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Mapping of groundwater vulnerability using optimized AHP-GOD Models and geospatial factors (Case study: littoral sedimentary aquifer of Ain Temouchent – NW Algeria

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Research Article

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Abstract

The monitoring and protection of coastal aquifers has become a primary priority and a subject of research with the integration of Vertical Electrical Sounding (VES) in order to map groundwater vulnerability to contamination, and to evaluate their aquifer protective capacity. A study aimed to to identify an exposure level of contamination for a sustainable use of the water resources in the aquifer of Ouled Taoui - Boujema aquifer situated in Ain Temouchent – Algeria. For this purpose, a dataset was established including 170 VES soundings, topography ASTER GDEM, geological maps and finally boreholes were acquired to develop the AHP (Analytical Hierarchy Process) by ordering the weightage of geospatial factors in vulnerability mapping. However, a GOD-LT model (G: groundwater type; O: aquifer overlying strata; D: aquifer depth and L: Longitudinal conductance; T: Topography slope and Th: Thickness) has been evaluated using optimized AHP as predictive model abbreviated GOD-L, GOD-LT and GOD-LTh. Furthermore, these factors are considered as the causal factors of aquifer vulnerability (AVCF's). The geospatial factors were derived on AHP-WLA (Weight Linear Average) for rating optimization. The pairwise comparison matrix was developed on the AVCF's factors for AHP-GOD. The validation result showcases that 72% of prediction consistency is optimized for GOD-L model compared to 64% for the standard GOD. The GOD-LT and GOD-Th demonstrated the best reliability under consistency index. However, the vulnerability to pollution is validated by using nitrate concentration, water corrosivity and the degree of aquifer capacity protection and can be efficient mapping for water supply and environmental assessment.

Keywords: Groundwater vulnerability, aquifer protective capacity, VES Sounding, AHP GOD-LT GOD-Th, WLA-AVCF's, AHP

1 Introduction

In the arid and semiarid countries of the world, water is a finite resource and is under pressure due to the contamination, inadequate sanitation, increased frequency of droughts groundwater, over exploration of pumping at unsustainable rates, inadequate water infrastructure, increased food requirements of a growing population, increasing water use and irrigation (Ghazavi & Ebrahimi, 2015).

According to the report of United Nations World Water Development, water scarcity is predetermined to rise affecting over 02 billion people are living in worldwide region experiencing water stress which exceeding 40 %. However, over 1.7 billion people are living in Mediterranean basins where water use exceeds recharge (United Nations, 2021).

Prevention of aquifers contamination is inspected as a primordial factor in the groundwater resources management and as such aquifer vulnerability modeling becomes imperative in the groundwater field. However, the groundwater vulnerability evaluation has been the topic of intensive research during the past years and therefore a several index methods have been developed to esteem aquifer vulnerability.

This paper presents a new hybrid scientific approach based on multi-criteria methods for decision support system such as the HMC "Hierarchical Multi-Criteria" integrated with geoelectrical surveys, in order to ameliorate the standardized model GOD by the modified groundwater models called AHP-GOD-L and AHP-GOD-LT. However, most hydrogeological models have been applied numerical rating and weighting using GIS which invoke that their system indexation was inadapted in karstic environment according the equivalent vertical permeability (Afonso et al. 2016; Gad et al. 2015).

Moreover, the groundwater contamination is a notion of the capacity of the aquifer to retain water with a greater or lesser degree of protection according to the aquifers properties. Hence, the groundwater vulnerability is considered as an intrinsic multilayer aquifer to understand the reverse relationship between superficial aquifer and the topsoil represented by the geoelectrical layers containing the geological information along profiles and lead to increasing the groundwater to contamination (Schnebelen et al. 2002). Nonetheless, there is another form of specific pollution taking into account their charachteristics (Hamza et al. 2007).

Meanwhile, researcher community were commonly use several vulnerability models in order to assess mapping the groundwater to contamination such as: AVI, GOD, SINTACS and DRASTIC. Globally, AVI model is adapted to the sensitivity mapping related to the geological thickness and aquifers permeability which are proportional to the covering layer fitted by lowest values of the permeabilities. This may impact the protection effect referred to aquitard layer (Yusuf MA. and Abiye TA. (2019), Obiora DN and Ibuot JC (2020)).

The geoelectrical surveys (VES) technique is very useful in groundwater identification of crackled basalt flows and make geometrical information in groundwater about the aquifer extension to investigate approximative depth, and the nature of lithology facies as well as groundwater quality assessment (George et al. 2014; Ibuot et al. 2013). Assessing potential water resources has become essential in semi confined environment. Many geological factors affect groundwater deposition in terms of hydraulic transmissibility, flow and storage (George et al. 2017; Ibuot et al. 2013). Variation in factors such as dissolved ions, soil media, thickness, grain size, and pore affect the groundwater potential. This study focused on the assessment of aquifer potentialities, corrosivity, giving useful information on water quality against drilling unproductive wells.

This paper emphasizes a contribution of geoelectrical data to simulate groundwaters variability model based on secondary geophysical attributes. Some factors are extracted automatically from (VES) surveys such as the approximative thickness determined explicitly both by transects modeling and indirect inversion techniques using IP2Win Software completed by calibration process between VES stations and Boreholes logs which serve as a good capacity protective in reservoir (Yusuf MA and Abiye TA 2019).

However, it is concluded that SINTACS model developed by Civita M and De Maio M (2004) and based on (piezometry (S), permeability (I), vadose zone (N), soil (T), aquifer media (A), hydraulic conductivity zone (C), and slope (S)) permitted the assessment of the vulnerability to groundwater contamination.

Concerning the DRASTIC model, it uses seven (07) factors to evaluate the vulnerability to pollution mapping such as: piezometry, natural recharge, geology nature, soil, slope, vadose area and permeability (Aller et al. 1987). According to Maria (2018), the GOD mapping is suitable for lateral variation concept over large areas in subsurface while the DRASTIC deals both lateral and vertical mapping giving less pronounced uncertainty in geo-environmental studies (Bouakkaz et al. 2019).

However, the numerical statistics infered in GIS-AHP intergration permitting strong simulation adopted is mainly conceptualized on geological, hydrological factors as well as the land cover often presenting limits of soil infiltrability to better assess the vulnerability of subsurface reservoir (LaMotte And Greene 2007; George et al. 2015). Consequently, the factor (L) defined in proposed GOD model introduced by (Foster 1987) (G: Groundwater Type; O: Lithologic nature - vadose zone; D: depth to water table) facilitate the semantics through which the ratio and degree of clay content can be deciphered to help determine the susceptibility to pollution.

In this concern, several modified GOD model have been integrated recently using GOD-T (Topography : slope influence) and GOD-Th (Thickness influence) to extend the outcome vulnerability map according to the topography (ridges and depression) which impact the migration of pollutants. Hence, GOD-T approach, related to AHP was tested to assess aquifer contamination and groundwater potential prediction (Saminu et al. 2021; Kehinde and Osayande 2017).

Furthermore, most researchers used the factor (L) as an indirect method for vulnerability of groundwater to contamination mapping (Abiola et al. 2009; Aweto 2011). The factor (L) is considered as auxiliary derivative parameter exploring the relation between thickness and resistivity determined directly from VES surveys dataset is non-invasive unlike other data sources for vulnerability modeling approaches (Keary et al. 2004).

In addition, the (L) parameter is considered an important factor in hydrogeology estimation having the ability to determine the geological nature of underground layers, to identify aquifer units to know the exact layer to be protected, as well as to estimate the thickness of each layer overlying the aquifer (Evans et al. 2017). Despite the many merits of the (L) parameter as mentioned previously, the results are subject to the principle of equivalence and the approach is insensitive to the possible presence of relatively resistive geological formations such as laterites and basalts (Oni et al. 2017).

In litterature, Ghazavi and Ebrahimi (2015) have explored two models (DRASTIC, GOD) in arid environments; Gad et al. (2015) have explored successfully the models GOD, PRAST and DRASTIC in the stratigraphy context (quaternary aquifer) in the delta region - Egypt. Maria (2018) conducted similar investigation on aquifer contamination using GOD, DRASTIC models. However, modified GOD based on calculating priorities of geoelectrical weight alternative against a set of criteria using peer comparisons of alternatives for each criterion of AHP, used to map groundwater to pollution were modified by the thikness for GOD-Th and the topography influence for GOD-T which has successfully integrated the vulnerability assessment as an added input parameter to improve the pollutants migration topographically controlled by gravity and prevented from migrating upslope (Khemiri et al. 2013, Adeyemo et al. 2016).

Globally, the geoelectrical method has been widely exploited in hydrogeological concern and specially to aquifer vulnerability mapping (Mosuro et al. 2017). Furthermore, The VES technique was implemented in the Ouled Taoui–Ouled Boujema – (Ain Temouchent, Algeria) because of its efficiency in delineating transversal sections of the geology using Schlumberger array with maximum current separation (AB/2=1000 m). The geoelectrical results were presented as curve types and maps in the Ouled Taoui – Ouled Boujema aquifer.

However, it was necessery to calibrate the weightage in AHP-WMA formalism in order to normalize the classification ordinal system and getting the strength and weakness of certain vulnerability models. Among these standardization by using causal factor of geophysical parameters such as longitudinal conductance (L) related to the resistivity and thickness which plays integration input in the assessment of aquifer vulnerability, according the uniqueness and equivalence principles in the aquifers nature. Hence, we propose an implementation of model AHP-GOD and L called AHP-GOD-L, AHP GOD-LT and finally AHP-GOD-LTh for the multi-evaluation of the vulnerability to groundwater pollution.

The standardized system GOD is considered as a scoring indexation to assesses groundwater vulnerability (Foster, 1987). The quantification of the risk assessment using GOD factors involving rating evaluating and classification is detailed by the range values of numerical rates which is classified from 0 minimum vulnerability to 1 maximum vulnerability. Indeed, the overlaying layers in the GOD model indices offer a rapid map vulnerability (Vias et al. 2005). Furthermore, the basis of the mechanism of the GOD-L model is derived from the mathematical algorithm relating the resistivity to the thickness properties of the subsoil such as the Total Transverse Resistivity (TTR), the longitudinal conductance unit (L) etc.

The geoelectrical factor (L) is defined as the sum of all the thickness of layers divided by all resistivity of the same layers for each surveys until the layers covering an infinite semi-resistivity of the substrate of the successive layers. It can be deduced from the interpretation of the factor (L) that the main natural protection of unconfined (isotropic aquifer) aquifers against contamination is impacted by the clay materials, which protective capacity relates the infiltration time to their low permeability (Braga And Francisco 2014).

Therefore, the degree of aquifer capacity protection is considered proportional by ratio dividing thickness and apparent resistivity through geological layers. In explicit terms, an overlying GOD factors using raster calculator - ArcGIS under GIS environment with high L ($L > 1$) offers a severity classes of degree of protection against contamination due to the highest geological thickness and poor resistivity.

According to Niwas S And Singhal (1981), the product $K\sigma$ (Hydraulic Conductivity times Electrical Conductivity) remains fairly constant in specific areas which the geologic setting and water quality are invariant over time. The impact of the macropore regulate fluid and reflect a primordial role to conserve the flow affecting by porosity and water resistivity of the sediment. However, similarity is equivalent between electrical path and hydraulic path at the pore level and resistivity values should reflect this concern which effective porosity is considered as constant in steady state which groundwater follow the path of least resistivity to obtain regularity in flow direction. Longitudinal conductance (L), gives an analogous estimation of the impermeability of a layer contributing to reduce transportation of contaminant pathways.

Inspirated from Braga et al. (2006), the lower resistivity in aquifer involves a clay formation represent a low hydraulic conductivity filter of contaminants in the subsoil. Nevertheless, it is noted that the efficiency in multi-criteria mapping using AHP technique has also been exploited to obtain a reliable model output. Thus, a specific data mining methodology called AHP was used to synthesize a derived Aquifer Vulnerability Causal Factor (AVCF's). The matrix generated by proper vector decomposed as 3rd level considered as fundamental scale at lower level of AHP GOD-L model exploited the uniqueness of GOD-L, GOD-L-T and GOD-L-Th models in decision process by using AHP for ArcGIS extension.

In addition, with the purpose of providing a quantitative mensuration of the degree of accuracy of the newly developed AHP for GOD-L, GOD-L-T and GOD-L-Th models respectively according to indirect geophysical parameters, topography and thickness of geological layers. Then, the water chemistry parameters such nitrates and water corrosivity were used for the validation process.

In areas where there is a high possibility of groundwater contamination impacted by human and agricultural practices, it important that the mapping of groundwater pollution is assessed for effective water protection. An example of such an environment is the sedimentary coastal aquifer of Ouled Taoui – Ouled Boujema located in the northwest of Ain Temouchent - Algeria. The area is well known for its small-scale farming instead mining geology, and environment ecosystem is influenced by salinity contamination.

In fact, the developed models AHP-GOD, AHP-GOD-L, AHP-GOD-L-T and AHP-GOD-L-Th has enabled a geospatial mapping approach and multisource dataset in coastal aquifer. Thus, it also prioritizes the contaminated zones related to the risk levels which are difficult to discern by the standardized model GOD. It is highly recommended that the developed AHP and groundwater vulnerability model approach should be the primary target for future water resources development in order to ensure permanent supply for human consumption in the zones of strong drawdowns in extreme case of withdraw more times their renewable water resources in a year due to excessive pumping in the agricultural vocation.

In fine, overall modified models in data mining AHP technique was modelled in order to map several vulnerability degrees to aquifer pollution according to the geospatial factors such as ASTER GDEM topography, VES: secondary derived geoelectrical factors (L, TTR). The determined physiochemical factors from the water chemistry results were explored for validation analysis conjointly with water corrosivity in geophysical manner in the Ouled Taoui – Ouled Boujema aquifer by integrating commonly used methods (GOD, GOD-L, AHP-GOD-L, AHP-GOD-LT, AHP-GOD-LTh, and optimized AHP-WLA-GOD-factors).

2 Materials and Methods

2.1 Study area

The sedimentary coastal aquifer of Ouled Taoui-Boujema is a part of Ain Temouchent region - Northwestern of Algeria and is geographically located between 35°45' and 35°50'N, Longitude -2°.2' and -2°.5' W. It covers an area of 184.78 km^2, forming of a coastal strip, limited to the northern part by the plain of Ghamra, to the western part by the Sabkha of Oran and Hassi El Ghella region, to the east by the Lake of Oran and to the south by the plain of Ain Temouchent (Fig.1). The zone is situated in the plain of Targa-Sassel, generally has a gentle topography slope, within elevations ranging from 0 to 395 m.

The area is characterized by the semi-arid climatic domain influenced by irregular rainfall between 300 to 400 mm/year. These regions have limited ground water continuities. At the same time, the increase in extension of irrigated areas in the Ain Temouchent region have quantitative and qualitative consequences on the deficit of groundwater resources.

Surface geophysical measurements provide an alternative approach for estimation of some of the aquifer properties. In this study 170 VES (Vertical Electrical Survey) from two campaigns 1 and 2 (1975-2004) respectively were conducted at preselected stations employing Schlumberger array. The points were selected through their proximity to the wells with the possibility to evaluate the unsaturated capacity protection to the multi-aquifers systems.

In order to completing the geological mapping, four (04) georeferenced and merged geological maps were harmonized at the 1:50.000 scale. The 1/50.000 geological map and data from the geophysical prospecting were conducted in the Ain Temouchent region, (Project STROJEXPORT Prague 1976 - Environmental studies and hydraulic research department. Hydraulics Consulting & ANRH - hydrogeological study of the district - Ain Temouchent - Operation N°5 311 1 019 00). Hydrology data such as water table, static level, piezometry and water chemistry are provided from both the agencies of ANRH (National Water Resources Agency) and ABH-OCC (Hydrographic Basin Agency- Oranie Chott Chergui). All datasets are provided in the manuscript and also data availability statement is archived in supplementary materials attached to this manuscript. The background to this research was conceived the variations in resistivity relating the geochronology geology pile and hydrogeology concerns related to their unsaturated zone.

Geologically, in the south of the plain, there are alluvial formations with a very friable or poorly coherent loamy sand character (Fig. 2), these sandy brown soils favor the development of significant agricultural activity. The location of the plain in a marsh area involving salinity of El Maleh stream (in Kaddour 2017). Therefore, under alluvial deposits, there are sandstone deposits (Upper Pliocene) and porous limestone (Upper Miocene, Messenian) containing significant water resources. In this plain, the lithological strata have made it possible to have a very indented hydrographic network, corresponding to the downstream sub-basin of El Maleh stream, drained by an exoreic watercourse which maintains a perennial flow throughout the year.

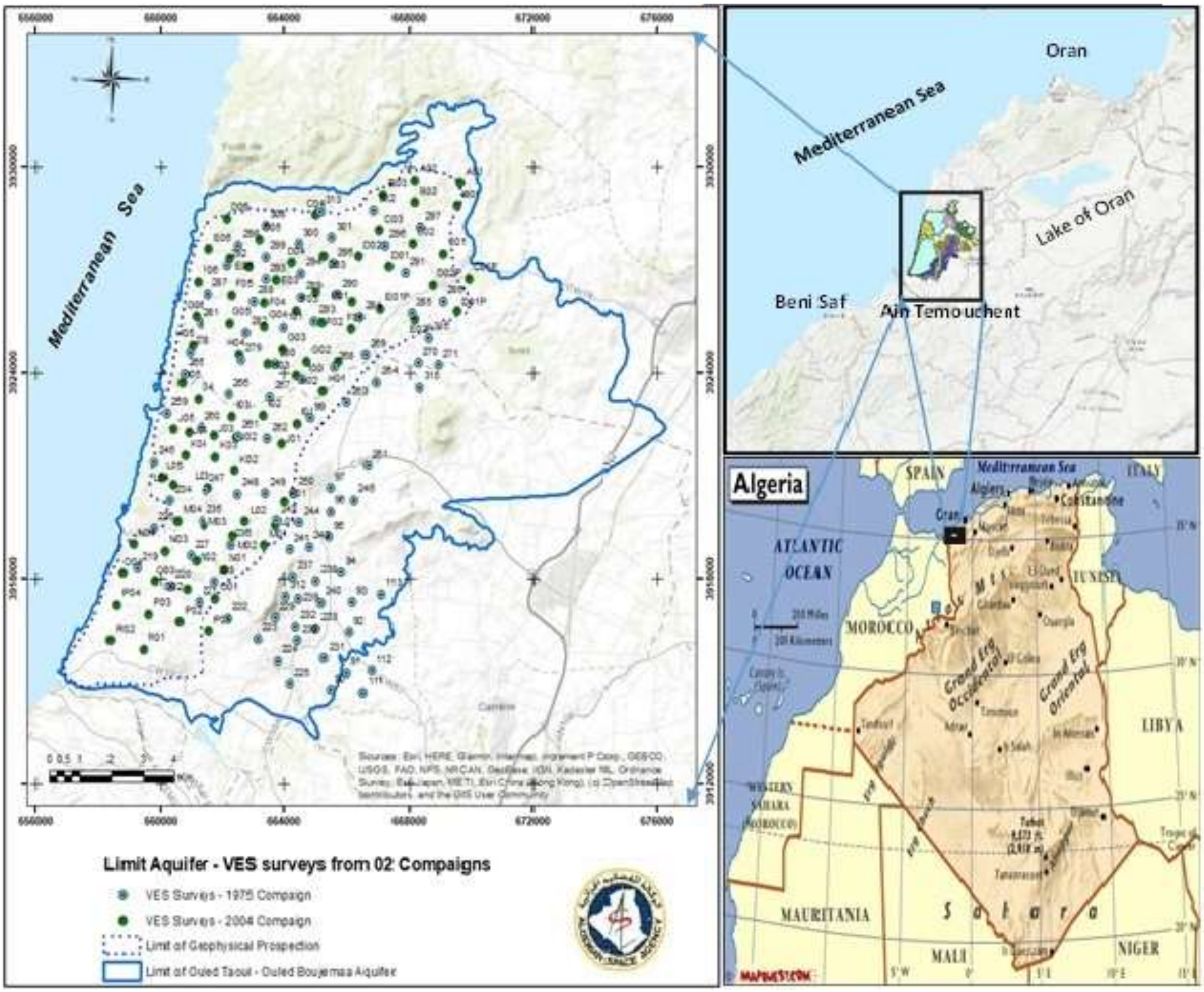


Fig. 1 Location of the study area Ouled Taoui-Ouled Boujema coastal aquifer

2.2 Geoelectrical Data extraction for vulnerability mapping in vadose area

Both ninety (90) and eighty (80) VES stations using Schlumberger double Dipole array were established through the study area from the years 1975 and 2004 respectively. The equipment has been used largely in groundwater monitoring, environmental and structural geology inquisition. Proceedings were established using Dipole-dipole Schlumberger configuration (J. LE PRIOL 1975; STROJEXPORT BURGAP – Prague & ANRH & Sourisseau 1975; Malinov 1973; ICOSIUM & ANRH 2002) via injecting continuous electrical current AB into the subsurface completing by regulation the voltage difference at the potential electrodes, which Schlumberger configuration is adapted geophysical transects according the current electrode separation AB/2 space increased in the centre of dispositive from 1.0 m to 100 m.

In order to achieve geophysical data processing, two datasets were performed through primary field data (Apparent Resistivity – (AB/2) inter-Electrodes spacing) and the processed data (secondary geoelectric data). The primary data was generated by investigating thirty probe points exploiting Schlumberger dispositive according a maximum spread of 200 m at (AB/2 = 100 m). The field generated from observed resistivity versus geoelectric spread was implemented in IP2Win software for obtaining geoelectrical layering and thickness for each VES point. However, VES surveys were used to compute the geo-electric factors including (L) and (TTR) (Dehni et al. 2020).

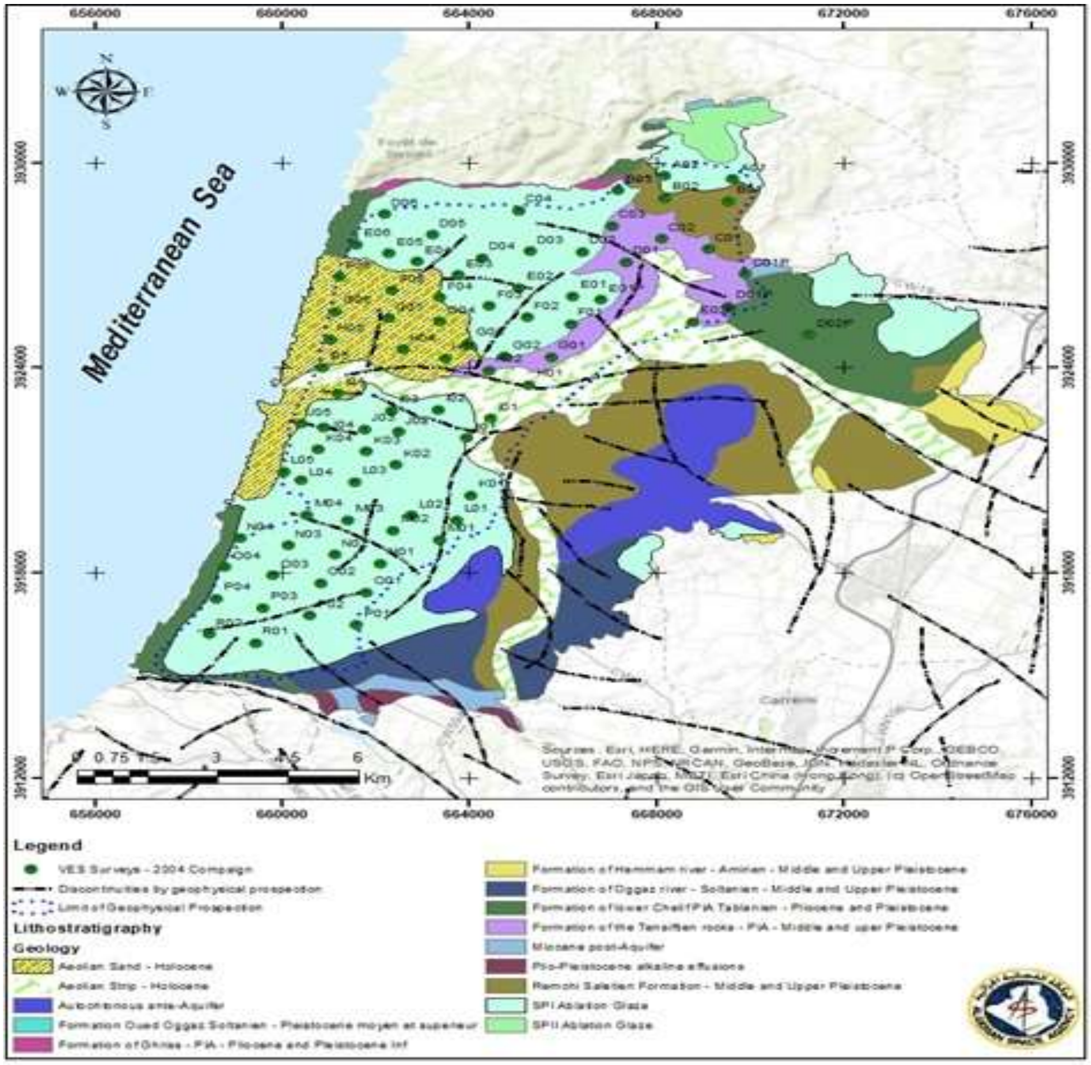


Fig. 2 Geology and litho-stratigraphy of the sedimentary aquifer and sampling site

The longitudinal conductance (L) is the geo-electric parameter used to define target areas of groundwater potential and is given by the mathematical relation (Eq.1).

$$L = {h1}/{\rho 1} + {h2}/{\rho 2} + \cdots . + {hn}/{\rho n} \tag{1}$$

The longitudinal resistivity (LR or ρ_l) is computed using the Eq. (2):

$$\rho_l = LR = {H}/{L} ; H = \sum_{i=1}^{n} h_i \tag{2}$$

Where: h_i : Depth to the bottom geoelectrical layer or thickness (m); H: the total thickness layer (measured along the profile for every lithological formation). $\rho 1$: Apparent resistivity measured.

The TTR is the secondary geophysical factor explored to define target aquifer potentialities which related directly to transmissivity. However, the highest (TTR) values reflect likely a highest transmissivity values in the aquifer. TTR is strongly correlated with aquifer transmissivity to establish the parametric equation in vadose zone approximately affect the underlying permeability. Thus, transmissivity factor has been estimated to assess the protection capacity of the unsaturated aquifer overlying the system in order to determine its ability of percolation water into the aquifer. Then, the hypothesis suggests the geologic materials having high transmissive water; will tend to allow high permeability into underlying systems. Consequently, TTR values were computed using the following formula (Eq. 3):

$$TTR = \sum_{i=1}^{n} h_i * \rho_i \tag{3}$$

2.3 Vadose Zone Protective Capacity

The protection capacity of the specified vadose area illustrates an ability of the cover unit to prevent and filter the percolation of the soil surface polluting liquid into the aquifer unit. This concept describes unconfined area protective capacity according proportional to its conductance L in terms of contaminants attenuation protection, impacting on the temporal dimension (infiltration time).

The second-order geoelectric parameter was evaluated under factors thickness and resistivity respectively that were mapped the aquifer capacity protected from contaminant attenuation in the unconsolidated aquifer. As stated by Oladapo et al. (2004), the groundwater protection ability from contamination over a vadose zone aquifer should be classified according to the conductance (L): Excellent ($L > 5$), very good ($5 \leq L < 10$), good ($0.7 \leq L < 5$), moderate ($0.2 \leq L < 0.7$), weak ($0.1 \leq L < 0.2$) and poor ($L < 0.1$).

Globally, the hydrologic conductivity equivalent to permeability is apprehending on the mathematical product of the resistivity and thickness, a second empirical definition agrees using the parameter (TTR), assuming proportionality in aquifer transmissivity to its transverse resistivity (Henriet 1976). The low resistivities in agreement with the permeability and porosity, the protective capacity in the Ouled Taoui – Ouled Boujema aquifer must be considered as being proportional to the rate between the thickness to the resistivity and to that of the longitudinal conductance (L).

The longitudinal unit conductance (L) allows by correlation analysis (bi logarithmic regression (natural logarithm) to map the aquifer potential protection by the clayey material (semi-captive and captive aquifer). Like the Ouled Taoui aquifer – Ouled Boujema presents a multi-layered aquifer, semi-confined to unconfined aquifer for top soil and captive at the basement level, we retain that the fissured medium is thicker and more transmissive than the unconsolidated area within low clay content (permeability and apparent resistivity are lowest).

Indeed, the inter-electrode spacing (AB/2) plays a key role in the characterization of the sub-horizons (more than three (03) horizon layers according to the - Conceptual Data Model). However, the criterion of detectability of the underlying geological layers recommends a significant depth of investigation plus an approached thickness on the geoelectric curve and during interpretation. This means that the detectability of a layer is proportional to the thickness/depth ratio.

The micro anisotropies lead to an overestimation of the thickness (principle of equivalence) and the geoelectric curves can be confused according to the number of geological layers detected (minimum of contrast between two layers) and the isotropic or anisotropic media overlap (principle of suppression) which anisotropy coefficient (λ) and (TTR) plays crucial roles to determine its capacity to prevent infiltration of unwanted fluids into the aquifer. The hardness and compaction of rocks are proportional to (λ).

For this purpose, if the electrical coefficient of anisotropy is fewer than 1 and does not exceed 2 in most of the hydrogeological studies, it was considered isotropic aquifer for good groundwater potentialities. Conversely, if λ is bigger than one demonstrates most heterogeneities in the aquifer. Compact rock at shallow depth increases λ expressing lowest permeability. Furthermore, areas with λ inferior to 0.5 were considered for ground water potential zones within high porosity and permeability. Thus, the values of λ for VES surveys are computed using mathematical equation (Dehni et al. 2020) (Eq. 4):

$$\lambda = \sqrt{(TTR / \rho_i)} = \sqrt{(L^* TTR)} / H \tag{4}$$

Consequently, an unconfined aquifer does not benefit from any protection (zero clay thickness) preserving a natural quality of groundwater. The degree of containment of the Ouled Taoui - Boujema aquifer (Ain Temouchent – Algeria) is ensured by the presence of significant thickness of clays allowing to delay the infiltration of contaminated natural recharge. The L values of the squared clay materials were proportionally related to the Travel Time (TT) (property of the capacity protection of contamination) and more electrically conductive than the aquifers. The mathematical relation (Eq. 5) is given by:

$$TT = Const * L^2 / dh \tag{5}$$

With: TT: working time; Const: Constant; L: Longitudinal conductance (Ω^{-1} or S: Siemens); dh: hydraulic head difference between the top and the base of the protection layer (m).

In order to avoid graphical re-interpretation of geoelectric surveys problems, many authors recommend regression analyzes between (L) related to the clay material according to geometrical factor linked to interelectrode displacement measuring devices (AB/2) (Mazac et al. 1990). Compilation outcomes were shown in the section "Results and Discussion" assuming the relationship of resistivity versus Hydraulic conductivities (Fig. 5).

2.3 GOD model for vulnerability evaluation

Several vulnerability models are cited by scientific literature. Among these models, we have applied GOD model introduced by Foster (1987). It presents the aquifer vulnerability through the vertical percolation of pollutants via the unsaturated zone and does not deal with the lateral migration of contaminants in the confined zone (Bouselsal et al. 2015).

However, the GOD method is an empirical approach in which the vulnerability is defined according to the inaccessibility under saturated areas, which make sense of the pollutant penetration and attenuation efficiency overlying layer in the saturated zone (Bouselsal et al. 2015).

The GOD model is considered as a numerical notation system, completed by weightage assessment from AHP method on the parameters influencing the infiltration of pollutants, namely: Type of the aquifer investigated (G), Lithology nature of weathered basement (O) and Depth (D) (D = Static level = DEM – Piezometry). Generally, rating less than or equal to 1 (0.1 to 1) are classified in the GOD model parameters as essential water potentialities in natural environment (Blanchard et al. 2016). The higher value of GOD model, impact the ground water vulnerability (Fig. 3). The GOD index is obtained by multiplying the three parameters according to the following equation (Eq. 6) (Murat et al. 2003; Latifi and Chaab 2017):

$$GOD\_index = G_C * O_C * D_C \tag{6}$$

The GOD model index has been evaluated in ArcGIS revealing the ground-water to pollution. We have made a classification system assuming different classes obtained which five classes will be retained, ranging from negligible to high (Tab. 1). In accordance to the GOD model optimized by using AHP-WMA technique, The three calibrated models such as AHP GOD-L, AHP GOD-L-T and AHP GOD-L-Th are modeled by AHP for ArcGIS extension and personal application under Excel program in order to obtain the weighting scores of AHP-WMA for each independent factors of AVCF's scheme illustrated in the next paragraph.

Table 1 Classification of groundwater vulnerability according to the GOD model

Vulnerability classes	GOD Index Interval
Absence of Vulnerability	0.0 – 0.1
Negligible Vulnerability	0.1 – 0.2
Low Vulnerability	0.2 – 0.4
Moderate Vulnerability	0.4 – 0.6
High Vulnerability	0.6 – 0.8
Extreme Vulnerability	0.8 – 1

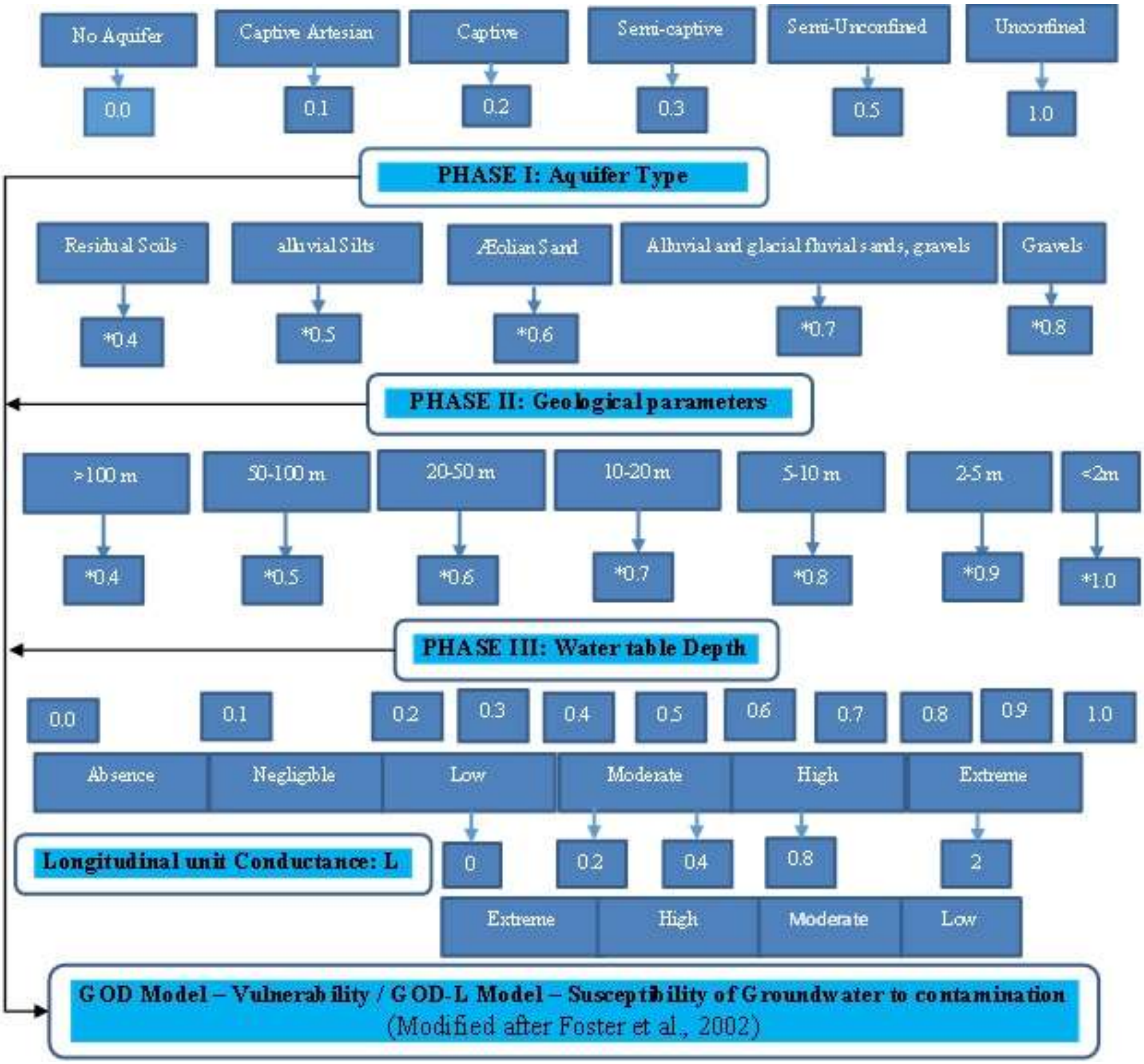


Fig. 3 Vulnerability of groundwater to contamination GOD and modified GOD: GOD-L

3 Results

3.1 AHP GOD-L for vulnerability evaluation

The GOD-L model is a primary proposed vulnerability model assessment to pollution. Its insight involves the statistical combination of all driven factors for the GOD method and the longitudinal unit conductance (L) using the (WLA: Weight Linear Average) algorithm. The procedure for developing the GOD-L vulnerability method involve exploiting the contribution of the weighted hydrological importance of the factors G, O, D, L, T and Th towards the aquifer vulnerability assessment.

The effectiveness of the AHP technique was explored for this analysis using normalized weighting. The AHP method suggested by Saaty (1990) was used to combine the different factors and assign different weights to each factor. Table 2 illustrates the Saaty scale norm and the reanalysis of the weights assigned to the expert opinion criterion. With the output of the SAATY scale, the pairwise matrix comparison was developed on the factors determined by electrical geophysics (Aquifer Vulnerability Causative Factors – AVCF's) allowing the development of the GOD-L model (Tab .03). By solving the matrix in Table 3, the normalized weights (WLA) were finally checked for consistency assignment which are sorted and grouped in each of the GOD-L indices. The same procedure was applied to other causative factors such as GOD-L-T, GOD-L-Th respectively.

Table 2 SAATY scale for weight assignment (Saaty, 1990)

Less important				**Equivalent**			**More important**	
Extremely (E)	**Moderate Low**	**High (H)**	**Moderate (M)**	**Important**	**M**	**M H**	**Strongly**	**E**
1/9	1/7	1/5	1/3	**1**	3	5	7	**9**

In order to achieve our peer-to-peer matrix comparison of each causal factors (L, T (slope Topography) and Th (thickness)), three (03) tables were enumerated to assess the vulnerability to contamination using AHP-WLA-GOD basis as shown in the table 3, 3.1 and 3.2 respectively. The tables related to matrix comparison based on 4 for GOD-L to 5 factors for both GOD-LT and GOD-L-Th, indicate that the Uniformity ratio approaches the value about 5% of consistency (< 10%) which is considered as acceptable criteria to ensure mapmaking integrity in underlaying data. However, the Uniformity ratio increase slightly the value around 5.8 % of consistency for GOD-LT and about 9.03% for GOD-Lth which reveal the influence of the thickness factor in dynamic flow (low hydraulic conductivity) and therefore a largely residence time for retaining the pollutant in the subsoil whereas the influence of the slope topography affect the water balance in the case of variable density assuming that the values of slope less than 5% allow to stabilize the hydraulic balance between freshwater and seawater interface.

Table 3 Comparison matrix for the four parameters by the AHP method for the causative factors GOD-L

	Aquifer Type « G »	**Lithology « O »**	**Depth « D »**	**Conductance « L »**	**Normalized Weight (W)**
Aquifer Type « G »	**1**	1/7	1/5	1/9	0.0421442
Lithology « O »	7	**1**	1	1/3	0.2135541
Depth « D »	5	1	**1**	1/5	0.170557
Conductance « L »	**9**	3	**5**	**1**	0.573744
Sum	**22**	**36/7**	**36/5**	**74/45**	**1**

Uniformity ratio = **5.05**% < 10% Acceptable criteria to ensure mapmaking integrity in underlaying data

Table 4.1 Comparison matrix for the five parameters by the AHP method for the causative factors in GOD-LT

	Aquifer Type « G »	**Lithology « O »**	**Depth « D »**	**Conductance « L »**	**T « Slope Topography »**	**Normalized Weight (W)**
Aquifer Type « G »	**1**	0.25	1/6	1/8	1/5	0.041169
Lithology « O »	4	**1**	1/2	1/5	1/8	0.091836
Depth « D »	6	2	**1**	1/2	1/2	0.170235
Conductance « L »	8	5	2	**1**	1/2	0.321991
T « Slope Topography »	**5**	**4**	2	2	**1**	0.383769
Sum	**24**	**12.25**	**5.666667**	**3.825**	**2.45**	**1**

Uniformity ratio = **5.7934** % < 10% Acceptable criteria to ensure mapmaking integrity in underlaying data

Table 5.2 Comparison matrix for the five parameters by the AHP method for the causative factors GOD-L-Th

	Aquifer Type « G »	**Lithology « O »**	**Depth « D »**	**Conductance « L »**	**Thickness « Th »**	**Normalized Weight (W)**
Aquifer Type « G »	**1**	1/4	1/5	1/8	1/9	0.030895
Lithology « O »	4	**1**	1	1/7	1/8	0.058837
Depth « D »	6	2	**1**	1/5	1/7	0.094756
Conductance « L »	8	3	5	**1**	1/3	0.290724
Thickness « Th »	**9**	**8**	**7**	3	**1**	0.5054904
Sum	**28**	**14.25**	**13.667**	**4.6583333**	**1.71230159**	**1**

Uniformity ratio = **9.03**% < 10% Acceptable criteria to ensure mapmaking integrity in underlaying data

Globally, it is primordial to determine the process searching for a vector expressing the alternative priority for the optimized criterion to which it is associated under consistency ratio (CR) that must be less than 10%. The optimized AHP-WLA-GOD-L was integrated algorithm in Eq. (7):

$$WLA = \sum_{i=1}^{n} W_i * R_i \quad ; \quad AHP - WLA = \sum_{i=1}^{n} N * W_i * R_i \qquad (7)$$

By substituting the left-hand side (part one) of Eq. (7) with AHP-WLA index and the right side (part two) of Eq. (7) with G, O, D and L factors, we developed and optimized the GOD-L vulnerability model for contamination protection by equivalence equation Eq. (8):

$$AHP - WLA - GOD - L_{Index} = \sum_{i=1}^{n} N * W_i * R_{RI_i} \qquad (8)$$

The criteria of Consistency Ratio (CR) obtained from AHP analysis (Eq. (9) and Eq. (10)) is about: 5.05 % (<10%: Accepted). Therefore, the second ratio called Consistency Index (CI) approaches the value of 0.0454 (less than

1) and the maximum variance $\lambda max = 4.1365$. Where: n is the variables number (causative factors) in the matrix. The mathematical equation for the (CI) is showed (Eq. 9):

$$CI = {(\lambda_{\max} - n)}/{(n-1)} \tag{9}$$

CR is the report between (CI) and proposed Random Index (RI), as illustrated in the formula: $CR = {CI}/{RI}$ (10)

If the CR ≤ 0.1 would be preserved for the matrix consistency.

In order to mapping vulnerability and sensitivity to groundwater pollution, the model developed AHP-WLA-GOD-L associated to the AVCF's were apprehended through which serve as a comparison by pair of the standard parameters GOD and the longitudinal conductance (L) determined by two investigative campaigns (1975 and 2004). The probability weighted and rating (R) for the classes of the AVCF's is used to predict how to test the inconsistency of the evaluation matrix were achieved in the following table (Tab. 4).

Table 6. Probability weighted and rating for the classes of Aquifer Vulnerability Causative Factors (AVCF's)

AVCFs' themes	Category (Classes)	Pollution Capacity Protection	Rating (R)	Normalized weight (W)
Groundwater hydraulic confinement (G)	Unconfined aquifer	High	4	**0.04**
	Confined aquifer	Medium	2	
	Semi-Confined aquifer	Medium-High	3	
	No-Aquifer	Low	1	
Aquifer Overlaying Strata (O) (Ohm*m) For AB/2 = 300 m	3.75 – 20	High	4	**0.21**
	20 – 50	Medium-High	3	
	50 – 150	Medium	2	
	150 – 431	Low	1	
Depth to water table (D) (m)	1.08 – 10	High	4	**0.17**
	10 - 30	Medium-High	3	
	30 - 60	Medium	2	
	60 - 95	Low	1	
Longitudinal Conductance (L) (Siemens)	0.02 – 0.3	High	4	**0.57**
	0.3 – 0.7	Medium-High	3	
	0.7 – 2.5	Medium	2	
	2.5 – 5.79	Low	1	

3.2 Global Methodology

The methodological approach for assessing the degree of vulnerability of the Ouled Taoui – Ouled Boujema aquifer to contamination depends largely on geophysical data acquired in the field and hydro-chemical analysis (Fig. 4). The methodology approach was presented in different steps such as:

- Acquisition of geophysical data, processing, interpretation and extraction of geoelectrical factors (thickness of the layer and resistivity of the layer);
- Derivation of AVCF's as well as assessment of their hydrological significance;
- Exploration of the potential of the GIS technique for the production of thematic AVCF's derived maps;
- Review of existing vulnerability modeling technique, GOD model and L model algorithms;
- Development of GOD-L vulnerability indexing technique algorithms through the application of a AHP analysis;
- Application of the GOD and GOD-L models algorithms to the mapping of the AHP-WLA-GOD-L map by the Aquifer Vulnerability Causal Factors (AVCF's);
- Validation of the AHP-WLA-GOD-L maps produced on the basis of the water chemistry analysis.

The way forward, will be to further develop common feasible methodology to prioritize improved AHP- Optimized approaches to map, calibrate and extract statistical weighting obtained by AHP-GOD– WMA-AVCF's approach, and to incorporate ordinal and equitable classification into improved vulnerability to groundwater contamination and planning. The whole methodology is illustrated by the following figure 4.

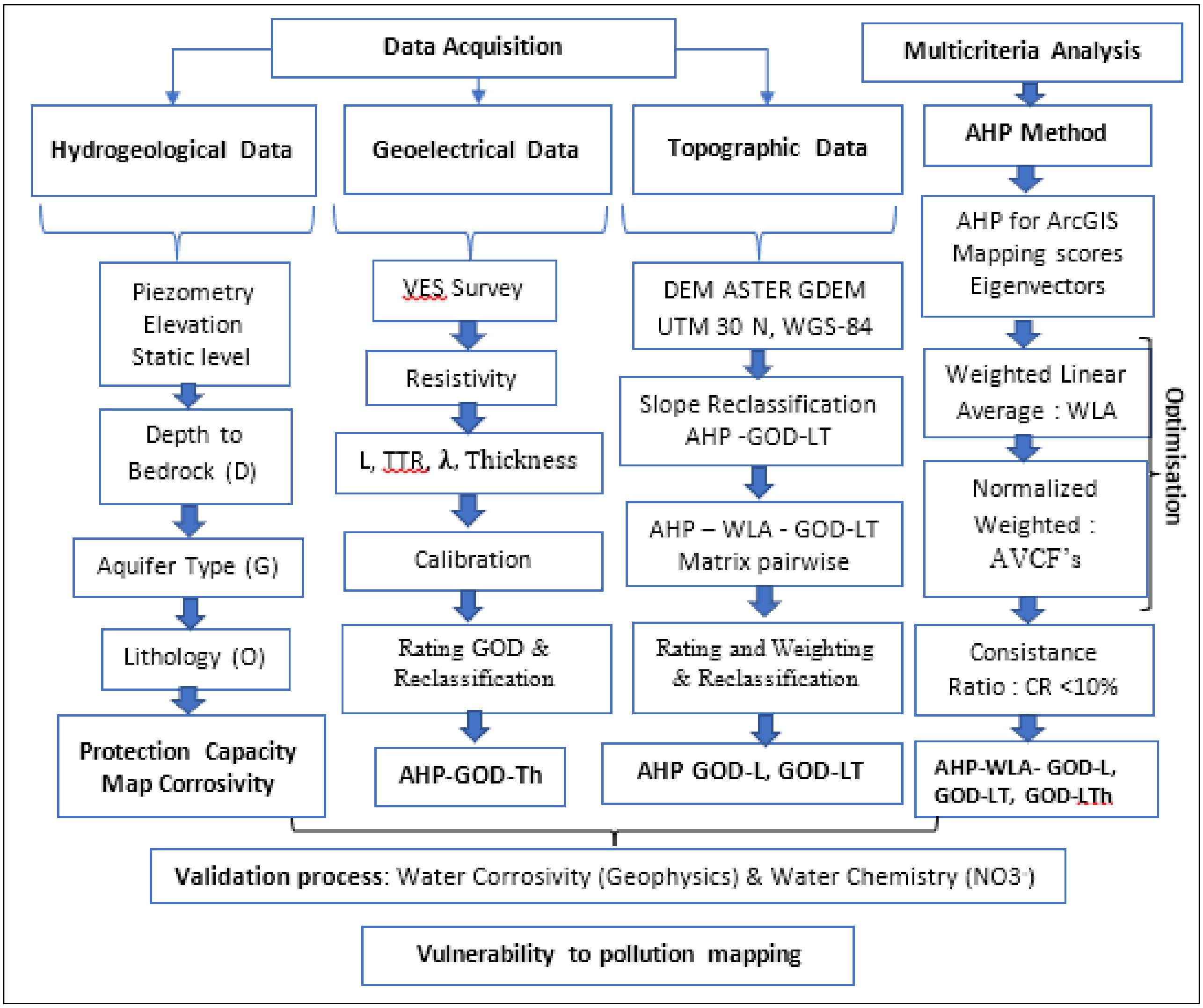


Fig. 4 Flowchart of developed methodology of vulnerability using GOD and AHP-WLA-GOD-L

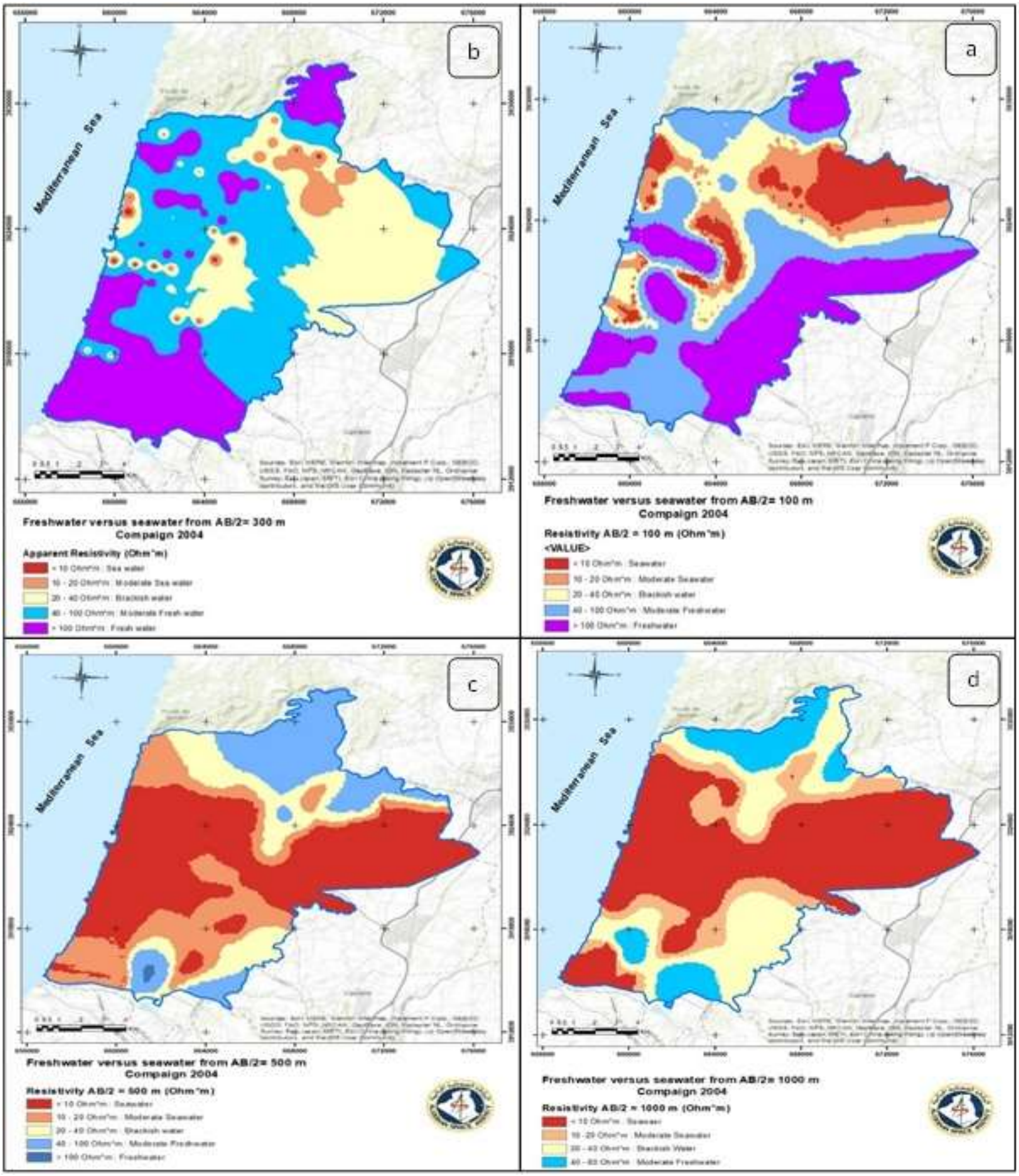


Fig. 5 Freshwater and seawater mapping using resistivity at different Spacing AB/2: a: AB/2 = 100 m; b: AB/2 = 300 m; d: AB/2 = 500 m; d: AB/2 = 1000 m – Campaign 2004.

The validated apparent resistivity for different spacing (AB/2) is accommodated by the longitudinal conductance (L) through the statistical characteristics (Min: Minimum, Max: Maximum, Average, Standard Deviation: SD) have been illustrated in table 6 and figure 5.

Table 7 Statistical parameters used to validate resistivity influence according AB/2 spacing

Parameters	L: AB/2 = 100 m	L: AB/2 = 300 m	L: AB/2 = 500 m	L: AB/2 = 1000 m
Min	0.02511	0.0898	0.0607	0.0657
Max	19.8104	5.738	12.6984	18.728
Mean	0.983	0.867	1.3966	1.8364
S.D	2.411	0.882	1.8658	2.572

From the table 6 related to figure 5, we concluded that L is more influenced by the electrode spacing (AB/2) and therefore by the investigation depth related to the vadose area threated by degree of aquifer confinement. The best optimized value of (L) is adequately described by the electrode spacing of AB/2 = 300 m (Among all S.D (Standard Deviation), the best S.D is about 0.882).

3.4 Vulnerability to groundwater contamination via the GOD model

The aquifer confinement (G: Parameter) is an essential first factor in the contaminant pervasion and greatly influences the vulnerability of the aquifer. The unconfined aquifers are more vulnerable than confined or semi-confined aquifers, because the presence of an impermeable layer can make the aquifer captive and limit the transfer of contamination (Fig 6.a). Thus, the second factor is related to the unsaturated zone which corresponds to the layers between the topographic surface and the maximum piezometric level. The interest of this zone lies essentially in its permeability and its attenuation capacity. Lithology is a factor reacting on permeability and infiltration (Ait El Mekki 2016). This parameter is of great importance in the regulation of the recharge and it is mapped in ArcGIS environment (Fig 6.b).

The strata lithology (O: Parameter) is very important in assessing the aquifer vulnerability, because nature can cause a rapid spread of pollutants to groundwater (Ewodo M et al. 2015). Indeed, lithology is closely related to runoff, infiltration and the degree of water pollution. These geological materials are of two types, unconsolidated formations (sands, clays, marls) and consolidated formations (sandstone, limestone, dolomites, etc.). The litho-stratigraphy map of the Ouled Taoui-Ouled Boujema aquifer has been mapped by several different sources, such as: the 1:50,000 geological map of Beni-Saf (2nd ed., 1995) by P. Guardia and M Chabi, the geological map at 1/50,000 of Ain Temouchent (1987) by P. Guardia Map N° 209 B11C5, and the study of geophysical prospecting in the region of Ain Temouchent, hydrogeological study operation N° 5 311101900, STROJEXTPORT – PRAGUE 1975.

Appropriate rating was assigned according to the GOD model (Aquifer Overlaying Strata – O) (Fig. 6.b). The analysis of the map of the parameter "O" made it possible to distinguish the dominance of the rate of 0.8 in the aquifer that it exceeds 60%. This rating has been attributed to the alluvial, sandy, sandstone and scree slopes formations. On the other hand, the rate of 0.9 was attributed to the formations of massive and chalky limestones (Fig. 6.b). The aquifer depth is among the most factors in assessing the vulnerability groundwater to contamination (Fig. 6.c). In particular, any attenuation of a pollutant takes place in relation to depth. It was inferred based on the disparity between the surface elevation potential (Z) and the piezometric surface elevation potential (h) (Sanz et al. 2022).

The Depth to ground water factor represents the vertical distance which a pollutant travels on subsurface to reach the ground water. Generally, aquifer ground water protection increases below the basement. Depth of the water table parameter was carried out using data from drillings, wells and pumping tests - 217 points) distributed over the entire study area dating to the winter period (September 2018) and by applying the Inverse Distance Weighting (IDW) interpolation method under ArcGIS 10.8 software. However, a depth classification according to the GOD model was followed, assigning rates to the GOD model (Fig. 6.c).

The three main parameters of the standard GOD model such as G, O, D respectively are mapped under ArcGIS 10.8 software for vulnerability to groundwater pollution (Fig. 6.d).

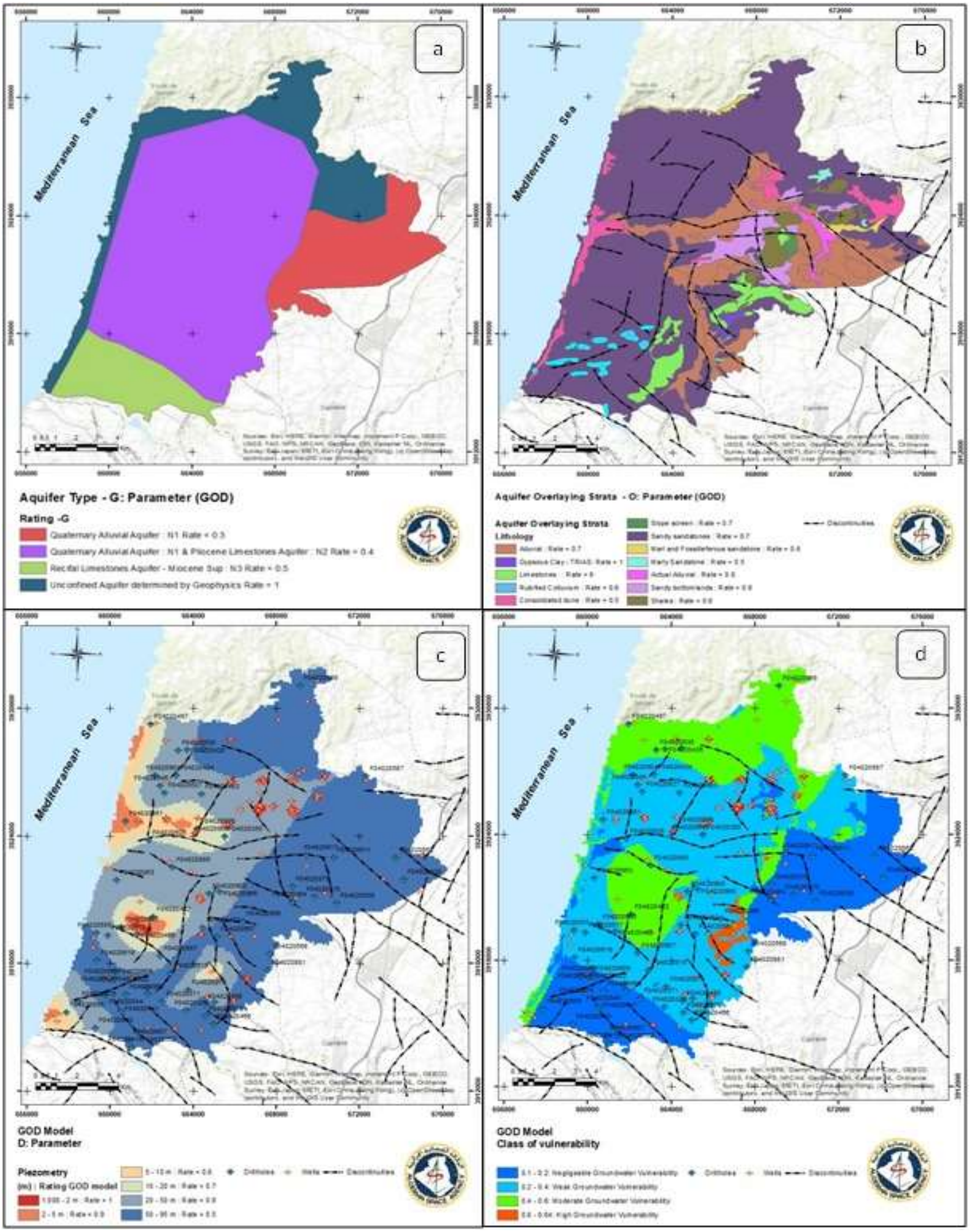


Fig. 6 Mapping the groundwater vulnerability to contamination using GOD model: a- G parameter; b- O parameter; c- D parameter and d- GOD model

3.5 Vulnerability to groundwater pollution via the modified AHP GOD-L model

The confinement of the aquifer (G: Parameter) is an essential first factor in the contamination dispersion and greatly influences the vulnerability of the aquifer. The powerful decision support system technique AHP GOD-L is firstly selected, and AHP-WLA-GOD-L is performed by optimizing objective weights. The results for both campaigns released in 1975 and 2004 are distinctly different by longitudinal conductance (L) to assess the aquifer vulnerability to pollution associated to the lateral variation in thickness which is affected by low resistivity materials.

The high values of aquifer susceptibility to contamination (0.6 > L > 0.8 Siemens) are localized in the Northern West and East parts of the Ouled Taoui-Ouled Boujema aquifer and decrease in southern part along the El-Hallouf stream connected hydraulically to the connected volcanic aquifer (Fig .7).

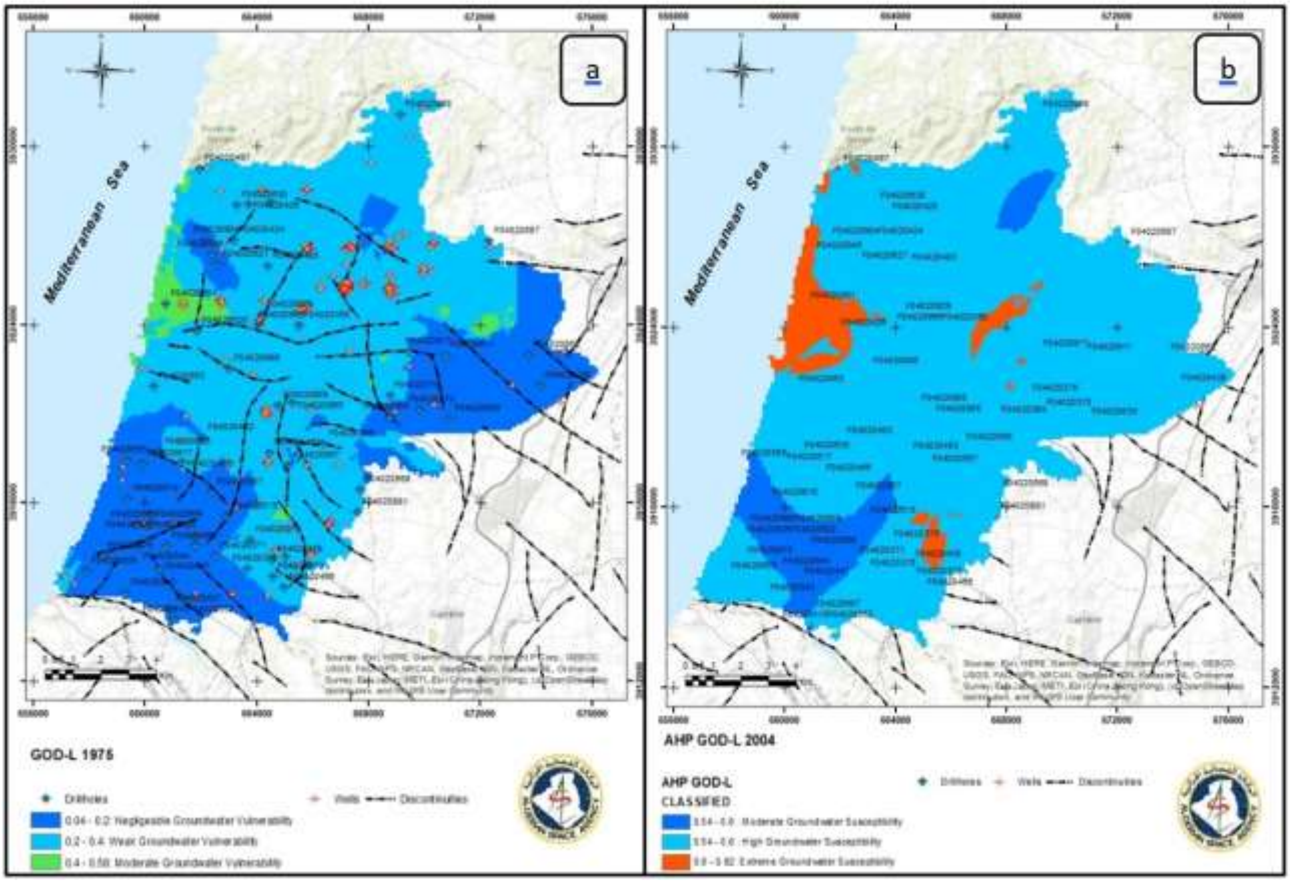
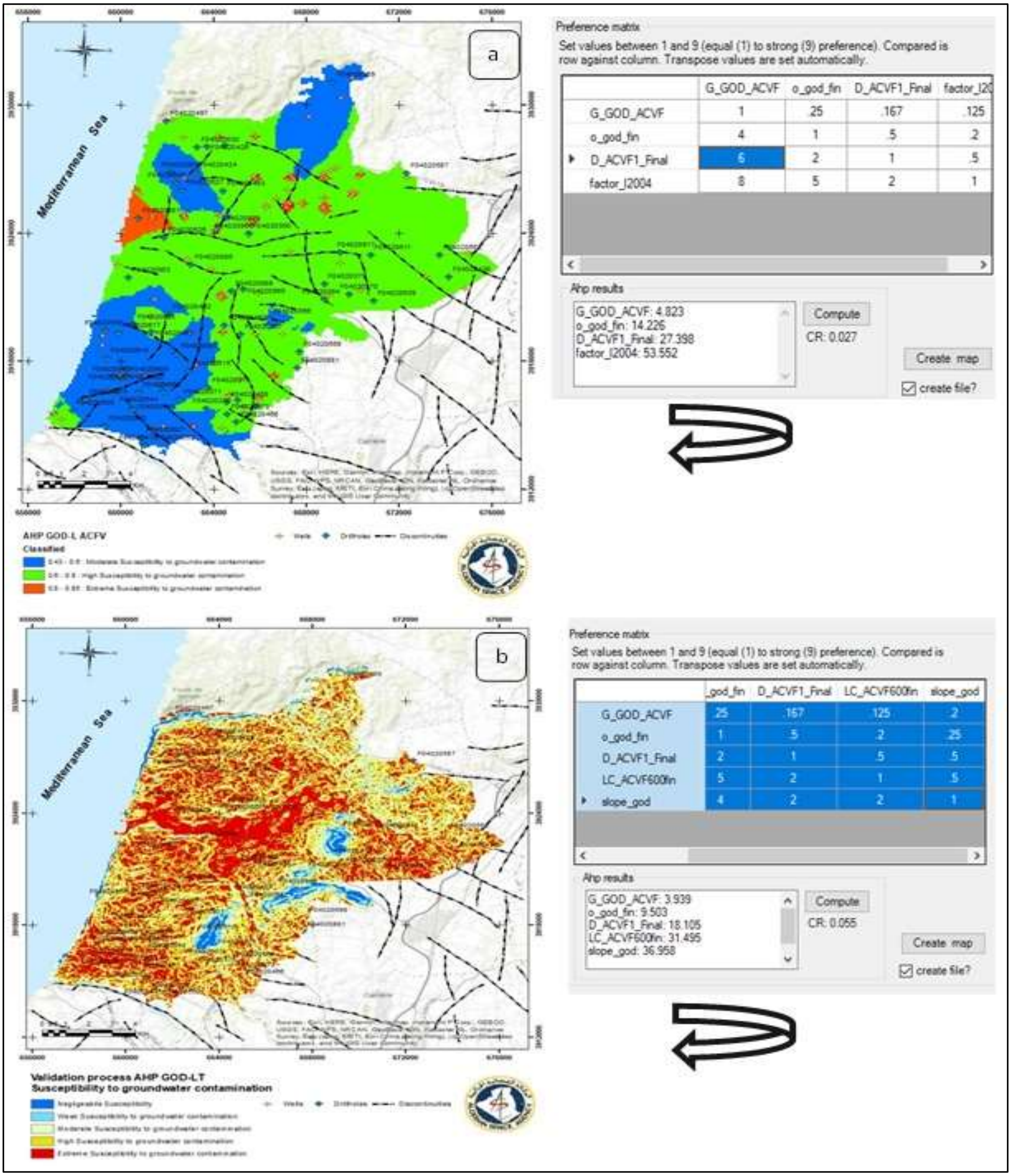


Fig. 7 Mapping groundwater vulnerability and susceptibility to contamination using: a- Vulnerability to groundwater contamination; b- Susceptibility to groundwater contamination AHP-GOD-L

3.6 Vulnerability to groundwater contamination by AHP-WLA-GOD-LT and AVCF's model

The highest degrees of vulnerability are located in coastal areas at downstream of El Maleh stream. This area covers 5 % of the lowland area and, corresponds to shallow-aquifer areas (1.5 to 30 m), associated with a highly permeable sediments at surface (dune, sandy and gravelly aquifer, etc.). Moderate vulnerability areas cover 45 % along the valley. The sedimentary coastal aquifer is composed essentially of gravel and sand that promote the vertical infiltration, in spite of the occasional presence of clay and marly intercalations. Regarding the visualization of the GOD model in 3D environment by using Leapfrog Geo 5.1, the lowest vulnerability prone surrounds the central plain of aquifer.

On the other hand, the piezometric depression indicate low vulnerability levels because the deepening of the bedrock reached 100 m, and saturated and unsaturated zones are a bit permeable. The inferred hydrogeological parameter of vadose zone with lithology/stratigraphy allow to review that low vulnerability areas exceeds the threshold of 50 % (Fig. 8).



Preference matrix

Set values between 1 and 9 (equal (1) to strong (9) preference). Compared is row against column. Transpose values are set automatically.

	G_GOD_ACVF	o_god_fin	D_ACVF1_Final	factor_I20
G_GOD_ACVF	1	.25	.167	.125
o_god_fin	4	1	.5	.2
▸ D_ACVF1_Final	6	2	1	.5
factor_I2004	8	5	2	1

Ahp results

G_GOD_ACVF: 4.823
o_god_fin: 14.226
D_ACVF1_Final: 27.398
factor_I2004: 53.552

CR: 0.027

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Preference matrix

Set values between 1 and 9 (equal (1) to strong (9) preference). Compared is row against column. Transpose values are set automatically.

	_god_fin	D_ACVF1_Final	LC_ACVF600fin	slope_god
G_GOD_ACVF	.25	.167	.125	.2
o_god_fin	1	.5	.2	.25
D_ACVF1_Final	2	1	.5	.5
LC_ACVF600fin	5	2	1	.5
▸ slope_god	4	2	2	1

Ahp results

G_GOD_ACVF: 3.939
o_god_fin: 9.503
D_ACVF1_Final: 18.105
LC_ACVF600fin: 31.495
slope_god: 36.958

CR: 0.055

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Fig. 8 Mapping groundwater susceptibility to contamination by optimized: a- AVCF's; b- AHP-GOD-LT

3.7 Geophysical, hydrogeological and hydro chemical implication - Validation process

According to Antonio Braga and Richard Francisco (2014), the hydro-geophysical validation remains very conclusive for the mapping aquifer capacity to contamination by exploitation an auxiliary variable in 3D Environment (Leapfrog Geo Geosciences software) such as: L, TTR, thickness according to classification shown in table 7 (Fig. 10).

Table 8 Classification of aquifer capacity rating based on the scaled factors: resistivity, thickness and L

Resistivity (Ohm*m)	Thickness (m)	L (Siemens)	Vulnerability Classes
< 10	> 25	> 3	Poor – Groundwater Freshwater Strong Capacity Protective
10 - 20	25 - 15	2 – 3	Weak – Freshwater Moderate Capacity Protective
20 - 40	15 - 10	0.3 – 2	Moderate – Brackish water Average Capacity Protective
40 - 100	10 - 5	0.1 – 0.3	High – Saltwater Low Capacity Protective
> 100	< 5	< 0.1	Extreme– Saltwater No Capacity Protective

The geospatial mapping of groundwater to pollution illustrates that the geoelectric parameter L is strongly depends on the spacing distance (AB/2) and it is very sensitive to the saturated thicknesses and a strong capacity protective of groundwater explains a delay of infiltration which is not explicitly related to the geological thickness since the area of transmissivity is related to the (TTR) (Fig. 9a).

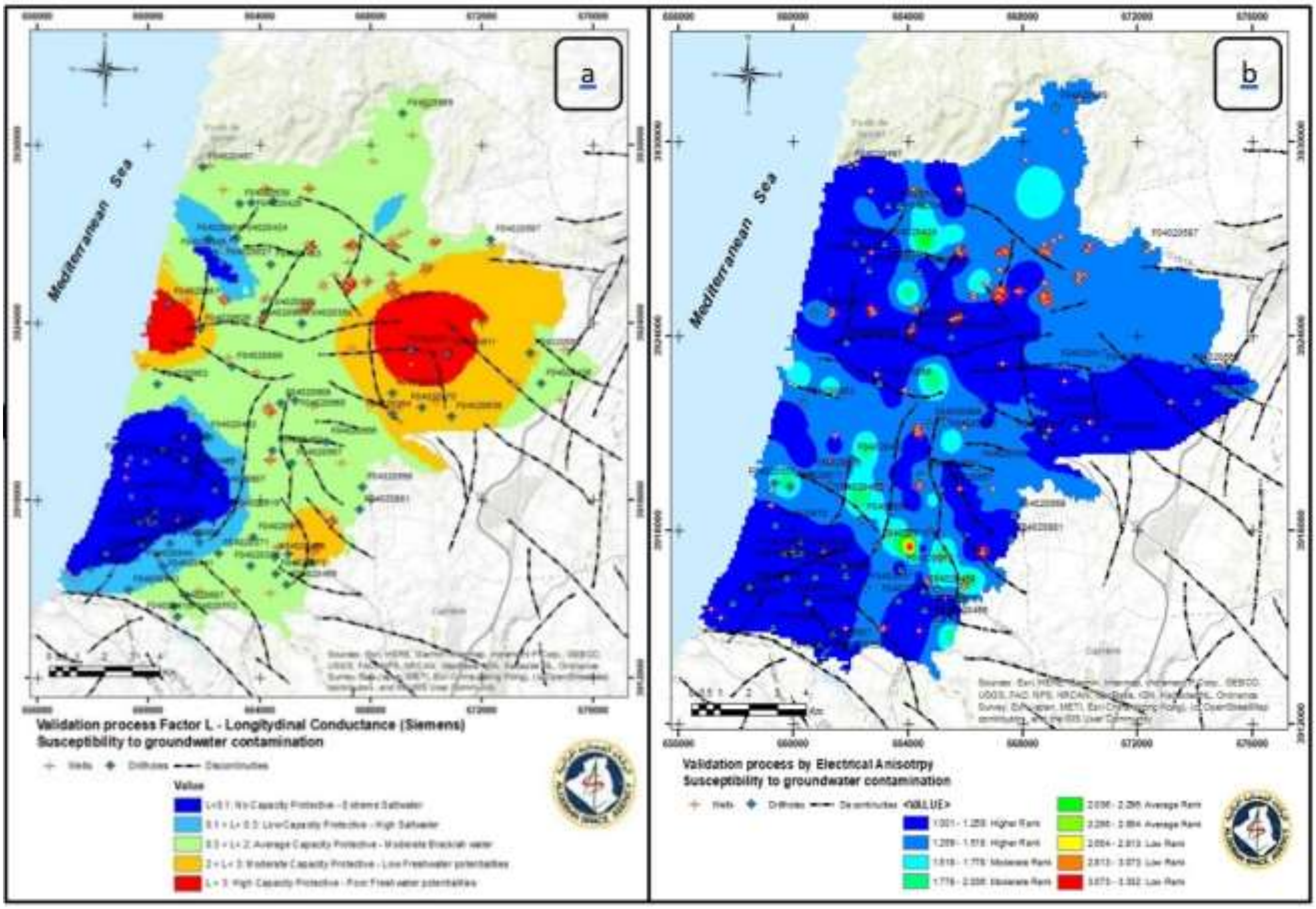

Fig. 9 Validation vulnerability versus geophysical factor (L) for groundwater capacity protective scale

Based on these geoelectrical estimates, the overburden coefficient of anisotropy (λ) was calculated for each sounding location VES and it varies ranges from 1 to 3.35 for the first campaign -1975 and 1 to 2.09 for the second campaign – 2004 which depicts the true variation of the anisotropic of the aquifer (Fig. 9b). The λ values revealed that the underlying basement rock is suspected by granite-gneiss (λ between 1.00 and 1.03) / granite-schist (λ between 1.03 and 2.09) as a result of alternating shale and fine sands considered as the underlying basement rocks. The area with high values of λ suggests that the discontinuity system have extended in all directions with different degrees of cracking, which had greater water reserve capacity in fissured rocks resulting in higher porosity.

A comparison of the L results according several spacing (AB/2) indicates that the aquifer protective capacity is poor to excellent in the Ouled Taoui – Boujema aquifer. The decrease in the L may correspond to the decrease in seawater intrusion. Therefore, the increase in the L could be interpreted as a decrease in the porosity and geological conductivity. The L values are used in evaluating capacity of protection which has the ability to filtering pollutants. High L indicated relatively high protective capacity map providing visual information for susceptibility zones which help protecting ground water under Leapfrog Geo v5 software (Fig. 10).

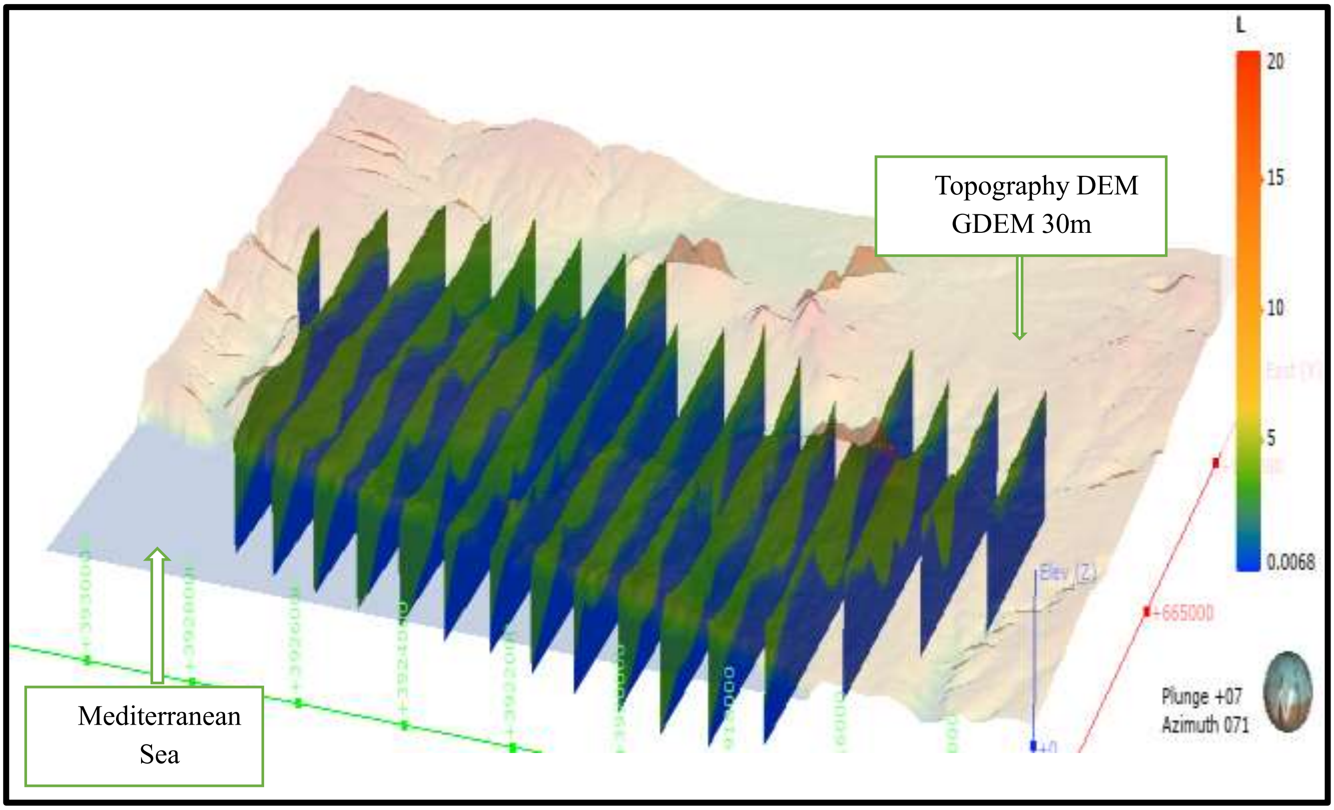

Fig. 10 3D Modeling using Geosections of the longitudinal conductance using Leapfrog Geo v.5

The estimation shows that the L values varies from 0.025 to 5.79 Ω^{-1} in the aquifer (Fig. 9a and Table 7). The clay overburden which gives relatively high longitudinal conductance protects the underlying aquifer. The capacity of protection of the overburden of L less than 0.1 Ω^{-1} can be classified as poor which can be seen on the southwestern to the aquifer central depression. Then longitudinal conductance (0.1 to 0.3 Ω^{-1}) is classified as having weak protective capacity which can be seen on the southwestern part while (0.3 to 3 Ω^{-1}) is classified as having moderate aquifer protective capacity which can be seen to cover most of the eastern part of the area mapped. The Clay material will reduce the resistivity of the weathered layer below 100 Ωm and consequently, decreases both the permeability within aquifer potentialities and affects therefore the principle of equivalence in geophysics formalism.

Consequently, unidirectional fault couldn't reveal the existence of groundwater potentialities and such prone is related more to low values of λ. The central, west and south parts of the aquifer appear to be more salinized because of seawater intrusion reflecting a decrease in the electric anisotropy (Bentekhici N. et al 2021).

Consequently, it indicates the presence of macro-anisotropy in the present geoelectric strata in the Ouled Taoui – Boujema aquifer, which is clear to distinguish the individual layers for a given geoelectrical model in sedimentary contrary to underlain volcanoes aquifer.

4 Hydrogeology and hydro-geophysics validation: Soil corrosivity, TTR and Transmissivity

From the hydraulic factors, we can also determine corrosivity, protective capacity, ground water potential and designation. Geological corrosivity is a geological impact that affects bedrock which is considered as a corrosive pollution can be inferred by aquifer resistivities. Table 8 below has shown various soil corrosivity as a function of resistivity (Ibanga and George 2016). Soil corrosivity makes it possible to identify potential water zones matching brackish and saline waters (Fig. 11). However, acid mine drainage is determined implicitly instead of monitoring of fauna - flora in mining (Liu et al, 2018).

Concerning the TTR values, there is an unequivocal relationship with the transmissivities (Braga et al., 2006). The TTR values varies from 5.38 to 41268.2 Ωm^2 according to the first campaign (1975) including 90 VES and therefore decrease from 2 to 23400 Ωm^2 for the second campaign (2004) using 80 VES survey. However, the TTR is proportional to transmissivity which is used to identifying groundwater content and suitable drilling areas.

Figure 11 shows the variation in the TTR can be classified as; less than 400 Ωm^2 to be poor with negligible transmissivity, then TTR between 400 to 1000 Ωm^2 is set to be weak groundwater potentialities, while 1000 to 2000 Ωm^2 is set to be moderate groundwater potentialities with moderate transmissivity and above 2000 Ωm^2 is very good groundwater potentialities with transmissivities.

From the map generated for the TTR it can be observed that more than 70 % of the aquifer investigated has poor to weak transmissivity related to their TTR value. The central part has good transmissivity depend on highest values of TTR whereas the northeastern part has moderate transmissivity near stream.

Hence, the depression around the basement is noticed in many zones delineated by local hydrogeological unities limit suggesting that the sediments are thicker. Conversely, the shallow aquifer is occupied by upper basement influenced by infiltration - runoff interaction in central socle where it will serve as groundwater potentialities.

4.1. Hydrogeological validation by Transmissivity and hydraulic conductivity

To achieve the validation process by hydrogeology concern, a cross-validation with the hydraulic parameter (k: hydraulic conductivity) and the apparent resistivity to reconstruct the parameter (Tr: Transmissivity) based on the multiplication of the parameter (k) with the parameter (H: thickness of the geological formation crossed). After correlation study, the calculation formulas are listed as follows (Eq.11 and Eq. 12):

$$Transmissivity = Tr = k * H \tag{11}$$

$$k = 8 * 10^{-6} * e^{-0.0013 * \text{Re}\,sistivity} \tag{12}$$

Where: Transmissivity: Tr in (m^2/d) and k: hydraulic conductivity in (m/j); Resistivity in (Ωm)

The substratum nature is influenced by (K) and (ρ). If the baseflow unit and current flow are mostly lateral, aquifer reveals that a linear fitting is indirect. Aquifers in semi-arid regions like Ouled Taoui - Boujema aquifer have a deep unsaturated zone, indicating a lack of potential recharge and the correlation from the second campaign (2004) is reach to 63.4% and it is considered more significant between transmissivity and longitudinal conductance (L). The regression equation established is proper to the sedimentary aquifer indicating the following relationship (Eq. 13).

$$Transmissivity = 6.6035 * L \tag{13}$$

The linear regression test on old electrical soundings from the first campaign - 1975 shows that for a spacing of AB/2=100 m we find a fairly good correlation in the vadose area of the Ouled Taoui – Boujema aquifer. This is due to the heterogeneity of the formations and the existence of faulting and drainage systems developed with a hard weathered, fissured and fractured basement at depth as well as the average density of geoelectric soundings covering only 65% of the aquifer (Fig. 12). In hard rocks, this relationship holds as long as the aquifer is weathered and fissured.

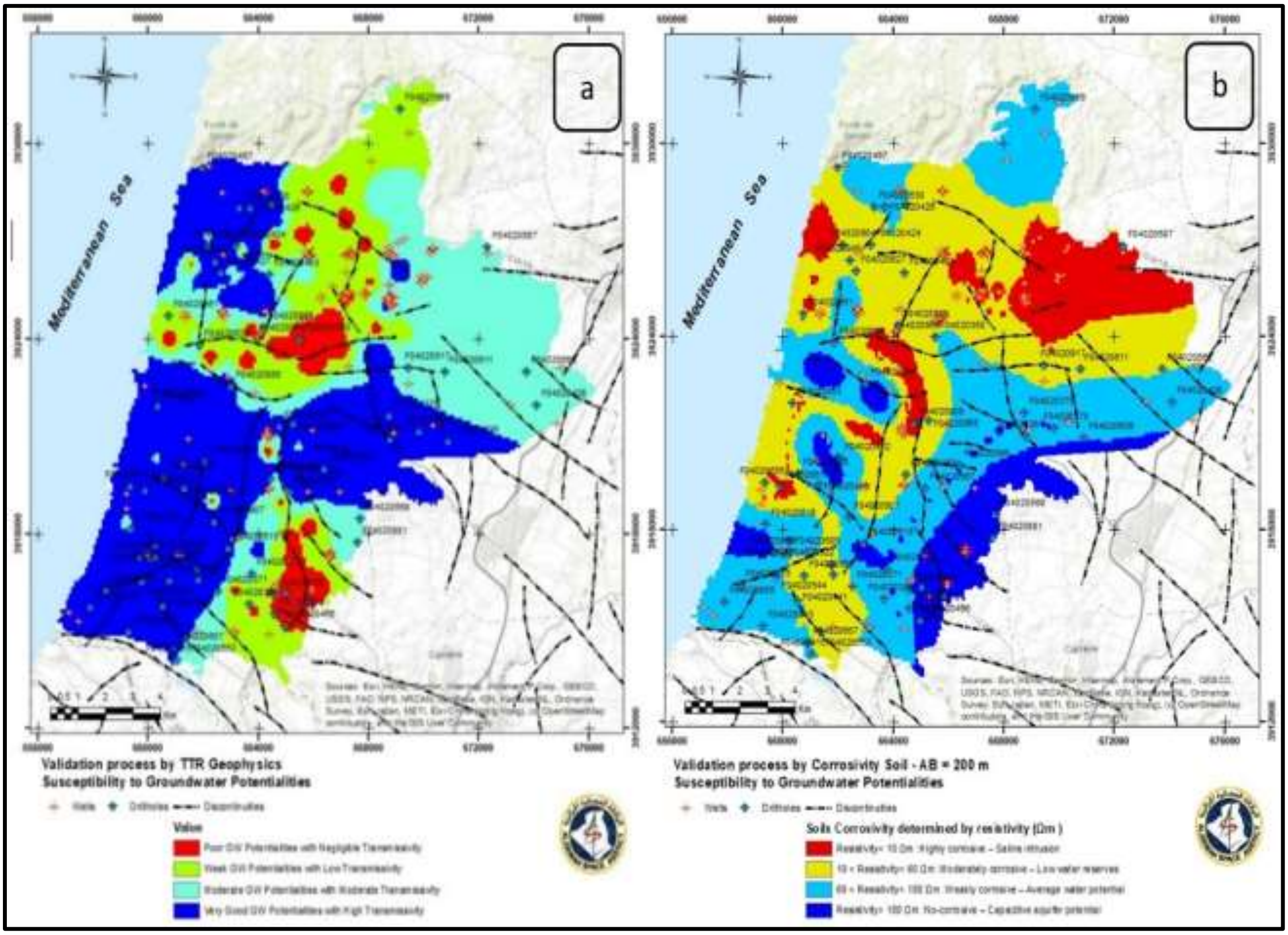

Fig. 111 Validation of groundwater prospect by using geophysical parameter: TTR and soil corrosivity

4.2 Water chemistry for the validation process

To validate our results, we carried out an analysis of the water chemistry quality in terms of nitrate. Several authors (hamza et al. 2007; Sbargoud 2013; Schnebelen et al. 2002) have verified the validity of risk models based on ground water chemical data. Water chemistry analysis carried out in both seasons June and December (2010) by the ANRH agency showed levels varying from 7 to 150 mg/l of nitrates concentration.

Very high values exceeding the potability standards ($NO_3 > 50$ mg/l) are classified with a high to very high vulnerability to groundwater pollution, while low values illustrate areas with a low to medium risk. Although AHP–WLA-GOD-L model has higher correlation differentiated to standardized GOD in Ouled Taoui - Boujema aquifer, the modified GOD–AHP model can be applied in areas with extensive nitrates concentrations (NO_3) in order to modify the rates and could be assess for groundwater quality remediation (Fig. 13a, 13b). Nitrate high-concentration is mapped for most areas which agriculture practices is abundant. Furthermore, this north-east zone is occupied through fluviatile hydrology within permeable material.

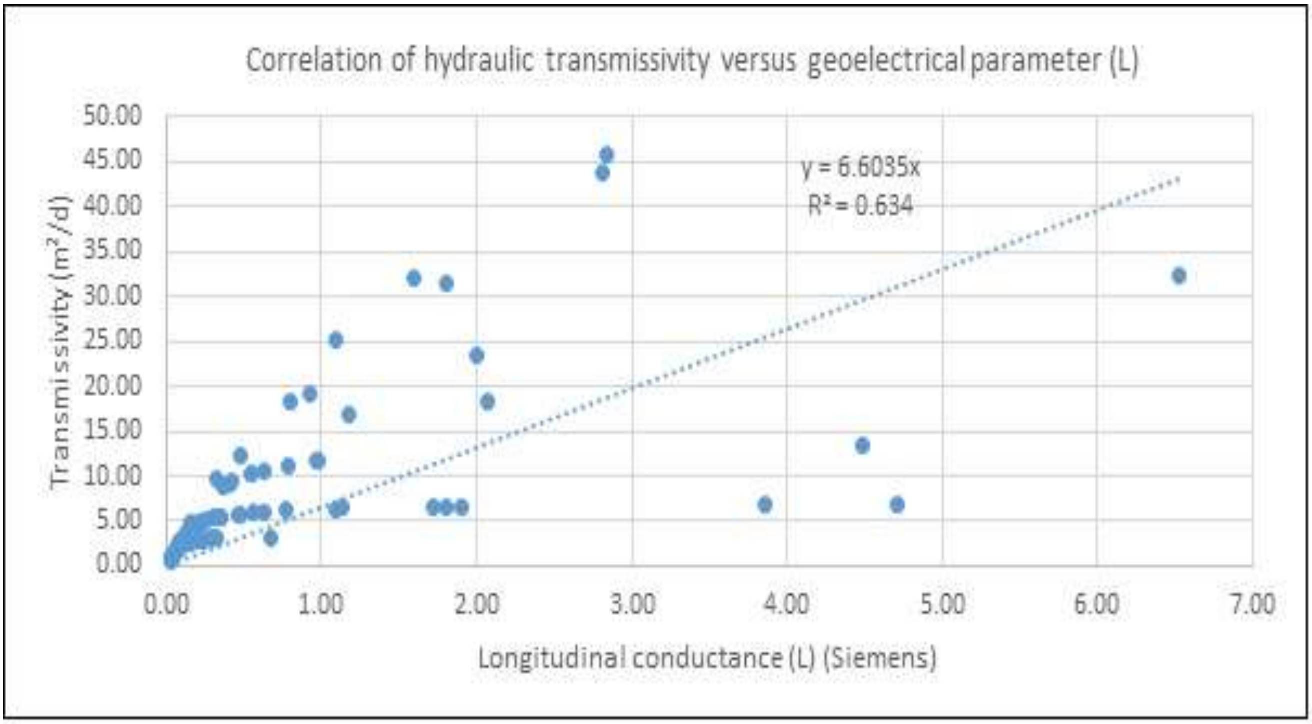

Fig. 12 Validation of hydrogeological factor according linear fitting between Transmissivity and conductance (L)

Globally, in most parts of aquifer, nitrate contents progressively decrease upstream, while still remaining relatively high at the El Maleh stream valley (40 mg/l). In the rest of the Targa plain, nitrate concentrations are close to 20 to 30 mg/l. Hence, soil fertilization practices and clay covering soil allow protection of groundwater against contamination. Further upstream, nitrate levels are below 20 mg/l.

Comparison of nitrate values concentrations distribution map and that vulnerability levels obtained by GIS-based approach, shows the following: The most samples with contents exceeding 45 mg/l correspond to the very high vulnerability zone; The concentrations values of nitrate are ranging between 10 and 40 mg/l, equally spread among the vulnerability zones (average, moderate and high); nitrate pollutant is closely diffuse in agricultural areas and evolves in an extensive and progressive manner on the northwestern part of the Ouled Taoui aquifer.

5. Conclusions

The contribution of this paper was to develop new integration and optimized hydro geophysical models called AHP-GOD-L, AHP-GOD-L-T and AHP-GOD-L-Th using matrix optimized by WLA technique that validate the causative factor (AVCF's) in the sedimentary coastal aquifer to pollution. The proposed models can serve as potentiality models which highlights an impact in contaminated groundwater. Therefore, constructed adaptative hydro geophysics model in GIS platform were validated essentially by the hydro chemical water quality for better focus in water resources monitoring with protection programs under soil corrosivity concept used in mining domaining.

Geophysical integration in GIS based AHP have apprehended some identification problems of factor that can reflect more reliability in hydrogeology mapping as transversal vision ameliorating the indexation scoring system of vulnerability model as GOD modified model because geoelectrical survey is rapid and can cover expansive and large areas in limited time and can penetrate a greater depth for estimating reserves exploration and mapping, monitoring and groundwater pollution protection.

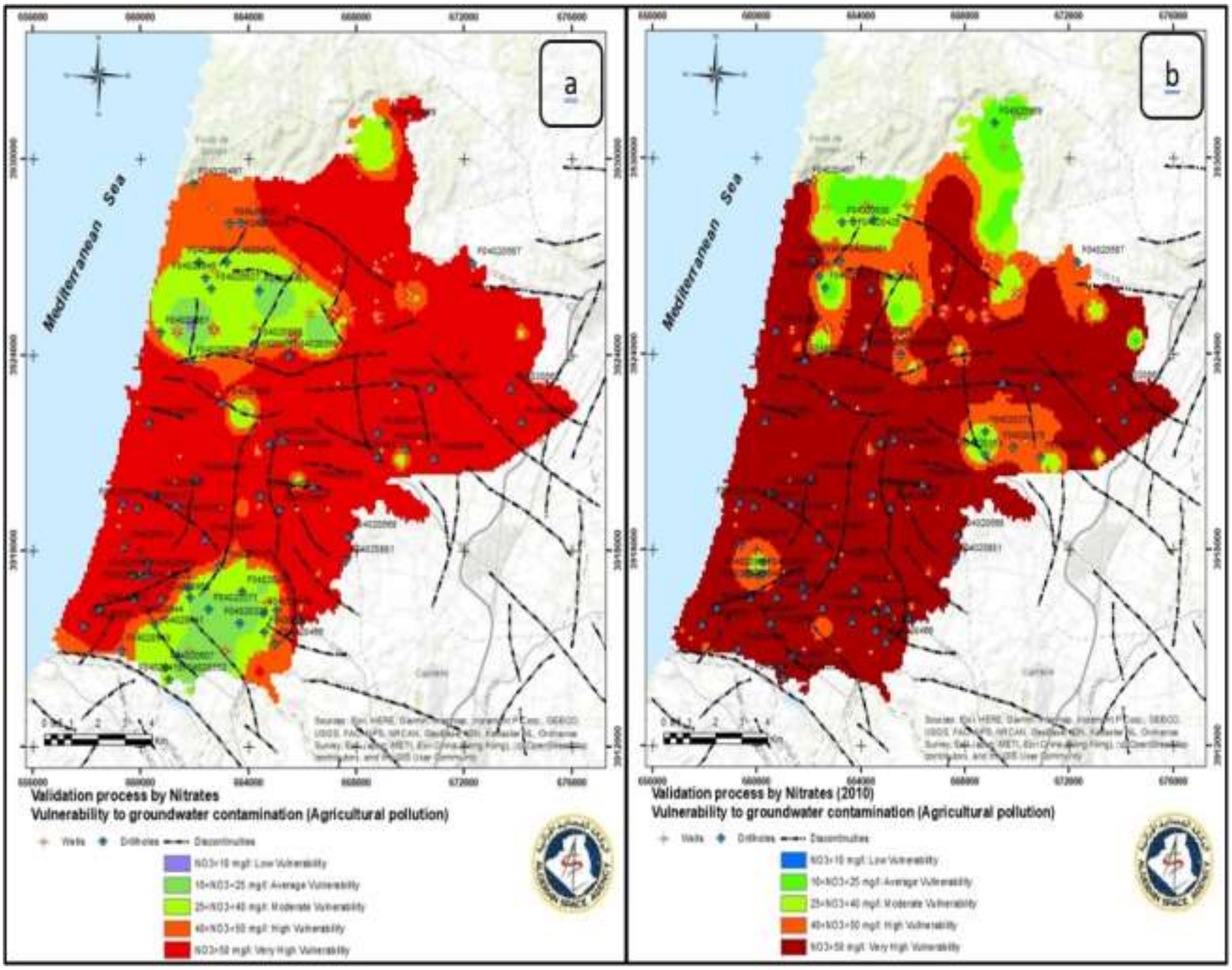

Fig. 13 Validation of vulnerability to groundwater contamination using hydro chemical parameter - Nitrate a: Old campaign (1975), b: second campaign (2010)

The integrated geo-electrical and hydro-geological factors were considered as new methodology based on AHP-WLA-GOD-L will improve a readily ground water potentiality. Regardless on the AHP-GIS integration, the conductance in GOD-L model may provide water preservation, conservation and protection of hydro system as the risk assessment.

The combined use of all approaches associated to GOD, GOD-L, AHP-WLA GOD-L and validated by AHP-WLA-GOD-L-T, aquifer capacity protective related to freshwater / seawater identification (L), electrical anisotropy influenced by hardness and compaction of rocks, TTR for groundwater prospect delineation and water chemistry analysis of the nitrate allows better mechanism within representativeness of vulnerability and susceptibility to contamination. This leads by distinction, depending in case between classification, ranging from low to very high susceptibility degree.

The difference in classes number is linked to the fact that class boundaries and dimensions that are assigned to different parameters are not absolute, but instead relative weight. This implies that standard classes limits may not reflect reality on the ground where hierarchical classes can encompass different hydrogeological units. Moreover, different works in literature showed that the limits may vary from one method to another, from one study to another. By the way, the GOD model underestimates the recharge parameter and aquifer permeability which are ignored by GOD method whereas the geoelectrical parameters facilitate the determination of the hydrogeologic factors such as hydraulic conductivity and transmissivity and perform most vulnerability intrinsic models.

Despite the deficiencies noticed in development of contamination-vulnerability-susceptibility maps using these intrinsic methods, reliability of results is slightly distorted. Obtained results help to acquire a good idea regarding the most sensitive aquifer, and to subsequently prescribe necessary protection measures. Vulnerability maps validation would have been more representative if the number of nitrate measurements was greater and well distributed over the whole plain. Finally, analysis of other contaminants (metallic, organic, industrial) would have provided extra values for validation process. The basic conditions for using nitrate as a calibration parameter should be satisfied.

In the case of Ouled Taoui –Boujema aquifer, Modified AHP-GOD-geophysical factors method proves to be the one that best reflects reality on the laterally groundwater contamination. However, it takes into account three parameters (L, resistivity and thickness) including reliability that depends on data used for their weighting and rating integration in GIS environment. Many of them as aquifer nature depth to groundwater associated to the recharge, hydraulic conductivity and unsaturated zone influence related to the lithological materials are produced via scaling-up of GIS-based multicriteria analysis AHP.

This would consequently generate vulnerability and susceptibility maps during integration of geoelectrical and hydrogeological parameters assessment process based on AHP-WLA GOD-L. After validation using AHP-WLA-GOD-L-T, TTR, vadose zone capacity (L), inter-electrodes spacing (AB/2), anisotropy coefficient (uncertainty) and nitrate contents observed in groundwater, we have noticed that GOD method provides results largely different from that generated by the hierarchical multicriteria, and can define three vulnerability classes: low, average and high, with a matching rate of 64%.

GOD and L methods raise four vulnerability classes and provide relatively similar results, particularly for high, average and low-vulnerability areas. By contrast, they differ in very high vulnerability class (5.1% for GOD against 15.4% with GOD-L). Finally, with a matching rate of 71%, AHP WLA GOD-L approach seems to better reflect reality on the ground where average vulnerability class (58%) predominates.

Globally, the authors concluded that the AHP-WLA GOD-L-T method could be adequate by overlaying slope depression within AHP-WLA GOD-L for vulnerability mapping in the aquifer. It substantiates that the tendency results of this approaches have a better transversality previously researched by many authors in the littoral aquifers in northern west of Algeria.

The aforementioned literature review, few scientific research has investigated AHP–WLA-AVCF's from modified AHP – GOD, which are relatively pioneering methods in groundwater vulnerability and assessment. The original vulnerability map can be modified and feasibility assessed with several methods, such as AHP-Wilcoxon integrated in optimization technique invoking both rating and weighting of the standardized GOD model, the overlay weighting, the Multiple pair-wise comparisons in neural network.

Essentially, this paper aims to employ the validation process based on geophysics such as L, TTR, coefficient of anisotropy, water corrosivity, and hydro-chemical analysis of nitrates to the expert opinions, which are highly useful for the mapping the vulnerability and susceptibility in multi-layer aquifer.

Thereafter, the expert judgment was applied into a square matrix to derive the optimized ratings and weights of GOD-L by using a pairwise-comparison matrix WLA and AVCF's for each level of AHP-GOD-L suited by AHP-GOD-L-T and AHP-GOD-L-Th to empower the decision maker to estimate the contribution of each factor independently. Thereafter, the GOD model as geospatial tool is not appropriate to different coastal aquifers and climate conditions.

Meanwhile, the center part of the sedimentary coastal aquifer Ouled Taoui–Boujema is generally invulnerable. However, this methodological scheme minimizes error in identifying both vulnerable and susceptible prone to improve the decision making regarding the coastal aquifer and also providing an important opportunity to proactively protect the sustainability of the coastal aquifers from contamination.

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