GROUNDWATER QUALITY IN COASTAL AQUIFERS IN MOROCCO

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ABSTRACT

The results of an initial research carried out in the several coastal aquifers are exposed. The studied areas are situated in the northern most part of Morocco. At the northeast are located the detrital aquifers of Smir and Martil-Alila, and in the northwest is located the detrital aquifer of Charf El Akab. The areas are underlain by detrital sediments of Pliocene to Quaternary age. Generally, groundwater has a high salinity and concentrations moder - ated to high of nitrates. The waters are meanly sodium-chloride type in Smir and Martil-Alila aquifers. The waters are sodium-chlorid- and calcium-bicarbonate type in Charf El Akab aquifer. The hydrochemical study of the water of the aquifers shows that the salinity is conditioned by human activities (waste water discharge, irrigation water, salt-water intrusion) and lithology (dissolution of evaporitic rocks), and by natural processes. In the Smir area, human activity has produced a series of negative effects on the hydrous equi - librium of lagoon "Merja" (recent construction of the Smir dam, and the installation of a marina in the outlet of the merja as well as the development of tourist facilities around the lagoon).

INTRODUCTION

Morocco is located in the westernmost part of the southern Mediterranean and has a surface area of 710,850 km^2. The country has a variety of landscapes, extending from the Mediterranean Sea in the N to the western Sahara in the S, and is characterised by great physical, climatic and social contrasts. The predominant climate in Morocco is of Mediterranean type, warm in the W and N and more continental inland, with considerable temperature variations. In the Atlas mountains, the climate is humid and snowfalls are frequent, while the S is characterised by a desert climate.

The oceanic area of Morocco comprises a large area in the W of the country. The advances of the central meseta divide this area into a series of basins and coastal plains that comprise 20% of the total surface area of the country, namely the Gharb with the river Sebou, Doukkala with the river Oum-er-R'bia, the Haou with the river Tensift, and Sous with the river Sous. Except for the river Moulouya, which flows into the Mediterranean, the principal hydrographic network of the country flows entirely into the Atlantic. All the above rivers flow from young mountains that constitute long dorsals of high ground flanked by plains and mesetas. Significant among these mountain reliefs are the Rif zone, where the highest mountain is Djebel Tidighine with an altitude of 2488 m, the Middle Atlas, and the High Atlas, where Djebel Toubkal, at an altitude of 4165 m constitutes the highest point of the Mahgreb. Finally, the Anti-Atlas is bounded to the S by the river Draa.

The coastline of Morocco is 3500 km long and contains fishing resources, tourist facilities and commercial ports.

According to recent surveys, the population of Morocco has undergone a rapid increase, rising from 15 million in 1960 to the present 30 million inhabitants. About 60% of the population live in coastal areas. The population increase has been paralleled by an ever-increasing demand for fresh water. This situation, which can be considered normal, has been aggravated by the effects of the drought that has affected the country over the last decade, and which has obliged the authorities to opt for one of the following policies:

- Increase the extraction rate of coastal groundwater, thus disturbing the fresh water / salt water balance.
- Obtain desalinised sea water.

REGIONAL GEOLOGY OF COASTAL ZONES IN MOROCCO

Both the Atlantic and the Mediterranean coastal areas contain important aquifers, whose characteristics are conditioned by the geological formations in which they are located. These aquifers include Plio-Quaternary, alluvial and deltaic deposits, together with sand-silt and fluvial-deltaic conglomerates. In addition to these detritic deposits, there is also karstic material such as the Calcareous Dorsal in the N, near Ceuta and Bokoya in the E, and also near the town of Al Huceima. These aquifers are not large and are interrupted by certain mountainous massifs, such as the Sébtide formations of Cabo Negro in the Tetouan area.

CHARACTERISTICS OF THE COASTAL AQUIFERS

The Moroccan coast contains many aquifers of varying nature. Table 1 describes some of their hydraulic characteristics.

These data summarise the situation of coastal groundwater in Morocco. High extraction rates in conjunction with an inappropriate policy of regional development have led to an imbalance in the fresh water/sea water equilibrium, producing a fall in the hydrostatic level, an inversion in the direction of groundwater flow and, finally, marine intrusion.

	Mediterranean coast			Atlantic coast		
Aquifer	Smir	Martil-Alila	Rhiss-Nekor	Charf el Akab	Bas-Loks	Marmora
Aquifer type	UA+ CA	UA+CA	UA+CA	CA	CA	UA+CA
Tr	$4.5.10^{-3}$	$9.5\ 10^{-2}$	6.10^{-2}	$3.2.10^{-3}$	$3.7\ 10^{-3}$	$8.6\ 10^{-3}$
Thickness	0-20	1-25	2-240	2-350	0-70	25
Max. Dep.	30	30	300	400	50	100
Flow E.	17	230	450	225	144	258
Estate	OE	OE	OE	OE	OE	OE

Table 1.- Hydraulic characteristics of some coastal aquifers in Morocco. UA : unconfined aquifer, CA: confined aquifer. OE: overexploited, Tr : Transmittivity (m^2/s) , Max. Dep. Maximum depth (m) . Flow E. : extraction rate (L/s).

STATE OF MARINE INTRUSION IN MOROCCO: THE AQUIFERS AFFECTED

Saline intrusion is a serious threat to fresh water resources in coastal aquifers. The fresh water/sea water equilibrium is always a fragile one, due to the high mixing potential between the two water types, and depends on the relation between recharge volume and water extraction rates. Industrial development, agricultural activities and the supply of fresh water to meet the demands of tourism, mainly in coastal areas, all lead to possible overexploitation of water resources and thus to an imbalance in the fresh water/sea water interface.

The problem of coastal aquifers in Morocco lies in their current state of overexploitation. The increase in demand, together with the impact of the drought that has affected the country over the last ten years, has given rise to high levels of extraction from some aquifers, such as those of Sous, Haouz, the Nador area (Rhiss-Nekor aquifer), around Tetouan (Martil-Alila and Smir aquifers), Rabat (Temara aquifer) and Casablanca (Rharb aquifer).

In general, few studies have been made of this question, but important work includes that by Stitou et al. (1995) and by Himi et al. (2001) on the aquifers of Martil-Alila, Smir and Oued Laou, by Tahiri et al on the Temara aquifer, by Hsissou et al. (1999) on the Sous aquifer and by Achhab on the aquifer of El Jadida.

The process of marine intrusion is well documented with respect to its origins and consequences, but its hydrodynamic and hydrochemical complexity can make it very difficult to characterise. Clearly, the most evident consequence of marine intrusion is the change in the saline content of aquifer water. This modification is due not only to the ionic effects of sea water but also to complex physical or physical-chemical processes that take place basically at the fresh wa-ter/salt water contact zone and which largely arise from the interaction between the liquid and solid phases of the aquifer.

With respect to the Tetouan littoral, and by integrating geophysical, hydrogeochemical and isotopic methods, a detailed cartography has been obtained of the fresh water/salt water transition zone. Electromagnetic prospection in the frequency domain was applied (Himi, 2001, and Himi *et al.* 2002), as were stable isotopes such as deuterium and oxygen 18, and the minority elements bromine, lithium and boron (Stitou, 2002 and Stitou *et al.* 2002). These studies revealed that in the Martil-Alila aquifer, the geometry of the basin plays a crucial role. The presence of Plio-Quaternary formations, which are thicker in the central part of the aquifer, mean that the aquifer-sea contact zone occupies a large area. Moreover, in periods of drought, the reduction in the flow of fresh water from natural recharge, accentuated by increased extraction, produces a flow of salt water inland, favoured by the high permeability of the aquifer in this sector.

WATER AUTHORITIES IN MOROCCO

The 10/95 Water Law defines instrumental, eco-nomic and legislative regulations for the establishment of a revised strategy for water use in Morocco. This law determined the basis for a new water culture, based on consensus, decentral-isation and on the participation of all water users, decision makers and policy creators.

The seven River Basin Agencies created by this law comprise the operational units needed to put into effect a water administration capable of achieving long-term socio-economic develop-ment and of improving the quality of life of the population. Another two organizations that inter-vene in water management are the National Office for Potable Water (ONEP), which is responsible for maintaining the quality of water destined for human consumption, and the Secre-tary of State for the Environment, whose inspec-tors monitor episodes of water contamination and determine re-sponsibilities.

Thus, numerous authorities are involved in water management, but the fact is that these have not prevented a continual degradation in the qual-ity and characteristics of this fragile but vital commodity.

Many methods have been suggested to solve the problem of marine intrusion, such as the installation of impermeable barriers and the recharge of aquifers by the injection of fresh water. Nevertheless, the simplest and most obvi-ous means is to reduce the rate of water extrac-tion; this solution is also the most economical and effective, even if the political will is sometimes absent. In the final analysis, however, a more rational use of water resources is required.

Marine intrusion is a particular hydrogeo-logic case that must be addressed with great care. To illustrate the phenomenon, we describe three aquifers located in the N of Morocco, namely Martil-Alila, Smir and Charaf el Akab (fig. 1). With respect to the methodology applied, a hydrochemical water-point monitoring network was established. These points comprised bore-holes drilled by the Loukkos River Basin Agency, in addition to private wells. All of these reached the aquifer systems in question, and were more numerous in the coastal area, where the problem of marine intrusion is more severe.

In the initial investigations carried out in these aquifers, the main physical-chemical char-acteristics of the groundwater were studied and attempts were made to identify the numerous processes that affect groundwater quality.

Hopefully, the results obtained will enable the administrative authorities of the areas in question to possess more information about this resource and thus groundwater management may be improved.

CASE STUDIES

The Smir aquifer

The Smir aquifer is located to the N of the town of Tetouan (fig. 1). It is bounded to the E by the Mediterranean Sea and has a surface area of 12 km^2 and a receptor basin of about 74 km^2.

Close to the NE boundary of the aquifer there is a lagoon known as Merja de Smir. This has a surface area of 3 km^2 and is of great eco-logic value, being a transit and breeding area for numerous migratory birds.

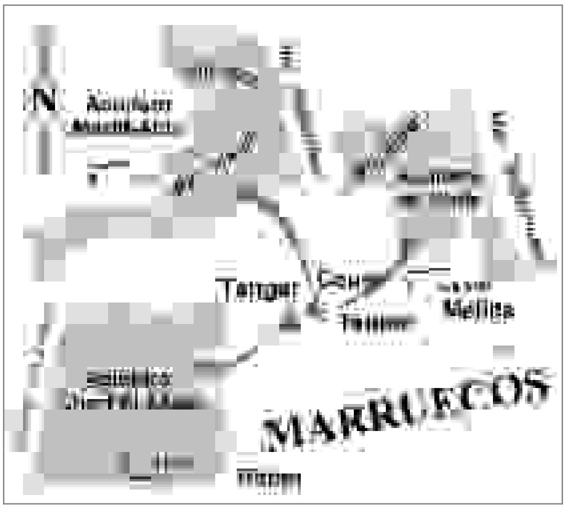

Figure 1: Geographic situation of the study zone.

In recent years, this zone has been the site of considerable development for agriculture and tourism (enabled by the obtention of surface and groundwater) and thus socio-economic advances have been achieved. However, this has also imposed a great deal of environmental pressure on an already fragile area (Stitou and Pulido-Bosch, 1995 and Stitou, 2002) and the long-term effects on the environment have yet to be fully determined. Furthermore, certain infrastructure construction projects, such as the Smir dam and a ma-rina, have also led to significant alterations in the natural water balance of the zone.

Hydrogeologic aspects

From the geologic viewpoint, and following Durand-Delga *et al* (1962), the study area was established as the so-called northern Rif, in the Inter-Rif zone. The preorogenic deposits that comprise the surrounding reliefs and part of the substrate of the aquifer (fig. 2) correspond to the Ghomaride and Sébtide complexes. The former is basically constituted of schists and phyllites, while the latter comprises gneisses, micaschists and quartzites.

The substrate of the aquifer is formed of postorogenic deposits, and corresponds to Pliocene-age marls and clays. At the top of all these, forming the Smir aquifer and with a thickness of approximately 20 m, are Quaternary alluvial deposits comprised of gravels, gravel and sand, sandy clays and silts.

From the hydrogeologic viewpoint, the Pliocene marls and clays behave as an aquitard and/or as an aquiclude. The Quaternary detritic deposits behave as an aquifer, although locally as an aquitard when the fine fraction is predominant. Groundwater depth is 0-4 m and transmittivity is around 138 m^2/day (Stitou and Pulido-Bosch, 1995).

The climate is sub-humid Mediterranean type, with an average annual precipitation of 600 mm and mean temperature of 16.3 ºC. Real evapotranspiration and useful rainfall during the period 1963-1991 (obtained by the Thornthwaite method, from daily data and assuming a field capacity of 50 mm) were 465 mm and 128 mm, respectively.

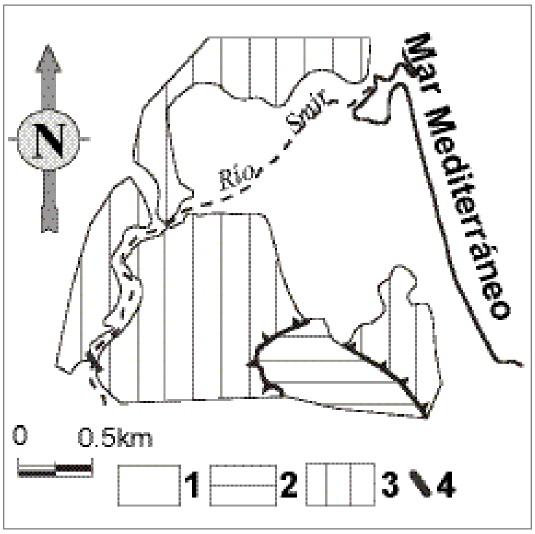

Figure 2: Geologic scheme of the Smir aquifer. 1: Quaternary; 2: Sébtide Complex; 3: Ghomaride Complex; 4: Smir dam.

Recharge of the Smir aquifer is effected mainly by the infiltration of precipitation (estimated at about 1.5 hm^3/year) and by the surface runoff generated on the receptor basin (approximately 1.8 hm^3/year). A small proportion of the infiltration is also derived by recharge from the river Smir and from the discharge of waste water from urban areas (around 0.5 hm^3/year).

Recharge from the river Smir has greatly diminished since the construction of the Smir dam. The Hydraulic Resources Authority in Tetouan calculated this recharge as being about 25 hm^3/year previously, which has now fallen to 1 hm^3/year. Output from the aquifer occurs by pumping from local wells, by groundwater flow into the Mediterranean and evaporation from the Merja lagoon.

This latter wetland comprises the zone where the Smir aquifer presents a hydrogeologically unconfined aspect. Its water is subject to evaporation, and so it comprises one of the natural outlets of the aquifer, with a volume estimated by Stitou and Pulido-Bosch (1995) at about 0.6 hm^3/year.

The increase in the uncontrolled extraction of groundwater to satisfy agricultural and urban demand, in conjunction with the decrease in surface runoff, has led to a severe reduction in water input to the Merja, and thus to a serious water imbalance. These circumstances produced a reduction in the surface area of the lagoon of almost 50%, with subsequent ecologic damage that has yet to be evaluated.

Groundwater quality

The physical-chemical characteristics of the waters in the Smir aquifer were studied by examining the results obtained from a network of 12 sampling points (all wells). "In situ" determinations were obtained of electrical conductivity, temperature and pH. In the laboratory, and using standard ASTM methods (1985) the Cl^-, SO_4^{2}, HCO_3^-, NO_3^-, Ca^{2+}, Mg^{2+}, Na^+ and K^+ ions were analysed. Table 2 shows the minimum, maximum, mean and standard deviation values for each of the variables analysed.

Temperature values were found to be 14-18 °C, close to the mean values for the area. The pH varied between acid and basic (5.6-8.0). The salinity of the samples obtained was extreme, ranging from 340-12,520 µS/cm.

The highest values were found close to the coast (near the lagoon) and to the NW and SE of the aquifer. With respect to the ions analysed, chloride and sodium were present in highest concentrations, reaching 7000 and 3900 mg/Lrespectively. Bicarbonate, though present in lower concentrations than the previous two, was also at a moderately high concentration, of 148-744 mg/L. Relatively high concentrations of nitrates, of up to 51 mg/L, were observed in some samples.

	Min.	**Max.**	**Mean**	**S.D.**
Cond	340	12520	2294	3318
T	13.5	18.0	15.6	1.3
pH	5.55	8.01	7.1	0.7
Cl^-	56	7019	850	1953
SO_4^{2-}	10	715	137	192
HCO_3^-	148	744	304	166
NO_3^-	0	51	19	18
Ca^{2+}	27	336	93	83
Mg^{2+}	11	251	56	64
Na^+	28	3909	481	1087
K^+	0.4	215	25	60.5

Table 2 : Minimum, maximum, mean and standard deviation (S.D.) of the variables calculated for the water samples taken from the Smir aquifer (Cond: conductivity in µS·cm^{-1}, T: temperature in ºC and ions in mg/L).

The Piper diagram in figure 3 shows that the main hydrochemical facies of the samples obtained from the Smir aquifer is sodium chloride, followed by a mixed water type and by calcium bicarbonate.

An important aspect is the possible existence of evaporitic rocks intercalated among the aquifer rocks, due to their contact with the sea. Therefore, the high salinity and relatively high concentrations of chloride and sulphate ions found in some samples taken from aquifer points inland could be related to these saline precipitates. Another process, in addition to the dissolution of evaporitic salts, and which could also contribute to the increased salinity of the aquifer, is the infiltration of waters derived from the evaporation concentration produced in the Merja lagoon.

Special attention should be paid to an aquifer point located near the coastline. Here, the salinity is very high (12,520 µS/cm), the facies is

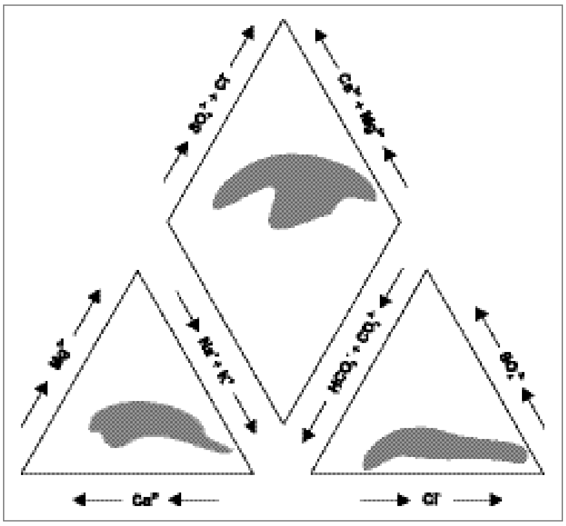

Figure 3: Piper diagram of groundwater in the Smir aquifer.

clearly sodium chloride, and concentrations of chloride, sulphate, bicarbonate, sodium, calcium and magnesium ions are very high. On the basis of currently available data, we cannot discard the possibility that a process of marine intrusion may be affecting areas of the aquifer close to this point. In the study zone, the main sources of contamination identified are discharges of untreated solid and liquid waste from the town of M'diq and from the tourist urbanisations in the region. The former are discharged directly into the Merja lagoon, while the latter are deposited at its edges. Residual substances from agricultural activities also comprise important localised sources of contamination. All these factors contribute to the high concentrations of nitrates found in some water samples from the aquifer.

The Martil-Alila aquifer

The Martil-Alila aquifer is in the N of Morocco (fig. 1) near the towns of Tetouan and Martil, and has a surface area of 87 km^2. In recent years, the population in this zone has grown considerably, which has led to a significant rise in demand for water from the aquifer, as well as to increased and uncontrolled discharge of solid and liquid urban waste materials.

Hydrogeologic aspects

The Martil-Alila aquifer lies in the internal domain of the Rif Cordillera. The rocks that outcrop around the aquifer (fig. 4) correspond to schists and pelites of the Ghomaride Complex, to micaschists and gneisses of the Sébtide Complex, to carbonate rocks of the Limestone Dorsal and to flysch deposits. The rocks of the aquifer substrate are fundamentally comprised of marls and clays. The materials constituting the aquifer are basically sands, gravels and conglomerates, of Plio-Quaternary age and with a thickness of up to 30 m. To the S of the aquifer, there is a more clayey predominance among the sediments.

With respect to the hydrogeologic characteristics of the aquifer, and in agreement with El Morabiti and Pulido-Bosch (1993) and *Direction Régionale de l'Hydraulique* (1998), the transmissivity varies within a fairly wide range, from 17-7690 m^2/d, with a mean value of 2074 m^2/d. The highest transmissivity values are found close to the courses of the rivers Martil and Alila. On the contrary, the lowest values are recorded towards the S of the aquifer. The storage coefficient is between $4.6.10^{-3}$ and $6.6.10^{-4}$.

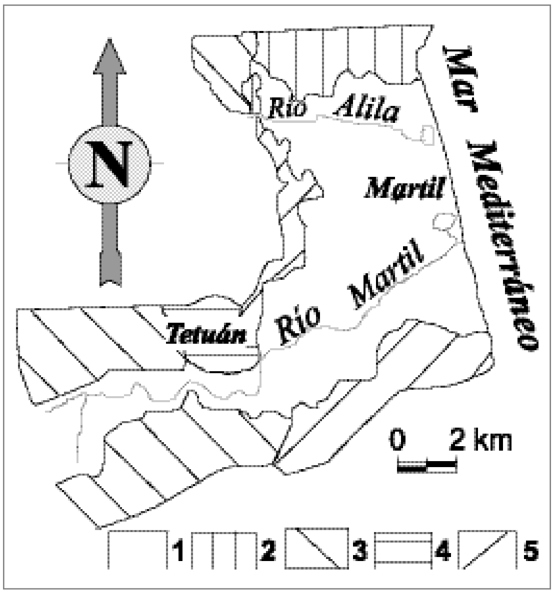

Figure 4: Geologic scheme of the Martil-Alila aquifer (1: Plio-Quaternary; 2: Sébtide Complex; 3: Flysch; 4: Limestone Dorsal; 5: Ghomaride Complex).

The infiltration of precipitation comprises the principal source of aquifer recharge, although another input is the water flow through the carbonate deposits of the Limestone Dorsal that forms part of the aquifer. A lesser source of recharge is the return from irrigation. Output from the aquifer is mainly due to pumped extraction, but flows to the sea have also been recorded.

The climate is sub-humid Mediterranean type, with average annual precipitation of 650 mm and mean temperature of 16.3 °C (during the period 1963-1995). For the same period, real evapotranspiration (obtained by the Thornthwaite method, assuming a field capacity of 50 mm) was 465 mm, while useful rainfall was estimated at about 128 mm.

The river Alila lies in the southern part of this alluvial plain, and presents a discontinuous water regime. The river Martil flows permanently through the N of the area.

Groundwater quality

The main physical-chemical characteristics of the Martil-Alila aquifer were studied on the basis of the samples obtained from different aquifer points. "In situ" determinations were obtained of electrical conductivity, temperature and pH. In the laboratory, and using standard ASTM methods (1985) the Cl^-, SO_4^{2}, HCO_3^-, NO_3^-, Ca^{2+}, Mg^{2+}, Na^+ and K^+ ions were analysed. Table 3 shows the minimum, maximum, mean and standard deviation values for each of the variables analysed.

The temperature values were between 20 and 26 °C, which indicates a certain degree of thermalism. The salinity of the waters in the aquifer varied greatly. The conductivity ranged from 250 to 6200 µS/cm. Chloride concentrations were 20-1410 mg/L. Sodium concentration varied between 14 and 827 mg/L, while nitrate concentration was fairly high, at almost 130 mg/L.

	Min.	Max.	Mean	S.D.
Cond	250	6200	2026	1884.7
T	20.0	26.0	22.0	1.9
pH	6.8	8.4	7.6	0.5
Cl^-	20	1410	503	448.0
SO_4^{2-}	14	695	224	199.9
HCO_3^-	91	524	300	158.4
NO_3^-	1	129	43	47.1
Ca^{2+}	17	371	128	114.3
Mg^{2+}	13	127	67	40.4
Na^+	14	827	278	229.3
K^+	1	41	10	11.4

Table 3: Minimum, maximum, mean and standard deviation (S.D.) of the variables calculated for the water samples taken from the Martil-Alila aquifer (Cond: conductivity in µS·cm^{-1}, T: temperature in ºC and ions in mg/L).

The Piper diagram in figure 5 shows that the predominant water facies in the samples obtained from the aquifer is sodium chloride, followed by mixed type and by calcium bicarbonate. The detritic nature of the aquifer, which is mainly formed by carbonate rock pebbles, is responsible for the calcium bicarbonate facies and the low salinity of some of the samples.

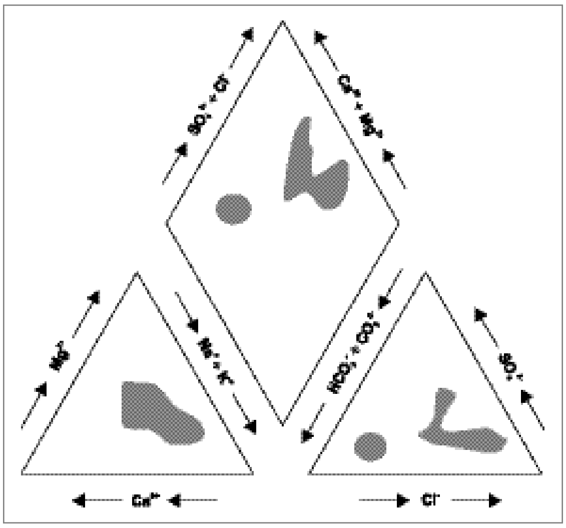

Figure 5: Piper diagram of the samples obtained from the Martil-Alila aquifer.

The fact that the Martil-Alila aquifer is close to the sea means we must also consider the possibility that evaporitic minerals may be intercalated within the aquifer, as a result of former episodes of varying sea level. This circumstance would explain why salinity here is greater than in other water samples. Nevertheless, among these samples some have a clearly sodium chloride facies while others are of a mixed type (being related to rocks of a more sulphate nature).

The conductivity measurements obtained by *Direction Régionale de l'Hydraulique* at a borehole drilled between the town of Martil and the coastline produced values exceeding 15,000 µS/cm, which leads us to consider that a process of marine intrusion may have occurred and could affect parts of the aquifer near the town of Martil.

Finally, evidence of the discharge of solid and liquid urban waste, mainly from the towns of Tetouan and Martil, in addition to waste materials from agricultural activities in the zone, comprise important local sources of contamination, as seems to be indicated by the high concentrations of nitrates in some of the water samples.

The Charf el Akab aquifer

The Charf El Akab aquifer is in northern Morocco, about 20 km S of the city of Tangier (fig. 1), and its waters are extracted to supply drinking water to this city. Due to the limited natural input of water to the aquifer at present, tests of artificial recharge using treated wastewater are planned. Due to their hydrochemical implications, it is important to note the presence of two highly saline marshlands in this area.

Hydrogeologic aspects

With respect to their geologic characteristics (fig. 6), the rocks that outcrop in the study area correspond to the post-nappe formations of the Charf El Akab basin, which has a surface area of about 20 km^2. Both on the northern and on the eastern edges of the basin there are outcropping rocks of the Rif domain. These are fundamentally sandstones and constitute the main relief features of these two boundaries. The aquifer is bounded to the W by the Atlantic Ocean and to the S and SE by an alluvial plain called Oued Tahaddart. The basin is characterised by its present subsidence.

The detritic sediments of the basin are of late Miocene age, and in these it is possible to distinguish a lower complex containing calcarenites, sandstones and bioclastic sands of late Tortonian age. Above these, in an intermediate position, rests a formation mainly constituted of marls and marly sands of early Messinian age. Finally, at the top of the whole series, is the outcropping formation fundamentally made up of sands and fine sandstones of late Messinian age (Medioni & Wernli, 1978). Towards the western boundary, and above the previous series, there are outcrops of sands and silts with dark-coloured Quaternary sands.

The calcarenites, sandstones and bioclastic sands of the Tortonian formation, together with the sands and sandstones of the Messinian formation, present the best aquifer characteristics, and so the boreholes made in this area mainly extract from these materials.

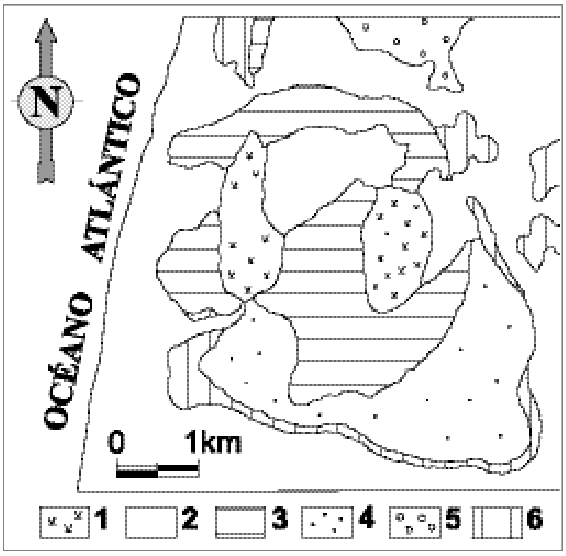

Figure 6: Geologic scheme of the Charf El Akab aquifer (1: marsh; 2: sands and silts with sands; 3: sands, marls and marly sands; 4: calcarenites and sands; 5: sandstones; 6: calcarenites).

Groundwater quality

The main physical and chemical characteristics of the Charf El Akab aquifer have been studied from the water samples obtained from a set of twelve aquifer points, corresponding to late Tortonian and late Messinian formations.

"In situ" determinations were obtained of electrical conductivity, temperature and pH. In the laboratory, and using standard ASTM methods (1985) the Cl^-, SO_4^{2}, HCO_3^-, NO_3^-, Ca^{2+}, Mg^{2+}, Na^+ and K^+ ions were analysed. Table 4 shows the minimum, maximum, mean and standard deviation values for each of the variables analysed.

The temperatures of the samples were fairly regular, from 21-25 °C. In general, the lowest temperatures were recorded in the boreholes that extracted samples from the Tortonian formation. pH values were acid to neutral (5.8-7.2). The conductivity of the samples was extremely varied, from 100-2900 µS/cm, although at one aquifer point (where samples were obtained from the upper formation and which was very close to one of the lagoons) the conductivity was 17,509 µS/cm.

The concentration of chloride reached 5627 mg/L at this same aquifer point, and for the other samples ranged from 24-242 mg/L. Relatively low concentrations of sulphates were recorded; these did not exceed 52 mg/Lexcept for two samples that contained 799 and 624 mg/L. Bicarbonate concentration was very irregular, but on occasion, high values were recorded (up to 634 mg/L).

	Min.	**Max.**	**Mean**	**S.D.**
Cond	100	17509	2248	5117,5
T	21	25	22,6	1,6
pH	5,8	7,2	6,5	0,5
Cl^-	24	5627	606	1666,6
SO_4^{2-}	4	799	151	280,3
HCO_3^-	5	634	223	186,5
NO_3^-	0	36,9	7,6	14,2
Ca^{2+}	2	98	52	30
Mg^{2+}	3	480	67	139,3
Na^+	3	3105	361	921,7
K^+	0,3	42,1	8,3	14,2

Table 4: Minimum, maximum, mean and standard deviation (S.D.) of the variables calculated for the water samples taken from the Charf El Akab aquifer (Cond: conductivity in µS·cm^{-1}, T: temperature in ºC and ions in mg/L).

The samples present nitrate contents that range from low to moderately high (37 mg/L). This latter value, well above that recorded at the other aquifer points (where it does not exceed 3 mg/L) is presumably related to local sources of contamination derived from agricultural activities.

The concentration of sodium varies from 3-3105 mg/L. Although the latter value is very high, the sodium content of most of the samples was below 90 mg/L. Calcium concentration did not exceed 98 mg/L, but magnesium contents were moderately high in most of the samples obtained, reaching 94 mg/L (except in one sample, where a value of 480 mg/L was recorded). The concentration of potassium was very high at two aquifer points, reaching 42 mg/L.

The hydrochemical facies of the samples obtained from the Charf el Akab aquifer were varied (fig. 7). At most of the aquifer points there was a predominance of sodium chloride and calcium bicarbonate water types, while a minority presence of magnesium chloride, sodium sulphate and mixed bicarbonate/chloride facies was observed.

The high levels of salinity, together with the relatively high concentrations of chloride and sulphate ions found in some of the samples obtained at aquifer points corresponding to both the upper and the lower formations, located in inland areas, could be due to the proximity of the aquifer to the coast, a fact that could have facilitated the formation of highly soluble evaporites within the rocks of the aquifer.

Two processes could also have contributed to the increased levels of dissolved salts in the aquifer water. The first of these would be the

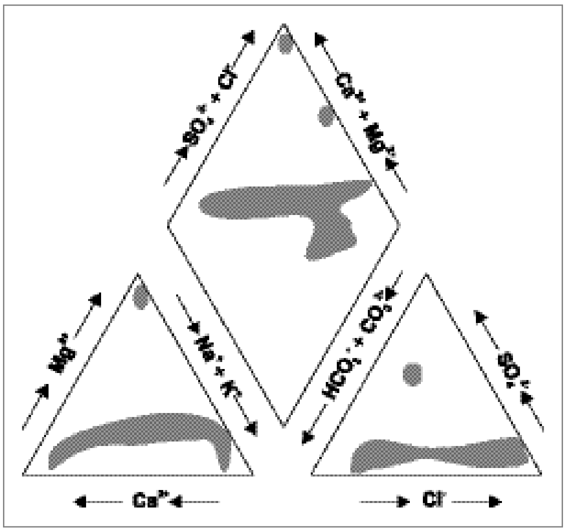

Figure 7: Piper diagram of the samples obtained from the Charf el Akab aquifer.

infiltration of water subjected to salt concentration and precipitation as a result of evaporation, due to the extreme aridity of the zone; this would mainly have occurred in the two lagoons in the area. The second factor is that in periods of little precipitation, its rapid evaporation would cause the accumulation of salts in the soil. These would subsequently be dissolved and would infiltrate into the aquifer when a subsequent and significant precipitation occurred.

Both of these processes, namely the infiltration of lagoon water and the infiltration of water containing salts leached from the soil, would mainly affect the boreholes extracting water from the upper formation.

PRINCIPAL CONCLUSIONS

Smir aquifer

The groundwater of the Smir detritic aquifer is of a mainly sodium chloride type. Its conductivity varies from 340-2580 µS/cm and high concentrations of chloride, sulphate and sodium are found.

The salinity of the aquifer waters is generally high and would be conditioned both by human activities (the discharge of solid and liquid urban waste and the uncontrolled discharge of agricultural surpluses) and by natural causes (concentration caused by the evaporation of surface waters). Special attention should be paid to the hydrochemical characteristics of an aquifer point close to the coast, where the salinity exceeds 12,520 µS/cm and where a process of marine intrusion could be starting.

Martil-Alila aquifer

The waters of the Martil-Alila aquifer are mainly of a sodium chloride facies. These waters present a certain degree of thermalism. Conductivity values are relatively high, on occasion reaching 6000 S/cm. Some ions are present at high concentrations; this is the case of chloride, which exceeds 1200 mg/L and of sodium, which exceeds 800 mg/L.

The different processes contributing to water salinity are associated with the concentration by evaporation and subsequent infiltration of surface water. Also involved are the uncontrolled discharge of solid and liquid urban waste, and of agricultural waste. This aquifer, too, seems to be affected by a process of marine intrusion in sectors close to the town of Martil.

Charf el Akab aquifer

This zone contains two areas of marshland where the water presents high levels of salinity. Most of the boreholes extract from areas of calcarenites, sandstones and bioclastic sands of Tortonian age and sands and sandstones of Messinian age.

The predominant hydrochemical facies of the aquifer water is sodium chloride and calcium bicarbonate. Water temperature ranges from 21-25 °C. The pH varies from 5.8-7-2 and the conductivity ranges from 100-17,509 µS/cm. Chloride is present at concentrations of 24-5627 mg/L, while sulphate concentrations reach 799 mg/L and those of bicarbonate, from 5-634 mg/L. Nitrate concentrations are moderately high, up to 37 mg/L. Sodium concentration varies from 3-3105 mg/L and calcium concentration is relatively high, up to 98 mg/L. Magnesium content can reach 480 mg/Land that of potassium, 42 mg/L.

The main processes that seem to condition water salinity in the aquifer are related to the dissolution of evaporitic salts and to the infiltration of water that is rich in salts, having been precipitated and concentrated by the high levels of evaporation that occur in this area. Additionally, there are localised sources of contamination related to agricultural activities; these could explain the relatively high nitrate ion contents found.

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