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Research Article

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Preliminary Evaluation of Groundwater Vulnerability to Contamination Using the Drastic Model; A Case of Greater-Accra Region, Ghana

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Abstract This study employs the GIS-Based *DRASTIC* model to evaluate vulnerability of groundwater to contamination of the Greater-Accra Region of Ghana. It therefore synthesizes both a computer-based GIS and the *DRASTIC* to demonstrate an effective method for groundwater contamination and aquifer vulnerability assessment. In Ghana, groundwater is predominantly used as a domestic water-supply (including drinking), irrigation and purposes of industrial consumption. Therefore, assessing the vulnerability to delineate aquifers that are more susceptible to contamination is very significant. The model is considered to have a significant control and potential of affecting groundwater contamination in general, and it consists of seven (7) major hydrogeological parameters (Depth to groundwater - *D*, net Recharge - *R*, Aquifer media - *A*, Soil media - *S*, Topography -*T*, Impact of vadose zone - *I*, and hydraulic Conductivity - *C*) combined to form its acronym "*DRASTIC*". A vulnerability map was therefore obtained using GIS computer program (ArcGIS 10.2) together with the DRASTIC method, after identifying and characterizing the degree of vulnerability by an index of each parameter. It however became evident from the vulnerability map that, the north-western part of study area was characterized by high vulnerability to contamination, while the central part however displayed a moderate aquifer vulnerability. The south-eastern part also demonstrated the least aquifer vulnerability, which makes it less susceptible to contamination from anthropogenic sources. This aquifer vulnerability map produced in this preliminary study can serve as a tool for prudent management and land-use planning of the groundwater resource by the city authorities.

Keywords Aquifer Vulnerability, Groundwater contamination, Hydrogeology, DRASTIC model

1. Introduction

According to the WHO, a major priority with reference to the Goal 6 (Target 6.1) of the proposed Sustainable Development Goals (SDGs), is to achieve universal and equitable access to safe and affordable drinking water for all by 2030 [1]. This will contribute to improved drinking water source, which should be available when needed and free of pollution according to the UN. But, due to the natural and anthropogenic complexity of water existence, access to this reliable potable water source continues to be a major challenge.

Ghana is fortunate to have quit a significant number of surface water resources, but sadly, these available surface water resources are unable to satisfy the water demand for socio-economic development nationwide. This is mainly due to pollution, especially for those taking their sources from mining areas [2]. In most developing countries including Ghana, groundwater is considered a major freshwater store within the hydrological cycle, and it stands as the most reliable, clean and safe water for domestic use [3-4], drinking, agricultural (mainly irrigation) and for industrial purposes [2].

Pollution of groundwater is a major issue because, aquifers that contain groundwater are inherently susceptible to pollution [5-6]. Therefore, groundwater vulnerability to pollution is generally the sensitivity of aquifer to pollutants. With regards to pollutants entering the subsurface environment, there is an assumption that, the physical and the natural environment may provide some degree of protection to groundwater against natural and anthropogenic impacts [7] especially with regard to subsurface pollution. Groundwater vulnerability to pollution however measures the degree of protection provided by the natural and artificial factors to keep pollutants away from reaching the groundwater. The vulnerability becomes high if the natural factors provide little protection to buffer the groundwater from pollution, whiles the vulnerability becomes low if the natural factors provide enough protection to shield the aquifer with regards to pollutants which enter the subsurface environment. However, land areas do not have same vulnerability to groundwater contamination; some are considered more vulnerable than others.

Groundwater vulnerability to contamination over the years, have been employed by many researchers including but not limited to [6, 8-12], to serve as a basis for developing land-use strategies to protect the groundwater from contamination. This research therefore aims to preliminary evaluate the vulnerability to contamination of the Greater Accra Region using DRASTIC model coupled with geographical information system (GIS).

2. Materials and Methods

2.1. The study area

The study area, Greater Accra Region, is located in the southern part of Ghana between the coordinates of $0^o30'0''$W and $0^o50'0''$E and $5^o30'0''$N and $6^010'0''$N (Fig. 1). The area is bordered on the North and East by the Eastern Region and the Lake Volta respectively, as well as, on the south and west by the Gulf of Guinea and the Central Region respectively (Fig. 1). It is the smallest region, considering the ten administrative regions of Ghana, and it occupy a total land surface area of 3,245 km^2, representing 1.4% of the total land area of Ghana. However, it is the capital and the second most populous city of Ghana, with a population of 4,010,054 (representing 16.3% of Ghana's total population) according to the 2010 population and housing census [13].

The main rivers that flow through the region are the Volta and Densu rivers. In addition, there are small seasonal streams flowing mostly from the Akuapim Ridge into the sea through numerous lagoons. Because the region is bordered on the south by the Gulf of Guinea, there are ecologically very important but highly polluted lagoons and wetlands.

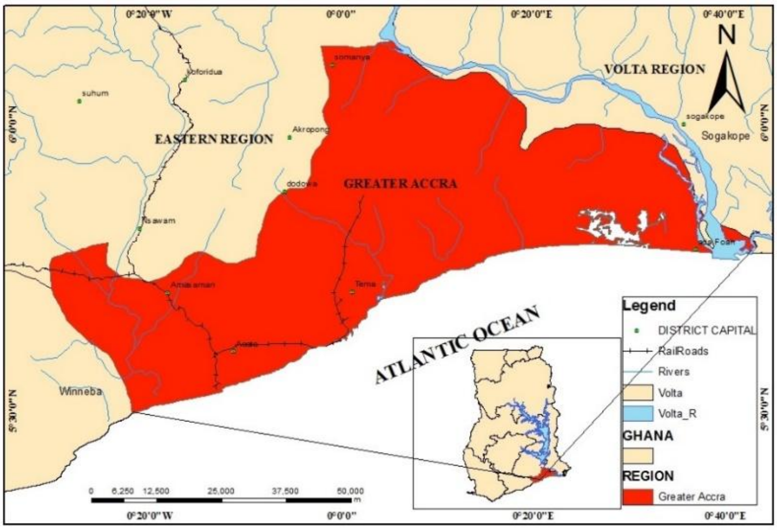

Figure 1: Location map of the study area

The climate is characterized by two rainfall seasons. The major rainy season occurring between May and July (peaking occurring in June), while the minor one occurs between September and October (peaking in October). Generally, the rainfall in the Accra Plains is low with mean annual rainfall of approximately varying between 740 mm and 890 mm [14].

The region is relatively dry since it falls within the dry coastal equatorial climatic zone with temperatures ranging between 20 °C and 30 °C with a mean temperature of 26 °C. The vegetation is mainly coastal grassland and scrub interspersed with thickets. The geology of the area (Fig. 2) consists of Precambrian Dahomeyan schist, granodiorites, granites gneiss and amphibolites to late Precambrian Togo series comprising mainly quartzite, phyllites, phylitones and quartz breccias [15-16].

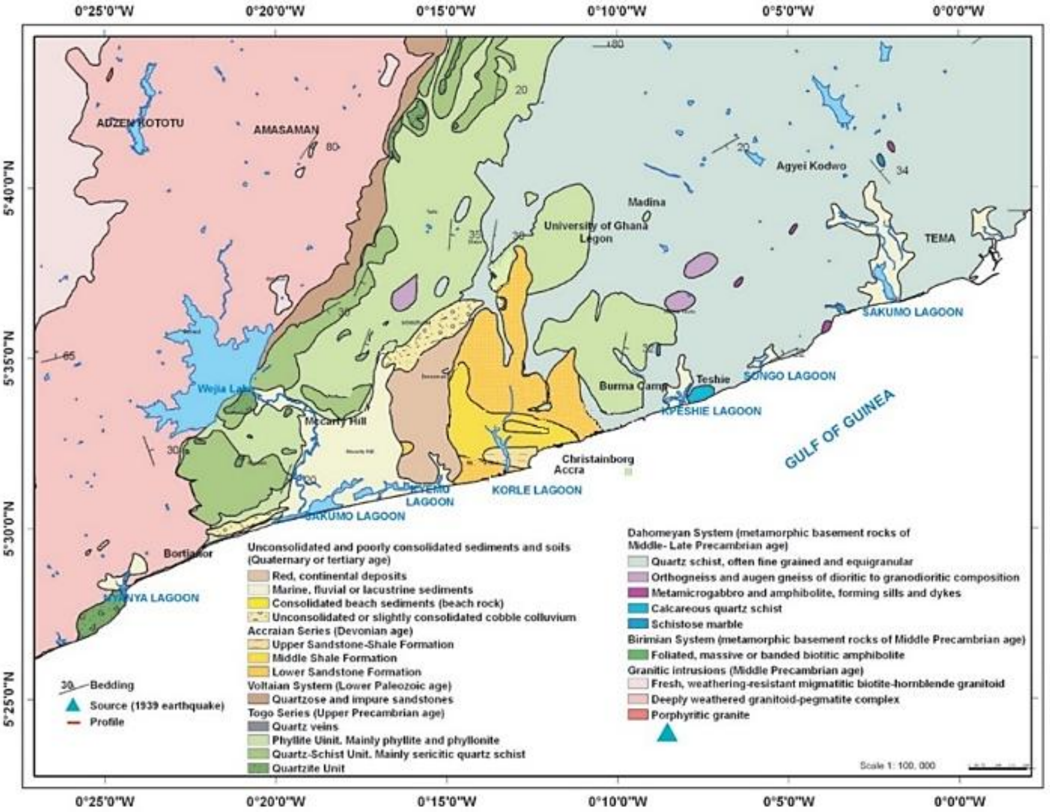

Figure 2: Geological map of the study area (modified from Amponsah et al., 2009 [17])

2.2. Groundwater Vulnerability Concept

2.2.1. The DRASTIC Concept

The study uses the DRASTIC model coupled with geographic information system, GIS (ArcGIS 10.2) to evaluate the vulnerability to contamination of aquifers and to produce the vulnerability map for groundwater contamination within the Greater Accra region of Ghana.

Vulnerability to contamination generally, refers to the sensitivity of groundwater to contamination, and is determined by intrinsic characteristics of the aquifer as described by Aller*et al*., 1987; El-Naqa, 2006; Wang, 2007 and Alwathaf *et al*., 2011 [8-10, 18]. However, the concept of groundwater vulnerability to contamination was originally familiarized by Margat (1968) [19], to raise awareness of the dependence of the groundwater system by human or natural impacts or both. This concept, according to Aller *et al*., 1987 [8], is based on the concept of hydrogeological setting defined as a composite description of all major geologic and hydrologic factors that affect and control the groundwater movement throughout an area. It was developed to be a proactive tool to illustrate the protection guide of groundwater against contamination, and the model evaluates the groundwater's intrinsic vulnerability (IV) by considering factors including; Depth to water table (D), net aquifer Recharge rates (R), Aquifer media (A), Soil media (S), Topographic (T), Impact of vadose zone media (I) and hydraulic Conductivity (C). These parameters together, give theacronym "DRASTIC", which consists of seven hydrogeologicphysical parameters known to affect the water transport from the soil surface to the aquifer, and also corresponds to the seven layers to be produced as input parameters for the modelling. Different ratings are consequently assigned to each parameter, and subsequently summed-up with their respective weights to produce a vulnerability rating or DRASTIC index (DI) determined by the expression (Eq. 1);

$$DI = \sum_{j=1}^{7} r_j w_j = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \text{Eq. [1]}$$

Where; *r* is the rating value, *w* is the weight assigned to each parameter and *D*, *R*, *A*, *S*, *T*, *I*, and *C* represent the seven parameters.

When the DI is computed as the weighted sum overlay of the seven layers (Figure 3), it is possible to identify prospective areas susceptible to groundwater contamination relative to one another. The higher the DI obtained, the greater the groundwater contamination potential [20]. Summarized data types obtained to construct thematic layers of the seven model parameters were digitized and converted to raster data-sets, which were subsequently processed using integrated ArcGIS 10.2 software to produce the groundwater vulnerability map. The highest or lowest vulnerability values obtained depending on the area covered, is linked with whether the aquifer is shallow or deep, with or without depth of the vadose zone.

According to Aller *et al*., 1987 [8], with the DRASTIC model, it is imperative to assume that all contaminants move with the water throughout the soil media and are introduced at the soil surface. DRASTIC only provides a tool for relative vulnerability assessment therefore; these assumptions cannot always be considered as the real situations on the ground. However, the advantage is that, this GIS-based technique provides efficient environment for the analyses, and is highly capable of handling larger quantity of spatial data.

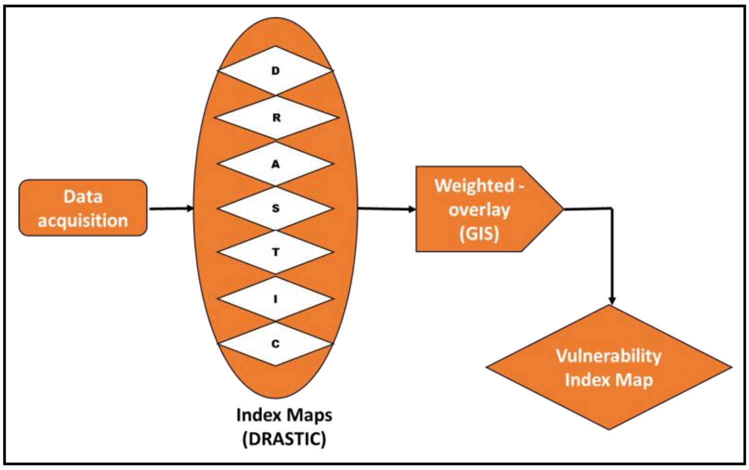

Figure 3: Aquifer vulnerability index map flowchart

Table 1: Borehole location and depth

Sample ID	Location		Ele. Z (m)	Well-Depth (m)	Water-Level (m)
	Long. (x)	Lat. (x)			
well-1	5.707556	-0.1950653	75	3.35	2.56
well-2	5.708383	-0.192865	82	6.2	4.297
well-3	5.708253	-0.192662	78	8.39	4.066
well-4	5.711101	-0.192173	70	5.4	3.82
well-5	5.712876	-0.1984	67	9.8	5.6
well-6	5.702827	-0.199797	68	5.1	2.37
well-7	5.701949	-0.198531	75	8.45	4.56
well-8	5.701493	-0.198518	83	7.5	4.99
well-9	5.701799	-0.19853	86	7.17	4.35
well-10	5.622389	-0.254733	41	6.31	2.22
well-11	5.620918	-0.253024	37	2.85	-0.14
well-12	5.620918	-0.253025	36.5	2.83	0.13
well-13	5.620008	-0.2530245	36.3	2.1	0.265
well-14	5.622055	-0.25435	47	3.49	-0.11
well-15	5.623126	-0.25748	62	13.35	11.61

The vulnerability assessment involves evaluating likely travel times from the ground surface to the water table, or to the aquifer in the case of confined conditions; the greater the travel time, the more potential there is for pollutant attenuation [7].

3. Results and Discussions

3.1. The DRASTIC Parameters Determination

Based on the DI values, a groundwater vulnerability map can be produced using the geographic information system (GIS). Highest or lowest vulnerability values obtained depending on the area covered will be linked with whether the aquifer is shallow or deep, with or without depth of the vadose zone. The advantage is that, this GIS technique provides efficient environment for analyses and highly capable of handling larger quantity of spatial data.

*Depth to water table (D)***:** The parameter is the measure of depth from the ground surface to the water table. It is therefore a measure of the depth through which a contaminant will travel before reaching the aquifer. Hence, the deeper the water table, the lesser chance for aquifer contamination. Likewise, the shallower the water table, the more vulnerable the aquifer is to contamination.

For the purpose of the study, the parameter was obtained by subtracting the water table level from the ground level (with surface level set at 0 m). In all eighteen (18) boreholes (wells) were randomly assessed (Table 1) from a section of the study area (Chantan, Abokobi, Racecourse, Lapaz and Akweteman), to determine an approximate range of depth-to-water table for the Greater Accra region (the study area). A mean depth-to-water table range of 1.5- 4.5 m which corresponds to the original DRASTIC parameter rating score of 9 (Table 2),was used to generate the Depth to water table rating map (Fig. 4).

*Net aquifer Recharge rates (R)***:** This parameter represents the amount of water which percolates to the water table by penetrating the ground surface. The recharge water therefore constitute the contaminants that are transported to the water table.

Since the principal source of recharge is precipitation and runoff, the net Recharge parameter was estimated using hydrological precipitation-runoff model from the study area in accordance with Pathak *et al*., 2008, which employs evapotranspiration (E), runoff (Q) and annual precipitation (P) or rainfall from the study area. The net recharge for the area was however estimated using Eq. [2].

$$R = P - (E+Q) \qquad \text{Eq.[2]}$$

Where, **R** is the net Recharge, **E** is the Evapotranspiration, **Q** is runoff and **P** is the annual rainfall or Precipitation.

Using the Soil Conservation Service (SCS) of the USEPA [10, 21], the runoff, Q of the study area was evaluated [eq 3]. The SCS runoff equation is given by Eq. [3].

$$Q = \left[\frac{(P - Ia)^2}{(P - Ia + S)}\right] \text{for } P > Ia \qquad [3]$$

Where, *I*a is the initial abstraction (assumed to be 0.2*S*) and *S*, is potential maximum retention after runoff begins. But, *S* is related to the soil by a curve number (CN) given as Eq. [4];

$$S = \left(\frac{1000}{\mathrm{CN}}\right) - 10 \qquad [4]$$

Where, *CN* is dimensionless number which depends on the hydrologic soil group (HSG), cover type, treatment, hydrologic conditions, and antecedent moisture conditions of the soil. With the SCS method, practically, all soils are classified into four HSGs (A, B, C, and D) according to their minimum infiltration rate. Type A and D soils have the lowest and highest runoff potential, respectively as shown in Table 3, which is a modification from USDA, 1986 [22] and Usul, 2009 [23]. The SCS method however, uses CN which is in the range 0-100, determined as a function of soil classification (soil groups), and land cover of the study area according to Usul (2009) [23].

The Greater Accra region is considered an urban area, therefore following the standard procedures of Ahmet (2012) [10], different CN for hydrologic soil group for urban areas applied, taking into consideration the soil types of the Greater Accra region. The mean annual Evapotranspiration, E and rainfall, P factors were however, accessed from the 15years data (from 1963-2013) obtained and processed by Adonadaga (2014) [24] for Greater

Accra, to determine the net recharge rate of the study area **(**Table 3). The net recharge map (Fig. 5) was then classified into ranges and assigned ratings in accordance with the original

Table 2: Depth to water DRASTIC model parameter [8]

Parameter	**Range**	**Rating (r)**	**Weight scale (w)**	**Index scale (w*r)**
Depth to Water (D)	0-1.5	10	5	50
	1.5-4.5	9		45
	4.5-9	7		35
	9-15	5		25
	15-22.5	3		15
	22.5-30	2		10
	>30	1		5

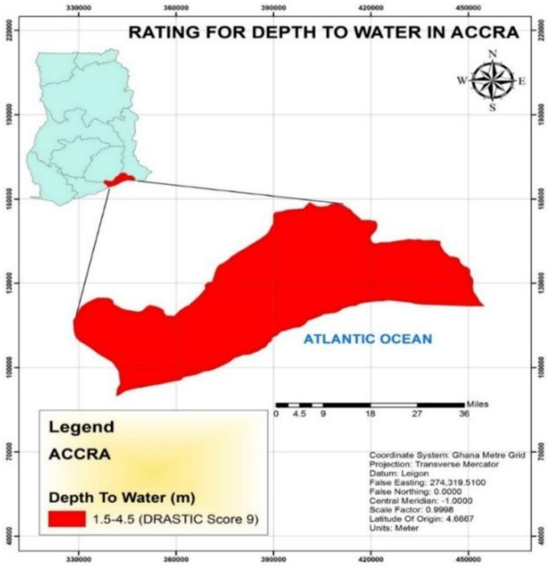

Figure 4: Depth to water table rating map

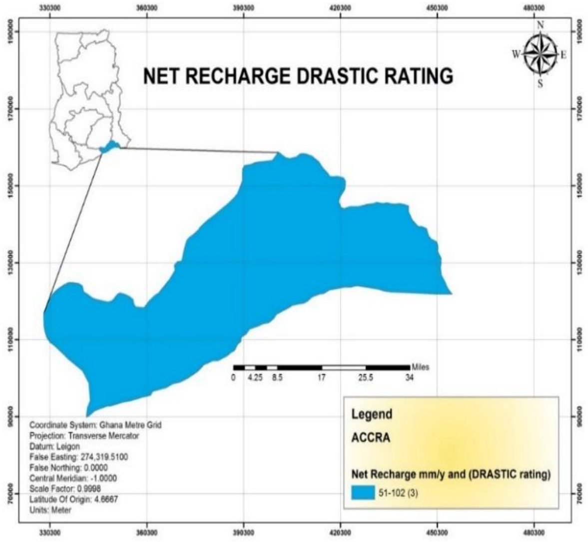

Figure 5: Net Recharge of aquifer map

Table 3: Hydrologic Soil Groups

HSG Classification	Definition	Runoff potential	CN	S	Ia	Q	R (mm/year)
Group A	Sand, loamy sand or sandy loam types of soils.	Lowest	89	1.236	0.247	823.51	97.01
Group B	Silt loam or loam	Moderately low	92	0.869	0.17	823.95	97.45
Group C	Sandy clay loam.	Moderate high	94	0.638	0.128	823.63	97.13
Group D	Clay loam, silty clay loam, sandy clay, silty clay or clay.	Highest	95	0.526	0.1	823.66	97.15

Table 4: Net Recharge of aquifer DRASTIC model parameter [8]

Parameter	**Range**	**Rating**	**Weight**
Net Recharge of aquifer (mm/y)	>254	9	4
	178-254	7-8	
	102-178	5-6	
	51-102	3-4	
	0-51	1-2	

Table 5: Modified net Recharge rating of the Greater Accra region

HSG Classification	Major soil types (Greater Accra)	Net Recharge (mm/y)	Rating	Weight
A	Leptosols, Arenosols, Acrisols: (very shallow, sand, loamy sand or coarser	97.01	3	4
B	Cambisols: (coarse medium- absence of clay)	97.45		
C	Solonetz, Luvisols, Gleysols, Fluvisols: (sandy loam, Clay loam, high clay content	97.13		
D	Vertisols, Solonchaks: generally clay loam, silty clay loam, and clay, Siltic and clayic	97.15		

Table 6: Original DRASTIC aquifer media parameters [8]

Parameter	Range	Rating	Rating	Weight
Aquifer Media	Karst Limestone	9-10	10	3
	Basalt	2-10	9	
	Sand and Gravel	4-9	8	
	Massive Limestone	4-9	6	
	Massive Sandstone	4-9	6	
	Bedded sandstone, limestone, and shale sequences	5-9	6	
	Glacial Till	4-6	5	
	Weathered metamorphic/ Igneous	3-5	4	
	Metamorphic/ Igneous	2-5	3	
	Massive Shale	1-3	2	

DRASTIC parameter (Table 4). This was further modified to get of the study area’s net aquifer recharge rate (Table 5) by considering the soil type of study area, as well as, the obtained recharge rates, using the ArcGIS 10.2.

The Aquifer media (A): The Aquifer media is considered the saturated permeable geologic zone which contain and transmit water in economic amounts, under ordinary hydraulic gradients. It however, controls the pollutant attenuation processes [23, 25]. The larger the grain size and more fractures or openings within the aquifer, the higher permeability and consequently, the lower the attenuation capacity of the aquifer media [8]. Likewise, the presence of coarse media makes vulnerability to contamination high. Considering the original DRASTIC aquifer media parameters according to Aller *et al*., 1987 [8] (Table 6), the geological map of the Greater Accra region (study area) was used to further determine the aquifer media index map (Fig. 6) for the study area using Table 7.

*The Soil media (S)***:** This media represents the uppermost weathered portion of the unsaturated zone which controls the amount of recharge that can infiltrate through the vadose zone, as well as, the aquifer media. It has a significant impact on the amount of recharge that can infiltrate the ground and hence, controls the ability of a contaminant to move vertically into the vadose zone [26] during infiltration process. However, it largely depends on the thickness and content of the soil media. Thus, according to Aller *et al*., 1987 [8], where the soil media is fairly thick, the attenuation processes of filtration, biodegradation, sorption and volatilization may be quite significant, and vice versa.

Considering table 8 and the soil type of the study area, the modified Soil media parameter (Table 9) was deduced. This was subsequently used to produce the Soil media rating map (Fig. 7) of the study area by loading the soil map of the study area into the ArcMap 10.2 software, and further digitizing, based on the available input data. The coarse soil media therefore have high rates in comparison to clay or fine soil aggregates.

Topography (T): This parameter is considered as the slope of the land surface, which dictates whether or not the runoff will stay on the surface (for longer or shorter period) to allow contaminant percolation to the saturated zone [27]. With regards to the study, the topography rating map (Fig. 8) was constructed with the use of elevation map of Ghana using the GIS software. The procedure yielded a digital elevation map (DEM) of the area. Flat areas were assigned high rates because they slow down the runoff. This may allow the contaminants to percolate down to reach the groundwater easily, whiles steep areas are assigned low rates due to the increasing rate of the runoff, with potential of moving along the surface (washing out) with the contaminants.

According to Figure 8, it is clear that, the area mainly consists of gentle slope spread across the area. The eastern,central and the southern part recorded values between 0 to 50 m with regards to elevation, making those areas highly vulnerable to contamination. The northern andthe upper west had elevation ranging between 50 – 100 m, whiles highest elevation range of 200-250 m, was recorded for the upper western part of the study area.

Table 7: Modified Aquifer Media Parameter

Parameter	Range	Rating	Weight
Aquifer Media	Granitoid (undifferentiated)	9	3
	Unconsolidated Sand, clay and gravel	8	
	Sandstone, Grit (Coarse, hard siliceous sandstone), Shale	6-7	
	Red continental deposits mainly Sandy Clay and Gravel	5	
	Quartzite Sandstone shale phyllite schist	4	
	Acidic, Ortho paragnesis Schist migmatite	3	

Table 8: Original DRASTIC soil media parameters [8]

Parameter	Range	Rating	Weight
Soil Media	Thin or Absent	10	2
	Gravel	10	
	Sand	9	
	Peat	8	
	Shrinking and or / aggregated clay	7	
	Sandy loam	6	
	Loam	5	
	Silty loam	4	
	Clay loam	3	
	Muck	2	
	Non Shrinking clay	1	

Impact vadose zone (I): The Impact of vadose zone media however, is known to be the unsaturated or the partially saturated zone between the soil layer and groundwater [10]. Therefore, for the purpose of this research, the aquifer media ratings were used to characterize the impact of vadose zone map which yielded the same map as in figure 6.

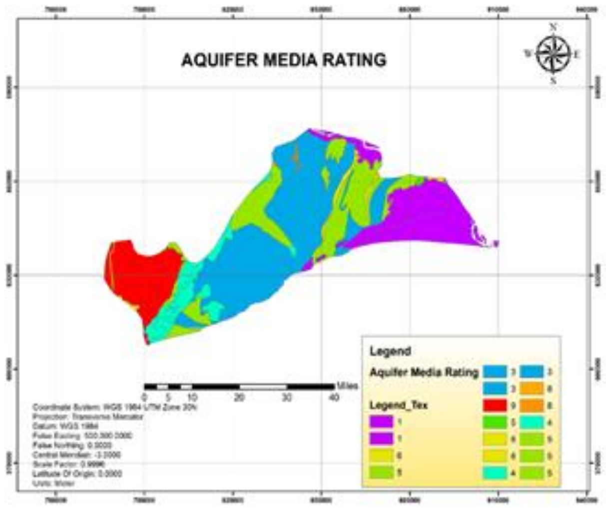

Figure 6: Aquifer Media Rating Map

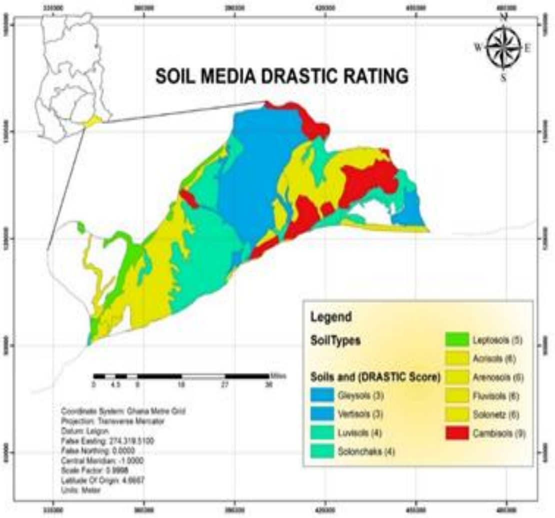

Figure 7: Soil Media Rating Map

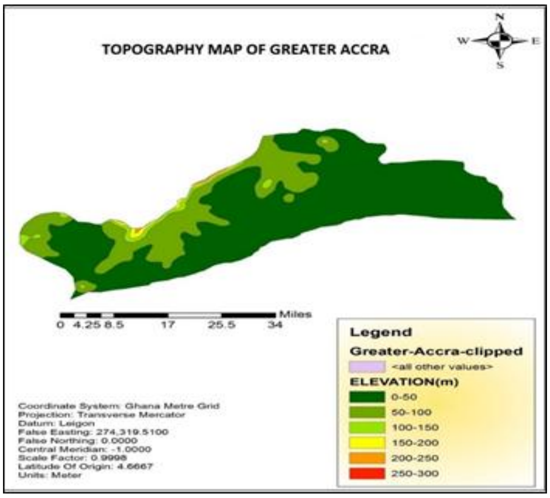

Figure 8: Topography (slope) rating map

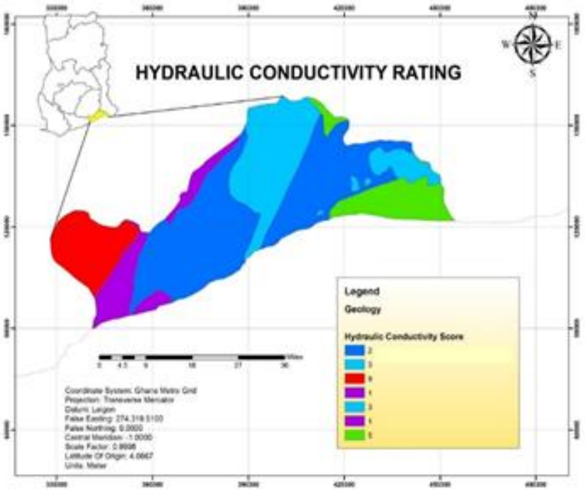

Figure 9: Hydraulic conductivity ration map

Table 9: Hydraulic conductivity showing approximated rating scores

Parameter	Range	Conductivity (1E m/s)	Weight	Rating
Aquifer Media	Granitoid (undifferentiated)	-3	3	9
	Unconsolidated Sand, clay and gravel	-5		5
	Sandstone, Grit (Coarse, hard siliceous sandstone), Shale	-8		1
	Red continental deposits mainly Sandy Clay and Gravel	-6		3
	Quartzite Sandstone shale phyllite schist	-9		1
	Acidic, Ortho paragnesis Schist migmatite	-7		2

Table 10: Modified DRASTIC soil media parameter

Parameter	Range	Rating	Weight
Soil Media	Cambisols Coarse medium , absence of clay	9	2
	Arenosols: loamy sand or coarser	7	
	Fluvisol: sandy loam	6	
	Leptosols: Sand or loamy	5	
	Solonchak: siltic and clayic	4	
	Luvisols: clay loam sans loam	4	
	Vertisols: Clay loam	3	
	Gleysols: Clay loam	3	

Hydraulic Conductivity (C): This refers to the ability of aquifer materials to transmit water, which in turn, controls the rate at which groundwater will flow under a given hydraulic gradient [8]. Thus, it is the amount of water that flows under an imposed hydraulic gradient. Therefore, the rate of transmitted contaminant along with water, is directly proportional to the flow rate of the groundwater.

Generally, hydraulic conductivity of a basin is studied by drilled wells. The study unfortunately, could not access satisfactory numbers of drilled wells. Therefore, for the purpose of this study, the hydraulic conductivity map was determined according to geological conditions.Therefore, by using the standard procedures of Ducci (2010) [28], hydrogeologic units (Gravel, Sand, Silty sand, Silt, Glacial deposits, Clay, Pyroclastic deposits, Clayey-marly sediments, Dolomite, Limestone and marble, sandstone, Volcanic rock, Crystalline rocks) were assigned ranges to correspond to their hydraulic conductivity.This made it possible to determine the DRASTIC scores for the hydraulic conductivity for Greater Accra region as shown in Table 9). Using the defined ratings of the hydraulic conductivity (from the aquifer media data), the obtained data is then converted to a raster data according to table10 to enable the generation of the hydraulic conductivity ration map (Fig. 9).

The overall DRASTIC Vulnerability Index Map: The weighted overlay of the seven parameters yielded the vulnerability index map (Fig. 10). The overlay of all the seven DRASTIC parameters, reveald that, Depth to water and hydraulic conductivity parameters greately influenced the DRASTIC Vulnerability Index Map (VIM), considering their respective weight of 5 and 3.

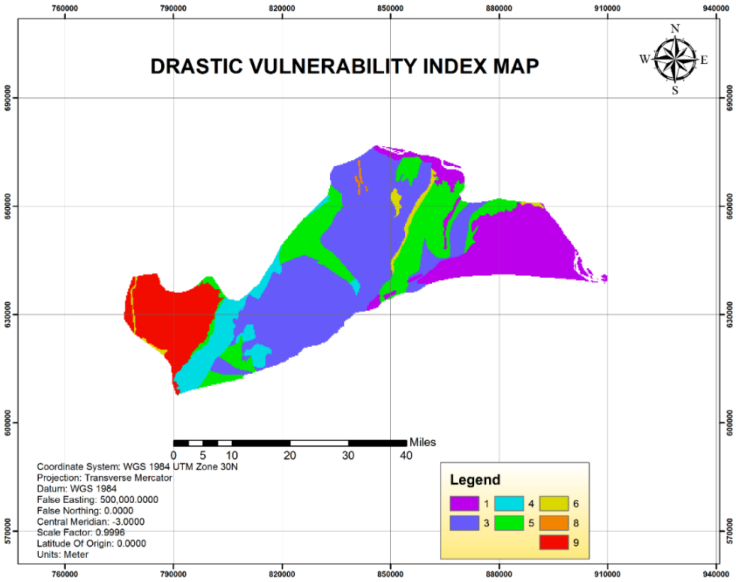

Figure 10: Overall Vulnerability Index Map of the study area

From the DRASTIC Vulnerability Index Map (VIM) of the study area, the north-western part is considdered to be the most vulnerable area to groundwater contamination showing the highest rating score of 9. However, in the central part, was considered moderate. The south-eastern part however, demonstrated the least aquifer vulnerability to contamination. This could be attributed to the lowest aquifer media score, due to the presence of clay and mudstone. As well as, the relatively low hydraulic conductivity, with soil texture mostly between fine and clay particles.

4. Conclusions

This preliminary study has been able to generate an aquifer vulnerability map of the Greater Accra region by virtue of a GIS-based DRASTIC model. This outcome can, however, serve as an initial tool for prudent management and land-use planning of the groundwater resource by the city authorities. The DRASTIC VIM produced, could allow decision-makers to evaluate current land use practices and make recommendations for changes in land use regulations and protect or prevent the groundwater from contamination.

Further monitoring and evaluation of the generated VIM of the study area could be built upon, to include potential sources of contamination. Moreover, apart from knowing the spatial distribution of the vulnerability of the aquifer in the entire study area, the model can also account for future changes in climate and land use conditions. This will also be a great resource to decision-makers to identify potential future threats to groundwater quality and take early steps to protect the resource. It is highly recommended that, the VIM could be further evaluated to include classifications of the vulnerability zones (thus, from very low to very high vulnerability) based on the surface area. This will provide needed information required by authorities and other stakeholders for groundwater resource protection, abstraction and management in order to achieve the desired goal of sustainable development.

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