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# Seasonal Assessment of Aquifer Vulnerability to Pollution in Garoua-Cameroon using the D.R.A.S.T.I.C Model

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**Abstract** Aquifers are the main sources of water in Garoua and due to a lack of knowledge of their vulnerability to contaminants for the management and protection of these aquifers, this study to assess their vulnerability to pollution within four hydrogeological seasons using the DRASTIC (Depth-to-water, net-Recharge, Aquifer-media, Soil-media, Topography, Impact-of-vadose-zones and hydraulic-Conductivity) model was a necessity. Depth to water (D) of 196 wells ranged from 0.2 to 11.87 m are assigned ratings of 5, 7, 9 and 10. Net Recharge (R) ranged between 0-35.4 mm/yr. with assigned rating of 1. Aquifer media (A) are alluvium, sandstone, granites, and gneiss with ratings of 10, 8, 10 and 7. Soil media (S) from 50 infiltrometer tests are sands, silty clay, clays and loam soils with assigned ratings of 1, 5, 7 and 10. Topographic (T) slopes from DEMs varied from 0% to 18% were classed into 7 ranges and assigned ratings of 1, 3, 5, 7, 8, 9 and 10. Impact of the vadose zone of sand, clay and gravel were assigned ratings of 3, 9 and 10. Hydraulic conductivity (C) from slug tests on 50 wells ranged from 0.12 to 0.7 m/day and was assigned rating of 1. The derivative DRASTIC scores of aquifer vulnerability to contaminants in Garoua were: 150 in the wet season, 146 in wet-dry season, 158 in dry season and 157 in dry-wet season. DRASTIC indices classified the area into a high vulnerability class in all seasons. These higher vulnerabilities to pollution could be due to porous sandstone formations, the presence of fractured gneisses and fractured granites. From single parameter sensitivity analysis, depth to water, aquifer media, topography and impact of the vadose zone layer tend to be the most effective parameters in the vulnerability assessment because their mean effective weights are higher than their theoretical weights. Highest vulnerabilities to pollution occur during the dry seasons; this is of particular importance since during these periods water is scarce thereby, decreasing the pollution opportunity as there is no transport medium into the aquiferous formations.

***Keywords:*** *Aquifer-vulnerability, Drastic-model, Groundwater-Pollution, Garoua-Cameroon*

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## 1. Introduction

Aquifer vulnerability is the ease with which contaminants reach the saturated portion of a formation. Aquifers act as a reliable solution to water supply problems in urban areas such as Garoua. These aquifers are exposed to many sources of geogenic and anthropogenic pollution; as such there is an obvious need for sustainable management and protection of these aquifers. For the protection of aquifers from pollution, various techniques have been developed for predicting areas prone to contamination by surface activities; cattle dumps, fertilizers, pesticides, and the leaching of mine tailings. Aquifer vulnerability is greatly influenced by the geologic setting of an area that controls the infiltration rate and residence time of groundwater flow through the region.

Groundwater within an aquifer has some vulnerability to pollution from anthropogenic activities [1]. Aquifer vulnerability to pollution was developed based on the fact that the physical environment may serve some level of protection to groundwater against human activities, mostly concerning pollutants entering from the surface. Many methods are widely used to assess vulnerability of aquifers to pollution. There exist three broad types which include; statistical methods, process-based methods, and overlay/index methods. The process-based method makes use of simulation models to predict contaminant transport; data required for this method are not often available and are estimated by indirect means. Statistical methods on the other hand use statistics to establish associations between spatial variables and actual occurrence of pollutants in groundwater; Statistical methods are usually region-specific and as such are not suitable for transfer from one region to another [2]. Furthermore, Overlay/index methods are a combination of attributes controlling the movement of pollutants from the unsaturated zone into the saturated zone and properties of the aquiferous formations. The Overlay/index methods often use aquifer vulnerability since the required data are available over vast areas, which make them suitable for regional-scale assessments [3]. The DRASTIC model is an example of overlay/index methods and is an excellent tool widely used for assessing the vulnerability of an aquifer to pollution [4]. DRASTIC encompasses a greater number of input data layers that reduces the impacts of errors of the individual parameters on the final result of vulnerability indices [5]. A major disadvantage of this model is the subjectivity in assigning numerical values to the descriptive entities and relative weights for the different parameters by some users [6]. When assigning numerical values with care and detailed knowledge of the geology of the area these errors could be reduced to a minimum.

A few works have been done on the chemical quality of groundwater in Garoua [7]. No works have been done on the contaminant flow paths of aquifers in Garoua till date. With a high population density, industrial activities, intensive agriculture, cattle ranching, presence of open latrines, and absence of sewage disposal facilities in Garoua, this work assessing the vulnerability to potential pollution of the aquiferous formations which will serve as a blueprint for the protection and management of these aquifers begs for attention.

### 1.1. Description of the Study Area

Garoua covers a total surface area of about 4,700 km$^2$ (Figure 1). Groundwater is the major source of water. It is characterized by a tropical climate having a dry season from October to April and a rainy season from May to September. The mean monthly temperatures vary from 26.1 °C in December-January to 32.7°C in April, with a mean annual value of 29°C. This area is characterized by mean annual precipitations of 1018m and the mean annual potential evapotranspiration is 1855mm.

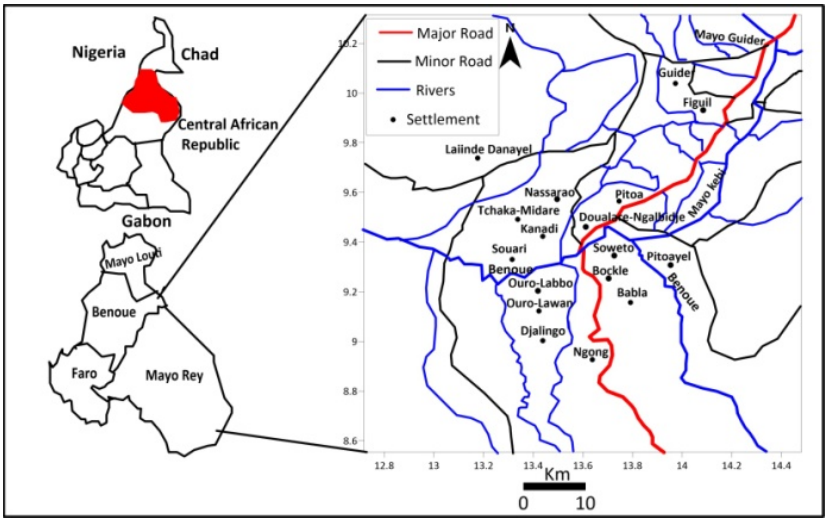


**Figure 1.** Garoua and environs (insert Cameroon and Northern Region with four Divisions)

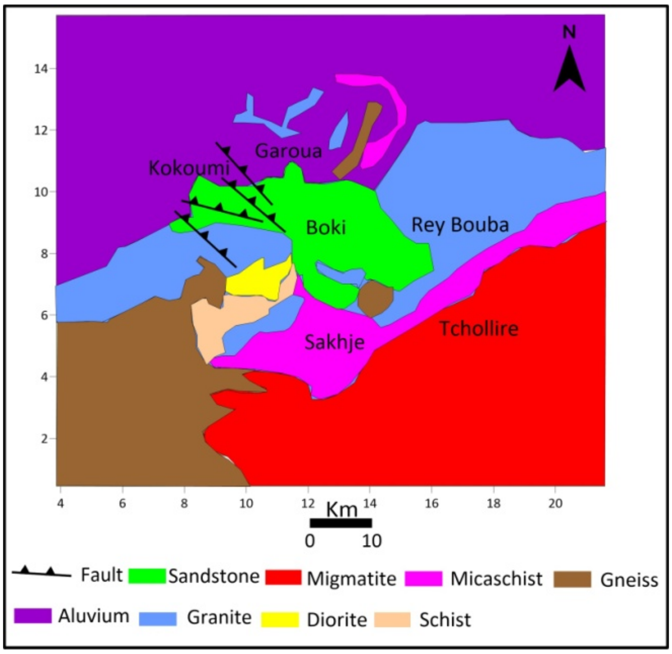


**Figure 2.** Geology of Garoua basin [14]

### 1.2. Geological settings of the Garoua Basin

The Northern region of Cameroon belongs to the mobile zone of Central Africa. This mobile zone is situated between the Western African craton and the Congo craton. The Benue trough is one of the most interesting sedimentary basins of West Africa because of the tectonic movements that account for the marine and continental sediments found there, and also because of the presence of volcanism and the intrusion of plutonic rocks. This trough is directed NE-SW and extends a distance of about 1000 km, with a width of 50–150 km [8]. The trough consist a great part of the sedimentary basin of North Cameroon, including the Garoua basin. Its origin is related to the opening of the South Atlantic during the Cretaceous, which led to the separation of the African and South American continents [9]. It is made of the sedimentary marine, continental series and is divided into three parts: the low, middle and high Benue. The high Benue includes the Gongola rift and the Yola-Garoua rift. The Yola-Garoua rift extends into Cameroonian territory and is directed E-W while the Gongola rift goes to Niger and is directed N-S. The Garoua basin is an intracratonic basin and part of the Benue Sedimentary Basin formed during the opening of the Gulf of Guinea. It is the eastward continuation of the Yola arm of the northern Benue Trough of Nigeria into the north Cameroon. The Benue trough is a NE-SW trending basin that spans from the Niger delta basin to Lake Chad. The trough strikes approximately NE–SW and is about 1000 km long and 100 km wide. This basin was formed over the Berremian-Aptian age and it is the biggest of a series of basins formed in northern Cameroon and south-western Chad at this time bounded to the north by the Mokolo Plateau and the south by the Adamawa Plateau. The structures are asymmetrical syn-sedimentary synclines superimposed on half-graben structures [10]. This basin-like many other sedimentary basins that belonged to the West and Central African Rift System is believed to have potential for hydrocarbons generation and accumulation.

The area of this study (Figure 1) is situated in the Cameroonian territory of the Benue rift (Yola Garoua branch) and especially in the formation known as Garoua sandstone. Its base is made up of two great lithological sets which underwent a metamorphic and tectonic evolution. The Garoua basin is an E-W to N120 trending trough that is filled by Middle to Upper Cretaceous marine sandstones [11]. The Basin is filled by continental sediments of Middle to Upper Cretaceous age. The bedrock is made up of igneous and metamorphic rocks of the basement complex, and volcanic rocks of the Tertiary age. This formation is characterized by sandstone sequences which are intercalated by clayey layers. X-Ray diffraction analyses carried out by [7] indicated that the sandstones are dominated mainly by quartz, feldspars, and kaolinite, but also include minor amounts of illite and calcite. The Garoua Sandstone formation is overlain by quaternary alluvial deposits of the Benue River and its tributaries, which are made up mainly of gravel, sand, silt and clay [12]. The dominant sedimentary facies in Garoua are indurated conglomeratic to coarse-grained alluvial sandstones with siliceous cement often rich in iron oxides and in some localities numerous intercalations of reddish ferruginous sandstones are seen. The depth of the basement is 4.4 km to 8.9 km. This represents the thickness of the sedimentary formation overlying the basement complex. Western parts of the basin exhibits numerous volcanic necks of the Cenozoic age while veins of basic rocks are outcrop to the east. The Garoua basin has outcrops of sandstone and intrusive granites, which form the basement complex below the sediments, and intrusive diorites along the Poli-Lere axis. Some hypo volcanic dykes are found within the Garoua sandstones (Figure 2). The basaltic lavas of this area are similar to those of the Cameroon volcanic line [13]. The Precambrian gneisses, migmatite, and schist outcrop in the southern part of Garoua Basin with an extension of the gneisses to the northeast. The intrusive granites outcrop extensively in the Garoua Basin in the northeast and southwest. These rock units from the basement complex below the sediments are referred to as the gneissic-granitic basement. Intrusive diorites also occur along the Poli-Lere axis [14].

The regional structural setting of the Garoua Basin is characterized by three major normal faults striking mainly in the NW-SE to NNE-SSW direction [15]. The continental crust underneath the basin (about 24 km) is thinner than the normal crust, but may be a little thicker to the east [11]. This thinning of the crust is due to extensional regional stress and the uplift of the Asthenosphere as a consequence and this result to isostatic compensation, leading to an average sedimentary pile thickness of about 6km [13,15].

### 1.3. Hydrogeology

The Garoua sub-basin has two aquifers; (1) The Garoua alluvial aquifer which is extensively utilized for water supply through hand-dug wells; it is of limited lateral extent. Aquifer tests results indicate that transmissivity in the upper part of the first aquifer varies between $10^{-1}$ and $10^{-5}$ $m^2 s^{-1}$ and the hydraulic conductivity ranges from $10^{-.4}$ to $10^{-5} ms^{-1}$ [7]. Groundwater mainly occurs under water-table conditions. (2) The Garoua Sandstone aquifer has a permeability of around 8 to 80 m/day; transmissivity of 300 to1700 $m^2$/day; and a storage coefficient of 0.025. Typically boreholes are between 40 and 200 m deep. According to [12], the Garoua Sandstone aquifer constitutes the most extensive aquifer in the Garoua basin and its thickness of increases towards the central part of the basin. The crystalline bedrock acts as the boundaries of the groundwater reservoir. The presence of many lenses of clay within the sandstone sequences imposes local confinement. The natural hydraulic gradients are low, owing to the low topography of the basin. The groundwater flow is generally towards the Benue River. Recharge is mainly through precipitation. The discharge of groundwater takes place by evapotranspiration wherever the water table is closer to the land surface, by the Benue River or/and its tributaries and by several wells tapping the aquifer.

## 2. Materials and Methods

### 2.1. Materials

The field materials and equipment used in the study are listed in Table 1.

**Table 1. Field Equipment, Specifications, and Functions**

| Equipment/Software | Specifications | Functions |
|---|---|---|
| **GPS** | Garmin GPSMAP 60CSx | For location and elevation |
| **PVC Slug** | 35 liter (40cm Dia) | For slug-in tests |
| **Stop Watch** | Taksun TS-1809 | To keep track of time |
| **Double Ring Infiltrometer** | Eijkelkamp m1-090 | Measure infiltration rate |
| **Water level indicator** | Solinst Model 102M | To indicate static water levels |
| **Measuring Tape** | Weighted measuring tape | Measurement of well diameter and depth |
| **ArcGIS** | Version 10.1 | GIS Drawing sampling / Tests location |
| **Global Mapper** | Version 11 | Geolocation of wells |
| **Surfer Golden Software** | Version 18 | GIS plotting contours for the spatial distribution |

## 2.2. Methods

**Table 2. Summary of the methodology used to determine DRASTIC parameters**

| Parameters | Summary of process | Units |
|---|---|---|
| **Depth to water** | Depth to water (D) is the depth of material from the ground surface to the water table through which pollutants travels before reaching the aquifer [17, 2]. Depth to water was determined by subtracting the static water level from the surface elevation of test sites. | Depth in Meters |
| **Net Recharge** | Net recharge was calculated by using the Chloride mass-balance method, Water Table Fluctuation Method, and Chaturvedi Formula | Millimeters per year |
| **Aquifer media** | Aquifer material was obtained through, field mapping, borehole logs, and the geologic map of Garoua. | Lithology |
| **Soil media** | Soil media was determined from double-ring infiltrometer tests ASTM D3385-03 standard test method and using Hillel [18] classification. | Infiltration rates(mm/min) |
| **Topography** | Topography was determined from field Surface elevation data using ArcGIS to plot the slope values on 90 m resolution Digital Elevation Map (DEM) of Garoua. | Slope (%) |
| **Impact of vadose zone** | Impact of the vadose zone which is the detailed lithological characteristics and rock units of the unsaturated zone were obtained from the lithological sections of some typical representative productive wells. | Lithology |
| **Hydraulic Conductivity** | Hydraulic Conductivity was determined from slug-in tests [19]. | Meters/day |

The DRASTIC model gives numerical indices that are derived from ratings and weights assigned to the seven model parameters. The ratings of the seven parameters range from 1 (least pollution potential) to 10 (highest pollution potential) depending on its value. Each parameter is assigned a weight ranging from 1 to 5, based on their importance and influence in affecting contaminant transmission viz pollution potential (Table 3) [6]. The DRASTIC vulnerability Indices were computed by using a linear summation of all factors according to the following equation (1):

$$DRASTIC\ Index\ (DI) = D_r Dw + R_r Rw + A_r Aw + S_r Sw + T_r Tw + I_r Iw + C_r Cw \quad \ldots(1)$$

Where D, R, A, S, T, I, and C are the seven parameters and the subscripts r and w are the corresponding rating and weights, respectively [6] as in Table 3. The DRASTIC index is divided into four categories: low, moderate, high, and very high. Each category reflects an aquifer's inherent capacity to be polluted. Higher DRASTIC index value shows a greater relative pollution potential risk [16].

The DRASTIC model was used to assess the pollution potential of the Garoua aquifer which was deemed to be appropriate due to; ease of acquisition of data, climatic conditions, aquifer distribution, aquifer settings and the existence of conditions that permitted direct measurement of field parameters required for the model as in Table 2.

**Table 3. DRASTIC Parameters [17]**

| Parameter | Range | Rating | Weight |
|---|---|---|---|
| **Depth to water (D)** | 0 - 1.5 | 10 | 5 |
| | 1.5 - 4.75 | 9 | |
| | 4.75 - 9.14 | 7 | |
| | 9.14 - 15.24 | 5 | |
| **Net Recharge R** | <35 | 1 | 4 |
| | 35-55 | 1 | |
| **Aquifer media (A)** | Alluvium | 10 | 3 |
| | Sandstone | 8 | |
| | Granite | 10 | |
| | Gneiss | 7 | |
| **Soil media (S)** | Clay | 5 | |
| | Silty clay | 7 | 2 |
| | Loam | 1 | |
| | Sand | 10 | |
| **Topography (T)** | <1 | 10 | 1 |
| | 1–2 | 9 | |
| | 2–4 | 8 | |
| | 4–6 | 7 | |
| | 6–12 | 5 | |
| | 12–18 | 3 | |
| | >18 | 1 | |
| **Impact of the vadose zone (I)** | Gravel | 10 | 5 |
| | Sand | 9 | |
| | Clay | 3 | |
| **Hydraulic conductivity (C)** | 0-3 | 1 | 3 |

## 2.3. Sensitivity Analysis

According to [20] the DRASTIC model is the implementation of assessment using a high number of input data layers which is believed to limit the impacts of errors and uncertainties of the individual parameters on the final output. Early researchers such as [21] have argued that a DRASTIC-equivalent result can be obtained using a lower number of input parameters and achieve a better accuracy at lesser cost. However, the unavoidable subjectivity linked with the selection of the seven parameters, the ratings, and the weights used to compute the vulnerability index has also been criticized [22]. In this research, an attempt has been made to infer whether it was really necessary to use all of the seven DRASTIC parameters to assess the Garoua aquifer vulnerability by performing model a sensitivity analysis. The rated DRASTIC parameters were first evaluated for interdependence and variability and two sensitivity tests performed; the map removal sensitivity analyses introduced by and the single-parameter sensitivity analysis introduced by [23].

Map removal sensitivity measure identifies the sensitivity of the suitability map toward removing one or more maps from the suitability analysis and is computed using equation (2):

$$\mathbf{S} = \left( \frac{\mathbf{V}}{\mathbf{N}} - \frac{\mathbf{V'}}{\mathbf{n}} / \mathbf{V} \right) \times 100 \qquad (2)\ [23]$$

Where $S$ is the sensitivity measure expressed in terms of variation index, $V$ and V' are the unperturbed and the perturbed vulnerability indices respectively, and $N$ and n are the number of data layers used to compute V and V'. The actual vulnerability index obtained using all seven parameters was considered as an unperturbed vulnerability while the vulnerability computed using a lower number of data layers was considered as a perturbed one.

The single parameter sensitivity analysis is used to assess the influence of each of the seven parameters of the model on the vulnerability measure. In this analysis real or effective weight of each parameter is compared with the assigned or theoretical weight.

The effective weight of a parameter is calculated using equation (3):

$$\mathbf{W} = \left( \mathbf{PrPw} / \mathbf{V} \right) \times 100 \qquad (3)$$

Where: W refers to the effective weight of each parameter, Pr is the rating value of each parameter, Pw is the weight of each parameter and V is the overall vulnerability index.

A statistical summary of the seven rated parameters of the DRASTIC model for vulnerability of ground water in Garoua area is shown in Table 5. Depth to ground water has the highest mean value and topography has the lowest mean value.

# 3. Results

## 3.1. Determination of DRASTIC Parameters

The DRASTIC model sums all data layers representing detailed hydrogeological behavior of the area of interest. The rating of each site's parameter depends on the data variation hence the extents of variation of each parameter encountered were carefully credited to obtain a unique range of each parameter relevant to each test site. The DRASTIC Model input parameters used were procured from various measurements, field data and literature. Seven thematic maps were prepared using these input data based on ArcGIS as follows:

### 3.1.1. Depth to Water (D)

It is a key factor that determines the depth of materials through which contaminants must pass before reaching the water table. The water levels of 196 wells were measured and the depth to the water in the study area ranges from 0.2 to 11.87 m (Figure 3) which lies within the shallow groundwater zone. Based on the ranges of [17], the study area is assigned ratings of 5, 7, 9, and 10. Shallow water depths increase the vulnerability to pollution. Shallow groundwater usually occurs between 5 and 80 m below the surface [6]. According to Figure 3 the depth to water table in Garoua is shallow which makes the area more susceptible to pollution because pollutants have relatively short distances to travel before entering the saturated zone.

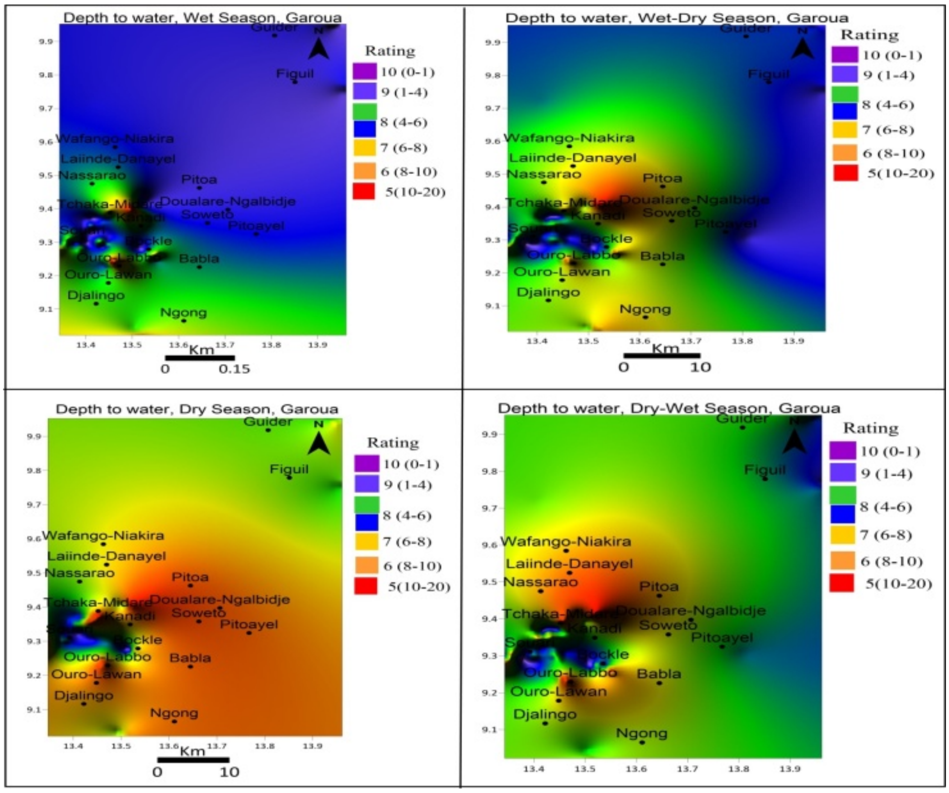


**Figure 3.** Depth to water rating map of Garoua-Cameroon

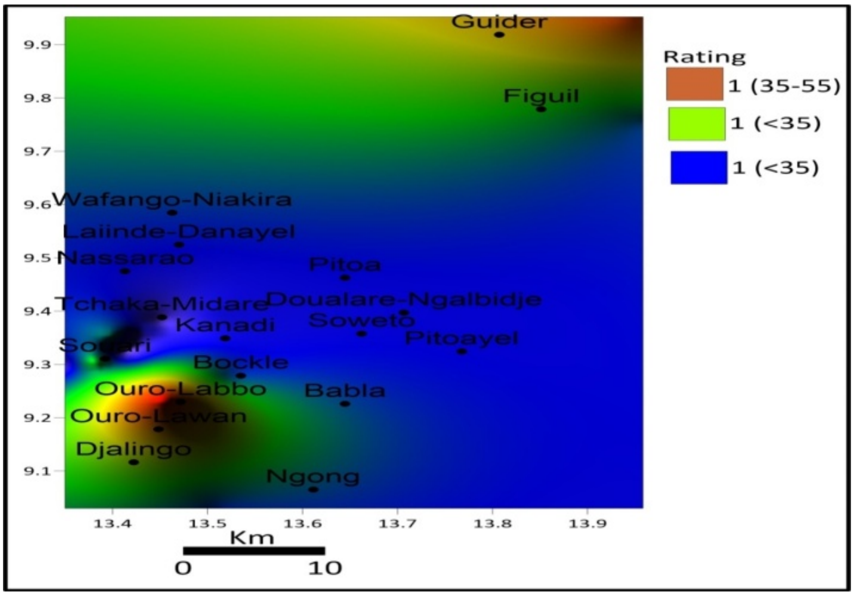


**Figure 4.** Net recharge rating map; Values are low with relatively high values at Ouro-Labbo

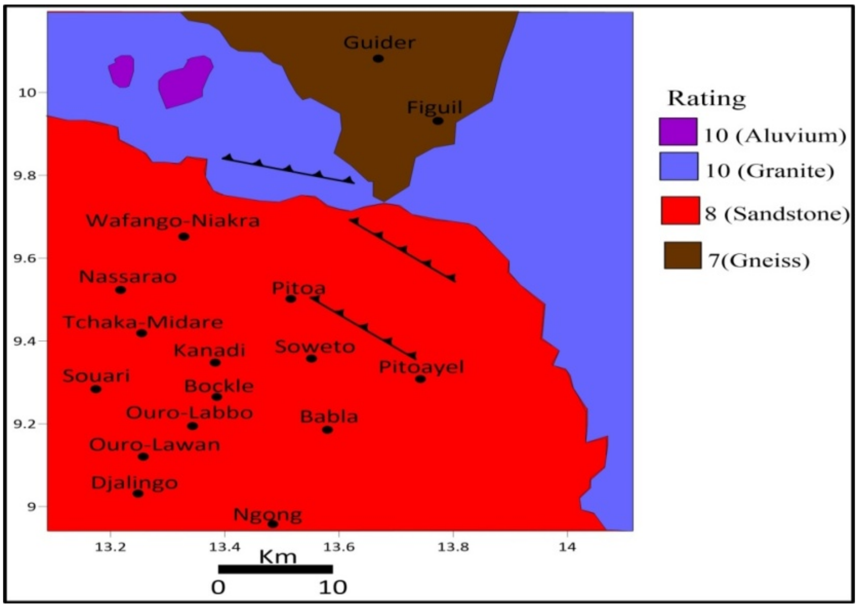


**Figure 5.** Aquifer media rating map: Comprising of Sandstone, granite, gneiss, and Alluvium

### 3.1.2. Net Recharge (R)

The net recharge ranges between 0-35.4 mm/yr. (Figure 4). The locations were assigned a rating of 1. Net recharge represents the total quantity of water applied to the ground surface through precipitation and infiltration to the water table. Higher net recharge reduces the vulnerability of an aquifer to pollution. The primary sources of recharge in Garoua are influent runoff from the Benoue River drainage and precipitation which infiltrates from the ground surface to the water table.

### 3.1.3. Aquifer media (A)

Groundwater flow, fate of contaminant and transport modeling are relevant components of most aquifer remediation studies [1]. The predominant aquifer media is characterized by alluvium, sandstone, granites, and gneiss giving locations ratings of 7, 8, and 10 (Figure 5). Aquifer media is the potential for water storage. High proportion of sandstone in the study area increases permeability which allows more water with contaminants to get into the aquifer. The contaminant attenuation of an aquifer is dependent on the amount and sorting of fine grains, higher grain size lowers the attenuation capacity of aquifer media and consequently, the greater the pollution potential [24].

### 3.1.4. Soil Media (S)

Soil types inferred from infiltrometer tests are sands, silty clay, clay, and loam soils (Figure 6) with assigned ratings of 1, 5, 7, and 10 respectively. Soil media constitute the upper weathered zone of the earth and acts as a passage for the downward vertical flow of contaminants to the water table. It plays a primary role in assessing groundwater intrinsic vulnerability. It has a significant influence on the amount of recharge that will infiltrate into the ground and the ability of contaminants to move vertically into the vadose zone [25]. Clay and loam can decrease soil permeability and restrict contaminant migration; hence, both classes of clay have the lowest rating values.

### 3.1.5. Topography (T)

Test sites slopes varied from 0% to 18%, and were classed into 7 ranges assigned ratings of 1, 3, 5, 7, 8, 9, and 10 (Figure 7). Topography controls the ability of a pollutant to be transported as run-off on the ground surface as streamlets, streams, and rivers or to remain on the ground where it may infiltrate into the underground. Low slope values will favor infiltration and increase vulnerability to pollution while for high values the reverse is true.

### 3.1.6. Impact of the Vadose Zone

The vadose zone is the unsaturated zone of subsoil above the water table and helps in the percolation of rainfall and surface flow. The vadose zone (unsaturated zone) has a key role in the percolation of rainfall and in surface-water flow. The unsaturated zones consist of an alternation of sand, clay, and gravel as in Figure 8 and were assigned ratings of 3, 9, and 10. It has a high impact on water movement if permeable and attenuates contaminant's penetration to groundwater; the highest weight value was given in the sand-gravel areas. The rating and weight values of this parameter are shown in Table 2.

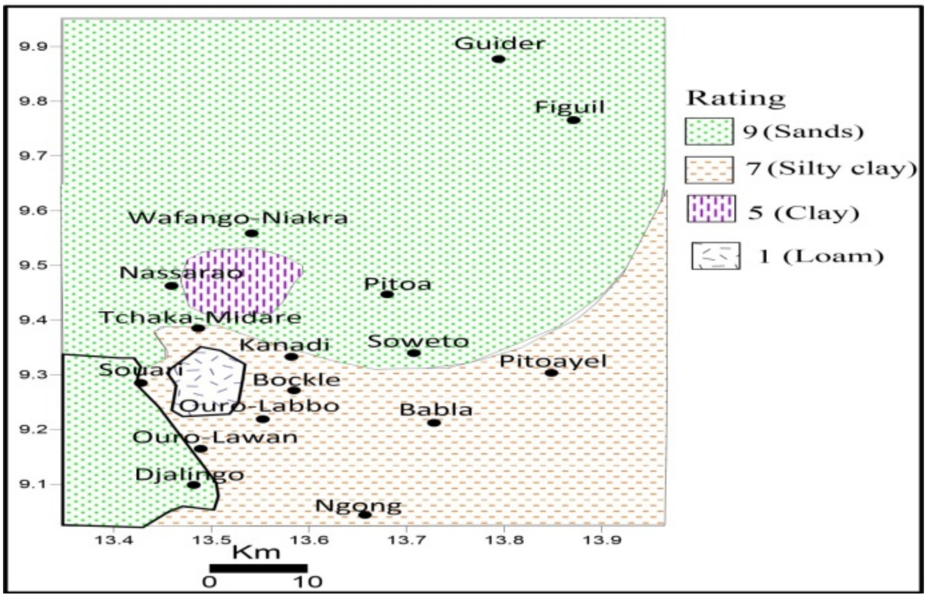


**Figure 6.** Soil media rating map in Garoua: Comprising of Sands, clay, silty clay, and loam

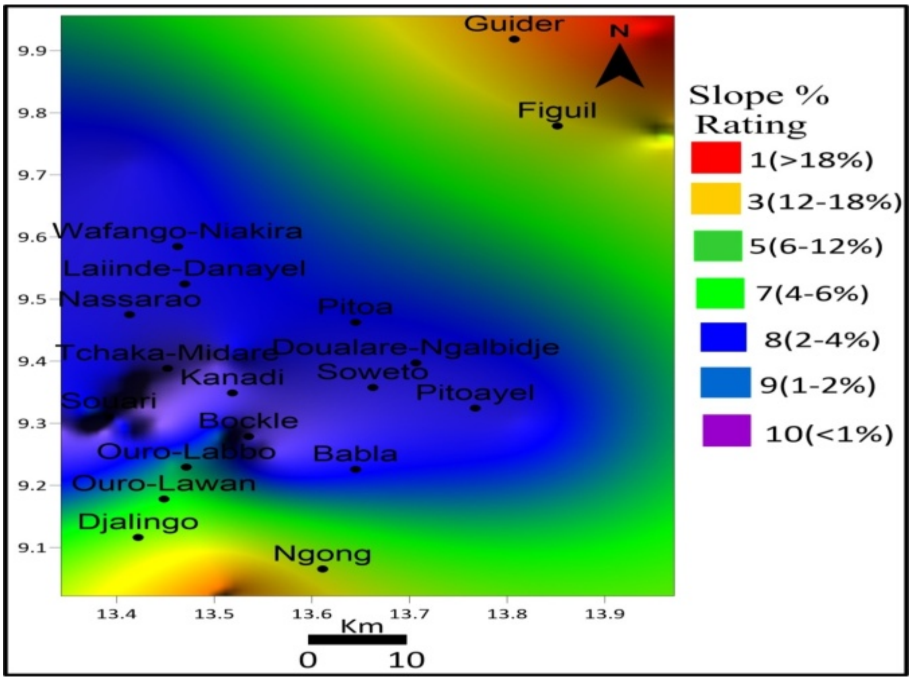


**Figure 7.** Topography rating map; generally high slope % values are at Guider and Figuil

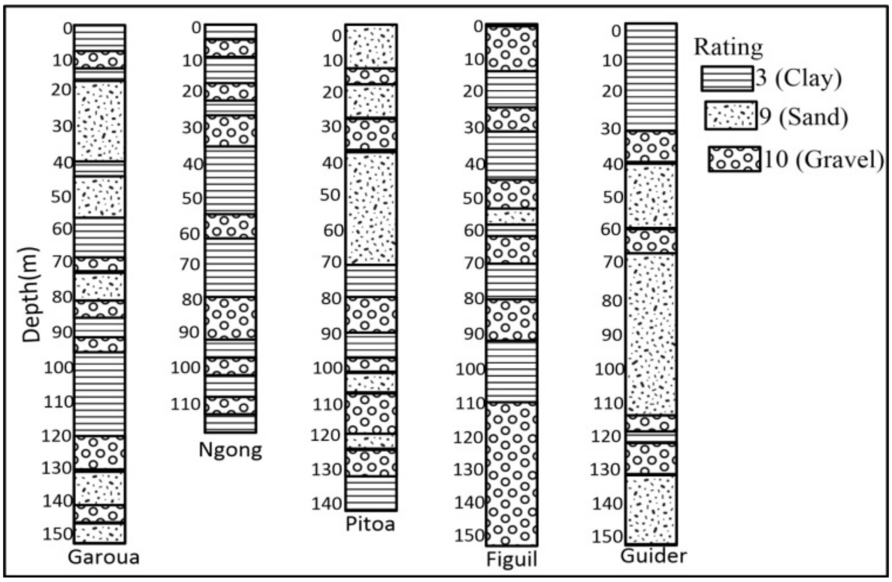


**Figure 8.** Impact of vadose zone rating map

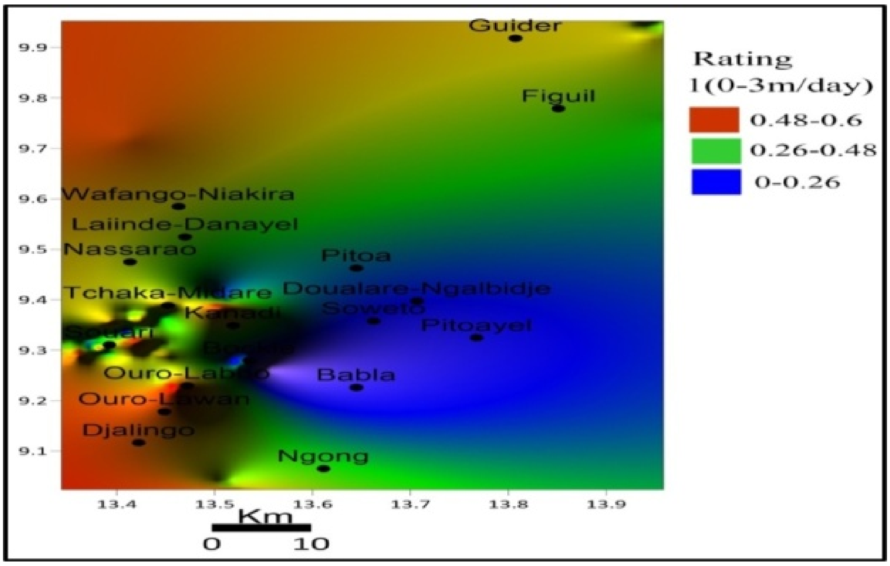


**Figure 9.** Hydraulic conductivity rating map

**Table 4. Seasonal classification of DRASTIC score values in Garoua [17]**

| Season | D | R | A | S | T | I | C | Index | Vulnerability Class |
|---|---|---|---|---|---|---|---|---|---|
| **Wet Season** | 45 | 12 | 30 | 14 | 1 | 45 | 3 | 150 | High |
| **Wet-Dry Season** | 45 | 4 | 30 | 14 | 5 | 45 | 3 | 146 | High |
| **Dry Season** | 45 | 4 | 21 | 10 | 30 | 45 | 3 | 158 | High |
| **Dry-wet season** | 50 | 4 | 30 | 28 | 15 | 27 | 3 | 157 | High |
| **Mean** | **46.25** | **6** | **27.75** | **16.5** | **12.75** | **40.5** | **3** | **152.75** | High |

### 3.1.7. Hydraulic Conductivity (C)

Field determined hydraulic conductivity values for test sites in Garoua range from 0.12 to 0.7 m/day (Figure 9). These test sites were assigned a rating of 1. Hydraulic conductivity is controlled by the properties of the aquifer and the fluid which determines the rate of groundwater solute (dissolved contaminants: pollutants) flow in the saturated zone. With an increment in hydraulic conductivity and thus groundwater velocity, the speed with which pollutants are transported also increases resulting in the rise in aquifer vulnerability to pollutants.

## 3.2. DRASTIC Vulnerability Classes

The DRASTIC vulnerability indices were subdivided into two classes of vulnerability, the area is characterized with an index of 150 in the wet, 146 in the wet-dry, 158 in the dry, and 157 in dry-wet seasons. Garoua is characterized by high aquifer vulnerability in all other seasons as in Table 4 and Figure 10.

An examination of the means of the DRASTIC parameters (Table 5) reveals that the highest contribution to the vulnerability index is made by the depth to water (mean = 46.25) closely followed by impact of the vadose zone (mean = 40.5). The third ranked contribution is aquifer media (mean = 27.75) followed by Soil media (mean value = 16.5), topography (mean = 12.75), Recharge (6) and the least significant is hydraulic conductivity (mean = 3) contributing lowest to the vulnerability index.

## 3.3. Sensitivity Analysis

### 3.3.1. Map Removal Sensitivity Analysis (MRSA)

The results of the map removal sensitivity analysis computed by removing one or more data layers at a time are presented in Tables 5.

Table 5 describes the single parameter variation of the vulnerability index (sensitivity measure) due to the removal of only one layer at a time. The study shows clear variation in the vulnerability index because of removing only one layer at a time [26]. However, the highest variation of the vulnerability index is expected upon the removal of the hydraulic conductivity parameter from the computation. This parameter shows a high relative mean value of variation index (11.54%) when removed from the computation. This could be attributed to the characteristic of the material found in the aquiferous formations in Garoua. The variation of vulnerability index seems to be [20] also relatively sensitive to the separate removal of net recharge, soil media, topography, and hydraulic conductivity with mean variation index of 9.31%, 6.08%, 8.85, and 11.54% respectively. The increasing mean of the variation index implies that the absence of these parameters will greatly influence the vulnerability index of the area. For the remaining parameters, their removal from the computation during the map removal sensitivity analysis involves a negative variation in the mean vulnerability index. As it can be seen in Table 5, the variation index varies from -17.06% to 11.54%.

**Table 5 Single parameter map removal sensitivity analysis**

| Parameter | Variation index (%) | | | |
|---|---|---|---|---|
| | Minimum | Maximum | Mean | SD |
| **D** | -33.08 | 9.48 | -17.90 | 12.19 |
| **R** | -3.90 | 11.55 | 9.31 | 2.98 |
| **A** | -27.09 | -0.93 | -7.95 | 5.20 |
| **S** | -12.38 | 12.82 | 6.08 | 6.40 |
| **T** | 1.30 | 13.62 | 8.85 | 3.21 |
| **I** | -34.63 | 2.29 | -9.94 | 10.32 |
| **C** | 9.11330049 | 12.29 | 11.54 | 0.63 |

### 3.3.2. Single Parameter Sensitivity Analysis (SPSA)

According to [27] single parameter sensitivity analysis is designed to compare their ‘‘theoretical’’ weights with that of ‘‘effective’’ weights in the aquifer vulnerability map. In this way, the ‘most effective impact’ parameters are determined by comparing the theoretical effect weight with the effective effect weight of each parameter. The effective weight is a function of the value of the single parameter with regard to the other six parameters as well as the weight assigned to it by the DRASTIC model [28]. The effective weights of the DRASTIC parameters exhibited some deviation from those of the theoretical weights [29]. Table 6 reveals that the depth to water, aquifer media, topography and impact of the vadose zone layer tend to be the most effective parameters in the vulnerability assessment because their mean effective weights, 32.18%, 22.24%, 5.43 and 24.22%, respectively, are much higher than their respective theoretical weights. Net recharge, soil media and hydraulic conductivity showed mean effective weight lower than their theoretical weight (Table 6). The importance of depth to water, aquifer media and impact of the vadose zone parameters (due to the significance of their effective weight obtained from the single parameter sensitivity analysis), highlight the necessity of getting more accurate data and detailed information about these parameters.

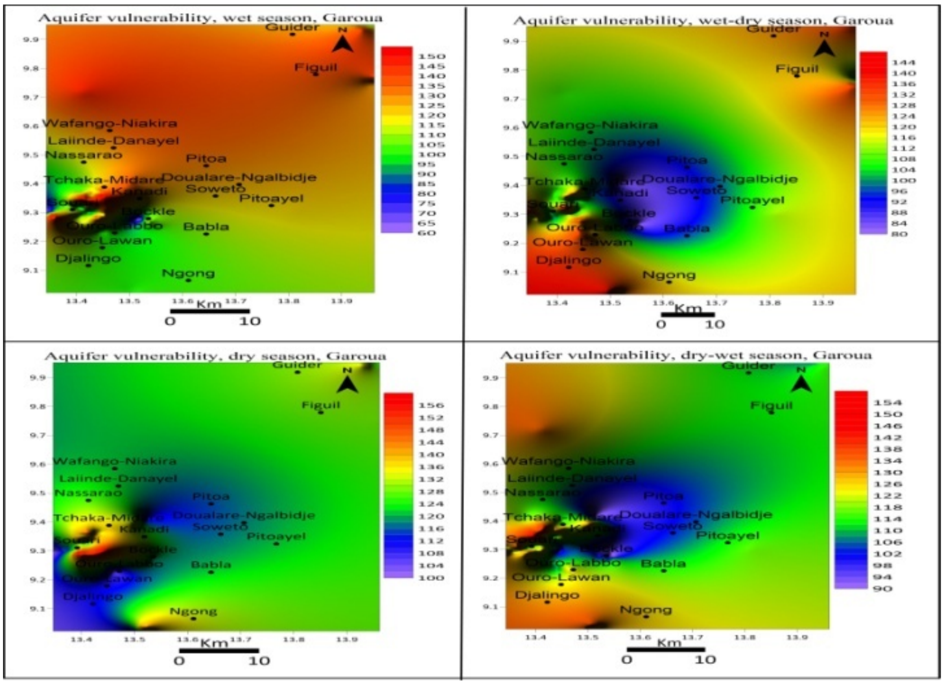


**Figure 10.** Variation of aquifer vulnerability to pollution in Garoua

**Table 6. Single parameter sensitivity analysis in Garoua**

| Parameter | Theoretical wt. | Theoretical wt. (%) | Effective weight (%) | | | |
|---|---|---|---|---|---|---|
| | | | Minimum | Maximum | Mean | SD |
| **D** | 5 | 21.74 | 4.81 | 47.37 | 32.18 | 12.19 |
| **R** | 4 | 17.39 | 2.74 | 18.18 | 4.97 | 2.98 |
| **A** | 3 | 13.04 | 15.22 | 41.38 | 22.24 | 5.20 |
| **S** | 2 | 8.7 | 1.47 | 26.67 | 8.21 | 6.40 |
| **T** | 1 | 4.35 | 0.67 | 12.99 | 5.43 | 3.21 |
| **I** | 5 | 21.74 | 12.00 | 48.91 | 24.22 | 10.32 |
| **C** | 3 | 13.04 | 2.00 | 5.17 | 2.74 | 0.63 |

# 4. Discussion

## 4.1. DRASTIC Parameters

**Deeper water levels (D)** give a longer time for a pollutant to reach the groundwater table, thus areas with shallow depths to water are more susceptible to contamination [30].

**The net recharges (R)** of the area were assigned low rating values which are indicative of low aquifer vulnerability to pollution [31]. The net recharge of an aquifer vulnerability to pollution is mainly controlled by factors such as; type of land use, soil type, and lithology of an area [20]; however, Garoua being dominated by sands helps contaminants to easily percolate into the aquifer since it has high porosity and permeability. Areas with low net Recharge (with rating of 1) as presented in Table 3 could be attributed to urban land use, concretes, gutters, and tarred roads preventing the downward penetration of rainwater.

**The aquifer media (A)** in the Garoua are made of sandy formations. As such are highly vulnerable to pollution which implies that pollutants can easily infiltrate the soil [32].

**The soil media (S)** actively operates in the permeation of contaminants through the formations and controls the recharge of the area. Soils of the study area are characterized as sands, silty clay, clay and loam soils. Sandy soils covered more than 50% of the area have higher ratings. Also a part of the area comprises of clay soils with pockets of sand, clay loam and sandy loam. Clay soils interrupt the flow of water and have least chances of groundwater pollution. Clay soils having small pore spaces do not allow easy flow of water.

**Topographic (T)** slopes had low values that limits runoff, giving more time for the contaminants to percolate down to the water table, while the few steep areas increased the runoff and could wash away contaminants.

**The vadose zone (I)** consists of sand, clay and gravel. Areas consisting of clay are characterized relatively lower vulnerability to contamination whereas areas with sand have high permeability for contaminants. **Aquifers with high conductivity (C)** are vulnerable to pollution as the plume of contamination can move quickly throughout the aquifers. Fractured and weathered Granite and Gneiss formations in Garoua had high conductivity values similar to work done by [33].

The DRASTIC vulnerability maps of Garoua present one class of vulnerability: high vulnerability class compared to those obtained by [34] in the Abidjan District. The vulnerability classes of Garoua increase to the northern and decrease to the southeastern regions making the northern part of the aquifer more vulnerable influenced by topography. [35] in the work outlined topography and the depth of the water table as parameters that had a strong sensitivity to the DRASTIC vulnerability index unlike in Garoua where the depth to water significantly affects the vulnerability of the aquifers to pollution since the wells are very shallow. The depth to water, impact of the vadose zone, the aquifer media, and the hydraulic conductivity significantly influence the aquifer vulnerability maps in Garoua. These results differ from those obtained by [27] who found topography, net recharge, and soil media to be the most influential parameters in Kakamigahara central Japan, and the other parameters having low to moderate impacts. In [27] it was opined that; the variability of all parameters depends on the hydrogeological characteristics of the study. The variation of vulnerability index seems to be also relatively sensitive to the separate removal of net recharge, soil media, topography, and hydraulic conductivity. The increasing mean of the variation index implies that the absence of these four parameters will greatly influence the vulnerability index of the area. They remain the most important parameters, though there is a need for all the other parameters for a more objective assessment of vulnerability. All parameters are important for vulnerability determination [35], while [36] limited the importance of parameters to the aquifer media and the soil media. The Garoua results are closer to those of [37] in the Russeifa region in Jordan that indicated aquifer media, depth to the water table, and impact of the vadose zone respectively as of increasing importance.

In this study, depth to water, aquifer media, topography and impact of the vadose zone layer tended to be the most effective parameters in the vulnerability assessment because their mean effective weights are higher than their theoretical weights.

# 5. Conclusions

The Garoua aquifers have been assessed using the DRASTIC model and GIS techniques for its vulnerability to pollution with the following conclusions;

(1) Depth to water, aquifer media, soil media, and impact of the vadose zone are the most relevant parameters affecting aquifer vulnerability in Garoua.

(2) The net recharge, topography, soil media, and hydraulic conductivity are important parameters in assessing the aquifer vulnerability in Garoua.

(3) DRASTIC indices classify Garoua aquifers as highly vulnerable to pollution in all seasons due to the porous sandstone formations, the presence of fractured gneisses

and fractured granites which could act as conduits permitting pollutants to reach the water table easily.

(4) The highest vulnerabilities to pollution occur during the dry seasons. However, it is noteworthy that during this period water is scarce thereby decreasing the pollution opportunity which reduces pollutant-transporting-media into these phreatic aquiferous formations.

(5) There is high aquifer vulnerability to pollution in Garoua aquifers; as such, decision makers and stakeholders must take appropriate measures to monitor and/or protect the phreatic aquiferous formations in Garoua, at all times.


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# Declaration of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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