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A Comparative Assessment of Vulnerability of the Oban Massif Aquifer System, SE-Nigeria, Using DRASTIC, GOD and AVI Models

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Abstract- The vulnerability of the aquifers of the crystalline basement Oban Massif to contamination was assessed using three different assessment models: DRASTIC, GOD and AVI. The results from computations of the models shows three vulnerability zones as indicated by DRASTIC, while GOD and AVI models identify two zones each. DRASTIC and AVI indicate a subjective coincidence of the defined vulnerability zones. The AVI model fits as a quick reconnaissance model satisfactory for vulnerability assessment within the study area, with less hydrological data requirement. Sensitivity analysis shows that the depth to groundwater is the major parameter that determines probable contamination.

Keywords- *Aquifer Vulnerability, DRASTIC, GOD, AVI, Oban Massif*

I. INTRODUCTION

Contamination of groundwater remains a clear and present danger to the sustainability of the resource and dependent habitats. This contamination leads to degradation of the quality and quantity of the resource and this has been reckoned to both natural and anthropogenic progenitors.

Aquifer vulnerability is the likelihood for surface or near-surface contaminants to reach the aquifer [1]. However vulnerability is not an absolute property; it is relative and dimensional [2].

Growing populations alongside expanding economic activities (industrial and agricultural) continually pose a stress point on aquifer systems in different geologic settings [3]. This has necessitated the recent interest in assessing the susceptibility of aquifers to pollution. These as evidenced in numerous literatures have been achieved by application of vulnerability assessment models: [4], [5], [6], [7], [8], [9] and [3] see table 1.These methods are parametric, inexpensive and simplistic in approach. However these assessment models are dependent on available or estimated information on aquifer systems, thus their indications are relative and subjective. A shortage or absence of adequate information on aquifer systems can make vulnerability assessment difficult.

This research attempts to compare the indications and coincidence of results as determined by three different vulnerability assessment models. This is expected to provide; (a) optimum choice of assessment model for particular geologic setting, (b) easily interpretable data that can be incorporated in decision making for groundwater management strategies.

TABLE I. EXAMPLES OF VULNERABILITY ASSESSMENT MODELS AND THEIR APPLICATIONS WORLDWIDE

Author	Aquifer type	Region (country)	Models used
Lobo-Ferriera & Oliviera (1997)	Sedimentary	Setubal (Portugal)	DRASTIC, SINTACS, GOD, AVI, SI
Rodney (2006)	Sedimentary	Carrol, Chariton (USA)	DRASTIC, Pesticide DRASTIC
Edet (2013)	Sedimentary	Calabar (Nigeria)	DRASTIC
Anane (2013)	Sedimentary	Cap-Bon (Tunisia)	DRASTIC, SI
Andreo et al., (2006)	Karst	Sierra de Libar (Spain)	PI, COP
Germain (2001)	Karst	Montana (Switzerland)	EPIK
van Beyena et al., (2012)	Karst	Central Florida (USA)	KAVI, SI
Jiménez et al., (2005)	Metasediments	Oaxaca (Mexico)	DRASTIC, AVI, GOD
Khadse & Kulkarni (2013)	Igneous (basalts)	Amravati (India)	DRASTIC
Ekwere & Edet, (2015)	Precambrian basement	Oban Massif (Nigeria)	DRASTIC

II. CHARACTERISTICS OF THE STUDY AREA

The study area is part of the Oban Massif located between longitudes 8° 00ˈ E - 8° 55ˈ E and latitudes 5° 00ˈ N - 5° 45ˈ N and covering an area of about 8,740 km^2 [17], figure 1. The massif is a rugged geologic terrain on the south-eastern fringe of Nigeria bordering the Cameroon volcanic mountain range. The massif exhibits an undulating topography straddled with isolated hills with heights up to 1,200 m above sea level at locations on the eastern arm of the geologic suite. V-shaped valleys are also common features and the hills are typically forested at the highest peaks [17].

The massif is well drained, controlled by weathered zones, fractured and jointed areas, coursing in two directions: southwards (seawards) and northwards to join the upper course of the Cross River in the Ikom depression [17]. The study area is characterised by tropical climate with two distinct seasons; wet (May-October) and dry (November - April). General temperature trend in the area is high with negligible diurnal and annual variations with monthly averages in the order of 27 - 34° C [18]. Annual precipitation regime in the area is about 2,300mm with annual mean daily relative humidity and evaporation of 86% and 3.85 mm/day respectively [17]. Regional run-off coefficient of the area is in the order of 0.21-0.61 and is due to topography and evaporation [19].

The massif is underlain by highly deformed Precambrian crystalline basement rocks; migmatites, granites, gneisses and schists, exhibiting varying degrees of weathering across the massif. These are intruded by pegmatites, granodiorites, diorites, tonolites, monzonites, charnokites and dolerites [20] and [21]. Weathered profiles, fractures and joints are prominent features within these rock suites and they control the movement and storage of groundwater as they are the main aquifers within the massif [17] and [18]. Development of weathered profiles is controlled by the variations in density and frequency of structural discontinuities across the massif and this ultimately affects the spatial configuration of the hydrogeological system [17]. Regional hydrogeological differentiation of the massif reveals a three layer hydro-stratigraphic model composed of; (a) a top unsaturated clayey sand (lateritic), (b) middle gravelly sand and decomposed bedrock and (c) fresh bedrock (fractured), [22] and [17].

Occurrence of groundwater in the area is under water table conditions in the weathered and fractured zones and static water level ranges from 0.00-10.50 m across the massif [17]. Groundwater yield variations also depend on the extent of fracturing and jointing [17]. Rates and levels of recharge to porous aquiferous media in the area suffer impedance due to the top lateritic cover characteristic of the area [19] and this is attributed to the high clay contents of the top soils.

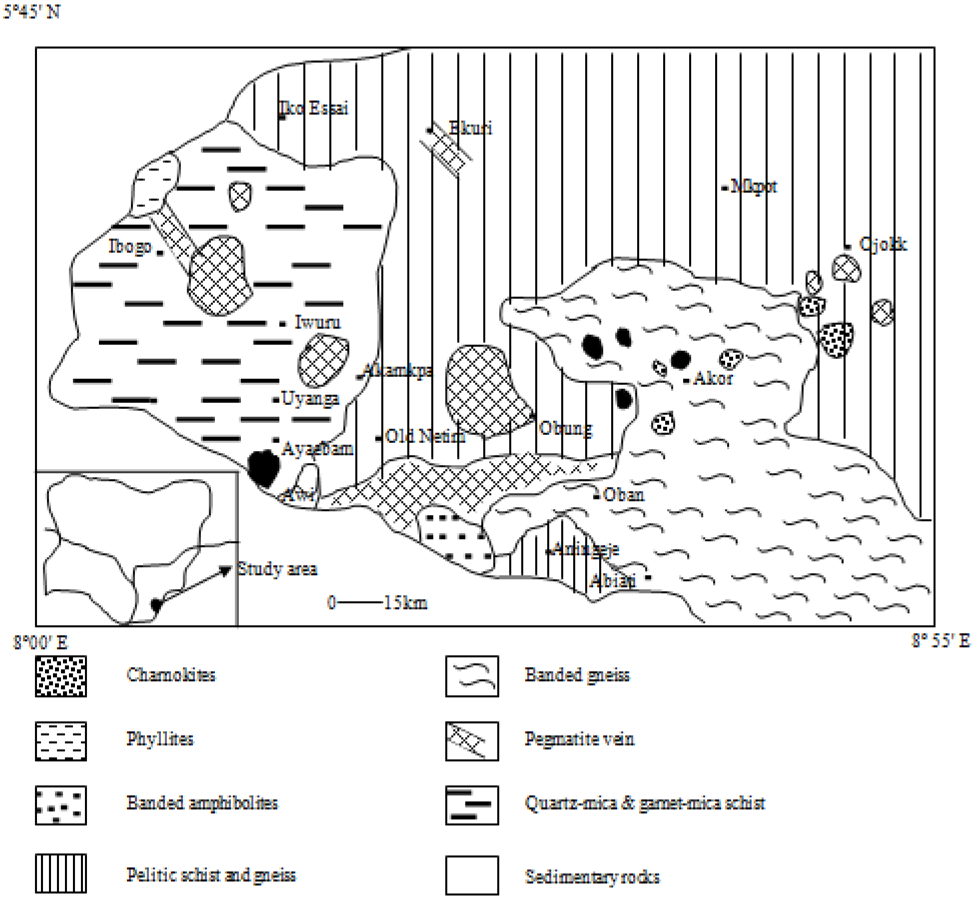

Figure 1. Geologic map of the study area (Oban massif): insert map of Nigeria (modified from [23]).

Possible sources of contamination within the study area include quarrying activities and associated processes, use of fertilizers, pesticides, industrial effluent discharges and indiscriminate disposal of other biodegradable and non-biodegradable wastes.

III. METHODOLOGY

The use of vulnerability models to assess susceptibility of aquifers to contamination goes beyond numerical score evaluation but also involves the delineation of areas with varying extents of vulnerability. These are best expressed in geo-spatial arrays as vulnerability maps and properly index for clarity. GIS provides a suitable tool for producing such easily readable and interpretable vulnerability maps. Assessment of a given aquifer system with different methods can give different indications. This research involves the use of both index and superposition methods; DRASTIC, GOD and AVI, as well as assessing the vulnerability suites as established by each of these methods. GOD and AVI methods only consider physical properties of the aquifer media, while DRASTIC includes chemical properties of attenuation [24].

IV. DRASTIC METHOD

The DRASTIC method involves seven environmental parameters; depth to groundwater table (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of vadose zone (I) and hydraulic conductivity (C) giving the acronym DRASTIC. Each of this parameter is assigned a weighting factor based on increasing level of significance between ranges of 1-5. The parameters are also sub-divided into ranges and assigned ratings on a scale of 1-10 (1 indicating the least contamination potential and 10 the highest). This rating indicates the significance of each unit on the quantification of vulnerability [8].

Based on weights and ratings of the DRASTIC parameters, the DRASTIC vulnerability index (DVI) is calculated using equation 1 below [24]:

$$DVI=D_wD_r+R_wR_r+A_wA_r+S_wS_r+T_wT_r+I_wI_r+C_wC_r \quad (1)$$

Where D_w, R_w, A_w, S_w, T_w, I_w and C_w are respectively the weights of depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity while D_r, R_r, A_r, S_r, T_r, I_r and C_r are their corresponding ratings.

The rating ranges component divides each DRASTIC parameter into several classes [25]. These ratings depend on local geological and hydrogeological settings, hence are subject to vary from one study area to another [8]. Based on the derived index scores a classification or categorization can be obtained and used to develop the vulnerability map. The assignment of numerical value of DVI scores to determine the areas of groundwater susceptibility to contamination is subjective to the user and relative with no specified units [6]. However, higher DRASTIC index shows greater groundwater pollution vulnerability [26] and vice versa.

V. GOD METHOD

This method was developed for areas with lack of information about the subsurface and groundwater [27]. This method basically considers only three parameters; (1) Groundwater occurrence (inexistent = 0, existent = 1), (2) Overlying lithology (this index varies from 0.4 to 1) and (3) Depth to groundwater (ranging from 0 to 1).

VI. AVI METHOD

The acronym AVI stands for Aquifer Vulnerability Index and this model is best employed in small areas where other models are not advisable [15]. The method calculates the hydraulic resistance designated as C and this corresponds to an estimation of the travel time of a contaminant through the unsaturated zone [28]. The hydraulic resistance as expressed in time unit of years is calculated by equation 2 below:

$$C = \Sigma_{i=no.\ of\ layers}\ Di/ki \quad (2)$$

Where Di is the thickness of the unsaturated zone, and ki represents the hydraulic conductivity. Values of the hydraulic conductivity are presented as Log C. The higher the value of the hydraulic resistance, the lower is the vulnerability of the aquifer.

The methods employed for vulnerability assessment assumes the aquifer system to be of three horizons: soil, vadose zone and the aquifer itself. This is regarded as a simplified aquifer system [15].

Table 2 shows the weights, ratings and ranges of hydrogeological parameters used in each of the methods.

TABLE II. WEIGHT AND RATINGS AS ASSIGNED TO THE DIFFERENT HYDROGEOLOGICAL PARAMETERS

Factor	Parameter range	Weight (w)	Rating range (r)
Depth to water (m)	0.48-10.50m	5	5-10
Net recharge (mm)	206.5-1,409.8mm/year	4	3-9
Aquifer media	Metamorphic & igneous rocks, sand/gravel	3	7-9
Soil media	Sandy-loam, sandy-clayey-loam	2	3-9
Topography (m)	<90 to ±141m	1	1
Impact of vadose zone	Gravel, sand, silt, clay	5	8-10
Hydraulic conductivity (m/d)	8.53-18.04m/day	3	2-10

VII. RESULTS AND DISCUSSION

Definitions for vulnerability levels are usually subjective and varied. The contamination potential for DRASTIC is a dimensionless entity and the scores for this as computed for the study area ranged between 163 and 186 [3]. Higher score indicates higher vulnerability potential. A subjective vulnerability index classification of three groups was established for this study. These were divided into low (< 170), moderate (170 – 180) and high (> 180) vulnerable aquifer areas. Plot of the DRASTIC vulnerability index map is presented figure 2.

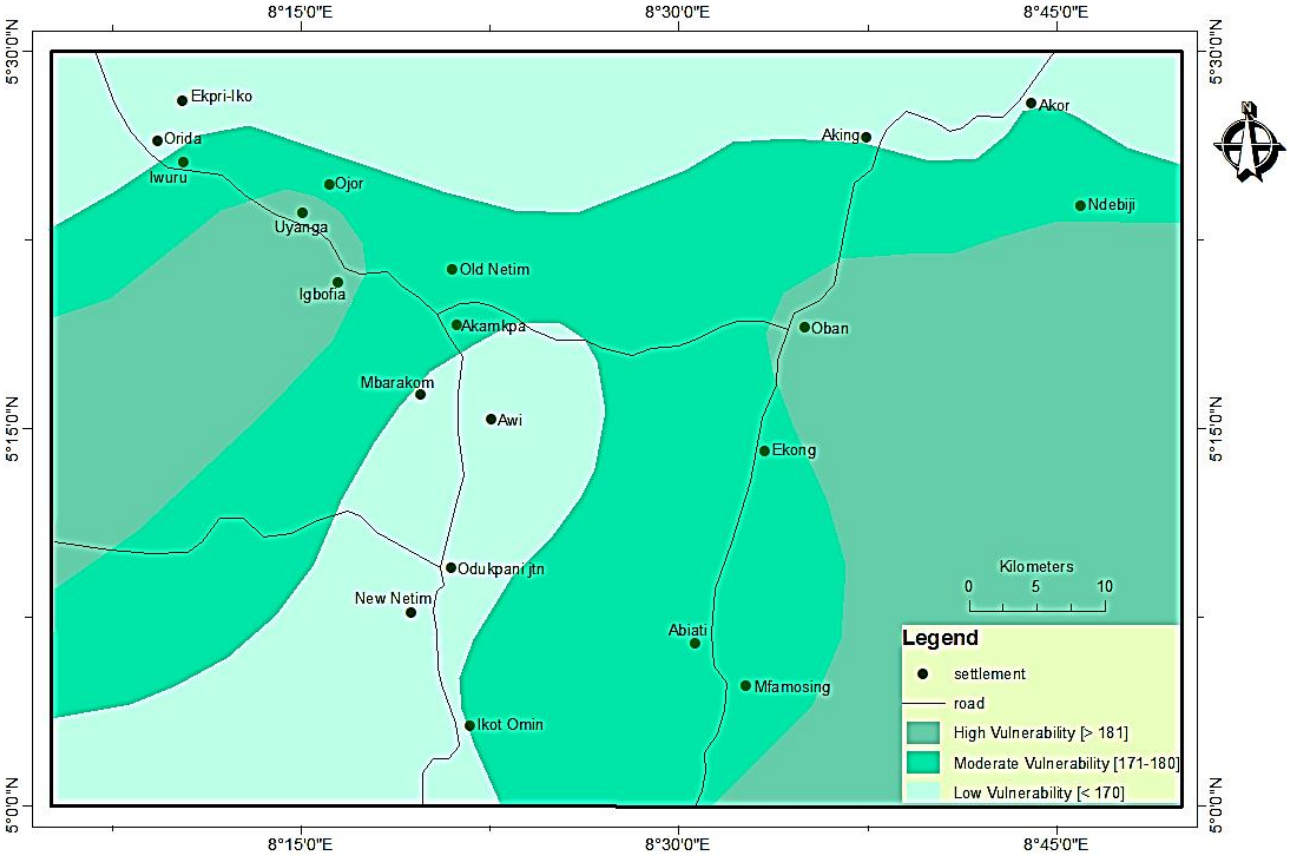

Figure 2. DRASTIC vulnerability map of the Oban Massif

The computation and plot from DRASTIC shows that the Oban aquifer system to be made up of three vulnerability zones; low, moderate and high. This subjective zonation corresponds approximately to 30%, 40% and 30% respectively of total aquifer area.

The GOD method defines two zones of vulnerability recognized as low and medium vulnerability (fig. 3), but of smaller dimensions compared to that demarcated by DRASTIC. The low and medium areas fall within the medium vulnerability area delimited by DRASTIC. The low vulnerability is defined by values of 0 – 0.3, medium 0.3 – 0.5 and high vulnerability for values higher than 0.5.

The AVI method demarcates three zones: high vulnerability areas with C values of 0 to -0.35, medium vulnerability areas with values of -0.35 to –0.50 and low with values less than -0.50. C values are the log of the hydraulic resistance (R).

It is obvious that the differences in results and demarcations of varying vulnerability zones by the three methods is due to the number of hydrogeological parameters employed in estimating the vulnerability.

The DRASTIC method may be considered to be more appropriate and reliable as it does employ more hydrogeological parameters compared to the other two methods. However for quick reconnaissance survey the GOD and AVI methods may be utilised as preliminary tools prior to a more detailed approach.

As a further approach to vulnerability assessment, a sensitivity analysis was conducted. This provides a means of assessing which of the environmental parameters is most susceptible to aquifer contamination and this is based on results from the DRASTIC method. The sensitivity analysis provides valuable information on the influence of weights and ratings assigned to each parameter and guides in decision making for assessment of significance of subjectivity [29].

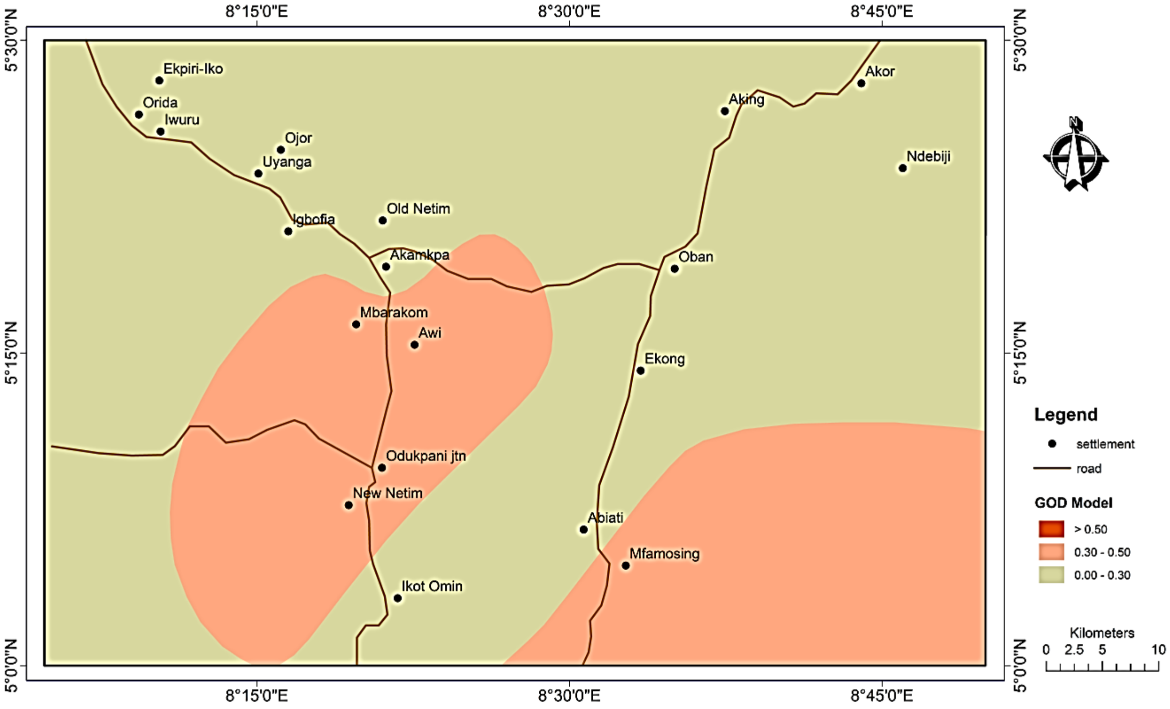

Figure 3. GOD vulnerability map of the Oban Massif

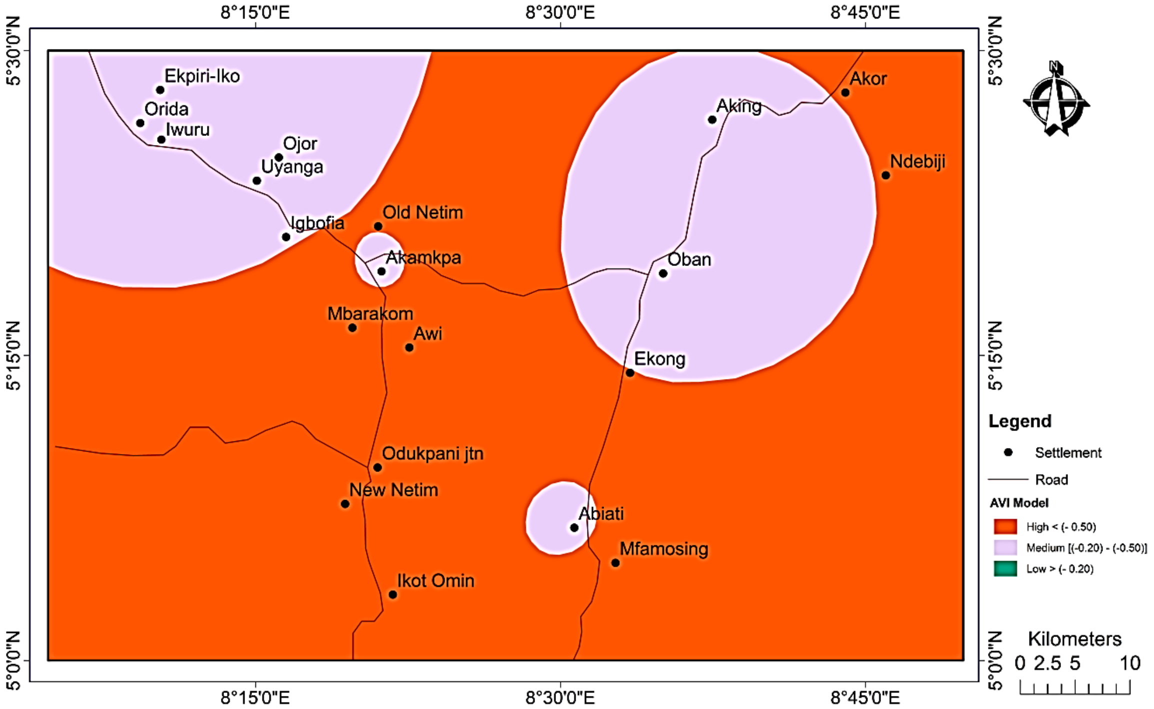

Figure 4. AVI vulnerability map of the Oban Massif

The sensitivity analysis involves the computation of vulnerability index values using six parameters instead of seven i.e. removing one of the parameters for each of the sub-areas [3]. Sensitivity (*Si*) and the variation index (Var_i) were calculated from the following expressions [30] and [29]:

$$Si = \left| V_i / N - V_{ix} / n \right| \tag{3}$$

$$\mathrm{Var}_i = (V_i - V_{ix} / V_i) \times 100 \tag{4}$$

where; V_i is the vulnerability index for the *i*th cell or sub-area, V_{ix} vulnerability index of the *i*th cell excluding the X_i parameter, *N* the total number of parameters used in obtaining the vulnerability for each cell and *n* the number of parameters used in the sensitivity analysis.

Results and assessment of sensitivity analysis [3], indicates highest sensitivity to contamination to be related with depth to the water level (D) as the aquifers are relatively shallow. Next of importance are impact of vadose zone (I), net recharge (R), aquifer media (A), soil media (S), hydraulic conductivity (C) and topography (T).

Also the variation indices were calculated and this indicated similar parameters behaviour as *Si* [3]. The highest value is associated with depth to water level (*D*), showing the major spatial variability corresponding to 27.5%. The order of variation decreases with *I* (26.3%), *R* (20.7%), *A* (14.8%), *S* (6.9%), *C* (3.5%) and *T* (0.6%), [3].

VIII. CONCLUSION

Three models; DRASTIC, GOD and AVI were used to assess the vulnerability of aquifers to contamination in the Oban Massif. The performances of these methods are dependent primarily on the number of geo-hydrological parameters employed. DRASTIC model indicates three vulnerability zones, GOD two vulnerability zones, while AVI reveals two zones of groundwater vulnerability. The DRASTIC method best describes the vulnerability of the study area as adjudged from the number of environmental factors employed. The DRASTIC and AVI models show closer coincidence of vulnerability within the study area. From indications, the AVI can be used as a quick vulnerability assessment model in areas of limited data on environmental parameters as may be required by other methods.

Sensitivity analysis indicates that depth to water is the most sensitive parameter of groundwater contamination.

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