Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

GIS-based Geothermal Potential Assessment for Northeastern Morocco

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Keywords: Geothermal potential, GIS, Weighted overlay, Boolean model, Northeastern Morocco

ABSTRACT

The developed activity around thermo mineral resource involves a wide range of scientific and engineering disciplines used by various researchers. In this paper, a geographic information system (GIS) is used as decision-making tool to target the most promising geothermal area in the northeastern part of Morocco. The method is based on the use of spatial relationships between geothermal manifestations, geological, geochemical and thermal data layers. The surface temperature map, the distance to lineaments, the productivity map and the salinity map were combined in GIS environment using two different models: namely the Boolean logic and the weighted overlay models. The result shows the region of Fezouane as favourable to develop a geothermal project

INTRODUCTION

Morocco is located at the junction between the African continent and the Atlantic Ocean, and is affected by the Alpine belt system, which is a result of an active collision zone between the African and European plates. The recent volcanism and the large number and size of surface thermal manifestations (hot springs), especially those present in the northeastern part of the country, have attracted several geothermal studies (Facca, 1968; Alsac et al. 1969; Rimi et al 1987; Zarhloule et al. 1999; Rimi et al., 2012).

The thermal waters are mainly hosted within sedimentary reservoirs, consisting of Liassic limestones with a thickness up to 500 m. The geothermal fluid is characterized by a complex deep circulation and it ascends through complex fault systems. The Liasic reservoir of Eastern Morocco belongs to the Atlas domain (Fig.1) which is characterized by a succession of NE-SW horst and graben structures of pre-Miocene age and by Plio-Quaternary basaltic volcanics, produced by crustal thinning. This reservoir feeds more than twenty-four thermal manifestations, with temperatures ranging from 26 to 54 °C. Some of these hot aquifers, e.g. Fezouane, near Berkane and Hammam Ben Kachour, at Oujda (Fig. 2) play an important role in the economy of the area (Zarhloule, 1999; Zarhloule et al., 2001). The purpose of this paper is to identify the most promising geothermal area in the northeastern part of Morocco through an investigation of the relations between a geothermal system and its surroundings, defined by geological and economical characteristics. Within this framework, the GIS environment was used to combine data from:

- Surface temperature (°C),
- Aquifer productivity (Flow rate (l/s))
- Distance to lineaments (km)
- Salinity (g/l)

The first two criteria are representative of the operating performance of the aquifer for geothermal purposes; the third is purely geological while the latter is called "economic". Indeed, the investment cost can rise in the case of mineralized waters which can be very aggressive and cause corrosion problems.

GEOLOGICAL BACKGROUND

A system of plains, plateaus and mountain ranges lying in the eastern parts of the Meseta-Atlas and Rif domains characterises northeastern Morocco (Fig. 2). It comprises the Eastern Middle Atlas, which continues through the Guercif basin to Beni Snassen, the Moulouya valley, the Oujda-Taza corridor, the “Pays des Horsts” and a crustal block without notable alpine

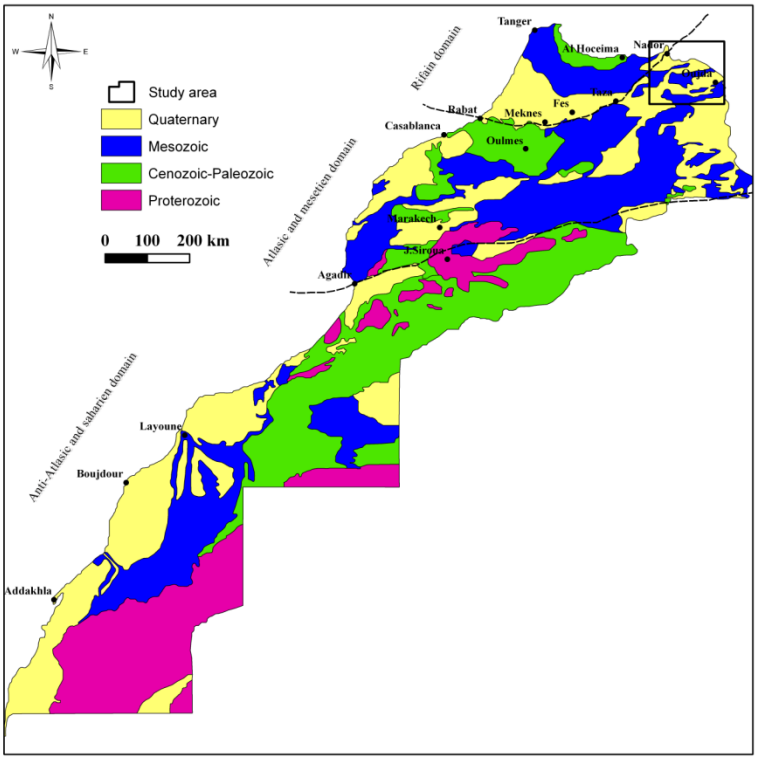

Figure.1: Main structural and geological features of Morocco

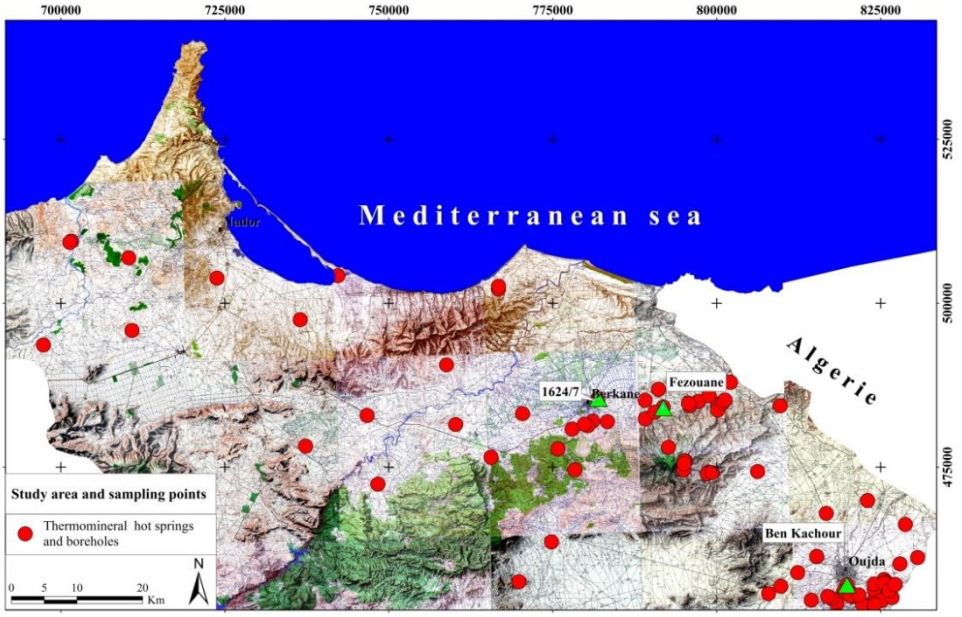

Figure 2: Study area with the main thermo mineral waters from hot springs and boreholes

deformation, which constitutes the High Plateaus. Three ENE-WSW structural units are recognised (Hervouët 1985; Hoepffner 1987; Riser and Laouina1995):

- The Eastern Rifian foreland, composed of the Gareb chaotic unit near the active Rif chain and a little deformed tectonic foreland (Terni Masgout, Beni Bou Yahi, Beni Mamou and Beni Snassen), prolonged eastward (in Algeria) by the Traras mountains.
- The Guercif and Taourirt-Oujda basins, which are filled with sediments of middle Miocene to Quaternary age, and are connected to the Tafna basin to the east (Algeria).
- The Taourirt-Oujda mountains, which show sub-horizontal Jurassic sediments affected by fault systems, whose development and geometry are strongly dependent on the pre-existing structures in the Hercynian basement. They are prolonged eastward by the pre-Tellian foreland of Tlemcen.

The rif domain, located northwards, belongs to the Betic-Rif belt and is part of the peri-Mediterranean Alpine chain. Together with the Atlas, this morpho-structural zone results from the superposition of several tectonic, compressive and extensional, phases of Alpine age. These phases have formed since the late Cretaceous. Most of these zones are ENE-WSW to E-W directed (e.g., "Pays des Horsts") and NE-SW (Middle Atlas, valley of Moulouya), reflecting part of the alpine geological evolution.

Several volcanic centres extend throughout Morocco, roughly in NE-SW direction since the Mediterranean coast to the Atlantic coast. In northeastern Morocco, Late Miocene-Pliocene volcanic activity led to the formation of shoshonitic edifices, with age ranging from 8 to 4.5 My, near Taourirt, and calcalkaline centres with age ranging from 6.2 to 4.8 My in the Oujda area, (Hernàndez and Bellon 1985; Bellon, 1976).

Magmatism in eastern Morocco developed during the Miocene. A more recent episode consisting of alkaline volcanic activity took place from 6 to 0.8 Ma, and occurred along a NE-trending belt extending from the Trans-Alboran zone to the Middle Atlas domain and the Anti-Atlas (J. Siroua volcano; see Fig. 1). The geochemical signature is similar to that of intraoceanic island basalts and suggests the role of an asthenospheric "hot lineament" (Chalouan et al., 2008).

GEOTHERMAL DATA

Geological and hydrogeological data from boreholes show the Liassic carbonates to be the main hydrogeothermal reservoir in the region. This reservoir is highly variable in thickness (50-1140 m) with a maximum depth of 1370 m. An example of this aquifer in Ben Kachour station is shown in Figure 3.The meteoric waters penetrate from the surface through the outcrops of the Liasic limestones in the southern part of the Angad plain, continue to descend through the same formation that becomes deeper going to the north.

According to Zarhloule (1999), the hot temperature and the artesian rise of most of the thermal springs in northeastern Morocco are due to groundwater circulating at depth within a framework of a recent volcanic area and a system of basement faults, forming horsts and grabens. Barkaoui (2013a) performed a thorough geochemical analysis of the main thermal waters in northeastern Morocco and made in evidence the high reservoir temperature. Surface geothermal manifestations are mainly located on a NE-SW line from Nador to Taza, and from Fes (Moulay Yacoub) to Oulmes south of the Rif frontal thrust, along the so-called Moroccan Hot Line (MHL). Tassi et al. (2006) confirmed that CO_2-rich thermal waters with ^3He anomalies are likely related to MHL. The contemporary presence of ^3He anomalies and minor recent basalt outcrops indicate that CO_2 originates from mantle degassing or deep hydrothermal systems in these thermal discharges.

Figure 4 shows the heat flow density map obtained from data available from Morocco and the surrounding regions (Rimi, 1999). The regional pattern highlights heat flux increasing northeastward, from less than 60 (north Mauritania) to more than 80-90 mW m^{-2} in the eastern Rif, northeastern Morocco, Alboran Sea and northwestern Algeria. The Gibraltar Arc region is characterized by a radial heat flow pattern, with increasing values from the outer ranges towards the central and eastern part of the basin.

The distribution of the geothermal gradient (Rimi, 1999; Zarhloule et al., 2010) is shown in Figure 5. The largest values are found in the northeastern part of Morocco, where they can reach 50 °C km^{-1}. This part of the country is also characterized by high residual magnetic anomalies related to widespread Quaternary volcanism.

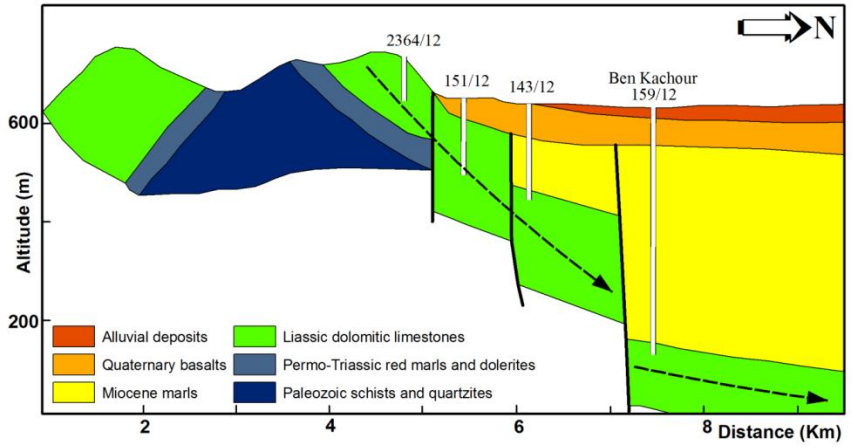

Figure 3: Geological cross-section for Ben Kachour thermal water

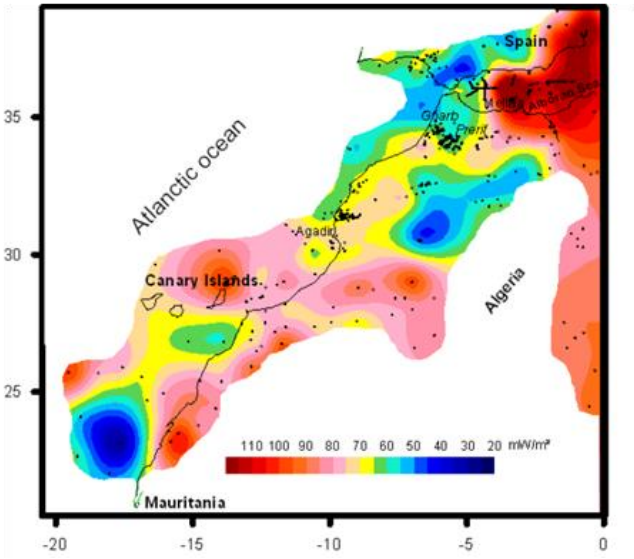

Figure 4 : Terrestrial heat flow density in Morocco and neighbouring regions (Rimi 1999)

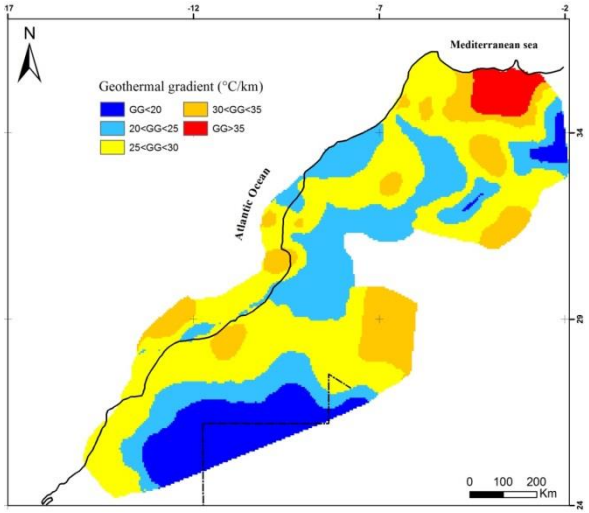

Figure. 5: Geothermal gradient map of Morocco (Zarhloule 1999)

MODELLING APPROACH

Geothermal areas have various natural manifestations at the ground surface such as hot springs, which are natural geothermal indicators. Basically geothermal exploration programs make use of such manifestations and other investigation techniques and measurements to identify prospective geothermal resources in the large scale. The decision-making process need to combine and analyze the results of a number of different surveys and studies. Thus, human errors are unavoidable during this complex procedure. To minimize them, the GIS can be a powerful tool for identifying prospective areas by employing various digital data layers. In this study ArcGIS was used as an effective tool for the integral interpretation of geoscientific data using computerized approach. This approach has been used to determine prospective areas by combining various digital data layers in NorthEastern Morocco.

Four parameters were used in this study: the temperature of the water at the surface, the productivity of the aquifer, the distance to lineament, and the salinity. The first two criteria are representative of the aquifer operating performance in the case of geothermal exploitation; the third is purely geological while the latter is called "economic." Indeed, Mineralised water may be very aggressive and can lead to corrosion problems which will increase the costs of investment. An integration models in GIS environment were programmed and run and then promising areas were marked as geothermal potential sites. The GIS (ArcMap 9.3) is used as a decision support system tool for performing site selection.

Thematic Layers for ArcGIS Analysis

To map the different criteria used to determine areas with geothermal potential, it is necessary to construct a prior mesh representing our study area. This step will be useful to overcome the problem concerning the bad distribution of the measurement points. In our case we used the DEM (Digital Elevation Model) previously created with ARCGIS representing Northeastern Morocco, and then our mesh was generated using "Data Management Tools".

1. Surface temperature

This parameter is to be determined directly in situ at the emergence point. The temperature variation depends on many parameters, among them: Geothermal gradient, the maximum depth reached by infiltrated water, the flow rate and the ascending movement of hot water (Barkaoui 2014). Data were taken from geothermal survey performed in 2013 and completed by the geothermal database from the agency of Moulouya hydraulic basin. Surface water temperature varies from 26 to 54°C in Northeastern Morocco (Figure 6).

2. Distance to lineaments

Faults allow groundwater to percolate towards the heat source and become heated to high temperatures. Generally, geothermal systems are associated with areas of active faulting; as these active fractures let the meteoric fluids circulate and penetrate deep to the crust. The lineaments data used in this study are based on the analysis of the gravity and the magnetic maps (El Gout 2010). To quantify the proximity of geothermal manifestations to lineaments and fractures, a distance to lineament map was generated using "Distance to lineaments" function in the "Spatial Analysis" module. (Figure 7).

3. Aquifer productivity

The aquifer productivity parameter corresponds to the assessment of the extractable water resource. We used mainly flow rate data from hot springs and geothermal boreholes. Those data come from geothermal survey 2013 and were completed by the geothermal database from the agency of Moulouya hydraulic basin. The spatial analysis of this parameter was performed with cell size equal to 400m on each side. The region of Berkane is characterized by flow rate reaching 97 l/s in Ain Aoulout spring (Figure 8). It is important to mention that the flow rates of the hot springs is variable depending on the season and therefore does not reflect 100% the productivity of the aquifer.

4. Water salinity

The salinity of deep groundwater reflects the chemical characteristics of the recharge water and reservoir rock. It depends at least on two factors

- Communication with surface water and other hydrogeological adjacent units;
- Geochemical exchanges within the aquifer.

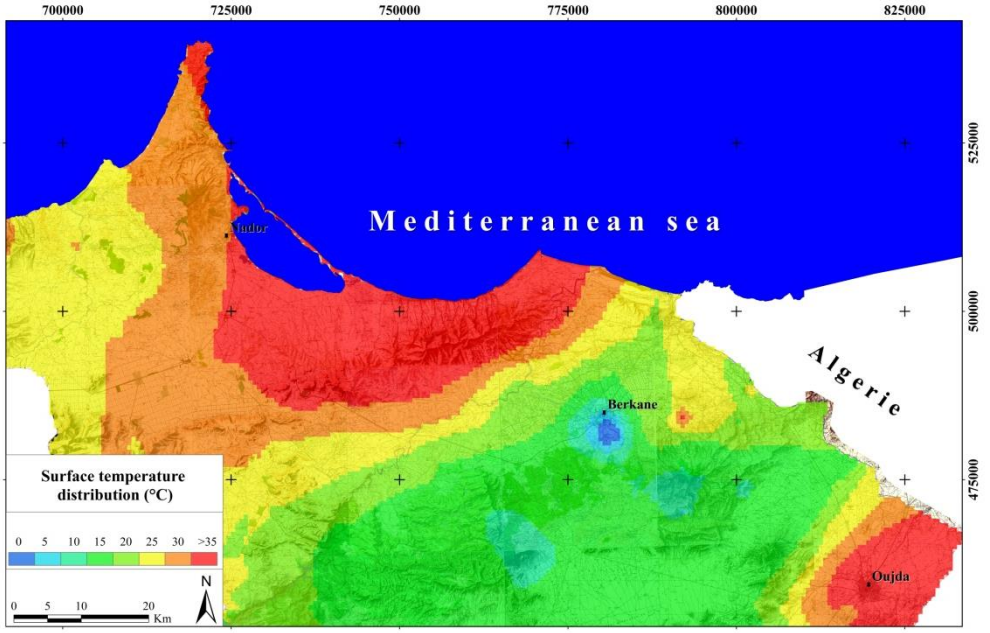

Figure. 6: Surface temperature distribution (°C)

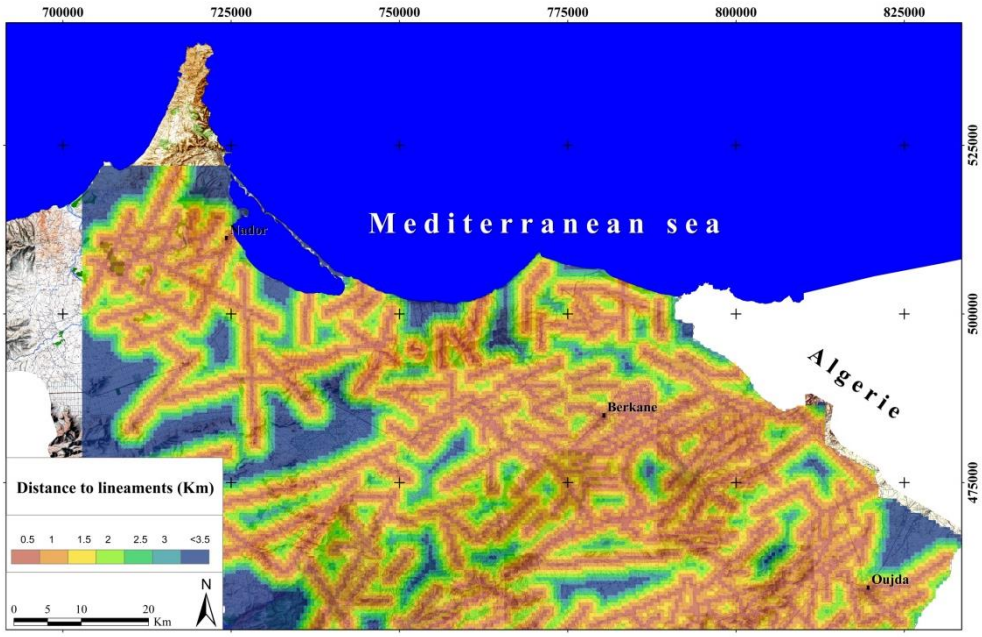

Figure. 7: Distance to lineaments (Km)

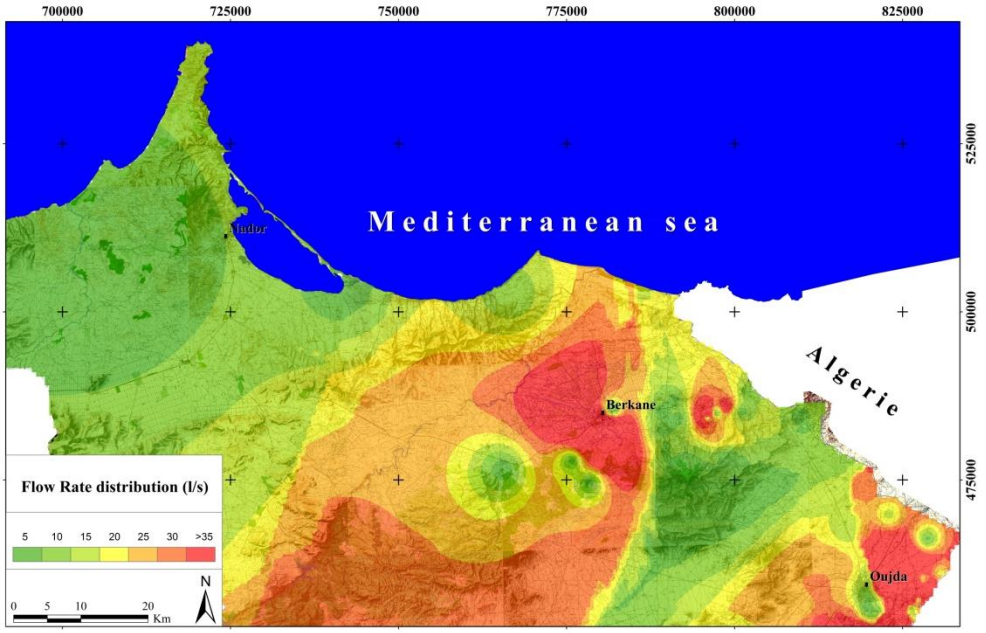

Figure. 8: Flow rate distribution (l/s)

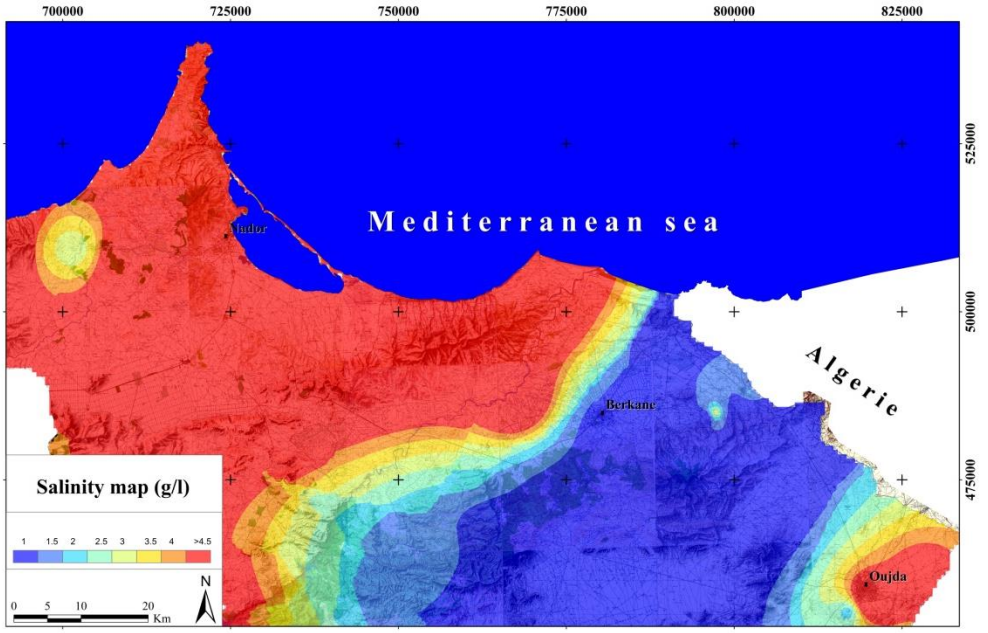

Figure 9: Salinity map (g/l)

A collection of salinity data was performed. This compilation of data can be used to determine areas that require material specific sizing due to the corrosive nature of the water with high salinity. Thermal water from the Eastern Rif are characterized with high mineralized water reflecting the influence of the Trias evaporitic rocks (Figure 9).

RESULTS AND DISCUSSIONS

To meet a specific objective, it is frequently the case that several criteria will need to be evaluated. Such a procedure is called Multi-Criteria Evaluation. After organizing our data into a dedicated geo-database, including vector and raster information, a series of transformations based on raster conversions and reclassifications were performed in order to homogenize the layers information. Two models were used to make in evidence the best area for geothermal exploration namely the weighted overlay and the Boolean logic models.

The "Weighted overlay model" represents one of the most used approaches to solve multi-scale and multicriteria spatial correlations under GIS environments. In this model each individual raster cell is reclassified into units of suitability. In this work, the value 5 was assigned to classes representing the most favorable conditions for the geothermal exploitation. Consequently the 3 and 1 values were assigned respectively to moderate and low promising conditions (Table 1). Working data were overlaid using a weighting system that reflects the influence of each layer in the overall geothermal potentiality evaluation process. Using a scale of 100% influence, The first two parameters (Surface temperature and Flow rate) were given the highest weight with 30% each one, while the distance to lineaments and the water salinity were given a weight of 20% each one. The resulting map makes in evidence three favorable locations for geothermal resource exploration (Figure 10). The three sites in red color are located in Fezouane region, and surrounding Berkane and Oujda cities. Those areas are effectively characterized by the existence of project using geothermal water for balneology. In the rest of the study area, the development of a geothermal project is still possible; however, the investment costs will be higher. These will be related primarily to the drilling operations, which must reach greater depths for high temperatures and also to the specific design of the used materials to avoid corrosion problems.

With the objective to confirm the first results, the Boolean logic model was applied as an alternative way to make in evidence the most favorable area for geothermal exploitation. This model is probably the simplest and best-known type of GIS model. Robinov (1989) introduced the use of Boolean operations for reasoning with geological maps. In effect, Boolean modeling involves the logical combination of binary maps resulting from the application of conditional operators (Bonham-Carter, 1996). Only one or zero values are assigned to each unit area, specifying whether it is satisfactory or unsatisfactory, respectively (Table 2). In our case we used the AND operator which yields the logical intersection of the fourth parameters. The query data is analyzed based on Boolean logic and entered in the Raster Calculator (from spatial analyst) according to the existing thematic layers. Unlike the "Weighted overlay model", in the Boolean logic we consider that all the parameters have the same influence on the final result. In this case the most favorable areas for geothermal project will be those with:

«Temperature > 28°C» **AND** «Flow rate > 25l/s» **AND** «Distance to lineaments < 1km» **AND** «Salinity < 2g/l»

Figure 11 highlights the favorable locations for geothermal exploitation based on the Boolean Model. First priority areas (red color) are those where the four parameters are present. Locations where three parameters are present will be considered as second priority areas, while third priority will be assigned to areas where just two or one parameter is present. According to this logic, The Fezoune region is qualified and confirmed as first priority area where geothermal project can be developed. Oujda and Berkane region are located in the area with second priority.

The obtained results from the two models make in evidence the important geothermal potential in north-eastern Morocco and confirm the previous obtained results (Barkaoui 2013a, Barkaoui 2013b, Rimi 2012). It is important to signal the positive geothermal anomaly detected in the borehole 1624/7 located west of Berkane. This hole (Figure 12) is characterized by an increase in geothermal gradient at 300 m depth from 29 to 127 °C km^{-1}. At the same depth, the lithology changes from clay to dolomite. At about 470 m depth, the temperature is about 50 ºC. The shape of the thermal profile suggests a conductive thermal regime both in the upper (clay) and in the lower (carbonate) section of the hole. The dolomitic formation continues to the hole bottom (1042 m depth). By extrapolating the thermal gradient inferred in the lowermost section of the hole, a bottom temperature of about 120 °C is inferred. The lithology change cannot explain the increase in geothermal gradient. As dolomite is expected to have a much greater thermal conductivity than clay, one would expect the geothermal gradient to decrease. An explanation for the anomalous pattern of the thermal gradient might be found in the advective heat transfer, which can occur at depth in the carbonatic formation. We may argue that heat advection occurring in the main deep thermal aquifer, encountered at 1042 m depth, can yield the increase in thermal gradient observed in the overlying dolomitic layers.

Geothermal potential criteria	Parameter classification	Rate	Priority
	T <20	1	Low
Surface temperature (°C)	20<T <40	3	Moderate
	T > 40	5	High
	Q<25	1	Low
Flow rate (l/s)	25<Q<50	3	Moderate
	Q>50	5	High
	D<2	1	Low
Distance to lineaments (km)	1<D<2	3	Moderate
	D<1	5	High
	TDS>2	1	Low
Salinity (g/l)	1<TDS<2	3	Moderate
	TDS<1	5	High

Table 1 Classification and rating of the geothermal potential criteria using the "Weighted overlay model"

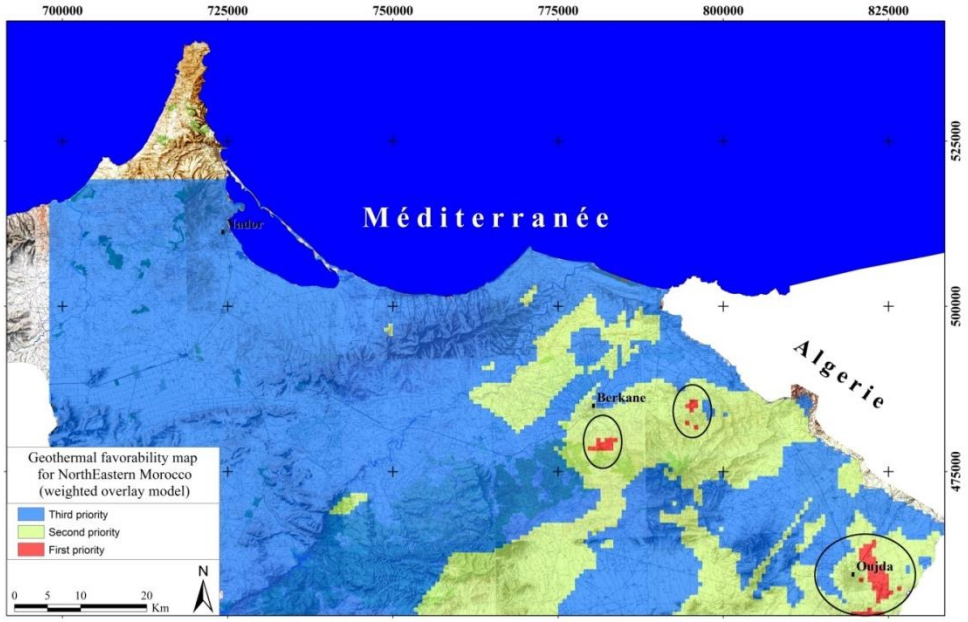

Figure 10: Priority map for geothermal exploitation using the "Weighted overlay model"

Geothermal potential criteria	Parameter classification	Rate	Priority
Surface temperature (°C)	T< 28	0	Low
	T > 28	1	High
Flow rate (l/s)	Q<25	0	Low
	Q>25	1	High
Distance to lineaments (km)	D>1	0	Low
	D<1	1	High
Salinity	TDS>2	0	Low
	TDS<2	1	High

Table 2 Classification and rating of the geothermal potential criteria using the "Boolean logic model"

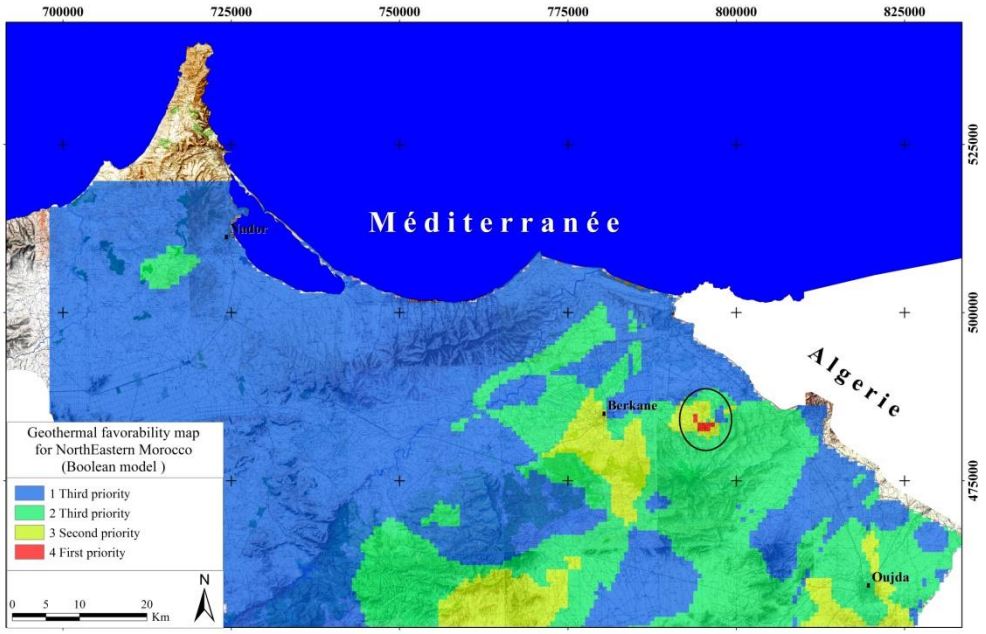

Figure 11: Priority map for geothermal exploitation using the "Boolean logic model"

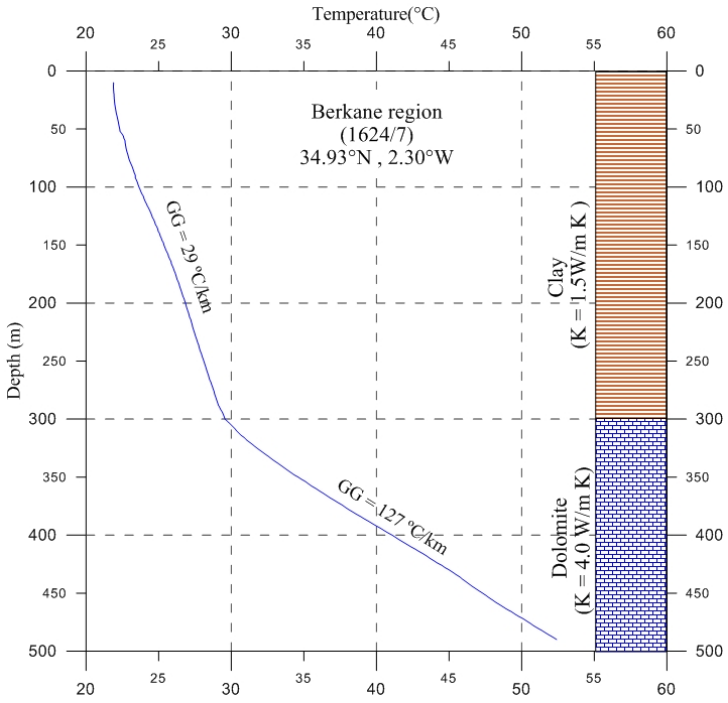

Figure 12 : Thermal profile of the borehole 1624/7 located in the region of Berkane (see Fig. 2 for the hole location)

CONCLUSIONS

The aim of this work is to find out the suitable area for geothermal exploitation. The GIS-based decision support system is used to combine data and for multicriteria analysis. The geothermal exploration data are used to find the optimum location for geothermal project in northeastern Morocco. The used parameters for such work can be different from region to other according to their availability and their accuracy. In this work, the surface temperature map, the distance to lineaments, the productivity map and the salinity map were combined in GIS environment using two different models: namely the weighted overlay and the Boolean logic models. Compared to each other, it is identified that the first one has more flexibility and ability for priority indication on spatial units of factor maps. However, either expert opinion is needed for weighting the maps, which will lead to subjective result, or the maps will be given equal importance. Results with the two models show the region of Fezouane as favorable to develop a geothermal project.

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