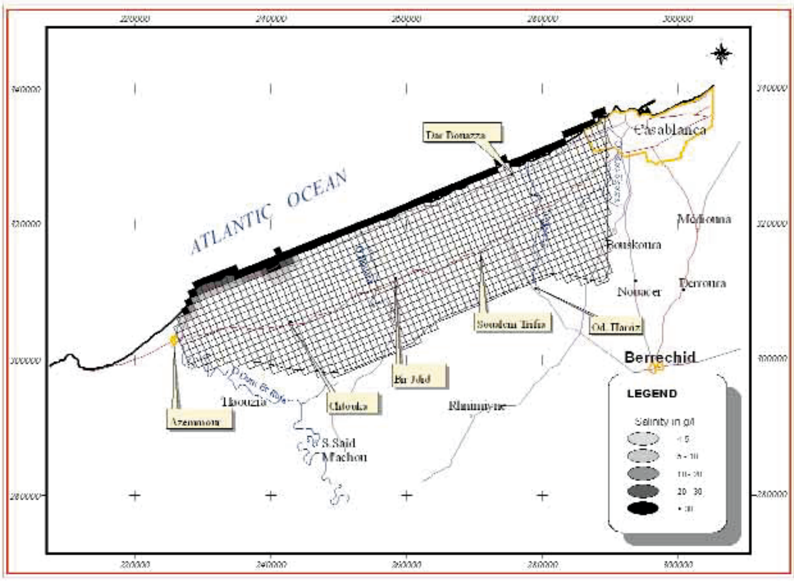


Figure 11. Results of scenario 2a in 2020.

Table.4. Calculated volumes of seawater intrusion (in Mm^3/yr).

Year	2005	2010	2015	2020	2030	2040
Scenario 1a	1.45	1.42	1.40	1.41	1.43	1.47
Scenario 1b	2.00	2.30	2.60	3.00	3.40	4.00

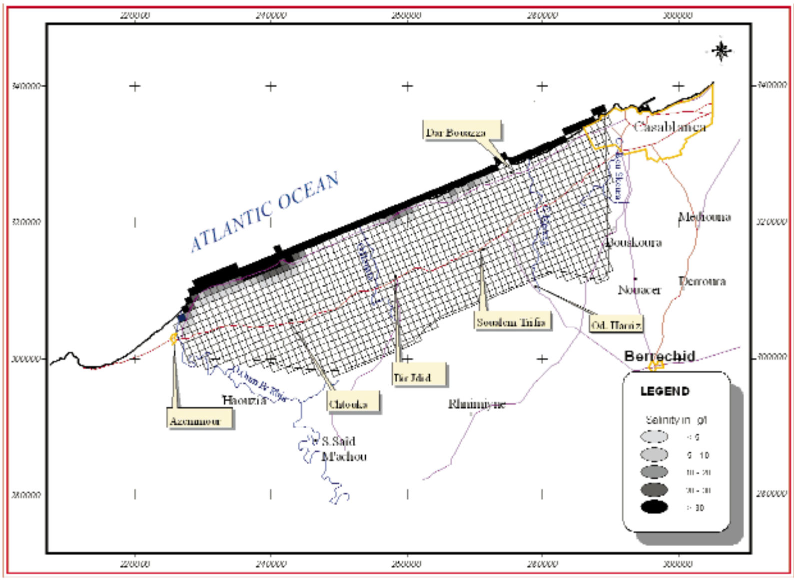


Figure 12. Results of scenario 2b in 2020.

In conclusion, we can say that the improvement in groundwater quality in the aquifer is conditioned by the withdrawal decrease and by increasing the discharge toward the ocean, which mainly depend on the aquifer recharge/discharge conditions. Hence, the predicted results from planning scenarios show that a sustainable management of the aquifer, especially in its coastal part, requires the use of surface water, which will contribute first to the economic development of the irrigated area by restoring the abandoned exploitation, and secondly to significantly improve groundwater quality in the invaded sectors of the aquifer by seawater intrusion.

Concluding remarks

This study constitutes a methodological approach to generalize modeling of seawater intrusion to coastal aquifers in Morocco. In fact, this phenomenon remained until now far from being well known for these aquifers. The present case study of the Chaouia coastal aquifer is an example of a pilot study to be developed for several coastal aquifers threatened by this phenomenon, as Morocco is extended over more than 3500 km of coastline.

All data used in this application have been analyzed, structured and organized in a database built-in via the GIS "Arc View " code and integrated into the conceptual model.

The coupled flow and transport code (SEAWAT) was used to analyze seawater intrusion in the Chaouai coastal aquifer in both qualitative and quantitative forms. The model results showed that seawater intrusion started by 1980-1985 in the south-western sector of the coastal part and developed within the time, due to intensive pumping from the wells and drought conditions.

The numerical model is also applied to test the response of the aquifer to two planning scenarios for a period of 40 years. The first one is the design of an irrigation project based on surface waters and stopping groundwater withdrawal in the south-west sector; and the second scenario is a continuous pumping from the aquifer. It is predicted that the first scenario will reduce considerably the quantity of seawater intrusion and improve groundwater quality, although in a slow manner in the south-western sector.

However, the results from the second scenario will induce a considerable quantity of seawater intrusion, and its extent progressed further inland, and will reach the north sector of the coastal part. Considering the missing data regarding aquifer, more recommendations are necessary to improve the results of this model:

– measurements of salinity along vertical profiles are necessary in the zone invaded by seawater intrusion. The measured values will contribute to improve the calibrated model;
– some tracing tests in the coastal part have to be carried out in order to estimate the dispersivity parameters of the aquifer;
– refinements of the cell grid used in the model have to be performed, especially near the shore, where the area is more threatened by seawater intrusion.

Acknowledgments

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