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Groundwater potential and quality mapping using GIS-RS modeling and Vertical Electrical Soundings (VES) in El-Hamiz Sub-watershed, Algiers, Algeria.

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Abstract

As climate change continue to become more severe, water supplies are becoming scarce and groundwater is becoming more and more exploited worldwide. Groundwater exploration relies mainly on hydrogeological studies and geophysical techniques (electrical methods). Although this technique is inexpensive, easy to implement, and not time consuming, it can be challenging to perform due to topographic effects or small area heterogeneities. Generally, a field trip is scheduled prior to any geophysical survey to scout the area of interest and locate the VES points on site. This costs time, money, and effort. The use of GIS and Remote Sensing analysis of the study area can facilitate the identification of appropriate areas for geophysical surveys. In addition, the final result of groundwater potential is useful in defining areas where VES can provide maximum and accurate results on groundwater occurrence and quality. this study concern groundwater exploration in el-hamiz sub-watershed part of the eastern Mitidja, Algiers. GIS-RS model was developed to highlight the groundwater potential zone and locate VES location. Furthermore, VES data determined the aquifer's parameters and highlighted a saline pollution.

Keywords: GIS-RS model; Groundwater; AHP; VES, Mitidja, Algeria.

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Introduction

With the population growth, industrial development and agricultural expand, Algeria is facing an increasing fresh water demand (Hamiche et al., 2015). The latter cannot be satisfied with surface waters that are becoming limited due to lack of rainfall induced mainly by global warming and climate change (Taylor et al., 2013). Consequently, Algeria has started exploiting its groundwater resources as an alternative to meet the growing water demand. Therefore, identifying areas with good groundwater potential and understanding the functioning of these aquifers is crucial for a sustainable exploitation and management of the resource.

The flow and occurrence of groundwater in a given area is controlled by many surface factors, including: Topography, Lithology, Geologic structures, Slope, Drainage Pattern, Land Use and Cover, and Climate. Usually, hydrogeological surveys coupled with geophysical investigations are relied on for the characterization and understanding of aquifers. Recently, the integration of Remote Sensing data (RS) and Geographic Information System (GIS) has been widely used in groundwater assessment studies and proven to be a highly effective tools providing reliable results (Ahmadi et al., 2020; Allafta et al., 2021; Gaber et al., 2020; Verma & Patel, 2021). This is due to the ability of Satellite Images to cover quickly large spatial scales which is extremely advantageous in groundwater investigation.

Furthermore, GIS is an advanced system permitting the effective processing and storing of georeferenced data (Selvam et al., 2019). Moreover, geophysical investigation methods such as Vertical Electrical Soundings (VES) have been widely used in hydrogeological studies (Akhter & Hasan, 2016; Hasan et al., 2020; Ndubueze et al., 2019; Oguama et al., 2020). Indeed, this method is easily implemented measure resistivity variation with depth and provide information about the water table depth and the aquifer's thickness. Such integrated Remote Sensing, GIS and Geophysical techniques provide valuable results in the delineation, assessment, and conservation of groundwater resources (Ibrahim-Bathis & Ahmed, 2016; Jha et al., 2007).

Despite the reliable results that geophysical methods produce, their implementation can sometimes be difficult because of various terrain factors: type of land use, topography, surface heterogeneities and lithology. These constraints can slow data acquisition and cost time and money. A careful preparation of the survey mission is essential for a thorough understanding of the study area. However, it is not always possible to acquire accurate detailed information, particularly for remote areas. Today, with satellite imagery, it is possible to map any region of the world, and subsequent processing enables the description of the entire study area.

This research highlights the contribution of GIS and Remote Sensing in the identification of high potential groundwater areas and even determine the optimal location for the implementation of Vertical Electrical Soundings (VES). This work is divided into two main parts; 1) GIS-RS model and 2) Geophysical Survey. In the first part, several surface factors that are considered to influence the presence of groundwater are combined. In the second part, a geophysical survey using VES is conducted to identify the different aquifer properties and better selection of new water wells location (Anderson et al., 2008)

The study area is the El-hamiz watershed, located in the eastern part of the Mitidja, one of the largest plains in Algeria. The groundwater resource hidden within the Mitidja basin constitute the main water source of Algiers water demand for agriculture, drinking and industrial use. However, to meet the increasing demand, authorities implement new wells within the plain. This, coupled with environmental issues such as pollution and rainfall scarcity, are threatening the sustainability of the resource in the study area. This aims of this work is to provide authorities with an accurate assessment of groundwater potentiality areas, to reduce the costs of traditional surveying techniques, and precise identification of aquifer properties for a better resource management.

Several remote sensing datasets, geological maps and climatic data were used to identify and map the different controlling factors and prepare thematic maps depicting their respective impact on groundwater occurrence and recharge process. These factors were selected after a detailed description and understanding of our study area coupled with a thorough literature review. They include: *Lithology, Geomorphological units, Slope, Line Density, Drainage Density, Land Cover, Rainfall and Elevation.*

The thematic layers were, then, superimposed and embedded using Overlay Analysis in a GIS environment after attributing a weight to each factor. The weights were determined using the Analytical Hierarchy Process (AHP) method, a promising technique that allows decision makers to identify the influence of each factor on the studied phenomenon. This technique has been widely used in several studies such as landslide assessment (Achour et al., 2017; Goumrasa, Guendouz, & Guettouche, 2021), flood assessment (Sami et al., 2020; Goumrasa et al., 2021;) and groundwater assessment (Aluko & Igwe, 2017; Ahmadi et al., 2020; Saravanan et al., 2020). The resulting map delineate the various groundwater potentiality areas and recharge zones. This final map allowed better selection of the 40 VES locations for optimal data collection. The different data were processed and correlated to determine aquifer parameters and groundwater quality.

Study Area

El Hamiz sub-watershed, located in the eastern part of the Mitidja and covers 283.21 km² with an average altitude of 325.30m (Fig.1). It is limited to the north and east by the Mediterranean Sea, to the south by the Atlas Blideen, to the west by the left bank of Oued El-Harrach. The watershed is cut by two large wadis, El Hamiz and Reghaia. The study area is marked by two main Morpho-structural units:

a) The Mitidja plain

The Alluvial Plain of Mitidja is located between longitudes 2° 19′ E and 3° 33′ E, and latitudes 36° 24′ N and 36° 49′ N. With 1450 km². It extends over 100 km from East to West and a width of 3 to 18 km with an average altitude of 100m. It is limited to the north by the Algiers Sahel (260 m altitude), to the south by the Blideen Atlas Mountains (1630 m altitude), to the west by Mount Bou Mad (1560 m altitude), and to the east by the sand dunes of Ain Taya and the Mediterranean Sea.

The surface of the study area is covered by a variety of alluvial sediments ranging from Pliocene to Quaternary age. Bennie & Partners (1983) studied and classified these sediments into several stratigraphic units, from the oldest to the youngest: Pliocene-Plaisancian formation, Pliocene-Astian formation, El-Harrach formation, Mitidja formation and recent alluvial deposits.

b) Blideen Atlas

The Atlas Blideen is located in the central part of the Tell Atlas, between 36°30' and 36° North latitude and between 3°20' and 2°40' East longitude. It covers an area of 26587 ha in the provinces of Blida and Medea. It is bounded in the North by the Mitida plain, in the West by the Oued Chiffa, in the South by the Oued Melah and in the East by the presence of the two basins. Its crest line oscillates between 1400 and 1600m altitude, over a length of about 8km. It shows an important altitude fluctuation with the highest point at 1627m at Koudiat Sidi-Abdel-Kader (Chrea Peaks) and the lowest point at 217m (Chiffa). The overall orientation W-SW and

E-NE entails a climatic and phytocentric dissymmetry between the two main slopes. The massif of Blida is part of the external zones of the Algerian alpine chain. It has been the scene of violent orogenic movements dating back to the last part of the Tertiary, which explains, especially in its central part, the very active features. It is composed almost entirely of fossil-free shales of Lower Cretaceous age with some marly limestone outcrops. These shales extend evenly to the south-southeast under clays varying between 40 and 60% and form the base on which the deposits of the later terrains rest: marly limestones, sandstones, sandy clays and conglomerates.

Data and Methods

The work conducted in this study is divided in two main parts following a methodology involving several steps as shown in the flowchart illustrated in Fig.2. First the GIS-RS model was built to obtain the Groundwater Potential Zone map (GPZ) that helped in the better selection of VES locations. The second part is the geophysical survey where 40 VES were conducted, a qualitative and quantitative interpretation was performed and the aquifer's parameters were determined.

1.Factors identification

After a detailed literature review and based on the study area's features, several factors believed to be controlling the groundwater occurrence and its recharge have been selected. These factors are as follows:

1) ***Lithology:*** geological formations play a major role in the occurrences and development of groundwater (Agarwal et al., 2013; Gaber et al., 2018). Indeed, the lithological nature of the formations bearing the aquifer dictate whether a water surplus can be transmitted and stored in the subsurface. This factor is highly important in groundwater assessment. For this study, the distribution of the different lithological units was obtained from the geological map provided by the National Agency for Hydraulic Resources (ANRH) at 1/50000 scale. First the geological map was degitalized and a verification survey was conducted on June 2021 to improve the map's accuracy. The results indicate different lithologies (fig.3a) where the northern part is mainly covered with recent alluvium (gravel, sand, sandstone) favoring groundwater infiltration and storage. While the southern part is marked by hard rocks (granites, schists …) indicating a reduced groundwater occurrence.
2) ***Geomorphological units***: these units represent the different landforms. They are very useful in delineating structures holding groundwater reservoirs (Rajaveni et al., 2017; Saravanan et al., 2020). the study area includes various geomorphological units as shown in (fig.3b). Streams with relatively thick sediment cover can be areas of high groundwater potential (Khan et al., 2021) . Furthermore, plains with slight slops are also considered as good aquifers as they increase the infiltration process. Whereas, units with steep slopes increase the runoff process and decrease the water infiltration. The northern part of the study area corresponding to the plain is regarded as an excellent groundwater prospect zone.
3) ***Slope:*** the slope gradient directly influences the infiltration of rainfall (Aluko & Igwe, 2017; Ahmadi et al., 2020). High slopes produce a smaller recharge since water runs rapidly off the surface of a steep slope during rainfall, not having sufficient time to infiltrate the surface and recharge the saturated zone (Yang et al., 2021). The slope map of the study area is produced in a GIS environment using Shuttle Radar Topography Mission (SRTM) Digital elevation model (DEM) downloaded from United States Geological Survey (USGS) website https://earthexplorer.usgs.gov. (Fig.2c) illustrates the slope variation in the study area. It is visible that the southern part of the study area is marked by steep slopes (>20°). while the northern part is characterized by slight slopes (0-5°).

4) ***Lineament density*****:** this factor is used to infer groundwater movement and storage (Sahli et al., 2019; Dar et al., 2020;). Indeed, high lineament density indicates high secondary porosity yielding a high infiltration rate (Allafta et al., 2021). The lineaments were extracted from an SRTM DEM and Landsat 8 image in a GIS environment and PCI Geomatica software automatically. We then performed a visual interpretation where all linear features corresponding to roads or topographic features were deleted. The resulting map (fig.2d) highlights an area of high line density towards the southern part corresponding to Blidean Atlas. This density suggests a high infiltration rate and an increased groundwater storage. The northern part, however, doesn't exhibit any visible lineaments.
5) ***The drainage density***: this factor is significantly correlated with the groundwater recharge; a zone with a high drainage density has a low groundwater recharge potential (Rajaveni et al., 2017; Verma & Patel, 2021). The drainage density map of the study area was prepared in a GIS environment from SRTM DEM (fig.2f). The map indicates a high drainage density in the southern part corresponding to a low recharge while the northern part is marked by a low drainage density corresponding to high recharge.
6) ***Land cover****:* modified land cover by human activity can significantly alter the recharge process and influence groundwater storage ((*Effects of Human Activities on the Interaction Of*, n.d.). Indeed, reduced infiltration surface due to building decreases the infiltration and lowers the stored groundwater while vegetated soils increases the infiltration process (Aluko & Igwe, 2017). In our study, the land use was extracted from ESRI landcover map (10m resolution) and reclassified in GIS environment. The resulting map illustrated in (fig.3e) depicts the prevailing land cover classes namely: water bodies, shrub area, crop area, grass area, tree area, built area, bare soils and flooded vegetation. The southern part of the study area is covered with shrub and trees favoring water infiltration, while the northern part is divided between built and crop areas indicating a reduced infiltration rate.
7) ***Rainfall:*** this factor is crucial for groundwater assessment, given that rainfall is the main source of groundwater (Ahmadi et al., 2020; Rajaveni et al., 2017). In our study, data collected from different meteorological stations distributed within the study area were used to map the rainfall distribution. Rainfall map illustrated in (fig.2f) indicates 3 main regions; a coastal area with low rainfall rates, a central area with a moderate rainfall rate and a southern part with high rainfall rate (>600mm).
8) ***Elevation*****:** compared to low altitude, generally, groundwater recharge is higher at high altitude, due to the effect of temperature, storm intensity and thin soil cover (Brown, 2002). Elevation map was obtained from SRTM DEM data in a GIS environment (fig.2g).

2. Analytical Hierarchy Process (AHP)

The AHP provides a rational framework for a necessary decision by quantifying its criteria and alternative options, and for relating these elements to the overall goal. This technique was first introduced by Saaty (1980). The input is a set of influencing factors based on expert's knowledge and thorough understanding of the studied phenomenon. The application of AHP method follows these steps:

1- Preparing a data base of the different influencing factors
2- Assigning weights to each factor based on their importance on a Saaty scale (Tab.1)
3- Determining the pairwise comparison matrix (Tab.2)
4- Establish the normalized pairwise comparison matrix
5- Determine the consistency index and consistency ratio of the matrix using the following equations eq (1) and eq (2):

$$CI = \frac{\lambda_{max} - n}{n} .... (1)$$

$$CR = \frac{CI}{CR} \dots\dots\dots\dots\dots\dots\dots\dots (2)$$

Where: CR is the consistency ratio, CI consistency index, λ_{max} is the principal eigenvalue of the matrix and n is the number of factors.

6- Verify of Consistency ration is inferior to 0.1 if it is the weights are consistent, if not the process is repeated.

Given that the recharge and storage of groundwater is controlled by the eight different factors simultaneously, the thematic layers were overlaid to produce a unique map. Indeed, the effect of one factor separately can be increased or decreased by another factor. Thus, sub-classes were ranked on a scale of 1-5 based on their relative influence (Tab.2). The final map was obtained using the Raster calculator on a GIS environment using the following formula eq (3)

$$GPZ = \sum_{i=1}^{n} AHP = L_w L_r + G_w G_r + S_w S_r + LD_w LD_r + DD_W DD_r + LC_w LC_w + R_w R_r + E_w E_r \dots . (3)$$

Where: GPZ is the groundwater potential, W is the weight and R is the rank, L lithology, G geomorphology, S Slope, LD Line density, DD drainage density, LC Land Cover, R Rainfall, E elevation.

3. Geophysical survey

Groundwater exploration relies mainly on hydrogeological studies and geophysical investigations. The combined methods provide the aquifer parameters, i.e. depth to water table, aquifer thickness, transmissivity, hydraulic conductivity, etc. VES are the most commonly used in groundwater exploration (Binley, 2015). It consists in the injection of a current **I** through two electrodes **A** and **B** and measure the potential differences between electrodes **M** and **N** (eq.4). Distance between electrodes are determined by the used array. For groundwater exploration, the schlumberger array is usually used as it provide more accurate results with depth (fig.4). The measured parameter is the apparent resistivity (eq.5) which describes the subsurface lithology, water content and quality. The obtained curve illustrates the variation of resistivity with depth. However, an inversion is necessary to determine the depth and the real resistivity of each layer. These inversions are usually performed using computer programs and software in which the input is the electrode spacing and the corresponding apparent resistivities, and the output is a subsurface model displaying the number, depth, thickness and resistivity of the layers.

$$\delta V = V_M - V_N = \frac{d}{2\pi}\left\{\left[\frac{1}{AM} - \frac{1}{MB}\right] - \left[\frac{1}{AN} - \frac{1}{NB}\right]\right\} \dots\dots\dots\dots\dots\dots . . (4)$$

$$\rho_A = \frac{\delta V}{I} \dots\dots\dots\dots\dots\dots\dots (5)$$

Following the potential groundwater area identification, a geophysical survey was planned. A total of 40 VES were conducted using the Schlumberger electrode configuration with a maximum AB electrode spacing of 700 m. The Syscal IRIS instrument was used to measure the apparent soil resistivity (ρ_a) and Bobachev (2002) IPI2Win software was used to display, process, and interpret the measured VES field curves. Furthermore, local lithologic vertical successions of productive wells distributed throughout the study area were used to calibrate the field-collected VES and map aquifer parameters throughout the delineated area.

Results and discussion

1- *Factors mapping*

Each factor mapped individually contribute to the understanding of the study area and thus to the geophysical and hydrogeological survey. VES are usually implemented in flat terrain. Rugged or sloped terrain delays the process, complicates the acquisition and require topographic correction during data processing. The slope map (fig.3c) helped identifying flat areas where it would be interesting to perform the soundings. On the other hand, the land cover is an important parameter in this type of survey because it is difficult to implement VES in paved areas (Arora et al., 2011). Therefore, the land cover map (fig.3f) was very useful in determining VES location. In addition, rock lithology is a key criterion for any geophysical survey. Indeed, some rock types resist to the passage of electric current and complicate the acquisition (Mohamed, 2006). By mapping the lithology of the area (fig.3a), we can understand the different outcrops distribution and their potential impact on the geophysical acquisition. Mapping and distribution interpretation of some factors selected during this study have significantly improved the location of optimal sites to facilitate geophysical acquisition.

2- *GIS-RS modeling*

The reclassified factor maps produced from satellite images were integrated in a GIS environment. The AHP method provided the weights of each factor based on its influence on groundwater recharge and occurrence. (Fig.5) is the resulting groundwater potential map categorized into five classes as follows: very low, low, moderate, high and very high-water potential. This map indicates that the northern part of the study area is marked by moderate to very high groundwater potential due primarily to its geology and geomorphology. Indeed, this part is composed of recent alluvium, a material highly porous and permeable. Also, alluvial plains constitute good groundwater storage areas (Rajaveni et al., 2017). They facilitate higher surface water infiltration and low runoff, especially with agricultural pans that have increased infiltration rates. Furthermore, due to the existence of rivers, flat terrain, and higher permeability, alluvial plains have very high recharge rates even areas away from the riverbed (Walker et al., 2018). The piedmont of the Blidean Atlas also acts as a main infiltration and recharge area due to its coarser materials and slower infiltration. This region presents a moderate groundwater potential as this region marks the limit of the Mitidja basin. Consequently, the water that infiltrates is trapped further away within the plain. The mountain range presents a low to very low groundwater potential. Indeed, at this altitude and with its rugged structure, it favors a maximum rainwater infiltration due mainly, to a high lineament density. However, the steep slope and lithology make these mountains a poor groundwater reservoir and all infiltrating water reaches the Mitidja plain. The combination of different factors selected for this study enabled the identification of groundwater potential areas and thus better locate geophysical survey points for time and money gain while acquiring maximum information on the resource.

3- *Geophysical survey*

The 40 VES were implemented across the plain based on the results obtained by the GIS-RS modeling. The surveyed areas are mainly agricultural as indicated by the land cover map. The purpose of these VES is to determine the main aquifer parameters (water table depth, lithology, thickness and water resistivity).

First, a qualitative interpretation was carried out to identify the type of VES curve obtained in the field (Tab.4). The curve types indicate 3, 4 and 5 geoelectric layers. The 4 layers curve is the most prevalent with 27 VES or 67% of the total soundings, the majority of which correspond to the AK type suggesting a resistant formation overlying a conductive formation. The resistant formation corresponds to coarse and heterogeneous Quaternary alluvium while the conductive formation corresponds to a sandy clay facies of the Astien. The HKH and HAK type curves indicate a hard lithology outcrop, while the KHK type curves suggest an altered section favorable to groundwater accumulation (Ndubueze et al., 2019). The remaining 15% correspond to a 3-layer terrain (A, K and Q). In addition, all the curves contain H and K type curves, which indicate a good groundwater storage (Omosuyi et al., 2007).

Furthermore, iso-apparent resistivity maps based on the apparent electrical resistivity values were created. They depict the lateral variation of the apparent resistivity measured on the same current electrode spacing and provide insight into the subsurface structure. They also reveal whether the apparent resistivity values are homogeneous or heterogeneous at different locations at nearly the same depth. The generated maps correspond to the current electrodes spacing AB/2 = 10, 50, 70, 150 and 200 m for depths of about 4, 20, 28, 60 and 80 m, respectively (fig.6). At a depth of about 4 and 20 m, resistivity values are relatively low, which is attributed to alluvial deposits (Saad & Tonnizam, 2012). At a depth of about 28 m, resistivity values increase toward the northwestern part of the study area due to the heterogeneous formation. At approximately 60 m and 80 m depths, resistivity values continued to increase and cover the entire area consistent with saturated sands (Lech et al., 2020).

Moreover, a quantitative interpretation was conducted to determine the number, thickness, depth and resistivity of each layers. RMS was set at <5% during the inversion process for more accurate results (Tab.4). For a better interpretation, results from VES 1, 7, 10 and 18 performed next to the water wells were compared with the existing lithology log (Fig.7). These results enabled the establishment of the local geoelectrical model illustrated in Tab.5.

Next, aquifer parameters, namely aquifer resistivity, depth, and thickness, were deduced from the interpreted VES data. These variables were then mapped for a more detailed representation of their variation across the study area.

(Fig.8) illustrates the aquifer’s depth as inferred from VES data. This parameter varies between 5 to 125m which is consistent with piezometric measurement conducted on site. However, the low depth values (VES30) are recorded in areas near the El-Hamiz wadi which indicate an interaction between surface water and groundwater in the area.

Aquifer thickness is an important measure of groundwater potential (Kumar et al., 2016). Indeed, as the thickness of the aquifer increases, the groundwater resource becomes more important. Based on VES results, alluvial aquifer thickness varies between 25 and 125 m (fig.9), which correlates with core sampling results previously conducted on the study area.

Aquifer resistivity is a major indicator of aquifer lithology and water quality. (Fig.10) depicts the spatial distribution of this parameter within the study area and indicates resistivities ranging from 25 to 140 Ω.m. Low resistivities (20-30) correspond to aquifers containing saline water (marine intrusion) or clay, while high resistivities (>35) indicate good quality groundwater in coarse-grained rock formations.

To validate this result, 17 groundwater samples were collected from boreholes scattered around the study area and their conductivity was measured to identify the water quality (Tab.6). Indeed, the ability of an electric current to flow through water is proportional to the amount of dissolved salts in the water (Dahaan et al., 2016). The preferred limit for EC in drinking water is 1,500 µS/cm(Sayato, 1989). A higher EC in the study area indicates salt enrichment in the groundwater. The EC can be classified as type I, if the salt enrichment is low (EC < 1,500 µS/cm); type II, if the salt enrichment is medium (EC 1500 and 3000 µS/cm); and type III, if the salt enrichment is high (EC > 3000 µS/cm). Based on the above CE classification, 29% of the total groundwater samples fall into Type I (low salt enrichment), 47% into Type II (medium salt enrichment) and 23% into Type III (high salt enrichment). The effect of saline intrusion may be the reason for the medium and high enrichment of CE in the study area. These results define three regions: saline, brackish and fresh water. This reflects the extent of saline pollution and requires further electrical soundings and physico-chemical analysis to better map the salt/fresh water interface and to establish sustainable management strategies for the resource.

Conclusion

Mapping and identification of groundwater exploitation areas has become extremely important due to the scarcity of water supply caused by severe drought periods. This requires hydrogeological studies, which are time consuming and produce local data, and geophysical surveys, which are more accurate but sometimes difficult to implement due to heavy equipment and site heterogeneities. The success of a groundwater exploration campaign requires a thorough understanding of the study area before any geophysical method is implemented. The present work has highlighted the important contribution of GIS and remotely sensed data in locating the potential groundwater area and in better selection of VES points. Indeed, the approach followed in this work has proven to be very useful in optimizing the amount of data collected, especially in remote areas where a field visit prior to a geophysical survey can be time consuming and expensive. Factor mapping effectively describes the study area, the GIS-RS model identifies areas of high groundwater potential and therefore better borehole location identification. Thus, field mission costs can be considerably reduced and authorities can save time. In addition, the location of the VES points determined by the GIS-RS model facilitated the field procedure and allowed a maximum data collection. Furthermore, the qualitative interpretation of the VES curves determined the subsurface model (mainly a 4-layer model), while the iso-apparent resistivity maps revealed a heterogeneous aquifer (alluvial aquifer). The quantitative interpretation based on IP2win software identified aquifer parameters such as depth, thickness and resistivity. For an accurate interpretation, the VES results were correlated with the litho-logs of nearby water wells and a local resistivity scale was established. The electrical method revealed a saline pollution phenomenon which was subsequently validated by electrical conductivity measurements of water samples collected from several wells in the study area.

Results of the present study can be useful to Algiers water management authorities for better location of new water wells, taking into account the saline pollution revealed by the geophysical study. The monitoring of this pollution requires additional VES data that are currently being conducted, following the results of this study, for a precise identification of the freshwater/saltwater interface. The concept developed in this work can be extended to remote areas where data are scarce to optimize the output of geophysical methods.

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose

Figures

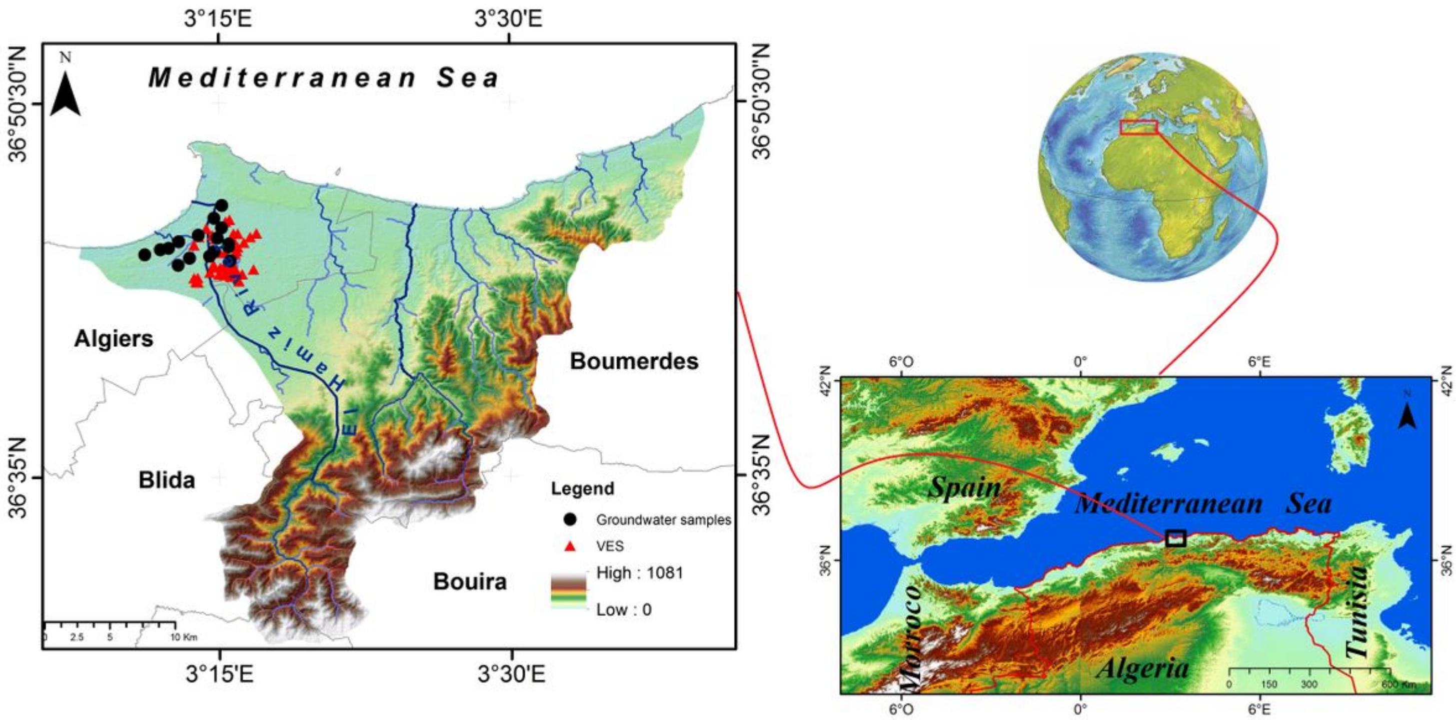

Figure 1

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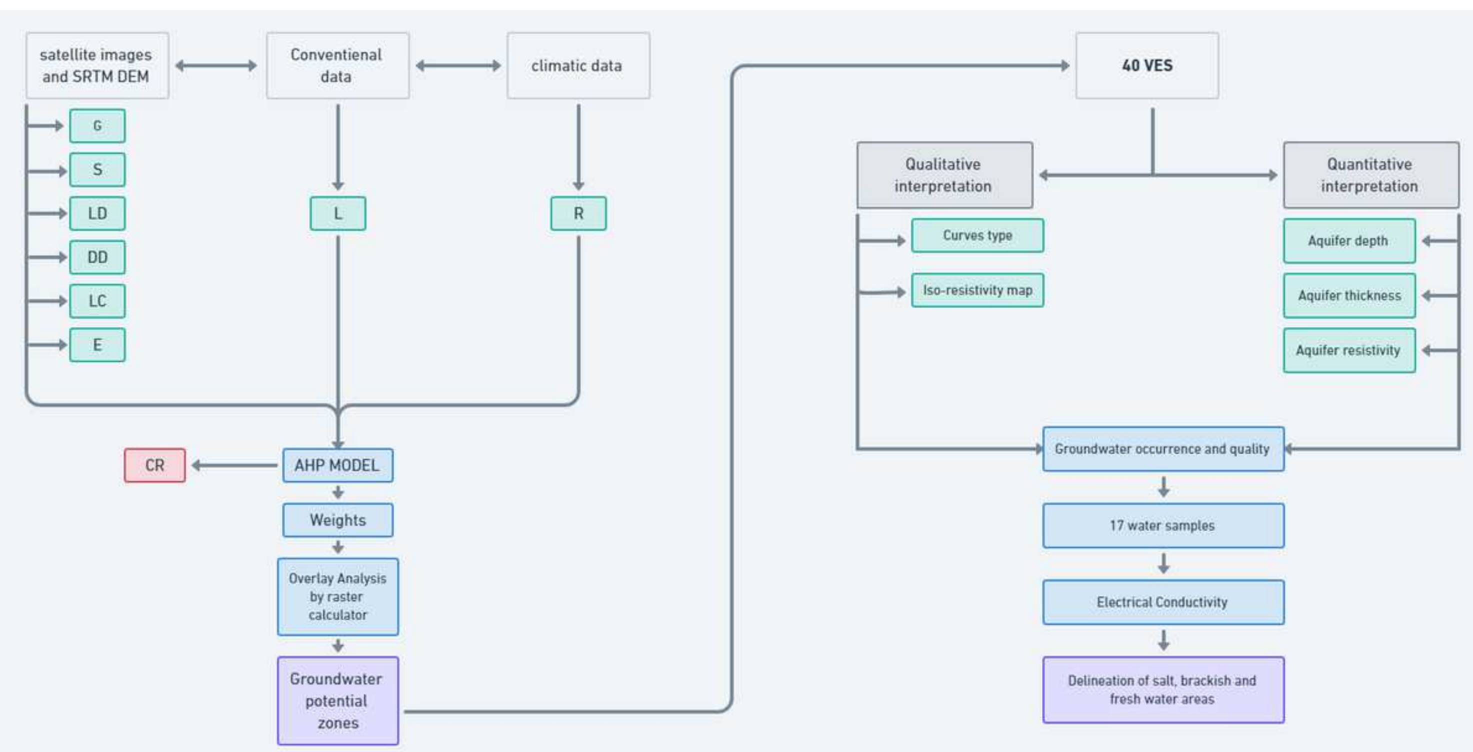

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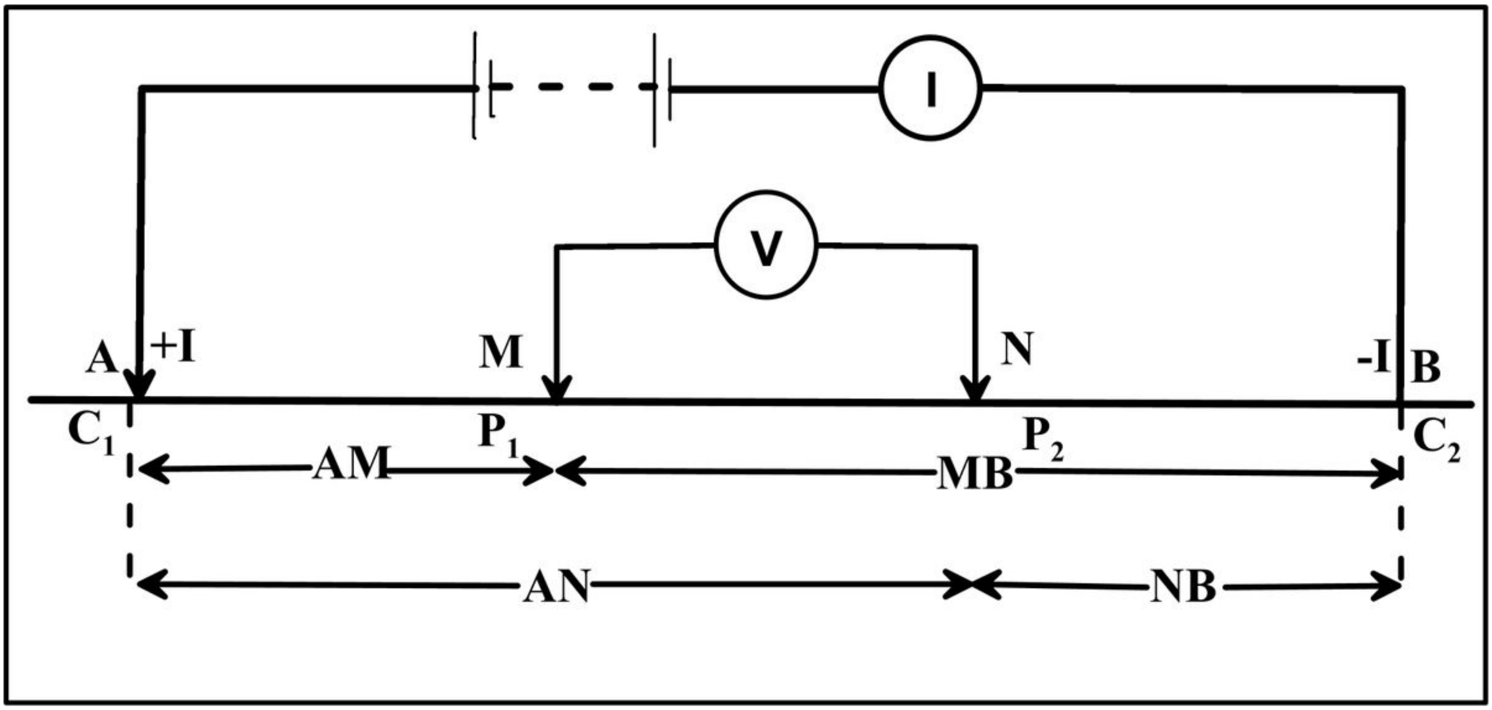

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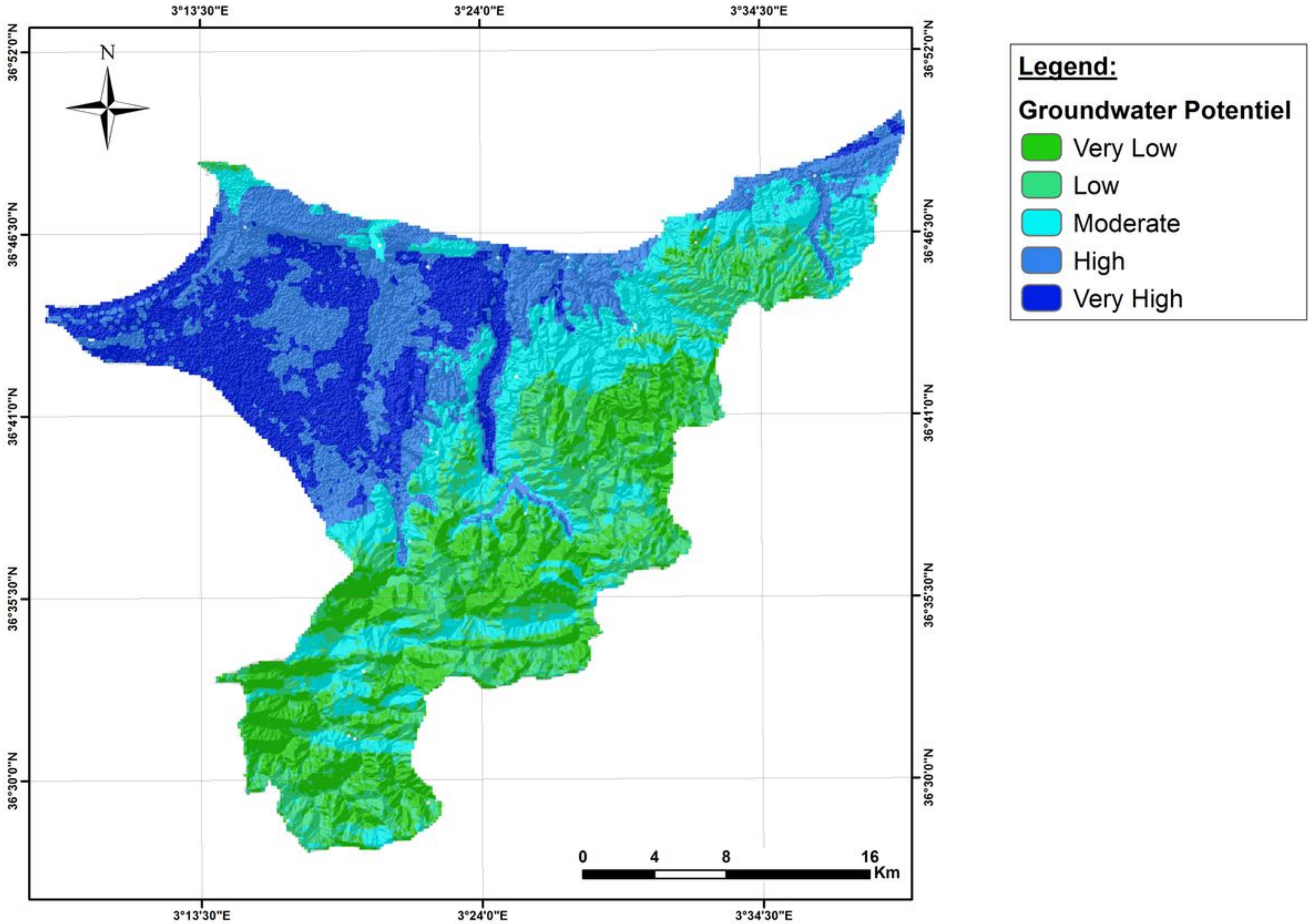

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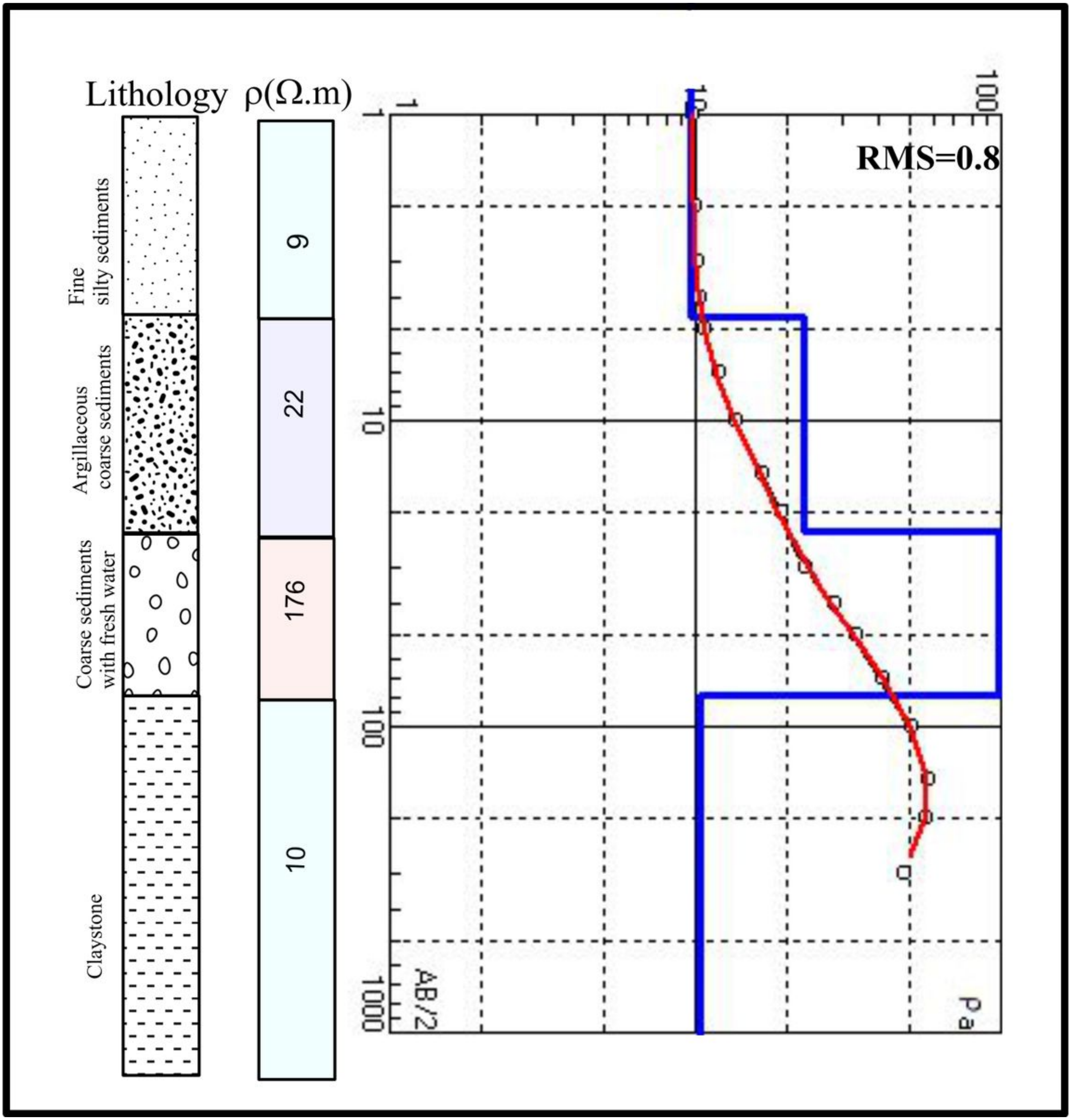

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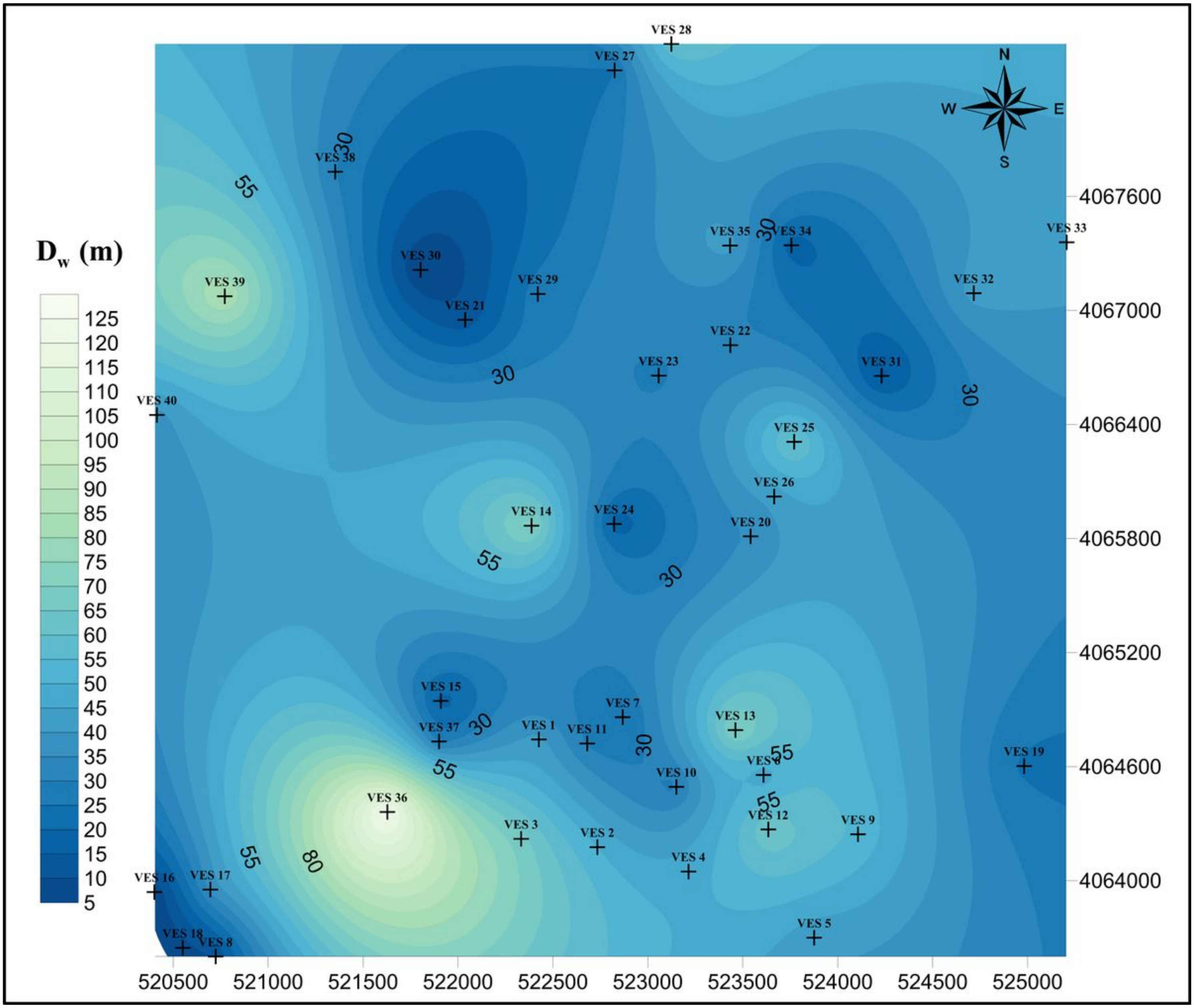

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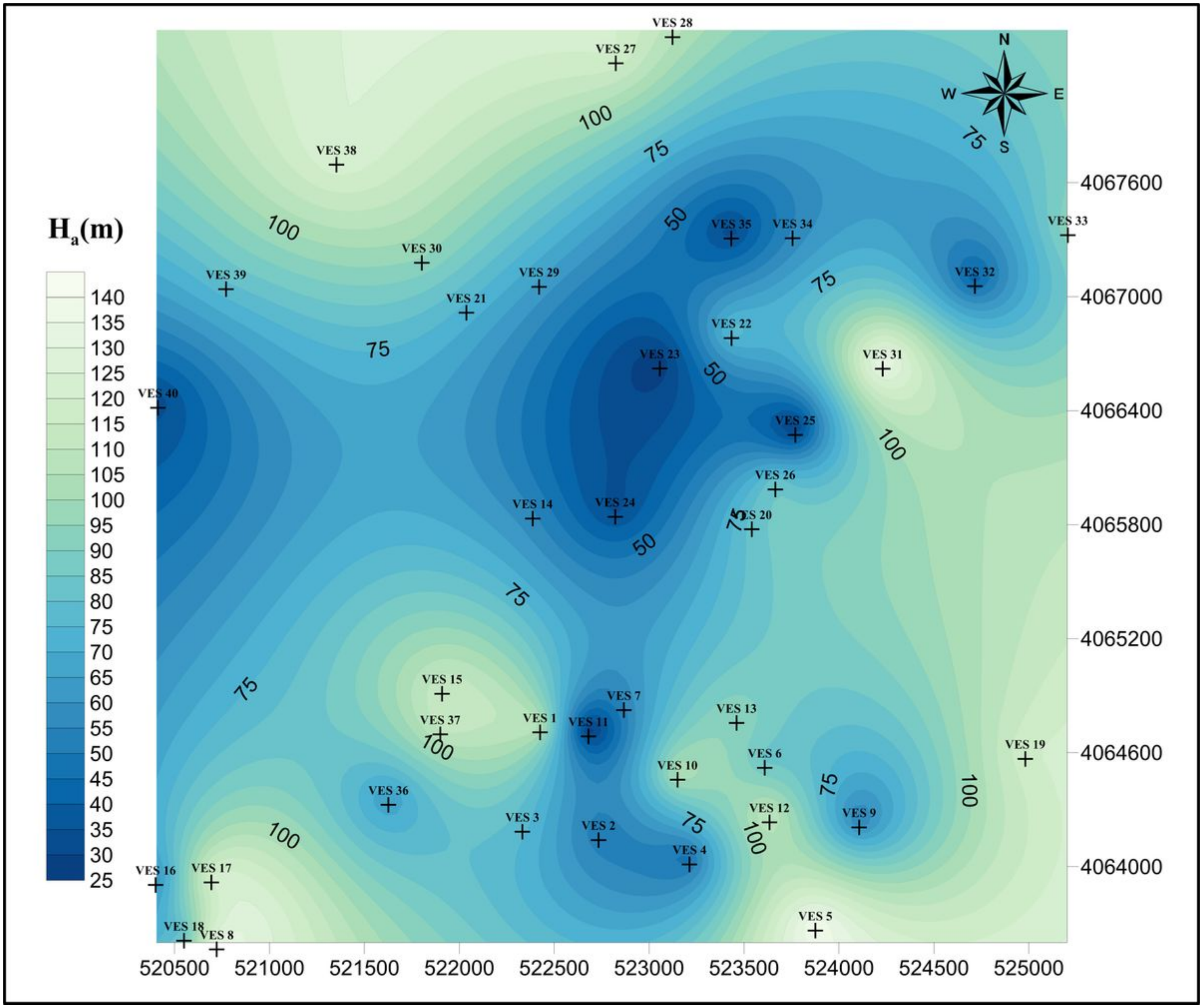

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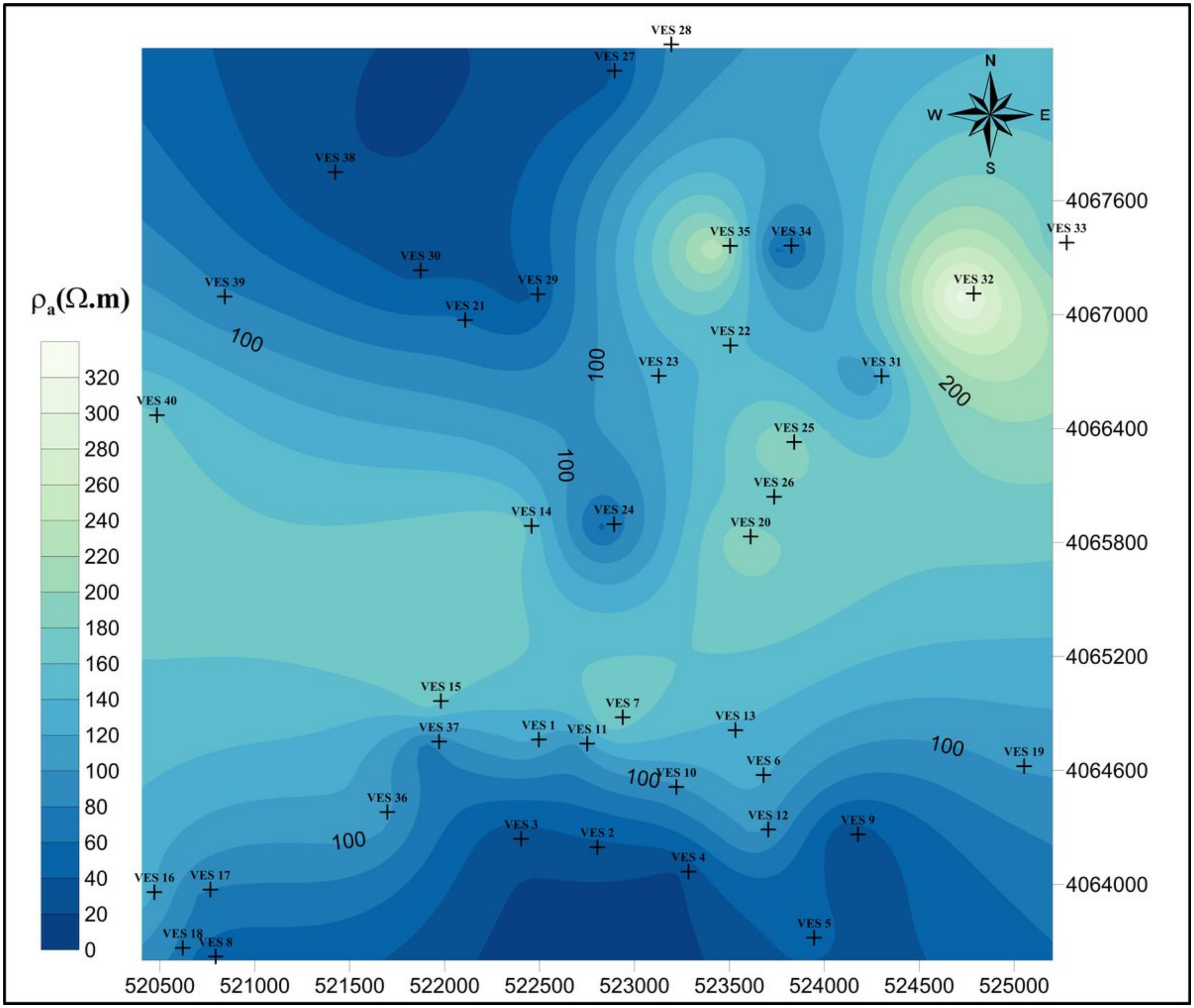

Figure 10

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