Geoelectrical investigation of saline water intrusion into freshwater aquifers: A case study of Nador coastal aquifer, Tipaza, Algeria

Abdelkader Bouderbala*, Boualem Remini and Abdelamir Saaed Hamoudi

Resumen

El agua subterránea en el acuífero costero plio-cuaternario de Nador tuvo una alta salinidad en el año 1995, debido a la intrusión de agua de mar, ya que la conductividad eléctrica (CE) superó 9.000 µS.cm^{-1}. Después de la construcción de la presa de Boukourdane, hubo una reducción del bombeo de las aguas subterráneas y se aseguró el riego desde la presa y con el agua resultante de la planta de tratamiento de aguas residuales.

El análisis físico-químico de la calidad del agua subterránea para el año 2013 muestra que hay una reducción de la salinidad en comparación con el año 1995, con valores de CE de menos de 4.400 µS.cm^{-1}. Esto indica también que más del 45% de los parámetros físico-químicos tienen valores por encima de los límites permisibles de la norma de la OMS para agua de consumo. El estudio geofísico está dirigido principalmente a la comprensión de las características geofísicas de las aguas subterráneas en Nador obtenido a partir de un estudio de la distribución de la resistividad eléctrica del subsuelo mediante la aplicación de las técnicas de sondeo eléctrico vertical (SEV) y tomografía de resistividad eléctrica (ERT). Un total de 47 SEV y 3 perfiles de ERT, se llevaron a cabo para entender la distribución de la resistividad de la zona. La interpretación de los resultados ha identificado un acuífero costero altamente salino y delinea el agua dulce río arriba a más de 2 kilómetros.

Palabras clave: acuífero costero, intrusión de agua salina, calidad del agua subterránea, métodos geoeléctricos, Argelia.

Abstract

The groundwater in Nador coastal plio-quaternary aquifer had high salinity in 1995, due to a seawater intrusion, where the Electrical Conductivity (EC) exceeded 9000 µS.cm^{-1}. After the implementation of Boukourdane's dam, a pumping reduction of groundwater occured, and the irrigation was ensured by the dam and the water resulting from the sewage treatment plant.

The physico-chemical analysis of the groundwater quality for the year 2013 shows that there is a dilution of the salinity compared to 1995 with values of EC less than 4400 µS.cm^{-1}. It also shows that more than 45% of the physico-chemical parameters have values above the permissible limits of the WHO standard for drinking purpose. The geophysical study is aimed mainly to understand the geophysical characteristics of groundwater in Nador plain by studying the electrical resistivity distribution of the subsurface saturated layers by applying the Vertical Electrical Sounding (VES) and Electrical Resistivity Tomography (ERT) techniques. A total of 47 VES and 3 profiles of ERT were carried out to understand the resistivity distribution of the area. The interpretation of the results has identified a highly saline coastal aquifer and delineates the freshwater in the upstream at more than 2 km.

Key words: coastal aquifer, saline water intrusion, groundwater quality, geoelectrical tools, Algeria.

A. Bouderbala*
Faculty of nature and earth sciences
University of Khemis Miliana
Ain Defla 44000, Algeria
*Corresponding author: bouderbala.aek@gmail.com

B. Remini
Department of Water Sciences
Blida University
Blida 9000, Algeria

A. Saaed Hamoudi
Department of Hydraulic
Chlef University
Chlef 2000, Algeria

Introduction

Algeria has a very long coastline of about 1200 km and 25% of the country's population live in the coastal zone. The high population density along the banks of coast increases the water necessity for the human activities. The coastal aquifers can be polluted by natural or anthropogenic pollution, such as marine intrusion, discharge of untreated wastewater and chemical weathering of natural geological deposits. The problem of seawater intrusion is one of the major threats to coastal area freshwater resources. Algeria has been identified as one of the countries where the problem has felt most severely (Bouderbala and Remini, 2014).

The plio-quaternary aquifer of Tipaza which is directly recharged from the infiltration of rainfall, was considered before 2000 the main source of groundwater in Tipaza province (Figure 1). The excessive pumping due to the rapid increase of water demand for agriculture and drinking purposes during the last two decades changed the balance between fresh water in the aquifer and saline water intruding from the Mediterranean Sea. On the other hand, drought conditions prevailed between 1985 and 2000, the groundwater pumped increased and the level of the water table decreased under sea level, reversing the groundwater flow. The piezometric levels indicate that groundwater reached its lowest level since 1995. Many wells dried and several farmers left their farmland. This severe decline in the groundwater levels is naturally associated with a significant deterioration of groundwater quality. The seawater migrated into the aquifer causing a considerable increase in the groundwater salinity, where the wells and drillings have registered high values of electrical conductivity exceeding 9000 $\mu S.cm^{-1}$ (in dry period 1995). In front of these situations, the majority of these hydraulic structures were abandoned in this sector, and the water demand has been ensured by Boukourdane's dam (Bouderbala, 2015; Bouderbala et al., 2016). Geophysical techniques combined with hydrochemical methods have been recognized as the most efficient tools to investigate the saline water intrusion. Geophysical methods are used essentially for the quantitative and qualitative assessment of groundwater resources. It has been successfully used to demarcate the saltwater–freshwater interface in different coastal settings around the world (Nowroozi et al., 1999; Abu-Zeid et al., 2004; Sherif et al., 2006; Bouderbala and Remini, 2014). The chemistry of groundwater is largely a function of the mineral composition of the aquifer through which it flows. The hydrochemical processes and hydrogeochemistry of the groundwater vary spatially and temporally, depending on the geology and chemical characteristics of the aquifer (Pulido-Leboeuf, 2004).

The present study illustrates the applications of geo-electrical techniques along with major ion chemistry of groundwater to assess the saline water intrusion and to determine the present status of groundwater quality in the Nador plain.

Study area

The Nador Plain, also called Nador Valley, is part of a large hill range known as the Sahel of Algiers. It is located approximately 75 km west of Algiers. The study covers an area of 19 km². It is bounded on the north by the Mediterranean Sea; in the south and east by the slopes of the Sahel; and in the west by the Chenoua Massif (Figure 1). It lies between latitudes 36° 33', 36° 36' and longitudes 2° 21', 2° 27'. This valley follows a syncline oriented NE-SW, whose main axis is occupied by the Wadi Nador, which gives the study area its name. The plain is characterized by a slope generally varying from 0 to 1%, while the hillslope and piedmont on the right part of the plain (the slopes of Sahel) and the left side of the plain (Chenoua massif) have slopes of 1 to 10%. The population of Tipaza and neighboring cities has reached more than 45000, with a yearly growth rate of 2.5%.

Geology and hydrogeology

The geological formations that outcrop in the study area are Pliocene and Quaternary terrains (Figure 1).

-The pliocene is constituted by clay and marl of middle Pliocene age, surmounted by limestone and sandstone of upper pliocene age, which forms the most important aquifer in this area. The clay and marl of middle pliocene form the substratum of the aquifer.

-The quaternary formations are visible in the centre of the plain, with a thickness that can reach 30 m. They rest in discordance on the upper pliocene layers and are formed by sands, clay, and gravel and conglomerate. These deposits have an important hydraulic conductivity of interstices (about 10^{-3} $m.s^{-1}$) and a transmissivity of about 10^{-2} $m^2.s^{-1}$. They are surmounted by a layer of clay and silts in surface.
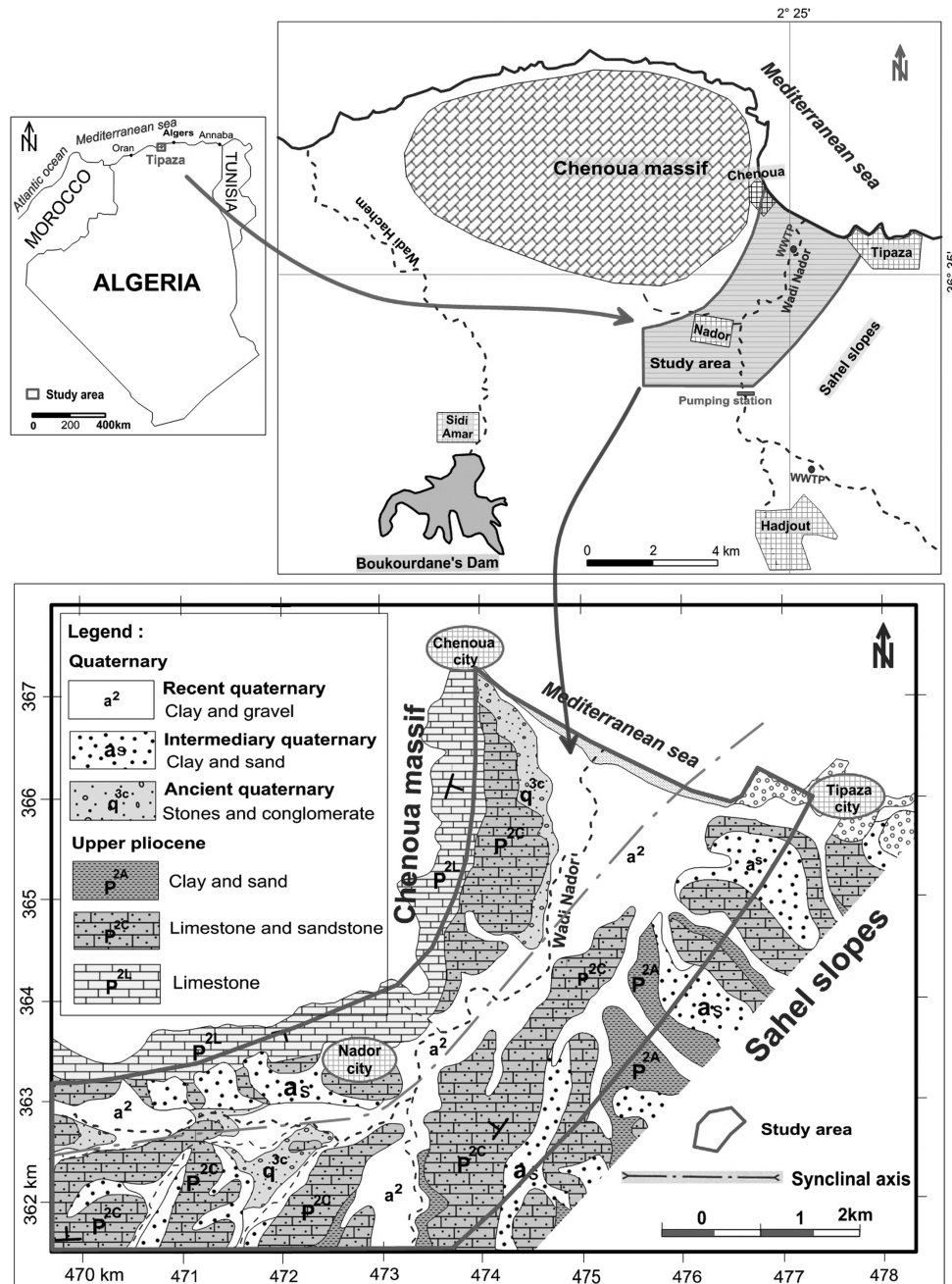
Figure 1. Geographic and geologic location of the studied area.

The Plio–Quaternary aquifer of Nador is formed by the Quaternary alluvium (sand, gravel and conglomerate), as well as sandstone and limestone of Upper Pliocene. In the centre of plain, the aquifer is confined under the impermeable layer of Quaternary (clay and sandy silt), while the aquifer in the two parts of the plain is unconfined. The aquifer's Quaternary and Pliocene horizons are in hydraulic communication. The substratum is formed mainly by marl of Middle Pliocene age.

The recharge to this Plio–Quaternary aquifer comes from the rainfall infiltration on the outcrops of the plain. The recharge also occurs by return flow of the irrigation water. The recharge of the aquifer by wadi Nador is very low because the flow is temporary, and the shores of the watercourses are clogged with clay.

The geological sections show that the thickness of the aquifer increases regularly

from upstream to downstream, reaching a maximum depth in the centre of the plaine of about 80m. However, the axis of the syncline coincides with the flow trajectory of wadi Nador. This indicates the continuity of the aquifer towards the sea. So there is a direct contact between the aquifer and the marine waters.

The hydrodynamic characteristics of the aquifer have been derived from bibliographic data pumping tests. Seven pumping tests carried out in the Nador plain show that values of hydraulic conductivity and transmissivity varied from 0.43 x 10^{-4} m.s^{-1} to 6.83 x 10^{-4} m.s^{-1} and from 5.28 x 10^{-3} m^2.s^{-1} to 2.01 x 10^{-2} m^2.s^{-1}, respectively, from the upstream to the downstream. This variation in values of the hydrodynamic parameters is due to the increased thickness of the aquifer, the structure of the aquifer and the inhomogeneity of layers constituting the reservoir.

Materials and Methodology

Hydrochemical methods

For the assessment of groundwater quality, 18 groundwater samples were collected in the dry and wet periods in 2013. Samples were analyzed for major and minor ions (Ca^{2+}, Mg^{2+}, Na$^+$, K$^+$, Cl$^-$, SO$_4^{2-}$, HCO$_3^-$, NO$_3^-$ and for physical parameters (pH, EC and temperature). Samples from all wells were collected in 500 mL polyethylene bottles, following the standard guidelines (Schoenleber, 2005). The samples were analyzed immediately for hydrogen ion concentration (pH), temperature (T °C) and electrical conductivity (EC). Other parameters were later analyzed in the laboratory of the National Agency of Hydraulic Resources. Concentration of calcium, magnesium, sodium, potassium, bicarbonate, chloride, sulphate, and nitrate were determined by standard procedures (APHA, 2005). Major ions like chlorides and bicarbonates were analyzed using volumetric methods. Calcium, magnesium, sodium and potassium were analyzed using atomic absorption spectrometry. Nitrates were measured by a colorimetric method. Sulphates were estimated by the UV–visible spectrophotometer. All concentrations are expressed in milligrams per liter (mg.L^{-1}), except pH and EC. The EC is expressed in microsiemens per centimeter (μS.cm^{-1}) at 25 °C. The reliability of all the obtained results was checked using the ionic balance of water.

Results indicate percentages ranging from -5 to + 5%, which corresponds to an acceptable reliability for the unit of the chemical results. The analysis of depths of the wells used in the study area revealed that all the measurement points are in the same hydrogeological context, with depths ranging from 8 m to 40 m, all capturing water from the Plio-quaternary aquifer. A pumping time of at least 30 min was required before the sample was collected. The pumps are usually installed near the bottom of the wells.

For this study, the analysis of samples in the wet period 2013 are also compared to these of the wet period 1995 to show the effect of irrigation by reuse water and pumping reduction in the groundwater quality.

Geophysical methods

The electrical geophysical prospecting method consists to determine the distribution of a physical parameter that is characteristic of the subsoil (the resistivity) on the basis of a very large number of measurements of apparent resistivity made from the ground surface (Store et al., 2000). The electrical resistivity of a geological formation is a physical characteristic that determines the flow of electric current in the formation. Resistivity varies with texture of the rock, nature of mineralization and conductivity of electrolyte contained within the rock (Kouzana et al., 2010). Resistivity not only changes from formation to formation but even within a particular formation (Sharma, 1997). Resistivity increases with grain size and tends to maximum when the grains are coarse, also when the rock is fine grained and compact. The resistivity drastically reduces with the increase in clay content which is commonly dispersed throughout as coatings on grains or disseminated masses or as thin layers or lenses. In saturated rocks low resistivity can be due to increased clay content or salinity. Hence the resistivity surveys are the best suited for delineation of clay or saline zone (Kirsh, 2009).

The subject of this geophysical investigation is to complete our previous study by Vertical Electrical Sonding (VES), through execution of Electrical Resistivity Tomography (ERT) profiles. The apparent resistivity measurements were conducted using a SYSCAL R1, IRIS instrument.

Vertical electrical sounding (VES)

VES is used to determine the resistivity variation with depth. It was applied in the ground assumed to be horizontal layered or with very little lateral variation. It's typically carried out in Schlumberger array, where the potential electrodes (M and N) are placed in a fixed position with a short separation and the current electrodes (A and B) are placed symmetrically

on the outer sides of the potential electrodes. After each resistivity measurement the current electrodes are moved further away from the centre of the array. In this way the current is stepwise made to flow through deeper and deeper parts of the ground. For large distances between the current electrodes, the distance of the potential electrodes is increased to ensure that the measured voltage is above the noise level and the lower detection level of the instrument (Telford *et al*., 1990).

The VES curves were interpreted using the available software program (WinSEV 6.0, 1D) and unacceptable errors in the apparent resistivity curves were removed during processing. The interpretation results were based as possible using all available drilling information through the surveyed area. A total number of 47 vertical electrical soundings were carried out in the survey area along 11 profiles (Figure 2). The Schlumberger array was applied with half current electrode spacing (AB/2) starting from 2 m to 800 m. In VES, the theoretical investigation depth is about AB/5 (Kirsch, 2009).This spacing is sufficient to reach adequate depths covering the plio-quaternary aquifer in the study area (Bouderbala and Remini, 2014).

The transverse resistance is also used in this study, it is defined as the product of the true resistivity and thickness of the aquifer (TR = thickness * resistivity of layer). This parameter is often identified as a good estimate of the transmissivity value of the aquifer matrix (saturated zone). The use of TR parameter for the saturated zones can help to delineate the influenced sector by seawater and to view the most favorable zones of good intrinsic hydraulic conductivity.

Electrical resistivity tomography (ERT)

ERT is an advanced geophysical technique used to imaging sub-surface structures from electrical resistivity measurements made at the surface. ERT profiles consist of a modeled cross-sectional (2-D) plot of resistivity (Ω·m) versus depth. After the reception of the pseudo-section of measured apparent resistivity, it is converted into true resistivity using RES2DINV inversion program in order to produce the 2D resistivity cross-section image (Dahlin, 1996).
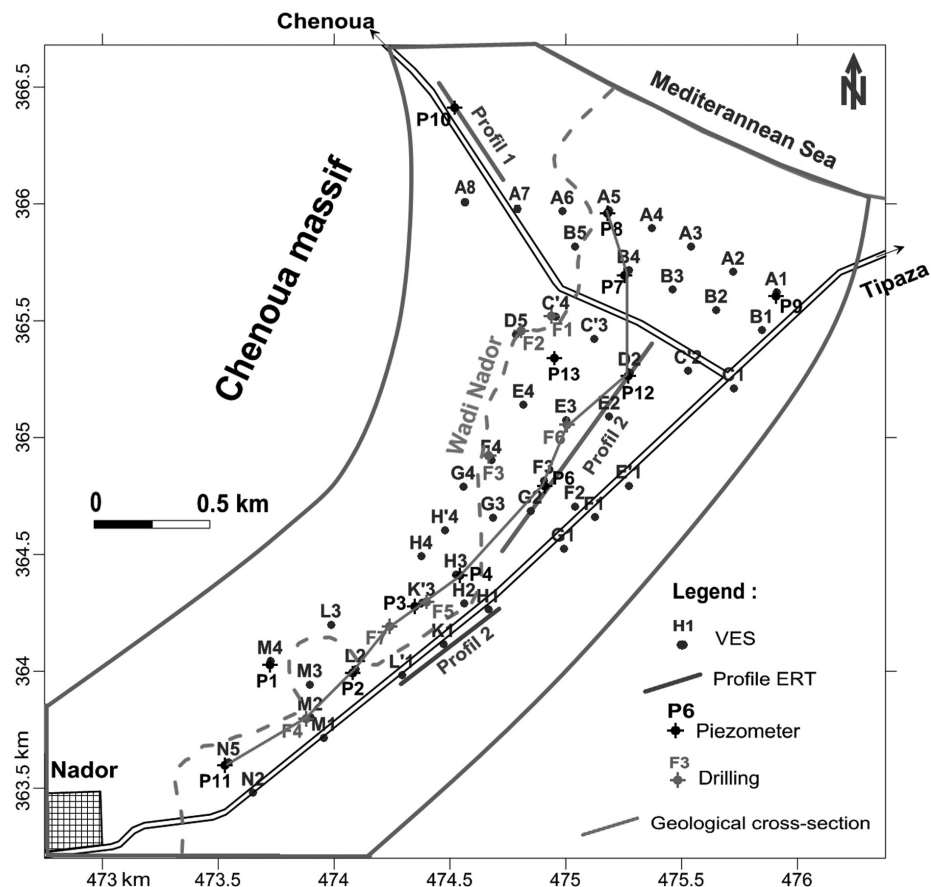
Figure 2. Situation of VES and ERT profiles in the study area.

The output from the RES2DINV displays three sections, i.e., measured and calculated apparent resistivity pseudo-sections and the inverse model resistivity section. The pseudo-sections are a qualitative way of presenting spatial variation of the measured or calculated apparent resistivity along cross-section and do not reflect the true depth and true formation resistivity (Dahlin, 1996).

In the present study, the geophysical investigation using ERT profiles has been carried out at 3 locations in the area (Figure 2). The locations of these profiles were chosen in three different places (upstream, centre and downstream of the plain) and based also on the available monitoring wells for calibration purposes. Wenner-Schlumberger array with 20 m electrode spacing was used to collect resistivity data, in order to reach an investigation depth of about 100 m.

Correlation of the VES and ERT results with geological information

The geoelectric resistivity of sediments is one of the most variable physical properties, especially in a very complicated sedimentlogical environment that dominates alluvial areas. Therefore, the ambiguities in interpretation may occur and it becomes very necessary to correlate the mesured VES data with the available drillings data (Gununagha Rao *et al*., 2011). This enables us to assign the geoelectric units to the corresponding lithologic units (a correlation must be found between

the resistivities of layers inverted from the VES data with the geology of drillings) and consequently put a reliable control on the interpretation of the subsurface sequence in the study area. Data from seven drillings were analyzed and used to correlate the results of the VES geoelectrical surveys and to determine the electrical characteristics of the rock units with depth.

Results and Discussion

Piezometric map

The studied aquifer is characterized by a thick reservoir of relatively high hydraulic conductivity and transmissivity, as well as a substratum that dips below sea level (approximately -80 m). This indicates a direct contact between the Plio–Quaternary aquifer of freshwater and the saltwater wedge, as illustrated in Figure 3. This poses an important vulnerability with respect to the marine water entries towards the aquifer (Bouderbala *et al*., 2014).

The analysis of the piezometric map related to the wet period (April 2012), allowed the characterization of the flow directions of the water table and the evolution of the hydraulic gradient of the aquifer (Figure 4). The map shows that the lines of groundwater flows converge towards the axis of the synclinal, which constitutes the principal drainage axis of the Plio–Quaternary aquifer. This map also indicates the existence of the piezometric water level '0 m' inside the plain. A reverse flow
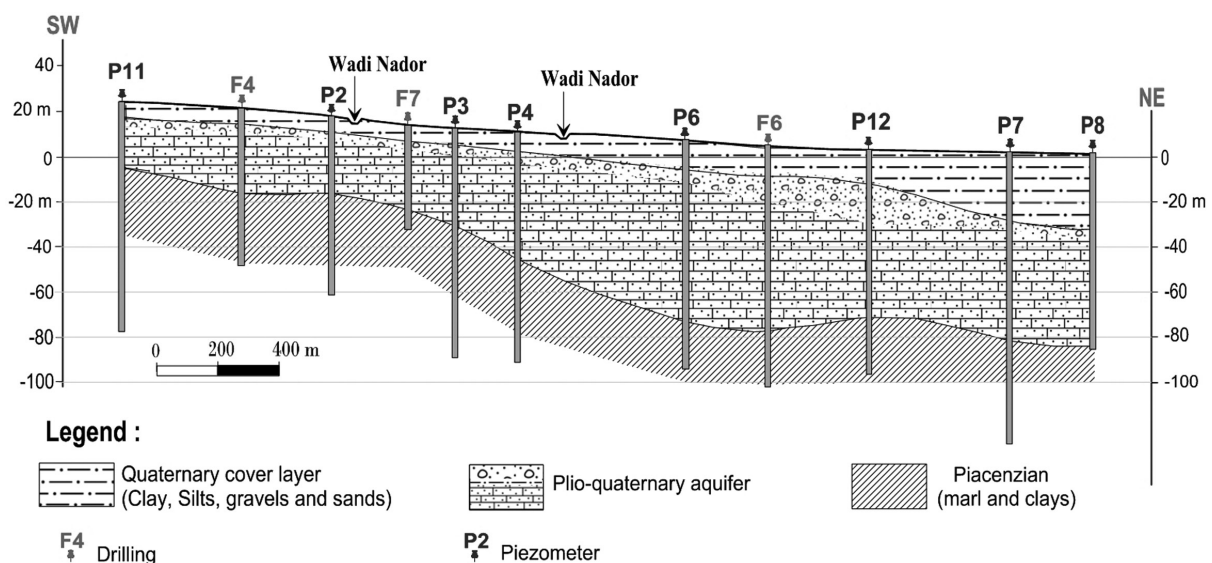
Figure 3. Geological cross-section parallel to the synclinal axis.

direction of the groundwater is observed. This change of direction is related to groundwater overexploitation from pumping near the sea, which generates an important mixture between marine water and groundwater. These mixtures are a consequence of groundwater salinization, in which the degree depends on the effective precipitation rate and pumping.

Geophysical study

Electrical resistivity of the soil can be considered as a proxy for the spatial and temporal variability of many other soil physical properties (i.e. structure, water content, or fluid composition). Because the method is non-destructive and very sensitive, it offers a very attractive tool for describing the subsurface properties without digging (Sarwade *et al.*, 2007). Seventeen VES were done near to seven drillings and ten piezometers. It is relevant to note that, at present, all the piezometers in the study area are clogged and have been abandoned; only three of the drinking water supply drillings remain operational, namely F3, F5, and F7. Examination of SEV models realized close to drillings and piezometers, which defined resistivities and thicknesses of the layers, permitted to determine the scale of resistivities for our electrical prospection, as shown in Figures 5a, 5b and 5c. (Bouderbala and Remini, 2014):

- Quaternary cover layer: between 5 and 25 Ωm;

- Plio-Quaternary aquifer with brackish water: between 6 and 36 Ωm;

- Plio-Quaternary aquifer with fresh water: between 30 and 50 Ωm;

- Plaisancian marly clays substratum: between 5 and 10 Ωm.

Vertical electrical sounding

The interpretation of the apparent resistivity values of VES has indicated three subsurface layers. A surface layer consisting of quaternary cover (silt, clay sand and gravel), a second layer consisting by plio-quaternary aquifer (stones and conglomerate of ancient quaternary, sand and limestone and sandstone of upper pliocene). The aquifer indicates a direct contact with sea, the thickness of the aquifer increases regularly from upstream to downstream. The bedrock (substratum) as a third layer consists of marls plaisancian (Bouderbala and Remini, 2014). The examination of 11 transverse geoelectric profiles together shows that the aquifer traces a syncline in a SW-NE orientation, whereby the sections also indicate dips down from the eastern and western borders towards the axis of the syncline. This
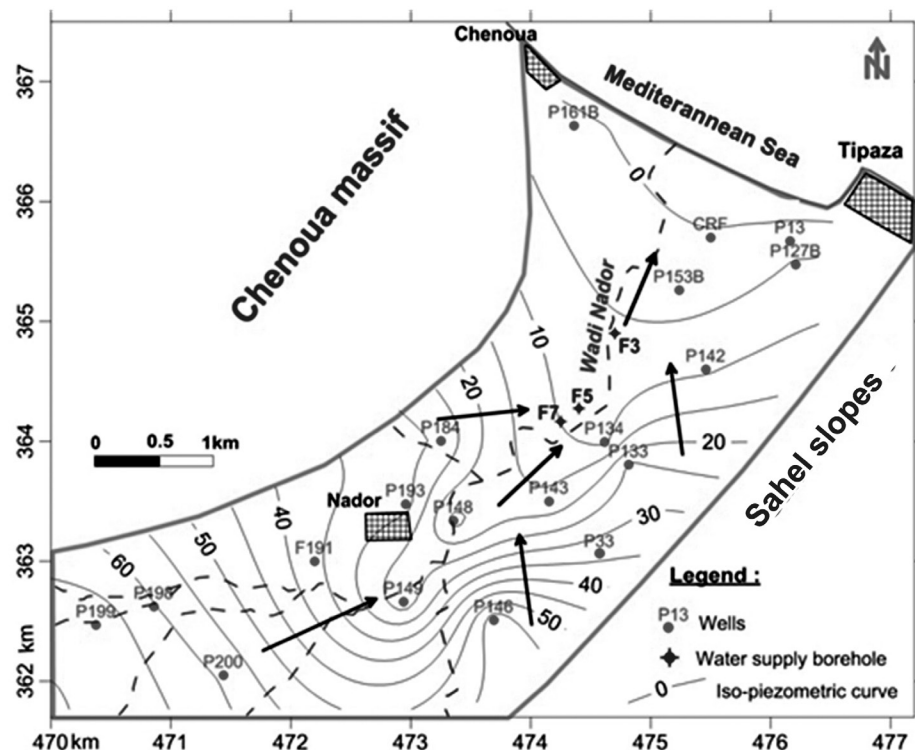
Figure 4. Piezometric map of Nador aquifer (April 2012).
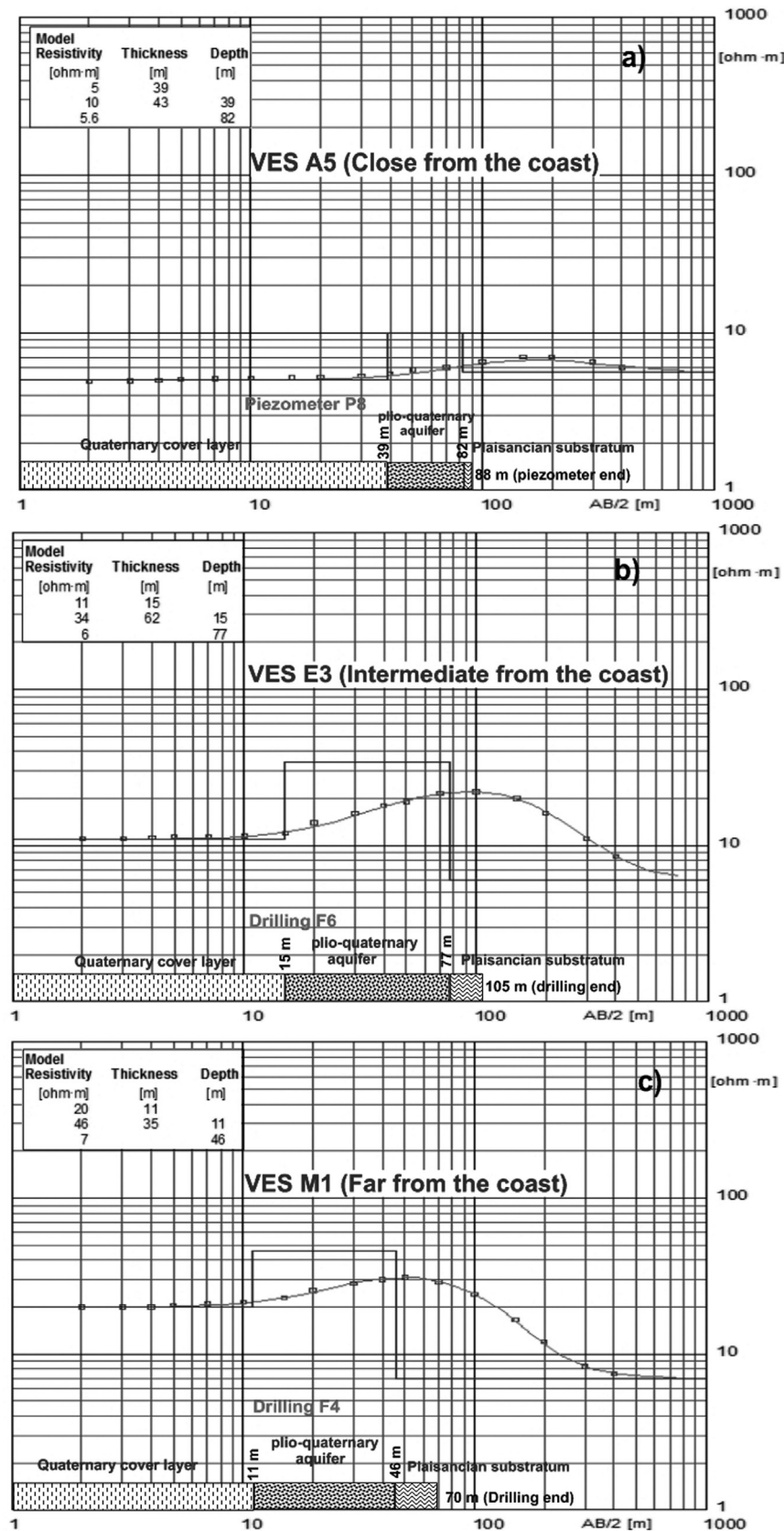
Figure 5. Examples of VES models realized near to drilling and piezometer
a) Close from the coast, b) intermediate from the coast, c) far from the coast.

aquifer's layers reach its maximum thickness of 60 m at the points VES D5 and E3. The cross sections also show how the Plio-Quaternary aquifer is overlaid by a variable layer (up to 30 m thick) of clayey sediments. Except where the aquifer formations outcrop on the east and western boundaries, these clays locally confine the aquifer.

The transverse resistance (TR) map of the Plio-quaternary aquifer (Figure 6) shows that the values of TR vary from 1800 to 600 Ohm.m² near the coast. The low values of TR near the coast are probably related to marine intrusion processes. However, the low values of RT in the upstream of the plain are related to the low thickness.

In the central sector, the values of transverse resistance are the highest of the plio-quaternary aquifer, where the thickness is more than 40 m, the resistivity is about 40 and 45 Ω.m . This sector is characterized also by good interstitial and fissure hydraulic conductivity, which can reach 6.83×10^{-4} m.s^{-1}. On the basis of this map, it is possible to delineate the extension

of saltwater into the aquifer, it is about 2 km inland, near the F profile.

Electrical resistivity tomography (ERT)

In the present study area geophysical investigations using ERT surveys have been carried out at 3 locations in the Nador plain. Wenner-Schlumberger array with 20m electrode spacing was used to collect resistivity data which provides adequate resolution of sub-surface. The depth of investigation is 50 m for profile 1,100 m for profile 2 and about 80 m for profile 3. The ERT profiles showed resistivity values that varied laterally and at depth (Figure 7).

The profile P1 (oriented NW-SE) was located in the coastal sector (500 m from the shore). It shows two distinct levels of resistivity, the upper layer with resistivity >15 Ωm until a depth of 25m, due to the existence of a quaternary alluvial formation (clay and gravel), while the low resistivity of < 5 Ωm, for a depth lower than 25m, is due to the saturated plio-quaternary aquifer with saline water.
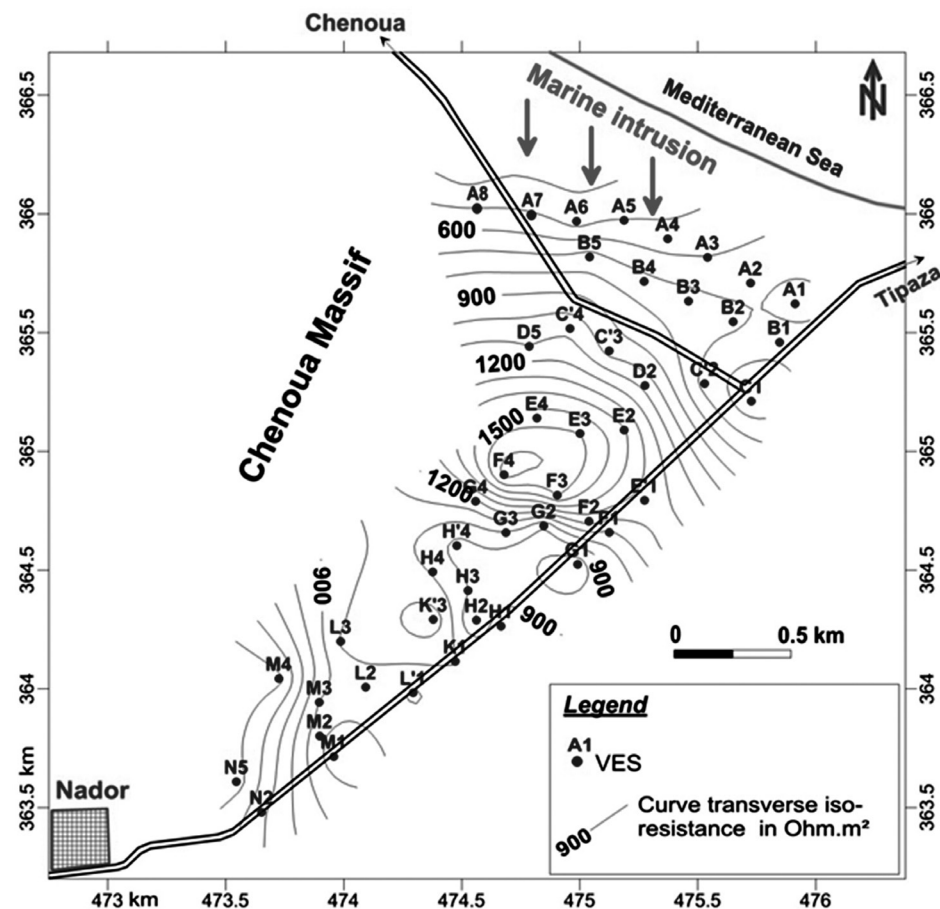
Figure 6. Transverse resistance map of the Nador plio-quaternary aquifer.
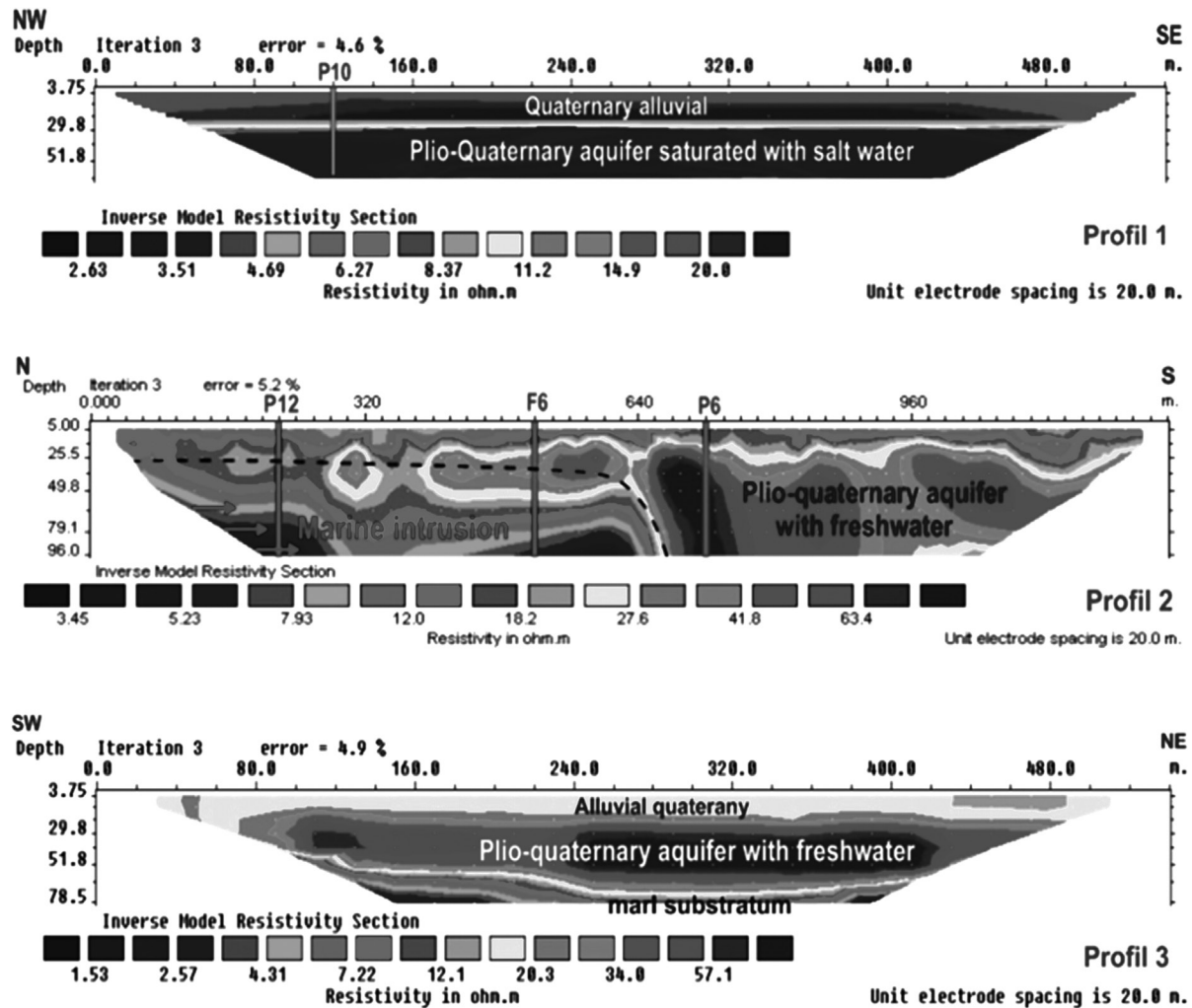
Figure 7. Geo-electrical resistivity profiles in the study area.

The profile P2 (orientated N-S), 1200m long, has been located in the center of the plain, perpendicular to the shore. The aquifer geometry and the extension of the salt wedge were ascertained from the electrical resistivity profile. It shows an upper layer of alluvial deposits with low resistivity of <20 Ωm, while at 25m depth in the north of the profile, the low resistivity value observed at depth between 50 to 100m is due to saline water after the overexploitation of groundwater accompanied to the low recharge rate.

Profile 3, was carried out upstream of the plain, 500 m long in the NE-SW direction. The layer in surface of quaternary alluvial exhibits moderate resistivity; between 10 and 12 Ωm, probably due to the presence of consolidated material mostly with silt and clay. Further, the profile shows, the freshwater saturated aquifer

below the top layer with resistivity ranging between 35 and 60 Ω.m. The variability of the values is due to the heterogeneity of the aquifer. It shows also the presence of marl substratum of middle pliocene in the base with resistivity lower than 7 Ω.m.

Hydrochemical study

The results of physico-chemical analyses during the wet periods of 1995 and 2013 are given in Tables 1 and 2. The results show that water is characterized by an electrical conductivity being ranged between 1520 µS.cm⁻¹ and 8950 µS.cm⁻¹ for wet water 1995, and between 1360 µS.cm⁻¹ and 4400 µS.cm⁻¹ for wet water period 2013. The pH values are more than 7.0 in the two periods which indicates that the Nador groundwater is slightly alkaline in nature.

Table 1. Physicochemical analysis of groundwater in the Nador plain, April 1995 (wet period).

N° of well	CE $\mu S.cm^{-1}$	TDS $mg.L^{-1}$	pH $mg.L^{-1}$	NO_3^- $mg.L^{-1}$	HCO_3^- $mg.L^{-1}$	SO_4^{-2} $mg.L^{-1}$	Cl^- $mg.L^{-1}$	Na^+ $mg.L^{-1}$	Mg^{+2} $mg.L^{-1}$	Ca^{+2} $mg.L^{-1}$	K^+
P199	1 572	1 055	7.7	5	495	195	236	205	28	175	0
P200	2 560	1 740	7.4	25	542	154	585	325	52	213	0
P198	2 700	1 785	7.3	4	535	148	584	314	45	199	0
F191	1 520	1 016	7.6	55	325	81	295	135	37	149	6
P149	2 035	1 398	7.8	85	570	182	234	114	42	216	0
P184	2 070	1 390	7.1	8	415	195	390	186	55	162	4
P193	2 100	1 415	7.3	30	654	203	285	150	57	215	0
P143	2 080	1 435	7.8	35	420	224	300	169	45	176	0
P146	1 965	1 350	7.5	39	605	175	430	208	105	224	2
P134	1 820	1 210	7.3	65	465	182	225	140	35	205	0
P33	1 490	980	6.5	55	385	150	188	115	30	175	0
CRF	8 150	5 405	7.8	78	507	594	3 155	2 408	160	85	7
P133	2 425	1 620	7.4	45	435	220	467	275	49	165	0
P142	2 375	1 595	7.6	85	545	140	342	245	30	165	4
127B	4 735	3 185	7.7	65	385	420	1 585	1 135	151	90	2
P13	5 575	3 755	7.6	72	455	507	1 875	1 345	188	102	4
P153	7 710	5 145	7.7	38	472	558	2 725	2 005	180	95	8
P161	8 950	5 962	7.8	50	482	580	3 335	2 565	142	67	12

**Table 2.** Physicochemical analysis of groundwater in the Nador plain, April 2013 (wet period).

N° of well	CE $\mu S.cm^{-1}$	TDS $mg.L^{-1}$	pH $mg.L^{-1}$	NO_3^- $mg.L^{-1}$	HCO_3^- $mg.L^{-1}$	SO_4^{-2} $mg.L^{-1}$	Cl^- $mg.L^{-1}$	Na^+ $mg.L^{-1}$	Mg^{+2} $mg.L^{-1}$	Ca^{+2} $mg.L^{-1}$	K^+
P199	1418	975	7.2	18	380	116	156	85	29	158	0
P200	1661	1095	7.1	45	325	151	236	149	41	146	3.91
P198	1505	1030	7.3	15	386	153	205	123	37	164	3.91
F191	1590	1070	7.65	4	391	122	238	141	31	168	0
P149	1360	940	7.1	15	333	130	166	100	29	153	0
P184	1550	1060	7.6	40	420	124	228	150	43	158	3.91
P193	1455	995	7.8	35	410	113	218	134	45	152	0
P143	1368	890	7.6	75	390	102	176	95	44	157	3.91
P146	1625	1080	7.15	30	385	118	219	115	46	142	3.91
P134	1545	1020	7.65	70	355	441	270	135	135	164	3.91
P33	1435	985	7.55	24	288	320	270	131	45	167	0
CRF	1755	1145	7.6	16	352	391	225	124	99	175	3.91
P133	2025	1395	7.35	15	395	495	630	310	171	158	3.91
P142	3880	2610	7.2	50	392	1005	1600	1025	232	128	3.91
127B	3645	2452	7.3	28	460	935	1425	848	238	194	3.91
P13	2505	1655	7.9	35	398	636	892	552	192	130	3.91
P153	2915	1935	7.1	42	335	770	1120	645	208	164	3.91
P161	4400	2885	7.1	72	469	1080	2001	1288	284	168	7.82

The groundwater samples in this area of the years 1995 and 2013 were plotted on the graphs as cations versus anions expressed in milliequivalent percentage on the modified form of tri-linear diagram of Piper proposed by Chadha (1999). Eight water types that can be identified from the diagram depend on the relationship between alkaline earths (calcium and magnesium), alkali metals (sodium and potassium), weak acidic anions (carbonate and bicarbonate) and strong acidic anions (chloride and sulphate).

In 1995 (Figure 8a), the majority of the samples (more than 83%) are plotted in the 7th field, representing the $Cl-SO_4-Na-Mg$ type, where the sodium and chloride are the dominant on groundwater thus showing a probable marine intrusion in part of the coastal area and urban pollution in the upstream area, where $(Na + K) > (Ca + Mg)$ and $(Cl + SO_4) > (CO_3 + HCO_3)$, such a water type generally creates salinity problems. While the rest of samples (less than 17%) are plotted in the 6th field representing $Ca-Mg-Cl-SO_4$ type, where $(Ca + Mg) > (Na + K)$ and $(Cl + SO_4) > (CO_3 + HCO_3)$, this water type is generally characterized by permanent hardness.

In 2013, the majority of the samples (72%) are plotted in the 6th field, representing $Ca-Mg-Cl-SO_4$ type, where $(Ca + Mg) > (Na + K)$ and $(Cl + SO_4) > (CO_3 + HCO_3)$, this water type is generally characterized by permanent hardness. While the rest of samples (27%) are plotted in the 7th field, representing the
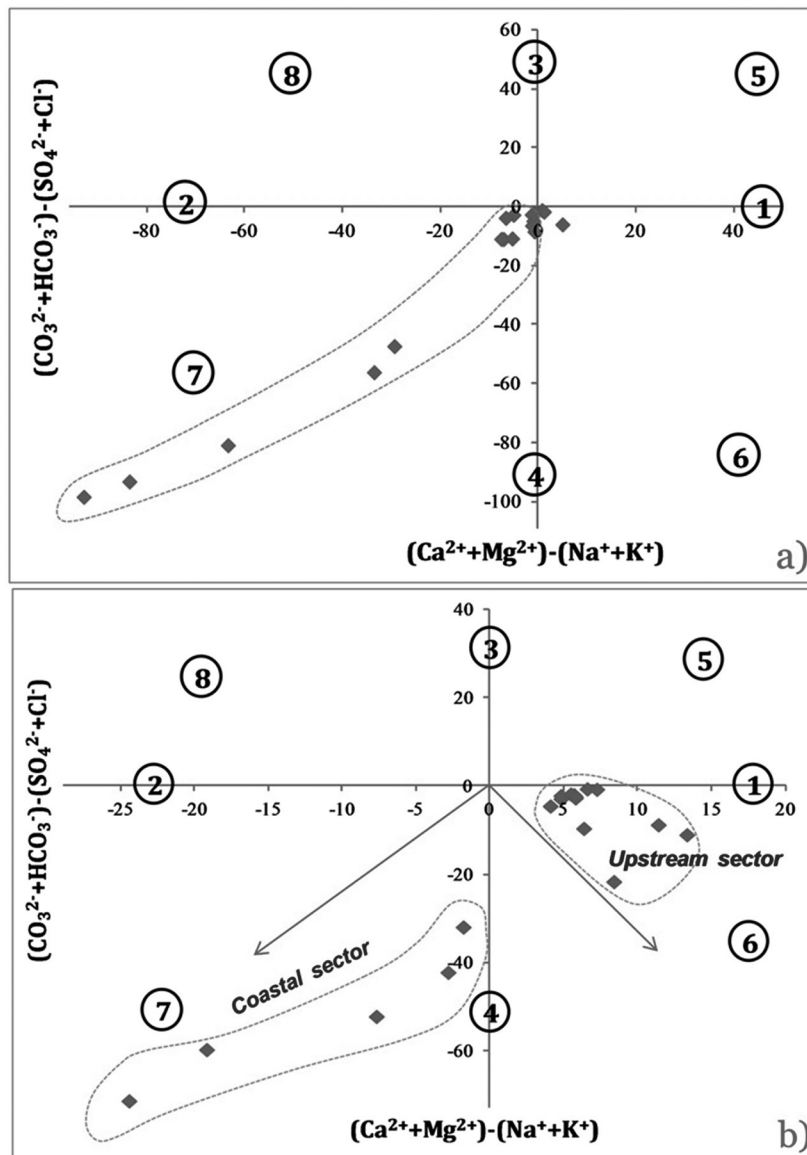
Figure 8. Chadha's diagram for groundwater of Nador plain a) in 1995 and b) in 2013.

Cl-SO_4–Na–Mg type, where the sodium and chloride are the dominant on groundwater thus showing a probable marine intrusion in this area, where (Na + K) > (Ca + Mg) and (Cl + SO_4) > (CO_3 + HCO_3), such a water type generally creates salinity problems. This indicate that the aquifer is essentially recharged by the excess of irrigation water coming from Boukourdane's dam and reuse water of wastewater treatment, and also due to the pumping reduction.

Electrical conductivity (EC)

Total ionised constituents of water denoted by EC greatly determine the quality of drinking water (Table 3). Groundwater had an average EC of 3435 µS.cm^{-1} in the year 1995 and had an average of 2090 µS.cm^{-1} in 2013. In 1995, only one groundwater sample (5.55%) with EC less than 1500 µS.cm^{-1} was permissible for drinking. Twelve groundwater samples were not-permissible for drinking, with EC range between 1500–3000 µS.cm^{-1} (66.67%) and five samples (27.78%) had EC higher than 3000 µS.cm^{-1}. Groundwater EC higher than 3000 µS.cm^{-1} depends on the weathering of the aquifer material, on the influence of anthropogenic activities polluting the ground surface and on a probable marine intrusion. While in 2013, after pumping reduction and the recharge by effective rainfall and by the excess of irrigation, five samples (27.28%) had EC less than 1500 µS.cm^{-1}, being permissible for drinking; ten samples (55.55%) were within the not-permissible for drinking with EC range of 1500–3000 µS.cm^{-1} and only three samples (16.67%) had EC higher than 3000 µS.cm^{-1}.

Total dissolved solids(TDS)

TDS is a measure of the combined content of all inorganic and organic substances contained in a liquid in molecular, ionized or micro-granular (colloidal sol) suspended form. In 1995, the TDS ranged from 980 to 5962 mg.L^{-1} in groundwater with a mean of 2302 mg.L^{-1}, and from 890 to 2885 mg.L^{-1} in 2013 with a mean of 1401 mg.L^{-1}. Classification of groundwater based on TDS is given in Table 4. Based on Davis and Dewiest (1966) classification, only one groundwater sample in 1995 was freshwater and five samples were freshwater in 2013, and the majority of samples were useful only for irrigation for the two years. High TDS may distort the taste of water and may cause gastrointestinal irritation in human beings (Howard and Bartram, 2003; Brindha and Kavitha, 2014).

Total hardness(TH)

TH depends on the calcium and magnesium content of water (Sawyer and McCarty, 1978) and is calculated as

TH (mg.L^{-1}) = 2.497 Ca^{2+} (mg.L^{-1}) + 4.115 Mg^{2+} (mg.L^{-1})

The totality of the groundwater samples in this area in 1995 and 2013 were very hard in nature (Table 5). Very hard waters may have adverse health effects like stone formation in kidney, calcification of arteries and other cardiovascular and stomach disorders. TH above 500 mg.L^{-1} (WHO, 2008) is not suitable for drinking.

Table 3. Classification of groundwater for drinking based on EC.

EC (µS.cm^{-1} at 25 °C)	Classification	1995		2013	
		Number of samples	% of samples	Number of samples	% of samples
< 750	Desirable	Nil	0	Nil	0
750 – 1500	Permissible	1	5.55	5	27.78
1500 – 3000	Not permissible	12	66.67	10	55.55
> 3000	Hazardous	5	27.78	3	16.67

Table 4. Classification of groundwater for drinking based on TDS (Davis and DeWiest, 1966).

TDS (mg.L^{-1})	Water type	1995		2013	
		Number of samples	% of samples	Number of samples	% of samples
< 500	Desirable for drinking	Nil	0	Nil	0
500 – 1000	Permissible for drinking	1	5.55	5	27.78
1000 – 3000	Useful for irrigation	12	66.67	10	72.22
> 3000	Unfit for drinking and irrigation	5	27.78	Nil	0

Table 5. Classification of groundwater for drinking based on TH (WHO 2008; Brindha and Kavitha, 2014).

TH (mg.L^{-1})	Water type	1995		2013	
		Number of samples	% of samples	Number of samples	% of samples
< 75	Soft	Nil	0	Nil	0
75 – 150	Moderately high	Nil	0	Nil	0
150 – 300	Hard	Nil	0	Nil	0
300 – 500	Moderately hard	Nil	0	Nil	0
> 500	Very hard	18	100	18	100

Conclusion

Geophysical and hydrochemical analysis were carried out in the Nador plain, to delineate the area affected by the saline water and to identify the salinity origin in this aquifer. The hydrochemical study reveals that the groundwater in this coastal aquifer is slightly alkaline in nature. The sequence of the major cations and anions in the groundwater for the coastal sector was $Na^+ > Mg^{2+} > Ca^{2+} > K^+$ and $Cl^- > SO_4^{2-} > HCO_3^-$ for 83% of the samples in 1995, and 28% in 2013. The alkali metal (Na) exceeds the alkaline earths (Mg^{2+} and Ca^{2+}) and strong acidic anions (Cl^- and SO_4^{2-}) exceed the weak acidic anion (HCO_3^-). The analysis of physico-chemical values suggest that the coastal samples fall under very poor quality classes and the groundwater in this sector is not suitable for drinking. It clearly indicates that this coastal sector is significantly affected by a seawater intrusion. Surface electrical resistivity surveys were carried out in this area, with the aim to delineate the salinity of groundwater and its subsurface configuration. The resistivity result revealed a decreasing for the aquifer layer in coastal sector which indicates increase of salinity with depth. The differences in resistivity are associated with the various lithology types and variations in water saturation. This allowed determining the extent of saltwater intrusion inland, approximately 1600 m into the Plio-Quaternary aquifer.

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