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D – data interpretation
E – manuscript preparation
F – literature search

Identification of marine intrusion in the plain of Collo, northeastern Algeria

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Abstract

The population increase, urbanization and intensification of agriculture and demands for water supply in the coastal plain of Collo led to excessive pumping of the unconfined aquifer with limited dimensions. This study aimed to characterize the effect of the overexploitation of the groundwater from the only unconfined aquifer in the region, what resulted in the inversion of the groundwater flow and the rise the possible seawater pollution that is shown in the water table map. The causes and effects of the saltwater intrusion were discussed. The interpretation of the electrical conductivity measurements, chloride and sodium maps have shown clearly the areas where values were the highest with tighter curves towards the sea, the wadis Guebli and Cherka. These values distribution indicated a marine source of salinity in wells and boreholes close to the sea and wadis.

Key words: *Algeria, coastal aquifer, Collo, marine intrusion, water salinity*

INTRODUCTION

Salinization process affects many coastal aquifers throughout the world, and their effects are of concern in subhumid regions, where aquifers are subject to overexploitation [ABDALLA *et al.* 2010; EL YAOUTI *et al.* 2009; SHIRAZI *et al.* 2015].

However, the water supply deficit in the northeastern coastal aquifers, with increasing population in a high rate, has led in the last years to a search for more reliable water sources and producing, as a consequence, an intensive exploitation of the coastal aquifers in the most densely occupied area in the alluvial plain of Collo where water demand has become increasingly significant, rises [ATTOUI *et al.* 2017]. This extreme exploitation associated with the difficulties in the process of natural recharge, due to soil impermeabilization associated with intensive urbanization has posed the system under threat of degradation, both in terms of water quantity and quality, associated to the risk of salt water intrusion [DJOUDAR *et al.* 2008]. Balance changes in the interface between freshwater and saltwater cause the advance of the salt wedge [HSISSOU *et al.* 1997].

Algeria like all the Mediterranean seaboard countries has experienced periods of drought over the past two decades, when more than fifty percent of the rainfall did not exceed the threshold of 600 $mm \cdot year^{-1}$, which is far from a rainfall of a Mediterranean coastal zone like Collo. The water table has undergone intensive exploitation of groundwater by about sixty wells, intended for drinking water supply and land irrigation, in addition to some boreholes located along the Guebli River which are unfortunately mostly stopped because of the high water salinity.

Many studies have been undertaken on the physical processes occurring at the freshwater–saltwater interface in terms of the flow and transport of miscible fluids of different densities [ABD-ELHAMID, JAVADI 2011; KHUBLARYAN *et al.* 2008]. Generally, studies based on the hydrochemical processes linked to marine intrusion in coastal aquifers cover are quite frequent [GATTACCECA *et al.* 2009; MA *et al.* 2007], whereas there are few examples of detailed monitor-

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ing of hydrogeochemical processes occurring in the freshwater–seawater transition band [ANDERSEN *et al.* 2005].

The phenomenon of marine invasion of coastal aquifers can expand over several kilometers inland and contaminate groundwater [TRABELSI *et al.* 2005]. The collected geological, geophysical, hydrodynamic, hydrochemical and hydro-climatic data and their analysis would provide an idea about geometry and structure of the coastal unconfined aquifer in the plain of Collo, and might enable us to know its hydrodynamic and hydrochemical aspects. Intensive and persistent use of groundwater from Collo aquifer has unfortunately created an imbalance of fresh and salt water interaction, which has moved the interface inland.

The objective of the current study was to identify the hydrogeochemical processes that took place in the freshwater–seawater transition over the coastal band when pumping was carried out in the alluvial plain of Collo along Wadi Guebli. To achieve this, the electrical geophysical survey has been carried out and served as a basic statement for a further estimation of the hydraulic parameters of aquifers and alluvium thickness to define potential zones for groundwater supply.

DESCRIPTION OF THE STUDY AREA

The plain of Collo belongs to the sub-watershed of Wadi Guebli located in the northwest of Skikda (Algeria). The plain is of elongated shape with a length of 8 km and a width of 5 km and an area of about 40 km^2 (Fig. 1). The climate of the area is Mediterranean with rainfall ranging between 800 and 1000 mm·year^{-1}, and making it amongst the wettest areas of Algeria.

The hydrographic network is represented by the Wadi Guebli that crosses the plain from the south to the north with its main tributaries Guergoura, Fessa and Cherka. The flow of these rivers is relatively permanent and plays a vital role in recharging the alluvial aquifer and restoring surface water level of Guenitra dam. However, they are unfortunately not equipped with hydrometric stations and consequently they are not gauged.

The geological structure of the study area is relatively simple; the valley is carved in metamorphic rocks (micaschists and Kabyle gneiss) beneath the marine sedimentary deposits. The Mio-Pliocene marls form the impervious bed of the alluvial plain. The surrounding metamorphic rocks are faulted and/or weathered, especially in the southern part [MARRE 1992]. This alluvial plain contains the main aquifer of the region (Fig. 2).

The aquifer formations are of quaternary age and have a heterogeneous composition. Their thickness ranges from 5 to 25 meters from the Northwest to the Southeast. The drilled boreholes on the plain crossed alternating sand, gravel and pebbles with clay passages before discovering the impervious Pliocene marl formation with some metamorphic rock outcrops.

The thickness and nature of the alluvial aquifer have been defined from the drilling data. The aquifer layer is characterized by high transmissivity values ranging, in the area located on the left side of Wadi Guebli to the Northeast from Koudiat Telezza, beteen $5.3\cdot10^{-2}$ m^2·s^{-1} and 10^{-2} m^2·s^{-1}. The transmissivity

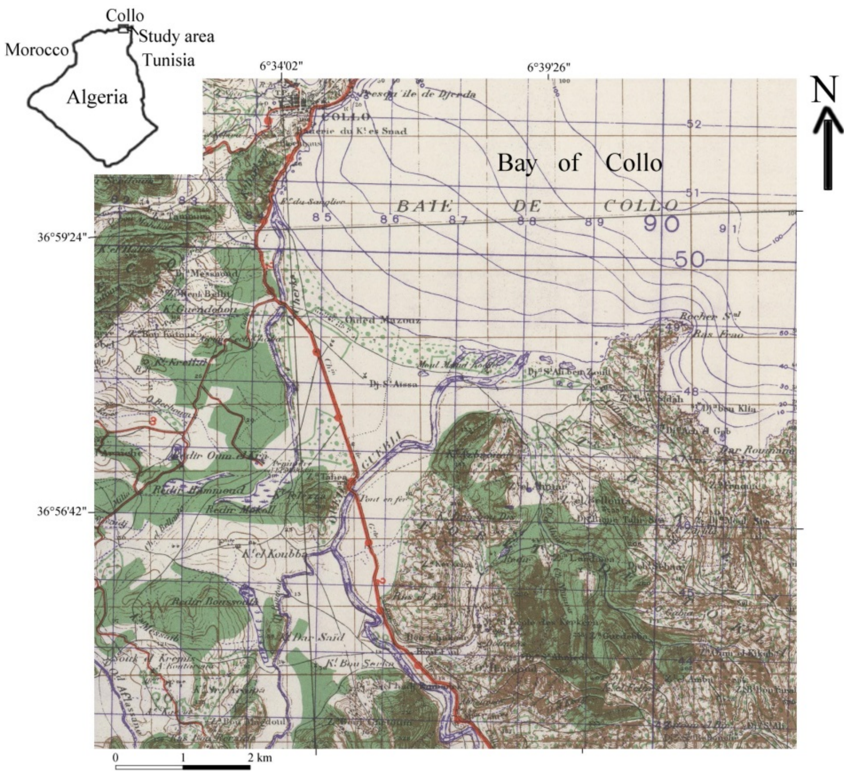

Fig. 1. Location map of the region of Collo; source: Algerian National Agency of Cartography [INCT 1966]

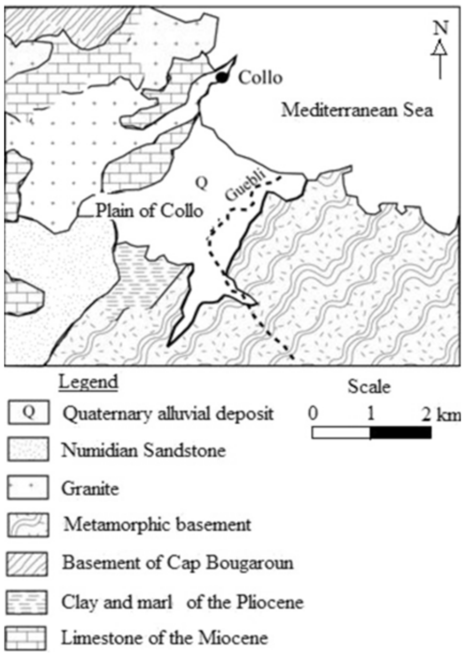

Fig. 2. Geological map of the study area; source: own elaboration

values decrease gradually away from this zone towards the southwest to reach 10^{-5} $m^2 \cdot s^{-1}$. The groundwater recharge of the aquifer occurs from the effective infiltration of rainfall and by leakage from Wadi Guebli in the downstream part. The groundwater outputs are represented by evapotranspiration, pumping and flow towards the sea.

MATERIALS AND METHODS

The geophysical, hydrodynamical and hydrochemical data were generated through a field survey. The old existing data were reviewed and used.

GEOPHYSICS

The aim of the geophysical survey was to determine the alluvium thickness and the marl bedrock morphology, to clarify the limit between the upstream silts and downstream sands and gravels, to locate the sand and gravel lenses in the south of Koudiat Télézza, and especially to delineate the invasion's extension of the seawater along the shoreline and near Wadi Cherka.

In 1965, the General Geophysical Company (Fr. Compagnie Générale de Géophysique – CGG) performed a geophysical study on the lower valley of Wadi Guebli and a transverse on a reservoir of Wadi Aflassane, related to the region of Collo. The company performed a total of 289 vertical electrical soundings, 14 conventional seismic transverses and 5 transverses that were carried out from different locations in the alluvial plain of Collo. The maximum electrode spacing of current electrode (AB/2) was extended to 100 m by Schlumberger electrode arrangements suggested that complete lithology of this coastal district.

GROUNDWATER FLOW

Groundwater levels were measured in a number of observation wells to ensure the reliability and consistency of the historical data and other information available in the water resources database of the National Agency of Hydraulics (Fr. Agence Nationale des Ressources Hydrauliques – ANRH, Constantine). Number of farms were also visited to assess the effect of groundwater deterioration on soil salinization and crops productivity.

The groundwater level was measured after pumping in the wells. As all wells were regularly exploited, it was not necessary to include a long pre-pumping period. The depth of the wells ranges from 7 to 50 m. Some wells were tapping the upper aquifer, while others tap the lower aquifer. Field measurements such as pH, temperature and electrical conductivity were carried out using multimeter electrode equipment. These data, which include well logs of boreholes and wells drilled prior to 2014 were collected from well drilling reports from National Agency of Dams and Transfers (Fr. Agence Nationale des Barrages et Transfers – ANBT).

The water level in the aquifer and definition of the hydrodynamic aspects of the aquifer were carried out by two piezometric records campaigns of 1965 and 2014 on 15 wells and on 4 boreholes in 2014.

HYDROCHEMISTRY

Geochemical properties and principles that govern the behavior of dissolved chemical constituents in groundwater are referred to as hydrogeochemistry [OBIEFUNA, SHERIFF 2011]. The chemical composition of groundwater is related to the solid constitution of rock weathering and changes with respect to time and space. Therefore, the variation on the concentration levels of the different hydrogeochemical constituents dissolved in water determines its usefulness for domestic, industrial and agricultural purposes.

The hydrochemical samples were analysed and treated using Aquachem software [CALMBACH 1997]. Chemical analysis of samples collected during two campaigns in dry period (November 2013) and wet period (April 2014) allowed to characterize the water quality of the reservoir and to monitor the probable position of the saltwater intrusion [SAJIL KUMAR *et al.* 2013].

According to some authors such as POUTOUKIS [1991], TELLAM [1995] and HSISSOU *et al.* [2001], the analyzed elements electrical conductivity *EC*, Cl^- and Mg^{2+}/Ca^{2+}, which are characteristic parameters of seawater, were established in order to identify groundwater mineralization process. Unfortunately, some other salts that could be present in water as bromides have not been analysed due to the lack of laboratory resources.

Irrigation water quality usually varies depending upon the types and quantities of dissolved salts. Therefore, water suitability for irrigation use is determined not only by the total amount of dissolved solids but also by the kind of salt [SARKAR, HASSAN 2006]. According to OBIEFUNA and SHERIFF [2011], the irrigation water quality is judged by four accepted criteria: (1) TDS, (2) relative proportion of sodium to other cations, expressed by sodium adsorption ratio (SAR), (3) chlorine (Cl^-) or/and boron contents, and (4) residual sodium carbonate [AGOUBI *et al*. 2013].

RESULTS AND DISCUSSION

The problem of salinity is a major threat to the coastal region of Collo that depends on groundwater depletion for water supply [LHADI *et al*. 1996]. Under some conditions, the salt water infiltrates inland and contaminates the fresh water located near the seashore [BOUTKHIL 2007].

Identification of the origin of the salinity in the groundwater is difficult due to the existence of several processes involved in the increase of the chemical elements' concentration.

GEOPHYSICAL APPROACH

The results of the data interpretation have revealed that the resistivity of the groundwater ranged usually between 7.2 and 40.4 Ω·m with a high proportion of values close to 20 Ω·m (corresponding to 0.3 g·dm^{-3} NaCl). In the neighborhood of Wadi Cherka the following resistivities have been obtained:

– 1.1 Ω·m at point CD6 corresponding to 7 g·dm^{-3} NaCl;
– 1.9 Ω·m at point JK1 corresponding to 3.5 g·dm^{-3} NaCl;
– 4.1 Ω·m at point JK2 corresponding to 1.5 g·dm^{-3} NaCl.

Analysis of the Nacl concentration was performed only in a small number of wells, and unfortunately we could not extrapolate them to other wells.

The processing of electrical probing standards "P10", "M11" and "Q9" has shown the existence of a resistant geological formation set, sometimes layered with a lining of conductive silt on a conductive substratum.

At the boreholes "Q9", analyzes of water samples taken from increasing depths showed, beneath the soft groundwater table (TDS 300–375 mg·dm^{-3}), a gradual increase of NaCl contents of 435 mg·s^{-1} at 13.5 m and up to 2760 mg·dm^{-3} at 20 m. The very low resistivity of impregnated sands raises suspicions about the significantly higher salt contents.

The limit of the seawater intrusion inlands is defined by the change in the resistivity value of the bed of the aquifer [TAJUL BAHARUDDIN 2012]. In the upstream part of the valley, the transverse resistance unit, which is defined as a product of the resistivity and the thickness of the formation of the deposits, was generally less than 500 Ω·m^2. However, at the outlet of Wadi Guebli in the plain, just to the east of Kerkera, a range of values greater than 1000 Ω·m^2 are corresponding seemingly to the coarse deposits of a fossil alluvial fan. At the confluence of the wadis Guebli and Boutout, an area having values greater than 1000 Ω·m^2 has indicated a lens of coarse material.

Moving towards the sea, the resistivity values have decreased steadily as a result of the gradual reduction of the overall grain size and the appearance of the salt wedge. The limit of seawater wedge has been represented on the map of transversal resistance values (Fig. 3).

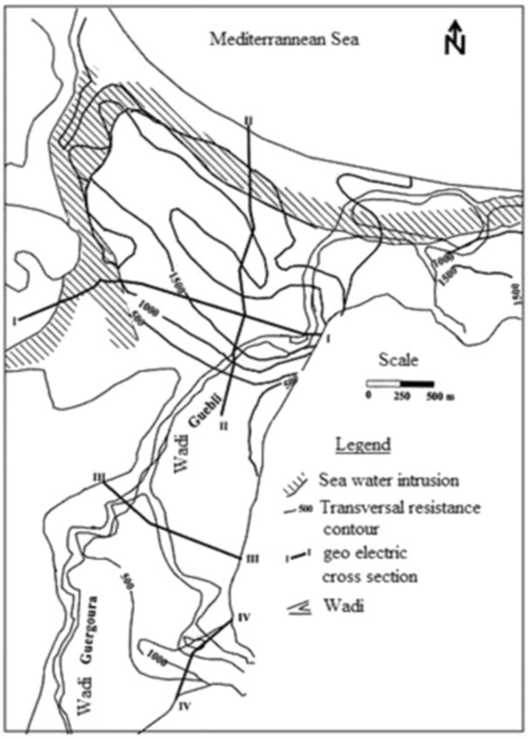

Fig. 3. Transverse resistance map in the plain of Collo; source: map established by the General Geophysical Company [CGG 1965]

For the valley located upstream Koudiat Telezza, the alluvium is essentially silty. The lenses of the coarse material, surrounded by high transverse resistance ranges, were the only effective drains of the water table. They could be found by some boreholes of less than 15 m deep.

The stratum of littoral sand and gravel occupied the lower valley. It was represented by the equal resistance curve of 1500 Ω·m^2 where boreholes recognized to be productive were concentrated. However, there was no doubt that the most conductive zone for the exploitation of the water table was defined by the values range above 2000 Ω·m^2. It really met the following three favourable factors:

– significant thickness of deposits reflecting a good transmissivity with the disappearance of silt;
– direct supply induced by Wadi Guebli, which, except from a surface layer of silt of 3 to 5 m of thickness flew into the sand massif at a distance of more than 1500 m from the sea, while the limit of the salt wedge was approximately 1000 m.

GROUNDWATER FLOW

The water table map was drawn using the observed water level in 15 wells and 4 boreholes spread over the plain. The groundwater flow generally was directed Northwest-Southeast with a piezometric dome that shared its waters between the two groundwater depressions formed around boreholes. The contour map has shown an inverse flow from the sea toward the Northeastern part of the aquifer. The hydraulic head evolution was illustrated in two maps representing the wet period in 1965 (Fig. 4) and in 2014 (Fig. 5), following a major agricultural activity in the 1990s and a significant demographic rate. To face a drought during the last two decades (1990–2014) and to satisfy the water demand, many supply wells were implanted, leading to the drop of groundwater level.

The drop in water level was observed in the floodplain area located downstream of Koudiat Telezza and specifically near wadis Guebli and Cherka, which partially and indirectly has contributed by conductance to groundwater supply.

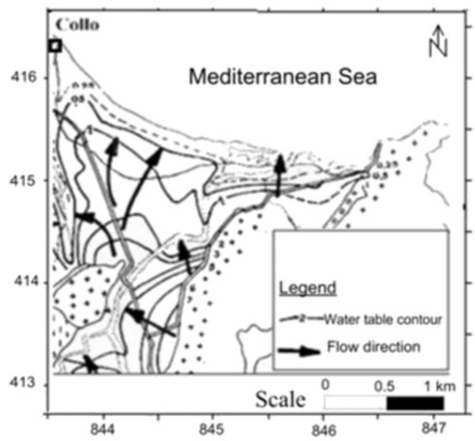

Fig. 4.Watertable map during the wet period in 1965; source: map established by the General Geophysical Company [CGG 1965]

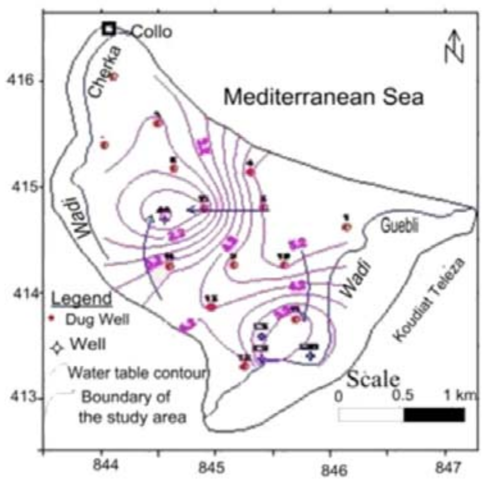

Fig. 5. Watertable map of the coastal aquifer of Collo during the wet period in 2014; source: own elaboration

CHEMICAL ANALYSIS

For better understanding and visualization of Collo water table mineralization, spatial distribution maps of electrical conductivity in the plains have been prepared during the wet and dry periods.

The interpretation of maps allowed us to distinguish two zones:

– the central part of the plain where the electrical conductivity values were low and were represented by distance of contour; these electrical conductivity values increased gradually as we got close to the sea and also to the wadis Guebli and Cherka;
– the eastern coastal area in the vicinity of the wadis, where marked tightening of electrical conductivity contour towards the sea and to the two orientations (wadis Guebli and Cherka), was indicated by a high mineralization of groundwater; these areas were characterized by very high electrical conductivity ranges, above 5000 $\mu S \cdot cm^{-1}$ and can reach 8400 $\mu S \cdot cm^{-1}$ during the dry period; they remained above 3000 $\mu S \cdot cm^{-1}$ even during the wet period.

This significant mineralization in the northeast and near the wadis could be explained by the phenomenon of seawater intrusion into the coastal aquifer as a result of the lowering of the hydraulic head due to intensive and frequent pumping from the aquifer. Moreover, electrical conductivity was noticed to be less significant in April than in November, probably due to the contributions of effective precipitation.

The electrical conductivity maps established since 1974 has highlighted a widespread of significant mineralization mainly in the coastal areas and the surroundings of the wadis of Guebli and Cherka. The contours that were ranging from few hundreds of $\mu S \cdot cm^{-1}$ to about 2000 $\mu S \cdot cm^{-1}$ during the 1974–1993 period increased from 2000 $\mu S \cdot cm^{-1}$ to 8400 $\mu S \cdot cm^{-1}$ in November 2012 and to 6550 $\mu S \cdot cm^{-1}$ in April 2014) in Section 7 close to Wadi Cherka.

Amongst the major chemical elements, easy-measured "Cl^-" remained a priori one of the best indicators of seawater intrusion. And regardless of the lithology, chloride contents were generally low in groundwater [Bodin *et al.* 2007]. However, chlorides encountered in large quantities in the groundwater were likely coming from:

– the dissolution of natural salt by the leaching of the mineral licks;
– the intrusion of seawater into the coastal areas;
– water discharges of domestic and industrial wastewater.

According to Bodin *et al.* [2007]:

– near the sea, the chemical composition of the rain is loaded with chemical elements contained in the atmosphere and in the soil, which has contributed to the mineralization of the aquifer; the chloride was one of the sensitive elements;
– in unconfined aquifers, the chloride concentration was linked to the precipitation of the chloride content; the concentrations generally measured in un-

confined aquifers were of few mg·dm^{-3} and ultimately depend on distance from the coast more than lithology;
– the dissolution of halite (NaCl) or the presence of salt water intrusion (coastal aquifer) could eventually lead to high levels of chlorides (several hundred mg·dm^{-3} to a few g·dm^{-3}).

By examining the contour maps of chlorides the following could be observed:
– the spatial distribution of chlorides in the study area took the same pattern of the *EC* for both dry and wet periods;
– the highest concentration were noticed in the coastal areas mainly to the northeastern area and the surroundings near the wadis of Guebli and Cherka;
– the chloride concentration decreased when moving away from the sea and wadis toward the centre of the plain.

As for the conductivity and chlorides, the potential source of the sodium ion could be linked to the seawater intrusion in the coastal areas [MDIKER *et al.* 2009; RAVIKUMAR *et al.* 2011]. Similarly, contour maps of sodium corresponding to periods of dry and wet periods have been established to notice its distribution in the study area. The coastal areas mainly those of the north eastern area and surroundings of the wadis Guebli and Cherka showed high sodium levels in both periods.

The analysis of electrical conductivity, chloride and sodium maps clearly showed the sectors where values were highly significant with tighter curves towards the sea, the wadis Guebli and Cherka. This distribution of values might call for a significant contribution of the marine source in the salinity of water in wells and boreholes located close to the sea and the wadis. Characteristically, a decrease in the ratio "rSO_4^-/rCl^-" and an increase of "rMg^{2+}/rCa^{2+}" might happen when getting close to the sea.

To highlight the marine influence on groundwater in the plain of Collo, the evolution of these ratios has been followed based on the distance to the sea by making five direction profiles NE-SW, orthogonal to the shore (Fig. 6). These stratigraphical profiles are represented by boreholes implanted in the aquifer having depths ranging between 15 and 25 meters.

Analysis of the ratios according to the five sections in both dry and wet periods has shown that the "rSO_4^-/rCl^-" ratio decreased when approaching the sea while that of "rMg^{2+}/rCa^{2+}" increased. Cl/*EC* ratio of the two periods has indicated a good correlation between the chlorides and the electrical conductivity (Fig. 7a and 7b). The observation of "Mg^{2+}/Ca^{2+}" and "rSO_4^-/rCl^-" ratios evolution, which depended on the distance to the sea has shown how high they were and would suggest a marine intrusion.

According to TODD [1961], the ratio $rCl^-/rHCO_3^-$ was specific to the marine invasion and contamination of groundwater by the evaporites. Contamination was significant when the ratio was higher than the unit. This was the case in the surroundings of the two wadis

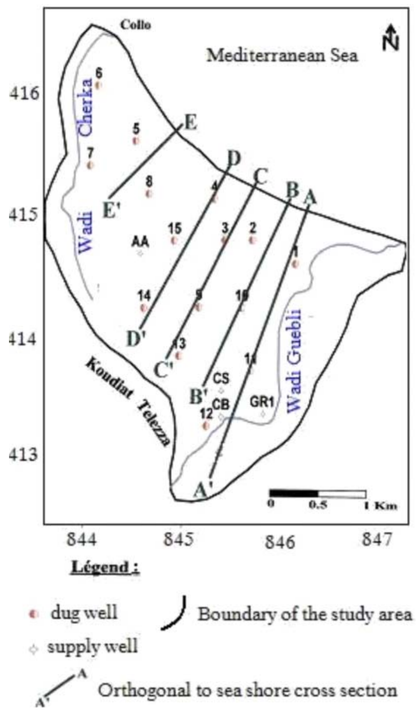

Fig. 6. Location map of the profiles; source: own elaboration

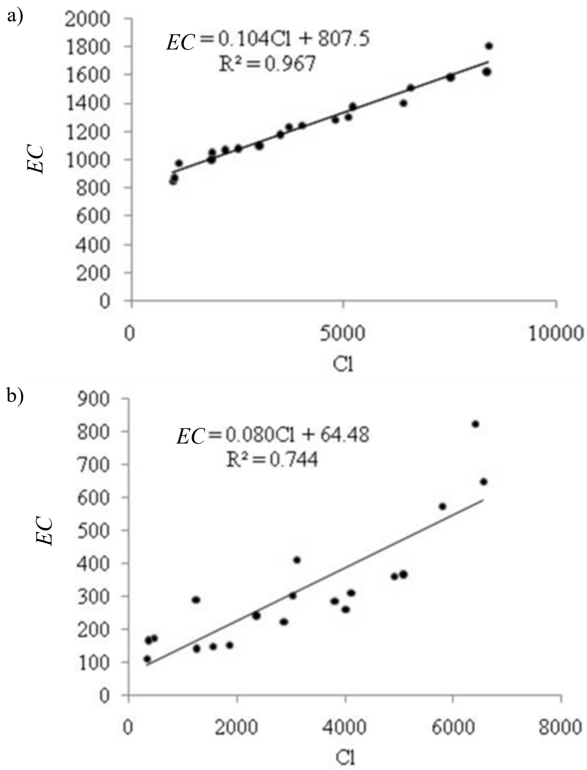

Fig. 7. Regression analysis of Cl/*CE* during: (a) November 2013, (b) April 2014; source: own study

Guebli and Cherka, which confirmed the high salinity of the nearby groundwater wells and boreholes. This high salinity was probably due to the intrusion of seawater that influenced these two wadis. Furthermore, the very small ratio (less than 1) in the center of the plain indicated a low marine contamination.

DELIMITATION OF SALT WEDGE IN THE COASTAL AQUIFER OF COLLO

According to the different approaches used to detect seawater intrusion in the coastal aquifer of Collo, we could define the location of the salt wedge in the North East and near the wadis, especially downstream Wadi Cherka and nearby the boreholes of Wadi Guebli (Fig. 8).

Comparing the maps in Figures 8 and 9, it was noteworthy that the salt wedge at the alluvial aquifer of Collo, was located to the northeast of the plain, in the vicinity of Wadi Guebli and downstream Cherka stream. This might be due to upstream rise of the marine water stream in the wadis, which explained their hydrodynamic contact with the water table and the result of high salinity in the southeast of the plain with a widening of the contaminated surface.

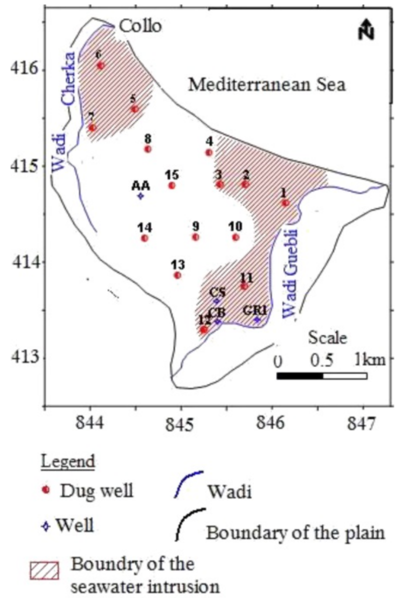

Fig. 8. Map of salinity and saltwater intrusion in the alluvial aquifer of Collo; source: own elaboration

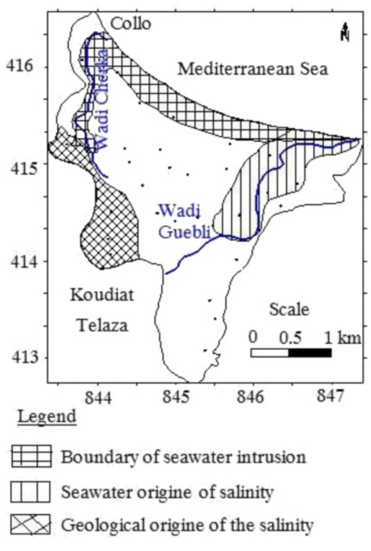

Fig. 9. Map of salinity and saltwater intrusion in the alluvial aquifer of Collo; source: map established by the General Geophysical Company [CGG 1965]

CONCLUSIONS

Drought witnessed for more than a decade has reduced the water resources in the region of Collo, where the supply of water drinking and irrigation water was favourably performed from the groundwater of the coastal alluvial aquifer, as the region was agricultural.

The situation was getting more exacerbated by the high demographic growth and the increase in the agricultural development.

The aquifer, composed of sand and gravel layer with a thickness ranging from 15 to 25 m, covered with a layer of sandy loam and silty clay and limited at its base by a substratum formed by alternating marl and Pliocene sandstone, has undergone intensive pumping that not only lowered the groundwater level, but have led to a gradual deterioration of the groundwater quality that became increasingly brackish.

Concerned about the situation of the coastal aquifer contamination, we wanted to know the extent of the pollution generated by the intrusion of seawater, using watertable map, geophysics (electric prospection) and physico-chemical analysis. The geophysical campaign has shown that the resistivity of the water table was usually ranging between 7.2 and 40.4 Ω·m with a high proportion of values close to 20 Ω·m (corresponding to 0.3 $g \cdot dm^{-3}$ NaCl). The very low resistivity of impregnated sands raised suspicions about a significantly higher content of salt. Towards the sea, the resistivity values decreased steadily as a result of the gradual reduction of the overall grain size sorting and the appearance of salt wedge. The amount of this latter was shown on the previous transverse resistance map. The limit of the marine invasion inland was completely defined by the change to lower resistivity values.

On a physico-chemical point of view, the delimitation of the salt wedge was conducted on the determination and distribution parameters indicating the salinity in groundwater such as electrical conductivity, chloride and sodium elements.

The interpretation of electrical conductivity, chloride and sodium maps have shown clearly the areas where values were the highest with tighter contours towards the sea, the wadis Guebli and Cherka. This distribution of values indicated a marine source of salinity in wells and boreholes close to the sea and wadis.

As groundwater was the main water resource for drinking water supply and irrigation water, it was essential to reduce the intrusion of saltwater wedge through an optimal management of the aquifer by redefining the exploitation method and implementing boreholes in the most remote areas of the shore, particularly given that they were the most transmissive.

Though, a periodic monitoring of the water level and the electrical conductivity of groundwater in the observed wells placed for this purpose between the catchment area and the sea would manage pumping so that the groundwater level would sufficiently high than the sea level in order to play the role of hydraulic dam and consequently might prevent marine intrusion.

Recommendations have to be made to the local authorities to establish a detection monitoring network using conventional observation wells for groundwater sampling, water level measuring and to specify the salinity of groundwater. The rational exploitation of the aquifer is crucial to attenuate the lowering of water level and to let it sufficiently higher than the sea level in order to create a hydraulic dam which consequently might prevent marine intrusion to ensure sustainable safe use of the resource.

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Identyfikacja intruzji morskiej na równinę Collo w północnowschodniej Algierii

STRESZCZENIE

Rosnąca liczba ludności, urbanizacja i intensyfikacja rolnictwa spowodowały większe zapotrzebowanie na dostawy wody na przybrzeżnej równinie Collo i doprowadziły do nadmiernego pompowania wody z warstwy wodonośnej o swobodnym zwierciadle i ograniczonych rozmiarach. Celem badań było scharakteryzowanie skutków nadmiernej eksploatacji wód gruntowych z jedynego w regionie poziomu wodonośnego o swobodnym zwierciadle. Wynikiem eksploatacji była inwersja przepływu wód gruntowych i zwiększone prawdopodobieństwo ich zanieczyszczenia przez wodę morską, co przedstawiono na mapie poziomów wód. Przedyskutowano przyczyny i skutki intruzji wód słonych. Interpretacja pomiarów przewodności elektrycznej i mapy rozmieszczenia jonów chlorkowych i sodowych ujawniły obszary o wartościach tych parametrów rosnących w kierunku morza i uedów Guebli i Cherka. Rozmieszczenie wartości stężenia badanych składników wskazuje na morskie źródło zasolenia studni w pobliżu morza i obu rzek.

Słowa kluczowe: *Algieria, Collo, intruzja morska, przybrzeżny poziom wodonośny, zasolenie wody*

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