



Geoelectrical investigations for aquifer characterization and geoenvironmental assessment in northern Morocco

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Received: 28 July 2018 / Accepted: 4 March 2019 / Published online: 11 March 2019
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Abstract

The Mediterranean mountains of Morocco (“Rif”) show an intense sensitivity to hydro-climatic hazards. Hydrologic achievements are thwarted by a series of constraints that request strategic consolidation. The acceleration of socioeconomic activities is causing an increasing pressure on water resources that are already facing insufficiency and degradation problems. This paper aims at geophysical characterization of the most important intramountainous alluvial aquifer on the Rif, Ghis–Nekor. Its electrical and hydrogeological properties are investigated through a correlation of 2D electrical resistivity tomography (ERT), vertical electrical sounding (VES) and borehole data. The results have shown that this monolayer coastal aquifer is constituted of large coarse sand, gravel and pebble deposits that overlay substrata of different hydrogeological and electrical types. A geoenvironmental survey was also carried out in the coastal zone and near the uncontrolled waste landfill of Beni Bouayach. The 2D ERT profiles indicate an increase of marine water intrusion (over 2 km) particularly on the eastern bank of the Nekor river. They also show a spread of the landfill leachate flow path beyond 1 km in the direction of the groundwater flow (to the North), towards an area of hydrogeological interest located east of the city of Imzouren. These results imply a socioeconomic and environmental vulnerability that evokes an immediate intervention to restore weakened equilibrium.

Keywords Geophysics · Aquifer geometry · Marine intrusion · Flow path · Coastal aquifer · Morocco

Introduction

In Morocco, water resource management is a crucial challenge that compromises landuse planning and territorial development strategies. Since 1960s, water control policies

were adopted to satisfy the increasing demand and to enhance an efficient use. However, the retrospectively analysis shows a continuous improvement of the achievements in the water sector but it also identifies a series of complex constraints. Indeed, the intense socioeconomic acceleration has generated an unprecedented pressure on limited water resources causing a constant decline in water availability, a quality deterioration and an increasing risk of water shortage (Bzioui 2004; Driouech 2010; Salhi and Benabdelouahab 2017; Sebbar et al. 2011).

The mountainous northernmost part of the country is particularly sensitive to the extreme hydro-climatic events, including recurrent floods and droughts giving evidence of the intense interannual rainfall variability (Benassi 2008; Esper et al. 2007; Ezzine et al. 2014; Tramblay et al. 2012). This alpine mountainous chain geographically called “Rif” is extended over 400 km of coastline and overlooking both the Atlantic and the Mediterranean seas. It belongs approximately to the Tangier–Tetouan–Al Hoceima administrative region known by its cultural and linguistic originality and its natural resources and landscape diversity making it an amazing pole of attraction.

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Geological and hydrological setting

As part of this area, the plain of Ghis–Nekor (over 100 km²) is a dozen kilometres southeast of the coastal city of Al Hoceima (Fig. 1). With a slope average of 1%, the

plain is surrounded generally by shale (code 14 in Fig. 1) and sandstone mountainous flysch (code 12), except in the northwest where limestones (code 11) appear and in the northeast where plio-quaternary volcanics (code 9) are outcropping. The eastern border is a piedmont consisting of a juxtaposition of alluvial cones (code 2), the largest of

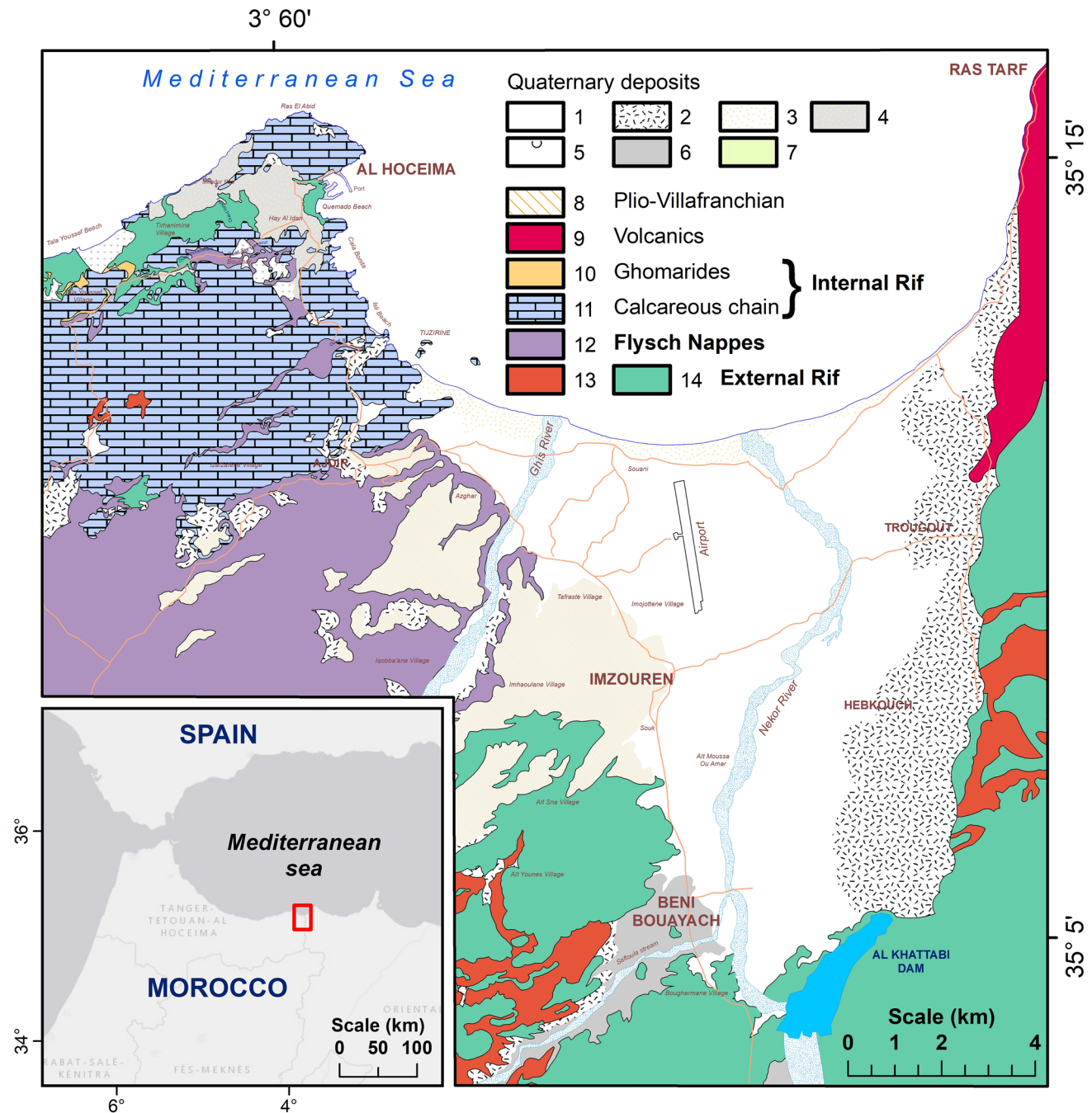


Fig. 1 Geographic situation and geologic setting of the Ghis–Nekor alluvial aquifer (modified from (Saadi et al. 1984)). 1: Alluvium and silt; 2: slope and scree deposits; 3: unconsolidated sand; 4: consolidated sand dune; 5: consolidated sand dune affected by subsidence

and solifluction; 6: encrusted surfaces; 7: conglomerates surface; 8: conglomerates, sandstone and silts; 9: volcanics; 10: hard sandstone and conglomerates; 11: limestones and dolomites; 12: flyschs; 13: clays and marls; 14: shales

which is to the southeast in the Hebkouch area where the Amekrane and Tirhounam rivers flow.

The Al Hoceima area is a complex of imbricated thrust sheets from north to south (Saadi et al. 1984). It is a part of the large Rif belt which is classically subdivided into internal, flysch and external domains (Chalouan et al. 2008; Nold et al. 1981; Piqué and Bouabdelli 2000). The internal domain (codes 10 and 11), called Rifides or Bokoya, includes the Federico-Ain El Hajar metamorphic unit (Sebides), the Al Hoceima nappe (Ghomarides) and the Jbel Amekran, Jbel Boussicour and Ajdir nappes (limestone Ridge). The flysch domain includes the two nappes of Jbel Tisirene–Oued Mechtak and Jbel Chouamat. External domain is widely extended in the south of Al Hoceima with the Cretaceous schists of the Ketama nappe (Salhi and Benabdelouahab 2017).

Geomorphologically, tree units can be distinguished (Salhi 2008):

The relief area characterized by the limestone chain of Bokoya (code 11) forming part of the internal domain of the rifaine chain. It is about 40 km long, has an average width of 7–8 km and an altitude that does not exceed 750 m. Its morphology is a combination of two types of forms: peaks at almost equal altitudes and deep valleys whose slopes have steep slopes.

This sector is subdivided into distinct morphological units, which are from north to south:

1. The Ras-al-Abid dolomitic plateau (Middle and Upper Triassic): it has the form of a rhombus bordered by northwest and northeast by high cliffs often reaching more than 150 m;
2. The “Al Hoceima–Talâ Youssef–Wadi Boussicour” strip mainly formed of schists and sandstones (Lower Devonian). It forms the northern coast between the beach of Sabadilla and the tip of Boussicour.
3. The broad strip of “Jbel Palomas–Jbel Assaguasaguane–Jbel Boussicour” formed mainly by Jurassic limestones and dolomites and separated from the previous strip by the valley of the Sidi Mansour river.
4. The strip of Jbel Amekrane (separated from the previous strip by the valley of the Isli river), which forms a karstic massif which encloses the southern depression (Tisirène flysch).

The plain area (code 1) crossed by Nekor and Ghis rivers, it is surrounded of schisto-sandstone flysch (codes 12 and 14) except in the northwest sector where appears limestone mountains (code 11) and in the northeast sector where outcrops a Tortonian andesitic massif (code 9).

The coastal Mediterranean strip (code 3) includes the coast and its marine and coastal formations around the city of Al Hoceima.

Within the Mediterranean context, the climatic analysis of the study area shows semi-arid conditions marked by mild wet winters and hot dry summers. Important intra- and inter-annual variations complicate the management process and increases the water deficit (effective rainfall hardly exceeds 4%).

Located at the most eastern part of the Tangier–Tetouan–Al Hoceima region, the Ghis–Nekor watershed is of the lowest rainfall within the regional context as shown in Fig. 2. The annual average rainfall is considerably low (350 mm) with a spatiotemporal disparity. The characteristics of the Mediterranean climate are quite marked; thus, it is observed that interannual rainfall variations are important and that the torrential aspect of the hydrological regime is accentuated. Monthly average temperature varies between 21 °C in July and 10 °C in January with an annual average of 16 °C. Comparison of rainfall data in regional weather stations shows a significant time variability and spatial disparity. The annual rainfall rarely exceeds 500 mm with maxima from November to January and minima in July–August. The frequent rainfall occurs during the October–May period (over 90% of the annual average rainfall). Else, rainfall regime is very irregular with recurrent extreme events like prolonged droughts or intense rainfall (such as the 200 mm of 26–30 November 2010, the 126 mm of 26–28 March 2007 and the 220 mm of 22–27 December 2000). Thus, the wet period covers 5 months (from November to March) while the driest months are July and August (Salhi and Benabdelouahab 2017).

The potential evapotranspiration (ETP), calculated after Linacre formula (Linacre 1993), indicates high annual values (over 1700 mm) with a monthly average of 144 mm (216 mm in August against 90 mm in February) and daily values ranging often between 8 and 3 mm. The real evapotranspiration (ETR), calculated after the water balance method (Custodio and Llamas 1976), shows daily values that vary between 0 and 4 mm and a pronounced drought period (294 days per year) mainly from April to August (172 days) and during September–October (Salhi and Benabdelouahab 2017).

Hydrological setting

The study area is part of the northwestern Mediterranean basin of Morocco characterized by intramountainous small to median watersheds drained by a few rivers (karstic supply) and an important density of torrential streams causing sporadic floods. The irregular and violent hydrological regime is caused by abundant, intense and sudden rainfall and to a dominant impermeable lithology combined with abrupt relief (El Gharbaoui 1986).

In the Ghis–Nekor watershed (Fig. 2) (1765 km² shared almost equally between Ghis and Nekor subwatershed),

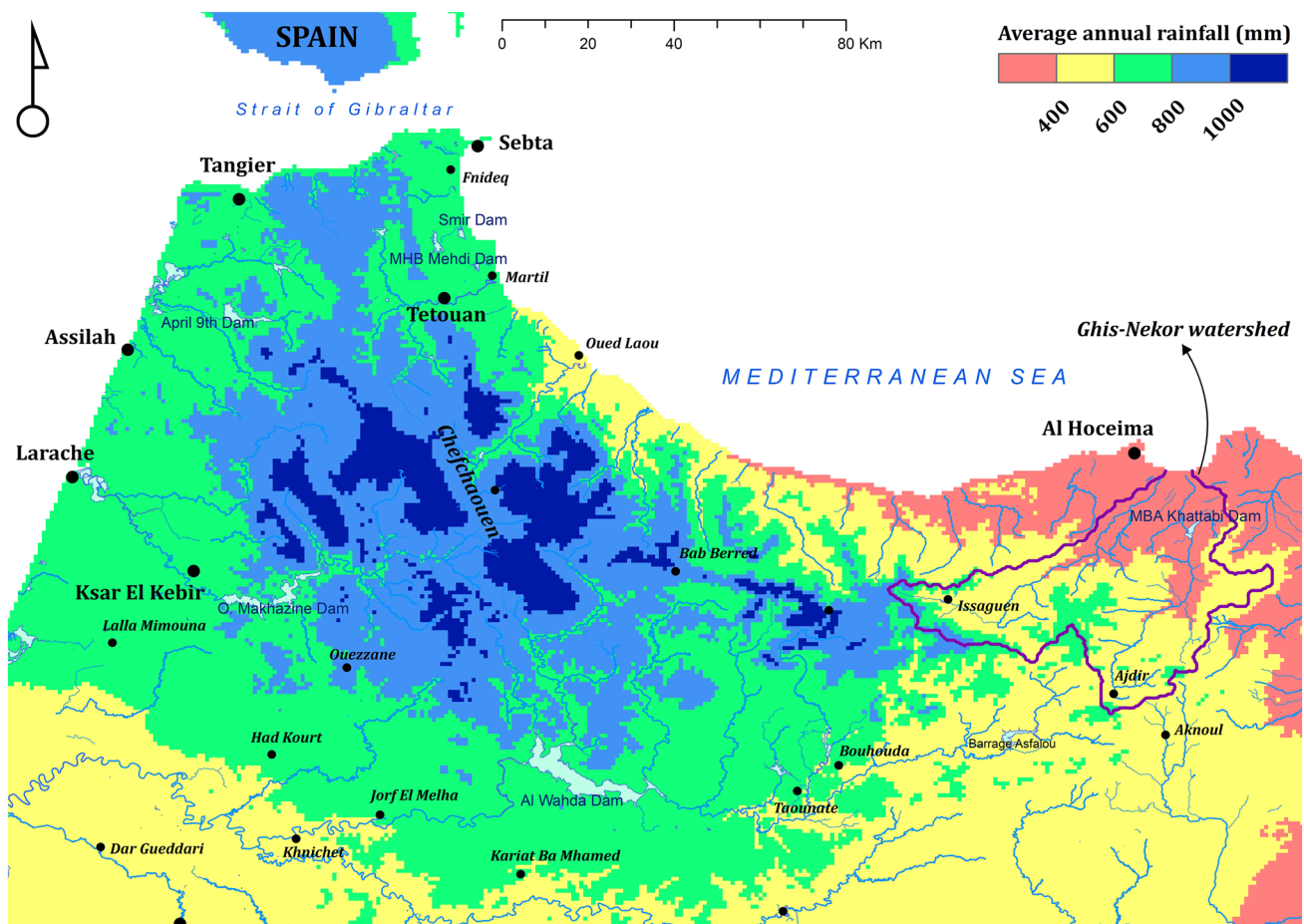


Fig. 2 The annual average rainfall in northwestern Mediterranean basin of Morocco (1970–2015)

a downstream 100 km² floodplain is longitudinally (from south to north) crossed by the two major rivers of Ghis (1.5 km across the plain) and Nekor (10 km across the plain). The watershed consists of a dense stream network, often intermittent, flowing from various directions toward the coastal plain (the preferential flow direction is from the south to the north) through the intramountainous valleys.

The watershed management was initiated by the construction of the two dams of Al Khattabi (Nekor subwatershed) and Joumoua on the Takarat stream, effluent of the Ghis river. A third dam is under construction on the Ghis subwatershed. At the plain level, a low stream density is perceived in the centre while it increases toward the mountainous borders (mainly western borders) where several intermittent torrential streams are observed; the most significant are “Saftoula” on the southwest border and “Amekrane” on the southeast.

The Nekor subwatershed (911 km²) is characterized by an average altitude of 1.4 km and average slope of 2.4% that decreases gradually to 0.8% at the plain. It is drained by the Nekor river (69 km length) that traverses mainly

impermeable bedrocks (Schists of the Ketama unit and marly flysch). Upstream, the river crosses gypsum layers that increase salty mineral amount. Since 1981 (Al Khattabi dam construction), waterflow at the plain level has dropped considerably (the river remains almost dry during several months of the year downstream the dam) affecting consequently the piezometric level of the Ghis–Nekor aquifer. The river bed is constituted of gravelly conglomerates with sandy–loamy cement (Photos 1 and 2 in Fig. 3). The gravel amount increases near shore line where several quarries have been installed (extracting sand and gravel directly from the river bed). These quarries are overpumping groundwater leading to a high marine invasion risk (Photos 5 and 6 in Fig. 3).

The Ghis subwatershed (854 km²) has an average altitude of 920 m and an average slope of 1.9%. Its river (78 km length) passes 1.5 km downstream the Ghis–Nekor plain (which is 6.5 times less than Nekor river). The river takes its name (*Ghis: mud in local dialect*) from the abundance of silty deposits during torrential episodes. Like the Nekor river case, many quarries are installed near shore line.



Fig. 3 Photos of the study area. 1: Dry course of the Nekor river; 2: gravelly conglomerates of the Nekor river bed; 3: implementation of an ERT profile at the Tifarouine stream; 4: quarry for gravel extraction on the Ghis river (near shore line); 5: excessive pumping in a

quarry near Ghis river mouth; 6: excessive pumping in a quarry near Nekor river mouth; 7: fine silty-clay salty deposits (saline surfaces) near the 1689/5 borehole; 8 and 9: the uncontrolled waste landfill located near Beni Bouayach city

Methods

This paper presents results from geophysical campaigns performed on the Ghis–Nekor plain. It consists of 22 Electrical Resistivity Tomography (ERT) 2D profiles and 154 Vertical Electrical Sounding (VES) supported by 84 scattered borehole data (Fig. 4).

ERT is a subsurface geophysical technique that consists in determining the lateral and vertical distributions of real electrical resistivities based on dozens of measurements made at the ground surface (Photo 3 in Fig. 3). The choice of configuration depends mainly on the structure types; Wenner

configuration is recommended for horizontal structures and for lower depth of investigation while Wenner–Schlumberger configuration is recommended for either horizontal (piezometric surface, layer limits, etc.), vertical or sub-vertical structure (faults, freshwater–saltwater interface, etc.) (Dahlin and Loke 1998).

In our case, ERT prospecting was carried out under Wenner–Schlumberger mixed array configuration with a multielectrode resistivity meter (48 switch) of 480 m line length and a standard 10-m electrode spacing. ERT field data were interpreted after a 2D resistivity modelling software designed to invert large data sets collected with

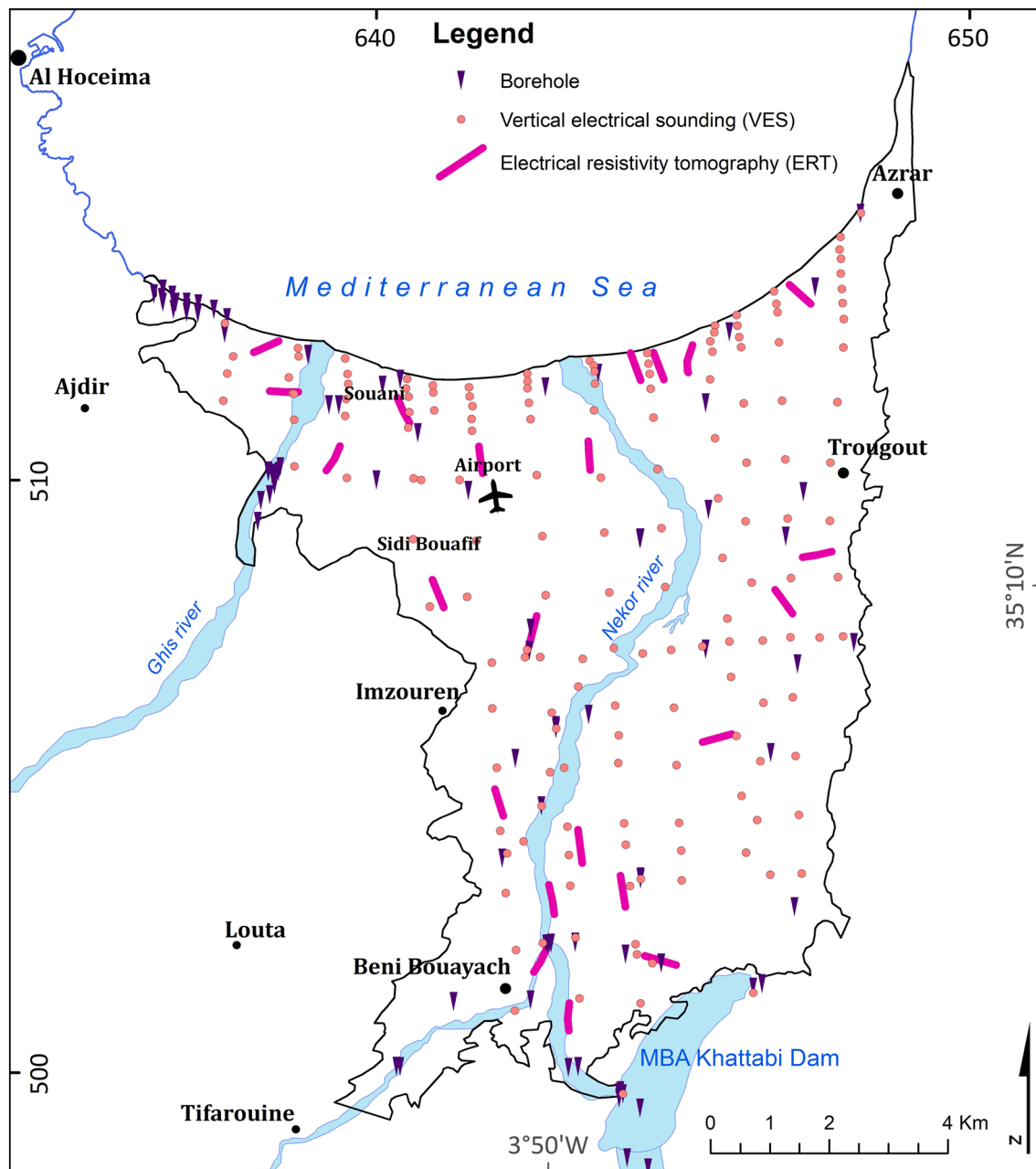


Fig. 4 Position of the field geophysical surveys used in the study

a multielectrode system (Loke 1999). This is designed to interpolate and interpret field data of electrical geophysical prospecting of electrical resistivity and induced polarization (Uhlemann et al. 2017). The inversion of the resistivity and IP data was conducted by least square method involving finite-element and finite-difference methods. The software can handle data from any electrode array and invert data from the most popular geophysical instruments (Hellman et al. 2016).

2D geoelectrical profiles were illustrated as images of real resistivity distribution according to a logarithmic scale. To

facilitate their interpretation, they were all oriented so that the first electrode (located at 0 m) is placed on the sea side (North) while the last electrode (located at 480 m) is placed on the Al Khattabi dam side (south).

ERT is increasingly being applied to environmental investigations to identify material properties and boundaries and to monitor variations in space and time of relatively large volumes of soil (Casas et al. 2008). It can provide high-resolution images of hydrogeological structures and, in some cases, detailed assessment of dynamic processes in the subsurface environment (Binley et al. 2002). Correlated with

borehole and VES data, it is also suitable to assess clearly saltwater penetration and the migration flow of a pollutant through the vadose zone (Benabdelouahab et al. 2018; Binley et al. 2002; Himi et al. 2017; Kumar et al. 2016; Lehtikoinen et al. 2009; Robert et al. 2012). Thus, it is used in this study for three purposes:

- To monitor the detailed lithological properties of the vadose zone (all the 22 ERT 2D profiles);
- To delineate the marine intrusion over the coastal zone (9 ERT profiles: 1, 2, 3, 4, 5, 6, 7, 8, and 19);
- To assess the pollution flow path of an uncontrolled waste landfill located on the dry stream bed of Nekor river eastern Beni Bouayach city (8 ERT profiles: 10, 11, 12, 13, 15, 16, 17, 20).

VES monitoring was carried out among 85 km² approximately under the supervision of the “Loukkos Hydraulic Basin Agency” (administration responsible for regional water management). The AB current electrodes spacing ranges between 1.5 and 10 km distributed mainly between 3 and 4 km (94 VES) and 6 km (53 VES). In fact, VES interpretation maybe mysterious for too large AB distance only if no other data are available for correlation. For long-distance AB, it is not easy to know if the apparent resistivity is due to structural changes in depth or to lateral heterogeneities by contrast of resistivities. In our case, both ERT profiles and borehole logs were used to solve VES mysteries.

The depth of investigation of a measurement depends on the distance between the two extreme electrodes (Roy and Apparao 1971). Thus, for the used Wenner–Schlumberger mixed array configuration, it is a common rule of thumb to say that the depth of investigation is of the order of 0.1 to 0.3 times the AB length (Barker 1989; Edwards 1977; Roy and Apparao 1971). However, the relationship between the electrode spacing and the depths of investigation is often not simple especially in complex aquifer systems. Moreover, several factors can facilitate, or not, a good measurement and resolution at large investigation depth (ground resistivity, intensity of the current and equipment sensitivity). In our case, the maximum depth of investigation was reached in VES 11GN12 (554 m).

VES field data were interpreted (in correlation with adjacent borehole data logs) after 1D forward modelling and inversion through an interactive, graphically oriented, forward and inverse modelling software for interpreting resistivity sounding data in terms of a layered earth (1D) model. Thence, the software supports most array configurations (Wenner, Schlumberger, dipole–dipole, etc.) for up to 60 measurements per VES. Sounding curves can be entered as apparent resistivity versus spacing between current electrodes (AB/2). Direct inversion allows to estimate the layered model directly from data curve, layer resistivity and

thickness. Smooth modelling enables automatic plotting for up to 19 layers in either automatic or user-defined parameters (Interpex 1988).

ERT and VES results

ERT and VES results were well correlated to close borehole data and were useful, thus, to establish lithological profiles and to assess a geoenvironmental assessment of the uncontrolled waste landfill flow path and the marine intrusion.

VES interpretation was complicated because of the low-resistivity contrast between schists and alluvium making it difficult to distinguish between them. Furthermore, lateral and vertical sudden variations of the quaternary alluvial deposits cause several ambiguities. However, abundant borehole data and 2D ERT profiles helped to overcome this.

Figure 5 illustrates three examples of borehole logs. The alternation of coarse sand and gravel intercalated with silty-clayey alluvial deposits is clearly observed. Clayey layers are also perceived at different depths in the three logs. Near the limits of the plain, the adjacent rock formations (limestone and schist) appear below the alluvial filling (borehole logs 315/5 and 285/5, for example).

Three examples of apparent resistivity curves with the best-fit layer and its lithological interpretation are presented in the following. VES 11GN12 (located at 2.5 km northern Beni Bouayach city) shows an eight-layered resistivity model (Table 1; Fig. 6) which indicates three thick resistant levels correlated with coarse sand and gravel separated by less-resistant levels of different thicknesses (alluvial deposit with silt and clay). The conductive basement (correlated with Schist) is identified at 328 m approximately. VES 15GN12 (located 1.9 km eastern the previous VES) shows two resistant coarse sand and gravel layers with an alluvial silty-clayey interlayer. Differently, the coarse sand and gravel (resistant) layer is not perceived in VES 15GN1 (located at the coastal area in the east bank

of the Nekor river). Instead, it is perceived a thick less-resistant level which is correlated to alluvial deposit with silt and clay.

VES interpretation indicates a depression oriented in the NE–SW direction which extends along the thick clay-marly conductive substratum overlaid by resistant coarse-grained alluvium. The lowest point is reached near the borehole n° 1971/5 (located 1.5 km to the ENE of the city of Imzouren) where the thickest permeable deposits are located.

VES reveals also the existence of a network of three geoelectric discontinuities perceived from both plain sides (about 1 km from eastern and western limits) and parallel to the shoreline (4.2 km northern Al Khattabi Dam). These discontinuities match the limit of the thicker alluvial deposits which correspond to an abrupt rise of the schistose deep

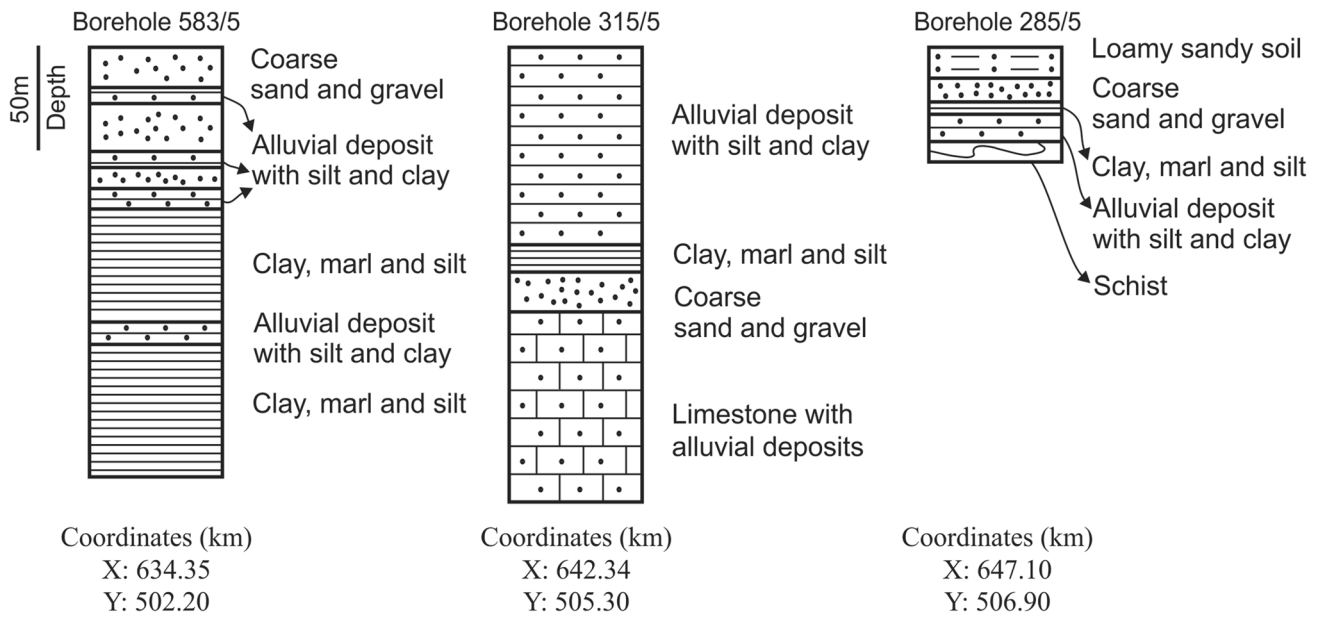


Fig. 5 Examples of borehole logs

Table 1 Examples of VES interpretation

Station n°	Coordinates (km) "Nord Maroc" System		Layer n°	Resistivity (Ωm)	Thickness (m)	Depth (m)	Geotechnical implication
	X	Y					
VES 15GN12 AB: 3 km RMS: 0.021	645.10	504.22	1	121	73.5	–	Coarse sand and gravel
			2	30	22.7	73.5	Alluvial deposit with silt and clay
			3	90	92.4	96.2	Coarse sand and gravel
			4	7	79.3	188.6	Clay, marl and silt
			5	14		267.9	Schist
VES 11GN12 AB: 6 km RMS: 0.025	643.21	504.15	1	136	94.8	–	Coarse sand and gravel
			2	25	16.9	94.8	Alluvial deposit with silt and clay
			3	88	122.2	111.7	Coarse sand and gravel
			4	27	16.2	233.9	Alluvial deposit with silt and clay
			5	91	66.6	250.1	Coarse sand and gravel
			6	8	11.7	316.7	Clay, marl and silt
			7	15	175.7	328.4	Schist
			8	6		504.1	Clay, marl and silt
VES 15GN1 AB: 3 km RMS: 0.019	644.56	512.26	1	22	2.2	–	Loamy sandy soil
			2	10	35.7	2.2	Clay, marl and silt
			3	28	229.1	37.9	Alluvial deposit with silt and clay
			4	12		267.0	Clay, marl and silt

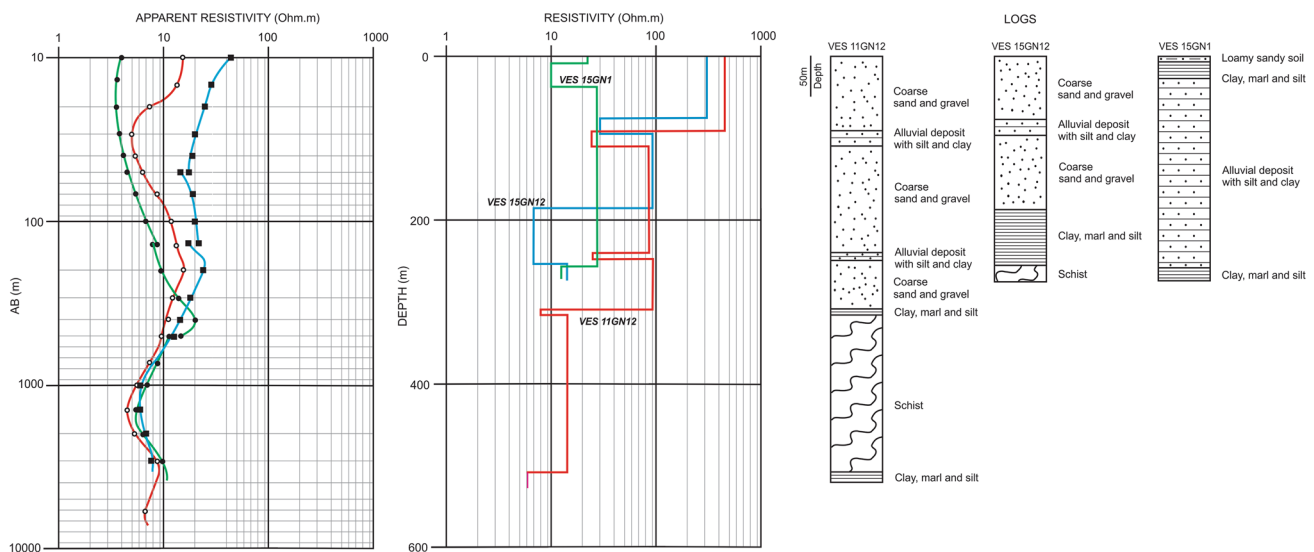


Fig. 6 Apparent resistivity curves for three VES with the best-fit layer and its lithological interpretation

resistant substratum due, probably, to geological faults in the east, west and south of the plain.

ERT survey aims at monitoring the vadose zone detailed lithological properties (hardly described due to discontinuous available VES and borehole data). Indeed, the vadose zone is the underlying, unsaturated, parent material extending downward from the soil surface to where it reaches the water table and the soil becomes saturated (Voroney and Heck 2015). It merits special attention since it represents the first, and most important, natural defence against groundwater pollution because of its strategic position between the land surface and the saturated aquifer and because of its environment which is generally more favourable for pollutant attenuation and elimination (Robins 1998).

Interpretation of resistivity results

ERT and VES inversion results (recovering all the aquifer) were well correlated to close borehole data and were useful, thus, to establish lithological profiles and for geo-environmental assessment (described in the following).

Lithological profiles

Lithological profiles (Fig. 7) were established after the correlation of mechanical drilling, VES and ERT results and it shows that the alluvial Ghis–Nekor plain (triangular tectonic structure that gives towards the coast) is constituted of large coarse deposits of sand, gravel and pebbles, sometimes silty-clayey. To the south, the schistous mountainous range (Albo-Aptian of Ketama unit) forms a deep impermeable bedrock which is affected by a network of normal faults (due to an

extensive phase). From the centre to the coast, this bedrock is overlaid by an irregular non-continuous clay-marly upper substratum.

Alluvial material was mainly deposited on the plain by the Ghis and Nekor rivers, and then by the surrounding torrential stream network. Thicker coarse deposits (beyond 400 m) are located on the two depressions (1 km approximately to the east of Imzouren city and near “Souani” beach) even if the average thickness exceeds 200 m.

The bedrock is mostly constituted of conductive clay-marly layer (resistivity values oscillating around 10 Ω m) which overcomes a deep impermeable resistant schistose substratum. The clay-marly layer is not permanently continuous; hence, alluvial deposits overlain locally the resistant substratum, particularly at the southern and northwestern edges where the deep substratum progressively rises and outcrops in the adjacent mountainous massifs.

Substratum map (Fig. 8) displays the aspect of the roof of impermeable layers independently of its electrical or lithological properties. It shows shallow depth at the southern, northeastern and northwestern edges (less than 25 m in some places) where mountainous impermeable rocks decline gradually beneath alluvial deposits (until 100 m depth). From there, a second declination is observed, principally in the south, to reach 200 m depth (1.5 km northern Beni Bouayach city). After that, the slope becomes abrupt and the roof deeper (beneath 450 m) particularly at 1 km eastern Imzouren city where a tectonic depression is perceived (derived from the collapse phase that gave rise to the Ghis–Nekor alluvial plain). In the north of this depression (near Borehole n° 1971/5), the substratum ascends slowly to 200 m depth (coastal zone). Two other depressions are observed in the North: the first is positioned at the meander

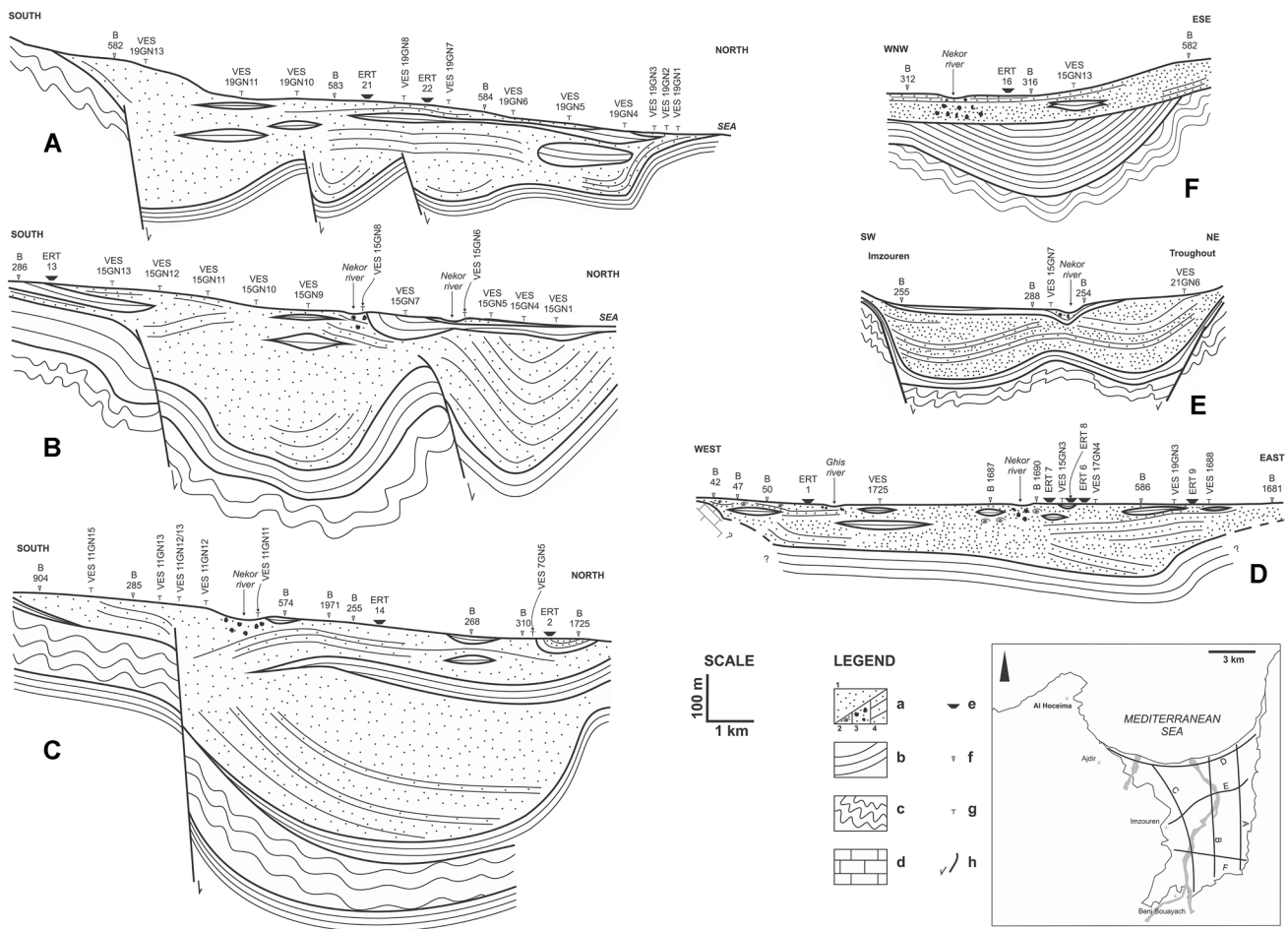


Fig. 7 Lithological cross-sections on the Ghis–Nekor aquifer. a₁, Coarse sand and gravel alluvia; a₂, abundance of shell sand; a₃, abundance of gravel and pebble; a₄, alluvial deposit with silt and clay;

b, clay, marl and silt; c, schist; d, limestone; e, electrical resistivity tomography (ERT); f, borehole; g, vertical electrical sounding (VES); h, fault

of the Nekor river (beneath 300 m depth) while the second is located near the “Souani” beach (beneath 400 m depth).

The aquifer thickness map describes the depth to the impermeable basement minus the depth to the water-table (Fig. 9). It shows that thickness varies considerably between 430 and 5 m (it is thin southern the plain and near the north-eastern and northwestern edges). Alluvia are thicker toward the two tectonic depressions located near Imzouren city (beyond 400 m on borehole n° 1971/5) and “Souani” beach indicating areas of hydrogeological interest (likely to give rise to several water-well drilling).

A special attention should be given to the lithology, thickness and permeability of the aquitard layers due to their special role in the protection of aquifers from pollution. In our case, it is composed of sandy-gravel alluvium, occasionally silty-clayey, traversed by dispersed clay-marly lenses and a large clayey level extended northern plain. The aquitard thickness is irregularly ranging between 1 m (coastal area) to 50 m (east) and it increases from west to east and from

edges to centre. Thus, it is thicker near the “Hebkouch” village (east) where an important alluvial fan of clayey deposits is observed.

Uncontrolled waste landfill flow path

ERT intended to delineate the marine intrusion on the coastal zone and the pollution flow path of an uncontrolled waste landfill located on the dry stream bed of Nekor river eastern Beni Bouayach city (Photos 8 and 9 in Fig. 3). In this last case, a network of 8 ERT profiles (Fig. 10) has been realized around the waste landfill. The profile 17 was executed a few hundred meters upstream the waste landfill in the dry stream of “Tifarouine” (effluent of the Nekor river). It shows a superficial thick (30 m) extended (beyond 100 m) resistant level (over 70 Ω m) interpreted as coarse gravelly alluvium (characteristic of the regional torrential stream load) on the beginning of the profile. This level continues laterally with lower resistivity values that range between 40

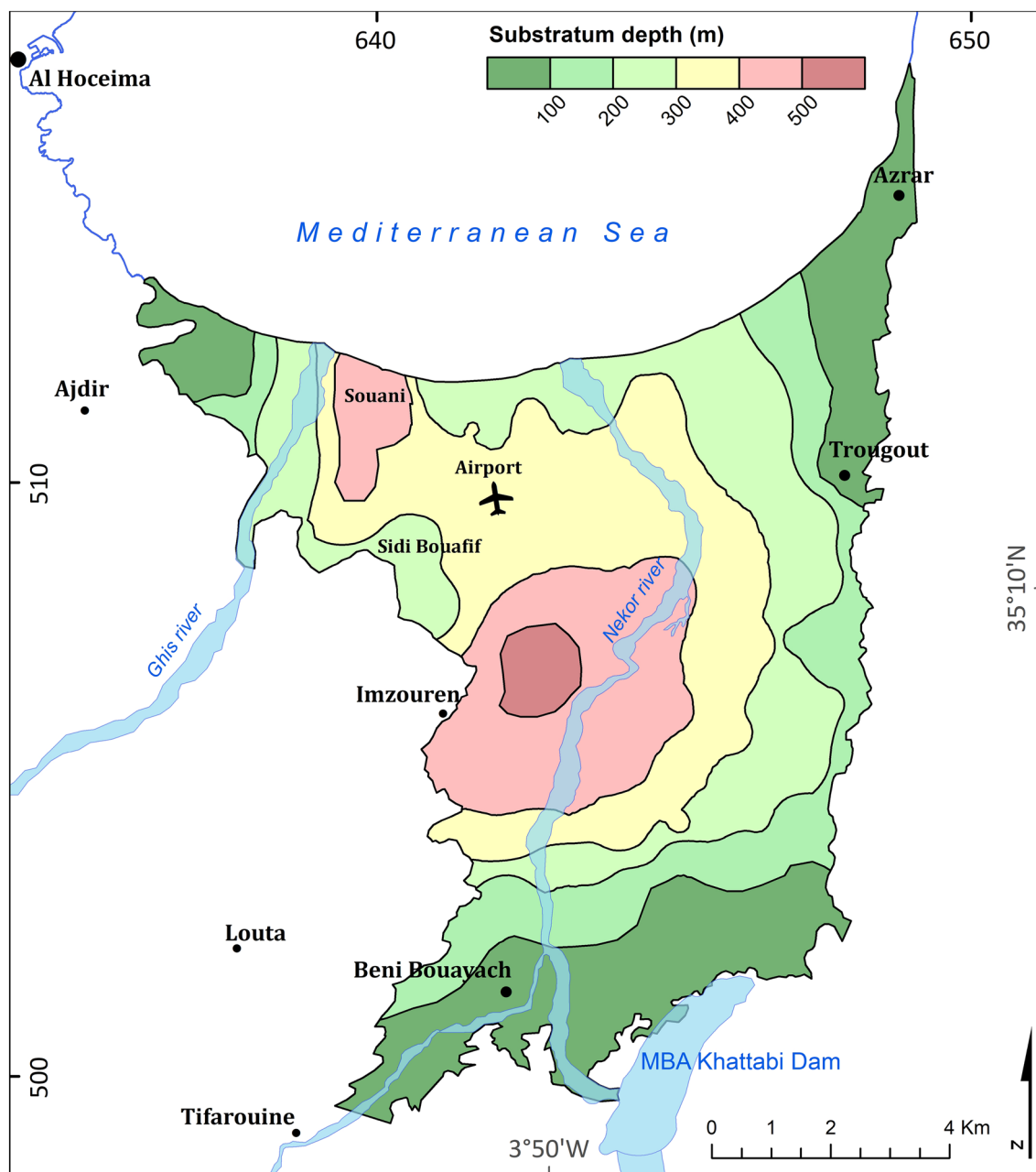


Fig. 8 Substratum map

and 60 Ω m interpreted as medium to coarse sandy-gravelly alluvium. A deeper thick conductive (under 25 Ω m) level is correlated to an increase of the silty proportion within the alluvial deposits.

At this emplacement, it should be noted the absence of conductive clayey covering layers which increases groundwater intrinsic vulnerability. Notionally, the protection of groundwater reservoirs is given by the covering protective layers with sufficient thickness and low hydraulic conductivity (correlated with electrically conductive clayey layers) leading to high residence time of percolating (Kirsch 2009).

The profile 12, located 1.3 km upstream the waste landfill, shows similar observations but different dimensions of the superficial resistant (thinner) and deep conductive (thicker) layers.

The profile 11, placed in the middle of the waste landfill, is surrounded by the boreholes n° 577/5 and 576/5 (500 m and 1.2 km, respectively, to the North) then by the ERT profiles 17 and 12 (to the south) which show the same similarities indicated above. Hence, the upper subsurface layer is constituted of thick, resistant, permeable sandy-gravelly coarse alluvium without any clayey protective covering

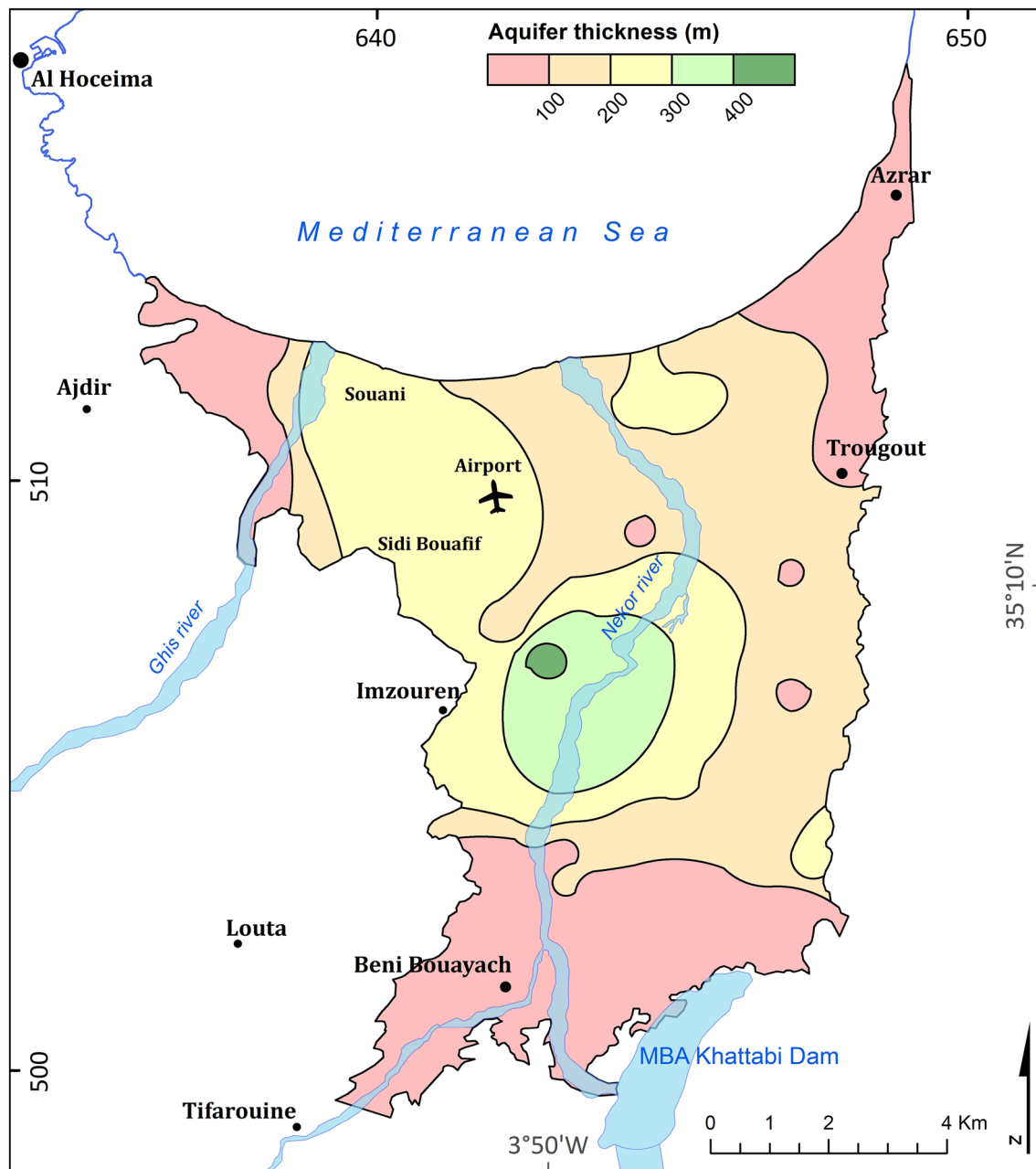


Fig. 9 Aquifer thickness map

layer. However, the profile shows a conductive leachate path (resistivity break between 120 and 220 m) ranging between 20 and 10 Ωm (observed in the landfill surface) flowing deeply (over 40 m towards the south and north of the profile) through the alluvial deposits. This landfill leachate flow path is perceived laterally beyond 1 km to the groundwater flow direction at the profile 15 (N.B.: this last was established over an embankment road responsible for the conductive continuous upper level). It is possible to identify the leachate from the background through the correlation with closer ERT profiles (ERT 16 and 10 in this case) and

with adjacent borehole log (n° 576/5). The deep leachate flow ends laterally 2 km to the North as shown in the profile 10 (correlated with the nearest borehole n° 315/5). It is not observed in the other profiles (10, 16 and 13).

Marine intrusion

A network of nine ERT profiles (Fig. 10) has been realized throughout the coastal zone to delineate the marine intrusion where the depth to water table ranges between 2 and 10 m; a decisive element to take into consideration when

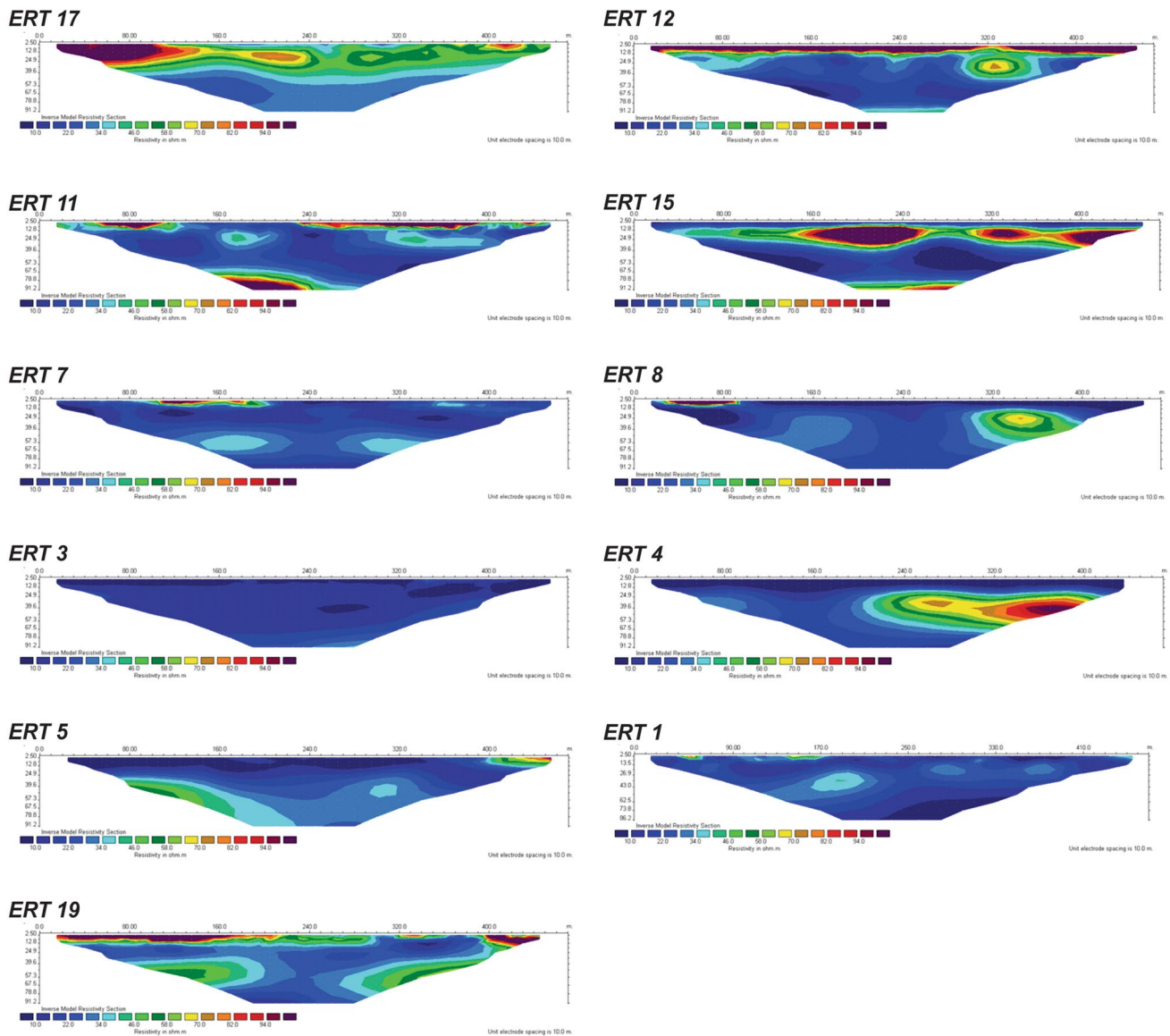


Fig. 10 Examples of the 2D electrical resistivity tomography (ERT) results

interpreting. Due to the low contrast between the marine intrusion and the ambient resistivity, it seems preferable to opt for a dynamic colour scale to improve the contrast. However, after several tests, a single-colour scale was chosen to facilitate the comparison of the resistivity ranges of the different profiles.

The profile 7 shows a thick (20 to 25 m) conductive plume (less than 11 Ω m) throughout the whole profile at a depth of 5 m (towards the shore) gradually deepening to a depth of 20 m inward. At the centre of the profile, a shallow conductive level (less than 9 Ω m) is correlated with fine silty-clay salty deposits. These saline surfaces, as indicated on the 1/50.000 Al Hoceima geological map (Choubert et al. 1984), are due to the capillary rise of the

highly mineralized shallow groundwater and to the deposition (hydrological and aeolian) of marine salty molecules.

To the east, the profile 8 shows that the conductive plume penetrates horizontally less than 150 m due to slower percolation caused by low permeability of fine silty-clayey alluvium correlated to resistivity values ranging from 10 to 30 Ω m. This shallow conductive plume corresponds to the lateral extension of the saline surfaces observed in the profile 7 and around the nearest borehole n° 1689/5 (Photo 7 in Fig. 3). Two resistant lenses (beyond 50 Ω m) match with sandy alluvial deposits.

The conductive plume extends again laterally and inward (beyond 2 km as observed on the profiles 6 and 9)

indicating an expanded saline water intrusion at the east of the coastal area.

On the west bank of the Nekor river, five profiles (3, 4, 5, 1 and 19) show a regression of the conductive plume (marine intrusion) towards the Ghis river. These profiles, correlated with several borehole log data (50/5, 1125/5, 1686/5 and 268/5), reveal abundant medium to coarse sandy-gravelly alluvial deposits. Excessive pumping (quarries for gravel extraction, irrigation) is also observed nearby the Ghis river. However, the detected marine intrusion regression is explained by the significant water flow of this river, which helps to maintain

the balance of the freshwater/saltwater interface at this area. Consequently, a special attention must be given to maintain this balance which should not be broken by the commissioning of the upcoming dam on the Ghis river.

Discussion

The geophysical surveys result shows that the alluvial plain of Ghis–Nekor consists of large deposits of sand, gravel and pebbles, with loam-clay passages. These deposits fill a

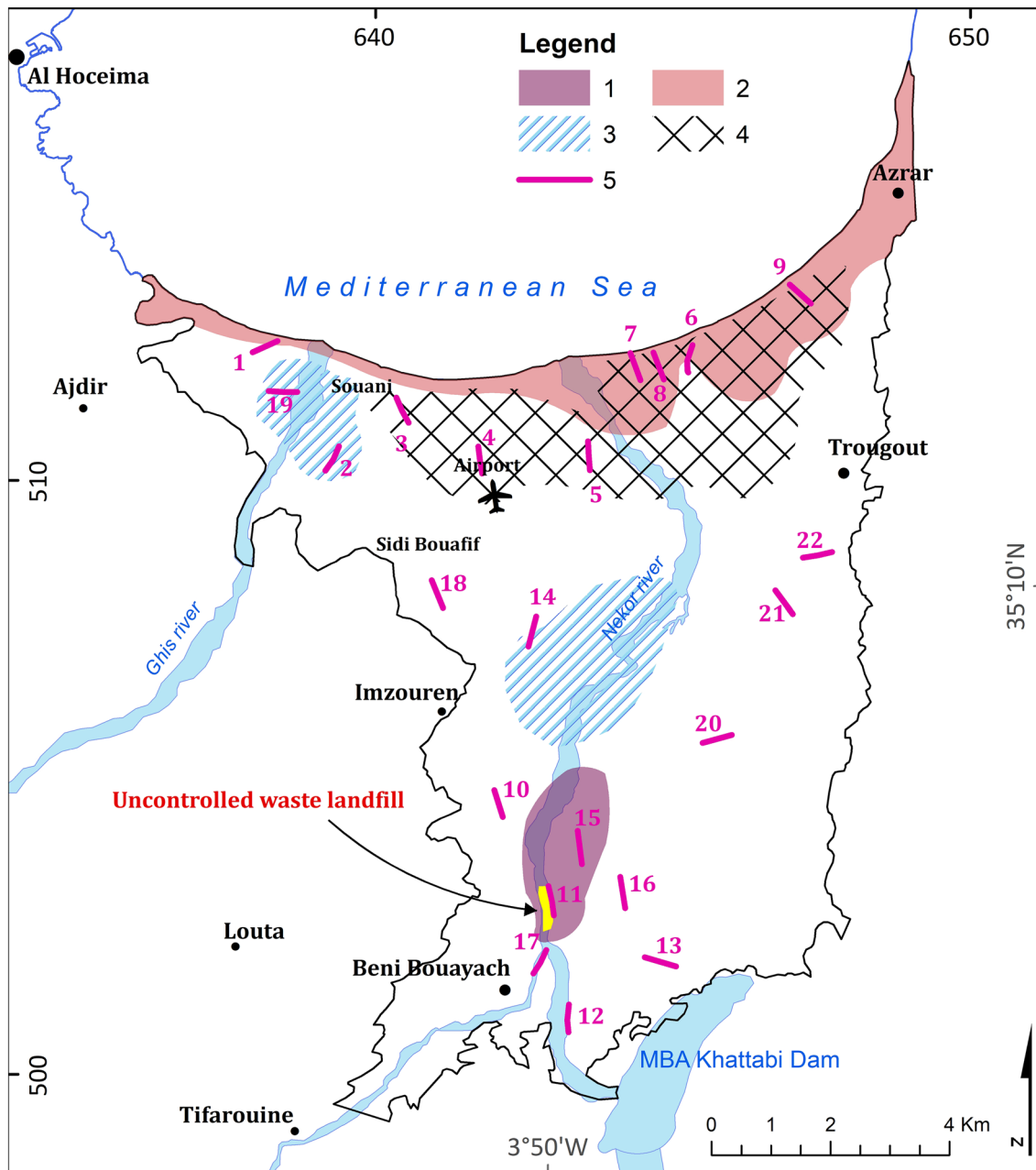


Fig. 11 Results of the geoenvironmental assessment with the position of electrical resistivity tomography (ERT) profiles. 1: Landfill leachate flow path; 2: marine intrusion; 3: areas of hydrogeological interest; 4: saline surfaces; 5: electrical resistivity tomography (ERT) profiles

triangular tectonic structure that opens to the North towards the Mediterranean Sea over 12 km approximately. The average thickness of the alluvial deposits exceeds 200 m with a maximum that exceeds 400 m in a depression located about a kilometre east to the city of Imzouren (near the 1971/5 borehole). This area (extended over nearly 5.5 km²) is hydrogeologically interesting due to its considerable accumulations of coarse alluvium.

The substratum is affected by a network of normal faults due to the extensive phase that led to the opening of the Ghis–Nekor valley. The electrical and lithological observations indicate substrata of geological nature.

Different lithological cross sections show that the intermediate clayey level is quite extensive but not continuous; it passes through a large part of the alluvial deposits while maintaining the monolayer nature of the aquifer.

The study of the marine intrusion indicates saline water penetration near the Nekor river and east of this last while intrusion is not detected on both the banks of the Ghis river. A map (Fig. 10) drawn from the interpolation of 2D resistivity results (Fig. 11) was correlated with lithological data to describe the morphology and extension of the marine intrusion; this last penetrates deeply (more than 2 km) where coarse alluvial deposits are abundant while it is restricted where fine fraction proportions are observed.

The monitoring of the landfill leachate flow path reveals a spreading plume (Fig. 10) that contaminates groundwater resources due to the high permeability (coarse alluvia) around the Beni Bouayach uncontrolled waste landfill. 2D resistivity profiles indicate an expanded contamination (over 1.5 km), facilitated by the groundwater flow oriented mainly from south to north. This contamination is approaching the area of hydrogeological interest located east of the city of Imzouren.

The Ghis–Nekor aquifer has a key role in maintaining the socioeconomic equilibrium of the province of Al Hoceima for its contribution to agriculture and drinking water supply. However, the succession of years of drought and the accelerated siltation of the Al Khattabi dam imply an increasing demand on its resources which constitutes a vital water alternative in this zone.

The repercussions of the contamination generated by the studied hazards (marine intrusion and landfill leachate flow path) will be manifested by serious negative impacts on the population health and well-being as well as on the socioeconomic development. The environmental fragility of the Ghis–Nekor aquifer requires special and immediate attention to stop pollutant activities and restore groundwater quality. Clandestine and excessive pumping must be prohibited especially near the coastal area and environmental awareness should be improved to prevent contaminations in the future.

Acknowledgements This study was supported by the National Centre for Scientific and Technical Research (CNRST, Morocco) under

Contract no. PPR/11/2015. It also was supported by the International Foundation for Science (IFS, Sweden) under Grant no. W5342-1. The authors acknowledge the relevant collaboration with the Loukkos Hydraulic Basin Agency (ABHL, Morocco).

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