Mapping of Ground Water Vulnerability for Landfill Site Selection Assessment at the Local Level— Case Study at the Mining Areas of Tarkwa, Ghana

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ABSTRACT

Municipal solid waste disposal by landfilling (mostly by open dumping) is common in Ghana and other developing countries. These landfill sites are mostly chosen without due consideration for the tendency of ground water pollution. This paper discusses and demonstrates the need for accounting for groundwater protection using pollution potential vulnerability modelling and mapping in the selection of landfill site. It is based on a case study in the Tarkwa Nsuaem Municipality of Ghana. Groundwater vulnerability maps have been developed by incorporating the major geological and hydrogeological factors that control the movement and contamination of groundwater, using overlay and indexed-based DRASTIC methods with GIS. These factors were rated, weighted and overlaid to create vulnerability maps showing areas prone to groundwater contamination at different degrees. The computed DRASTIC Index (DI) ranges between 93 and 154 and this was categorized into five vulnerability classes, namely "Very Low", "Low", "Moderate" "High" and "Very High". Landfill sites in the high and very high vulnerability areas were not recommended for development unless special provisions were available to guarantee adequate ground water protection. It is recommended that this approach should be integrated into landfill site selection analysis to help reduce the risk of groundwater pollution in the disposal of waste.

Keywords: *DRASTIC, Landfill Siting, Groundwater Vulnerability, Tarkwa Nsuaem Municipality*

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1. INTRODUCTION

Solid waste generation in Ghana and other developing countries is increasing at high rate due to the rapid population increase as well as the change in living standards and consumption patterns (Anon., 2010). Consequently, there is the need to expand existing landfill sites and prospect for potential landfill sites. Studies have shown that some existing landfill sites have polluted the groundwater (Jaseela *et al*., 2016; Ubavin *et al*., 2015; Aderemi *et al.*, 2011). Such landfill sites were selected without prior consideration to the potential of groundwater contamination from the waste materials. That being said, there is the need for a scientific tool that aid decision makers and land planners in planning for sustainable management and selection of landfill sites in the future. Thus, the focus of this research work is to generate groundwater pollution risk map for landfill siting analysis in the study area. A case study method is used, with the Tarkwa-Nsuaem municipality as the study area.

1.1. Location of Study Area

Geographically, the study area lies in the Tarkwa Nsuaem Municipal Area (TNMA) of Ghana. It is located between latitudes 50° 00′ N and 5° 25′ N and longitudes 1° 48′ W and 2° 10′ W and shares boundaries with Prestea Huni-Valley District to the north, Nzema East District to the West, Ahanta West District to the South and Mpohor Wassa East District to the East (Fig. 1). TNMA is accessible by trunk road and railways from major cities like Takoradi and Kumasi. The study area has an area of about 950 km^2 and a population of about 90,477 (Kwesi *et al.*, 2019; Anon.., 2014; Yankey *et al*., 2011).

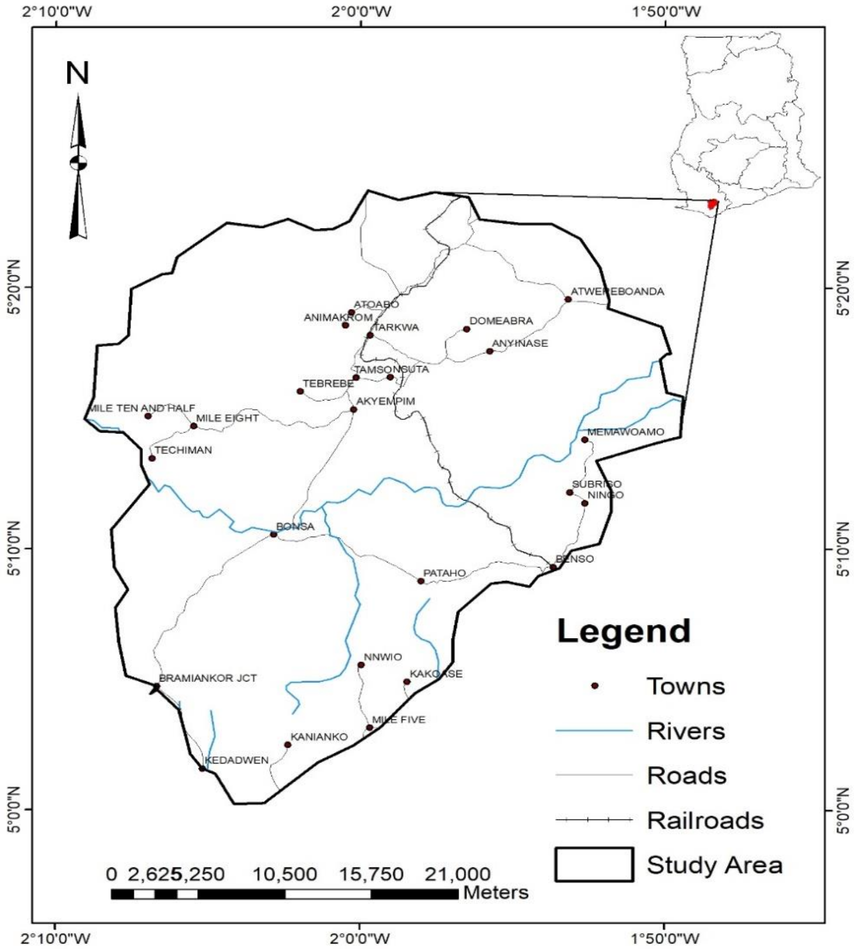

Fig.1 Map Showing the Location of Tarkwa Nsuaem Municipality

1.2 Geology and Hydrogeology

The study area is located within the Tarkwaian Group and forms part of the West Africa Craton. The Tarkwaian Group comprises a sequence of coarse, clastic, fluviatile meta-sedimentary rocks consisting of the Kawere conglomerates, Banket Series (Phyllite, Quartzite and Conglomerate hosting gold mineralisation), Tarkwa Phyllite and Huni Sandstone (Fig. 2). About 20 % of the total Tarkwaian rocks within the study area is made up of intrusive igneous rocks, which form conformable to slightly transgressive sills with small number of dykes. The Tarkwaian is underlain by the Birimian Supergroup (Kesse, 1985). The study area is faulted and jointed with the most prominent joints trending in WNW to ESE direction (Hirdes and Nunoo, 1994). The Tarkwaian and Birimian rocks of the area do not have adequate primary porosity. They are largely crystalline and inherently impermeable, unless fractured or weathered (Ewusi *et al.*, 2017). Groundwater occurrence is therefore associated with the development of secondary porosity and permeability. The zones of secondary permeability are often discrete and irregular and occur as fractures, faults, lithological contacts and zones of deep weathering (Kortatsi, 2002). The zones of secondary permeability are often discrete and irregular and occur as fractures, faults, lithological contacts and zones of deep weathering (Kortatsi, 2002).

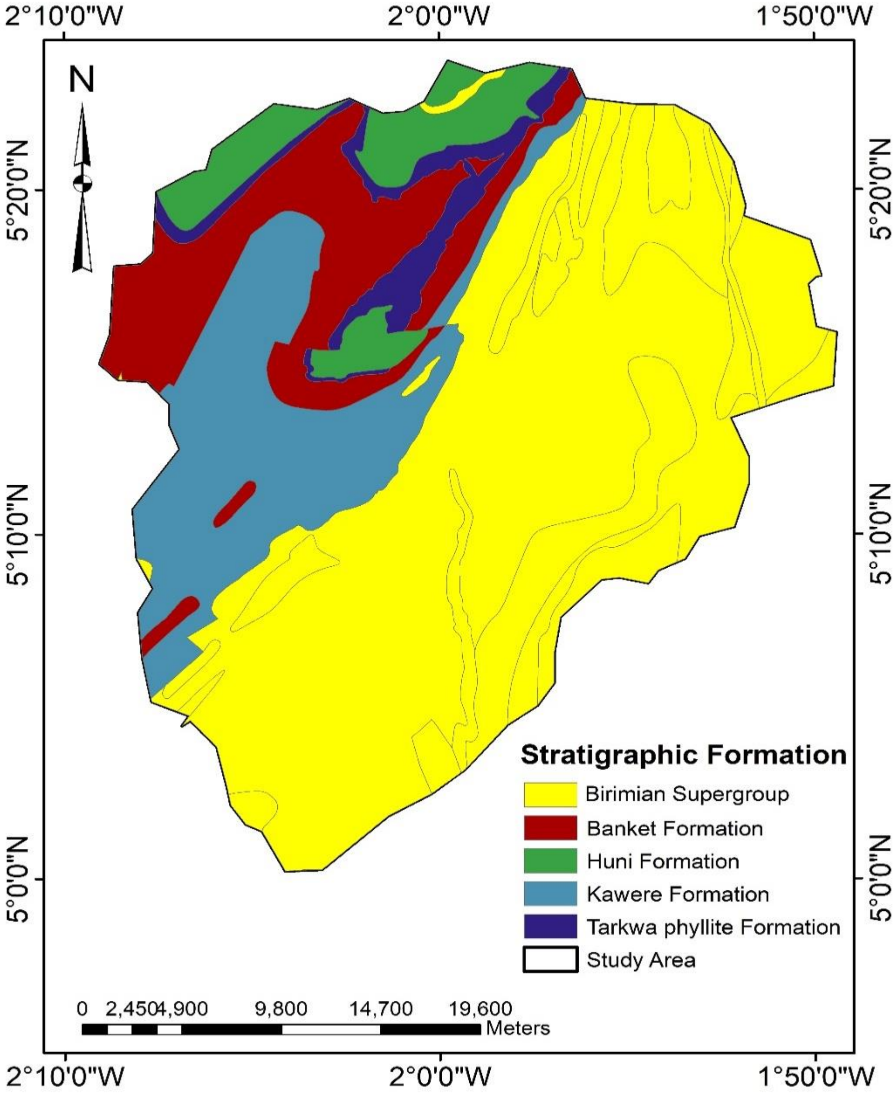

Fig. 2 Map Showing the Geology of the TNMA

Groundwater in the Tarkwa area occurs in two distinct hydraulically connected aquifer systems; an upper weathered zone aquifer and a deeper un-weathered aquifer or fractured zones and dyke contacts (Junner *et al.*, 1942). The weathered zone aquifer is generally phreatic and the principal groundwater flow occurs where relic's quartz veins are more abundant. The regolith is generally dominated by clay and silt rendering the aquifer highly porous, with high storage but low permeability. Thus, the aquifers are either unconfined or semiconfined depending on the clay and silt proportion. Aquifers are recharged by direct infiltration of precipitation through brecciated zones and the weathered outcrop (Kortatsi, 2002). Groundwater recharge and actual evapotranspiration have been estimated at between (11-17) % and 54 % respectively of annual rainfall (Kuma, 2007)

1.3 Socioeconomic and Environmental Background

TNMA is one of the important mining centres in Ghana that attracts many people from other parts of the country, Africa and the world. It is also an important commercial and transit centre for traders and migrant workers in mining and related businesses. These conditions have contributed to rapid urbanisation, high population growth rate, high waste generation volumes and disposal problems, illegal mining operations and land use conflicts, environmental pollution, both surface and ground water contamination problems and other related social problems in the area (Kwesi, *et al*, 2019; Anon., 2014; Kusi-Ampofo and Boachie-Yiadom, 2012; Kuma and Ewusi, 2009; Anon., 2009; Anon., 2008).

2. MATERIALS AND METHODS USED

2.1 Data Sources

Secondary data was used to carry out this research work. The hydrogeological parameters were obtained from previous publications. The Digital Elevation Model (DEM) for the slope analysis was obtained from ASTER Global DEM (GDEM). ASTER GDEM is a product of METI and NASA. The Soil media data was obtained from soil map of Ghana published by FAO ISRIC.

2.2 Groundwater Vulnerability Analysis Methods

Many approaches have been developed for assessing groundwater vulnerability and can be grouped into three major categories (Tesoriero *et al.*, 1998): (1) overly and index methods; (2) methods employing process-based simulation models; (3) statistical methods. In overly and index methods, factors which are controlling movement of pollutants from the ground surface into the saturated zone (e.g., geology, soil, impact of vadose zone, etc.) are mapped depending on existing and/or derived data. Subjective numerical values (rating) are then assigned to each factor based on its importance on controlling pollutants movement. The rated maps are combined linearly to produce final vulnerability map of an area. The groundwater vulnerability evaluated by such methods is qualitative and relative. The main advantage of such methods is that some of the factors controlling movement of pollutants (e.g., net recharge and depth to groundwater table) can be evaluated over large area, which makes them suitable for regional scale assessment (Thapinta and Hudak, 2003). With the advent of GIS digital maps technology, adoption of such methods for creating vulnerability maps is an easy task. Several overly and index methods have been developed. The most common ones are the DRASTIC method (Aller *et al*. 1987), the GOD method (Foster, 1987), The AVI rating method (Van Stempvoort *et al*. 1993), the SINTACS method (Civita 1994), the German method (Von Hoyer and So¨fner 1998), the EPIK (Doerfliger and Zwahlen 1997), and the Irish perspective (Daly et al. 2002). Process-based methods and statistical methods are not commonly used for vulnerability assessment because they are constrained by data shortage, computational difficulty, and the expertise required for implementing them.

2.3 The DRASTIC METHOD

The DRASTIC method, which is the most popular overlay and index method used to evaluate intrinsic groundwater vulnerability, was selected for the research work, due to its efficiency and ease of application (Al-Abadi *et al.,* 2014). It is an overlay and index method designed to produce vulnerability scores by combining several thematic maps. It was originally developed in USA under cooperative agreement between the National Water Well Association (NWWA) and the US Environmental Protection Agency (EPA) for detail hydrogeological evaluation of pollution potential (Rundquist *et al*., 1991). The word DRASTIC is acronym for seven factors deemed most important in or for the control groundwater pollution within a hydrogeological setting. Hydrogeological setting is a composite description of all major geologic and hydrogeological factors that affect groundwater movement into, through, and out of, a given area. These factors are: *depth to water, net recharge, aquifer media, soil media, topography (slope), impact of vadose zone,* and *hydraulic conductivity* (Fig. 3). The DRASTIC numerical ranking system contains three major parts: *weights, ranges* and *ratings*. The significant media types or classes of each parameter represent the ranges, which are usually rated from 1 to 10 based on their relative effect on the aquifer vulnerability. The method yields a numerical index that is derived from ratings and weights assigned to the seven parameters. The seven parameters are then assigned weights ranging from 1 to 5 (usually) to reflect their relative importance (Table 1). The DRASTIC Index is then computed applying a linear combination of all the factors according to the following equation:

$$DRASTIC\ Index = \boldsymbol{D_r}.\boldsymbol{D_w} + \boldsymbol{R_r}.\boldsymbol{R_W} + \boldsymbol{A_r}.\boldsymbol{A_w} + \boldsymbol{S_r}.\boldsymbol{S_w} + \boldsymbol{T_r}.\boldsymbol{T_w} + \boldsymbol{I_r}.\boldsymbol{I_w} + \boldsymbol{C_{w.}}\boldsymbol{C_r} \quad \ldots (1)$$

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.

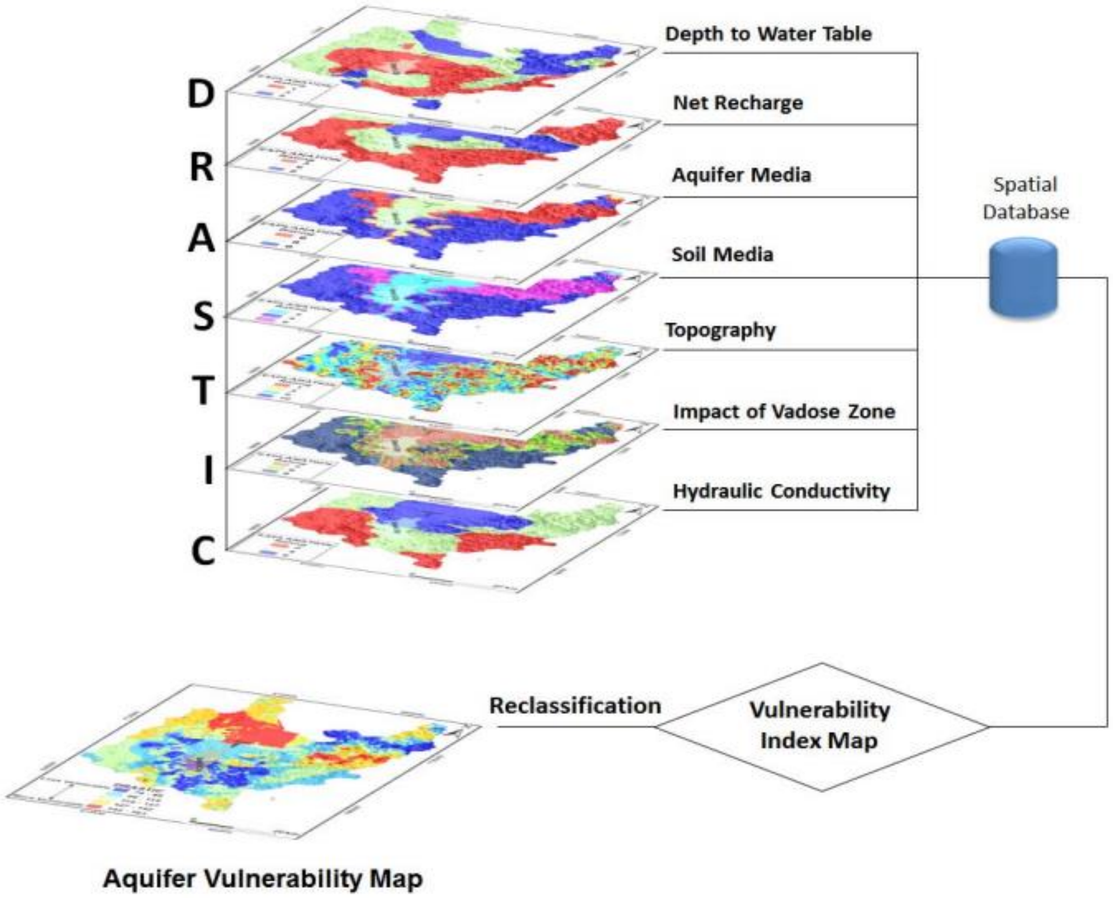

Fig 3 Flow Chart of the DRASTIC Model

Table 1 Ratings and Weights for the DRASTIC Parameters

Parameter	**Range**	**Rating**	**Weight**
Depth to Water table (m)	3.50 - 5.05	9	5
	5.05 - 8.05	7	
Net Recharge (mm)	70 - 136	5	4
	136 - 175	6	
	175 - 220	8	
	220 - 298	9	
Aquifer Media	Volcanic rocks	2	3
	Quartzite/Conglomerate	4	
	Phyllite	5	
	Sandstone	6	
Soil Media	Silt	2	2
	Laterite	4	
Topography (%)	0 – 2	10	1
	2 – 6	9	
	6 – 12	5	
	12 – 18	3	
	>18	1	
Impact of Vadose Zone	Laterite	4	5
	Sand, silt and gravel	4	
	Silt	2	
	Silt, sand, fractured Quartzite	5	
	Silt-sand, fractured Sandstone	6	
Hydraulic Conductivity (m/day)	0.06 - 0.30	1	3
	0.30 - 0.50	2	

Source: (Aller *et al*., 1987; Al-Zabet, 2002)

3. RESULTS AND DISCUSSIONS

3.1 Depth to Groundwater (D)

It is the depth from the ground surface to the water table in unconfined aquifer and to the bottom of the confining layer in confined aquifer. It represents the depth of material from the ground surface to the water table through which a contaminant travels before reaching the aquifer. The shallower the water depth, the more vulnerable the aquifer is to pollution and vice versa. The depth to groundwater data was interpolate d across the study area using the Inverse Distance Weighting (IDW) method. The resulting raster output was reclassified and rated according to Table 1. The depth to groundwater ranges from 3.5 to 8 m (Fig. 4).

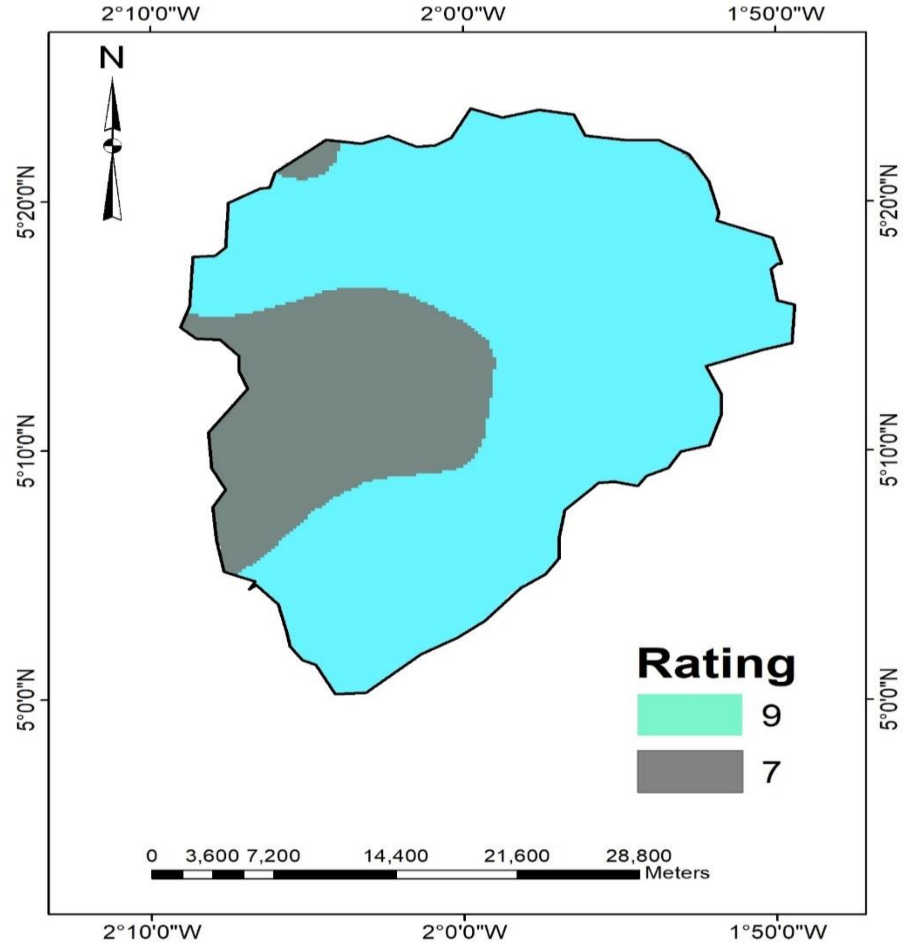

Fig. 4 Depth to Groundwater Map Showing the DRASTIC Ratings

3.2 Net Recharge

Net recharge is the total quantity of water per unit area, in millimeters per year, which reaches the water table. Recharge is the principal vehicle for leaching and transporting contaminants to the groundwater. The primary source of recharge in the study area is precipitation (1 500 mm to 1 933 mm per year), which infiltrates through the ground surface and percolates to the water table.. Though precipitation in the study area is relatively high, the net recharge is controlled by the subsurface geologic materials; land use and land cover conditions of the area. The net recharge data was interpolated over the study area using IDW interpolation technique. Fig. 5 shows the ratings of the net recharge for the study area.

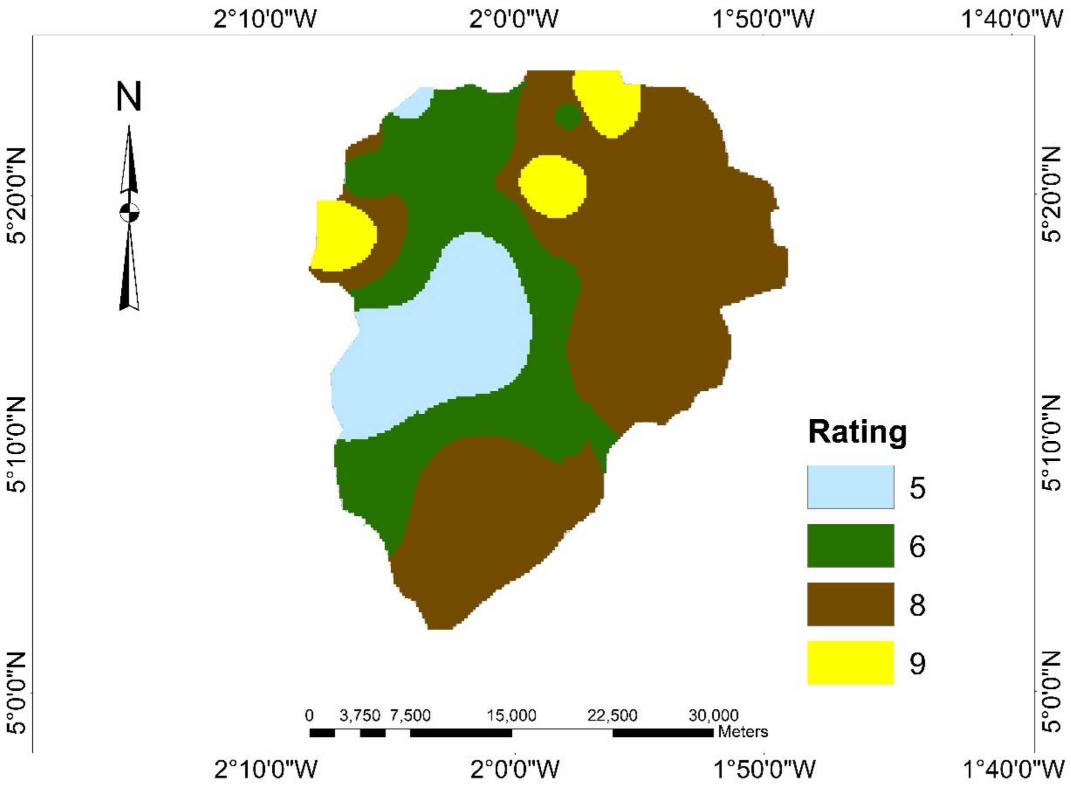

Fig. 5 Map Showing the Net Recharge Ratings

3.3 Aquifer Media

It is consolidated or unconsolidated rock, which serves as an aquifer. Based on the geological description of the study area (Kesse, 1985), the aquifer media was classified as fractured volcanic rock, Phyllite, quartzite, sandstone and conglomerate, which has a rating of between 2 and 6 and a weight of 3 (Table 1). Fig. 6 is a map showing the ratings of the aquifer media.

3.4 Soil Media

Soil media is the upper weathered zone of the earth, which averages a depth of six feet or less from the ground surface (Alwathaf and Mansouri, 2011). The predominant soil types in the area are laterite and silt. Laterites have larger grain sizes than silt, hence high draining capability than silt. The higher the draining capability, the greater the risk of groundwater contamination by infiltration. Consequently, the laterite was assigned a rate of 4 whereas the silt, a rate of 2 (Table 1). The vector layer of the soil map was converted to a raster grid and reclassified by the rating factors (Table1) to produce the map presented in Fig. 7.

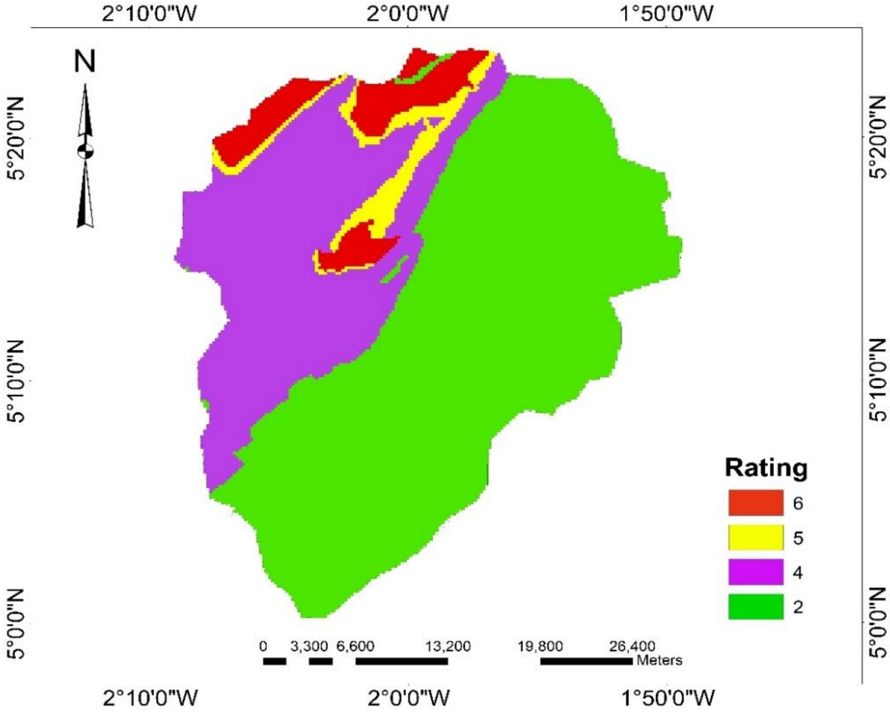

Fig. 6 Aquifer Media Ratings Map for TNMA

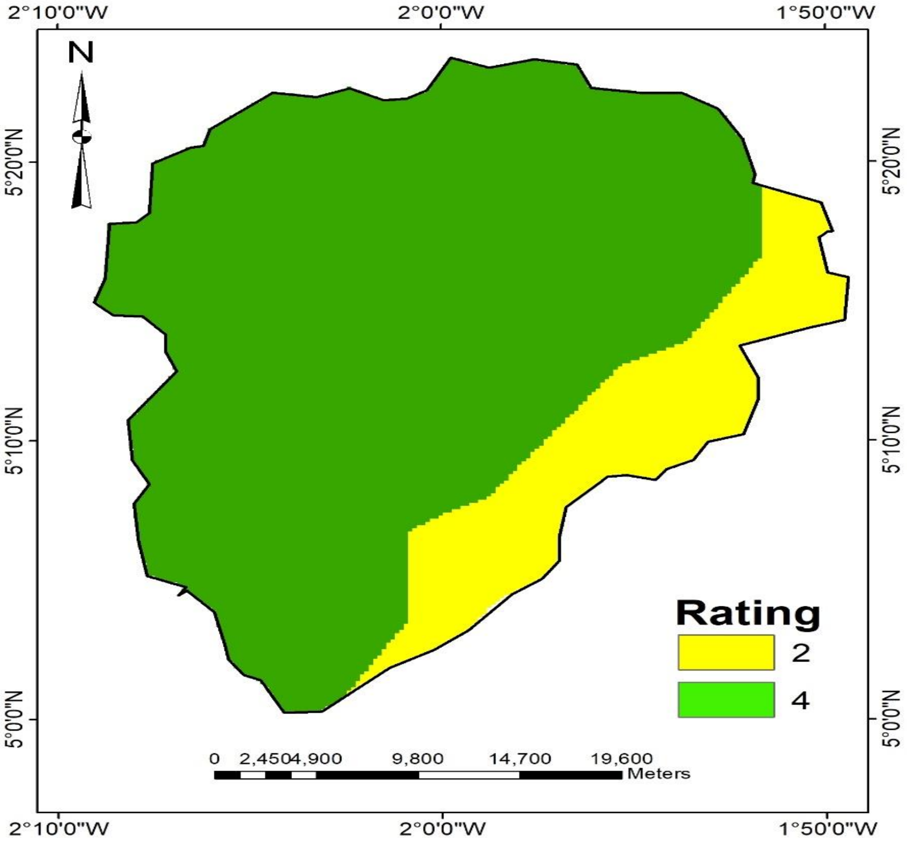

Fig. 7 Soil Media Ratings Map for TNMA

3.5 Topography

Topography refers to the slope variability of the land surface. Topography helps control the likelihood that a pollutant will run off or remain long enough to infiltrate through the ground surface. Where slopes are low, there is little runoff, and the potential for pollutants to seep through the ground is high. On the other hand, where slopes are steep, runoff capacity is high and the potential for pollution to get to the groundwater is lower. Digital elevation model (DEM) was used to calculate slope percentages. The resulting slope map was reclassified according to Table 1, to generate the slope ratings map (Fig.8).

3.6 Impact of Vadose Zone

The vadose zone is the unsaturated zone above the water table. The texture of the vadose zone determines the time of travel of the contaminant through it. The constituents of the vadose zone include silt, laterite, quartzite, conglomerate, sand, sandstone, and silt with gravel. They were rated according to their grain size and degree of permeability. Fig. 9 shows the impact of the vadose zone ratings map.

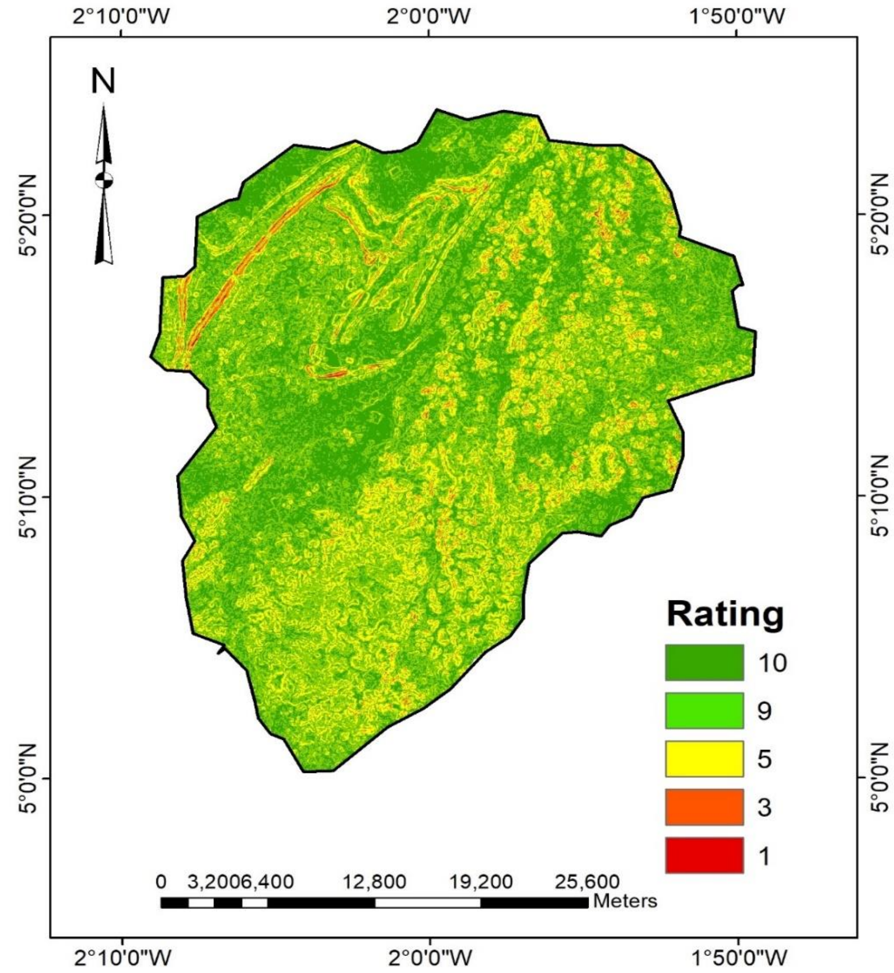

Fig. 8 Topography Ratings Map for TNMA

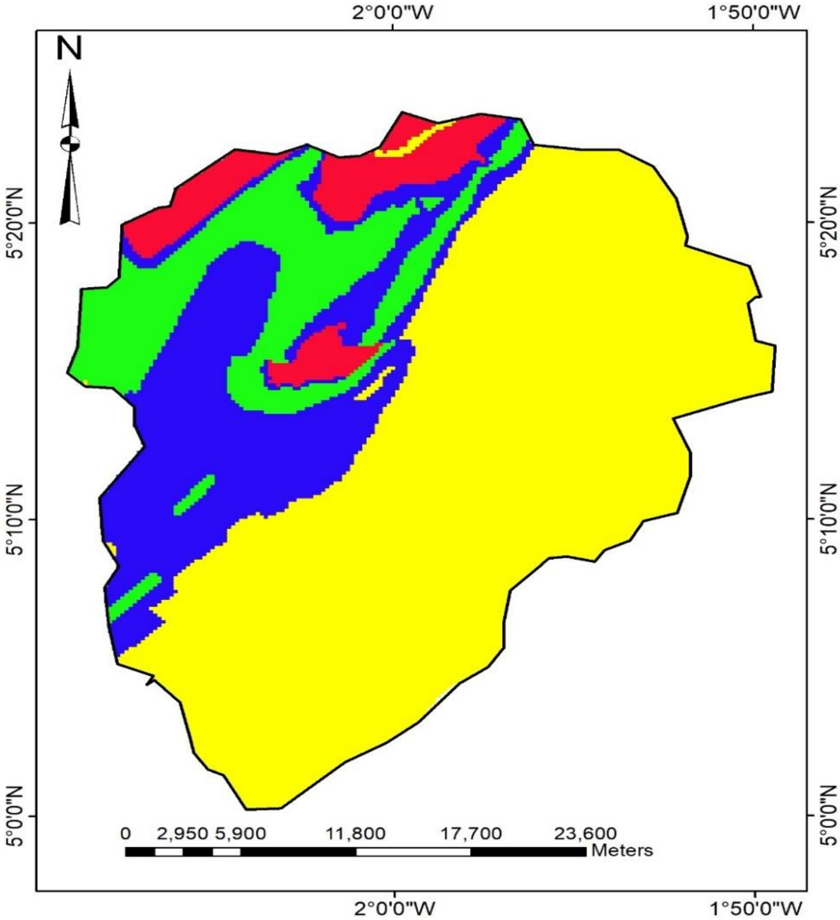

Fig. 9 Impact of Vadose Zone Ratings Map for TNMA

3.7 Hydraulic Conductivity

Hydraulic conductivity refers to the rate at which water flows horizontally through an aquifer. The higher the hydraulic conductivity, the more vulnerable the aquifer. The hydraulic conductivity within the study area ranges between 0.06 to 0.5 m/day. The hydraulic conductivities of the shallow aquifers within the study area were reclassified according to the criteria of DRASTIC model using reclassify tool in spatial analyst extension of ArcGIS environment (Fig. 10).

3.8 DRASTIC Index (DI) and Vulnerability Map

The DRASTIC Index map was created using the raster calculator in spatial analyst tool in ArcMap 10.3. Equation 1 was used to generate the index map. The output index map was reclassified according to Table 2 to produce the final groundwater vulnerability map (Fig. 11). The groundwater vulnerability map shows that the very high to moderate vulnerability classes occur at the northwestern part of TNMA and occupies about 30 % of the study area. The DI of the classes range from 119 to 154 respectively. Very low to low classes with DI of 93 to 119 respectively, occur at the southern part of the study area. It can be inferred that the southern area with low vulnerability belongs to the Birimian Supergroup. The aquifer media is made of volcanic rocks with very low hydraulic conductivity (0.076 m/day). Silt, which has relatively low permeability, is the predominant soil and vadose zone material. Thus, the groundwater vulnerability of the southern part of the study is low. Conversely, the northwestern part of the study area is characterised by moderate to very high vulnerability. Sandstones, Phyllite, sand, gravel and laterite, with relatively high hydraulic conductivities (0.1 to 0.4 m/day) constitute the aquifer and vadose zone media. Thus, the moderate to very high vulnerability of the northwestern part of the study area.

Table 2 Evaluation Criteria for Degree of Vulnerability

Class	**Vulnerability Potential**
93 - 110	Very Low
110 - 119	Low
119 - 130	Moderate
130 - 145	High
145 - 154	Very High

(Source: Aller *et al.*, 1987; Civita and De Regibus, 1995)

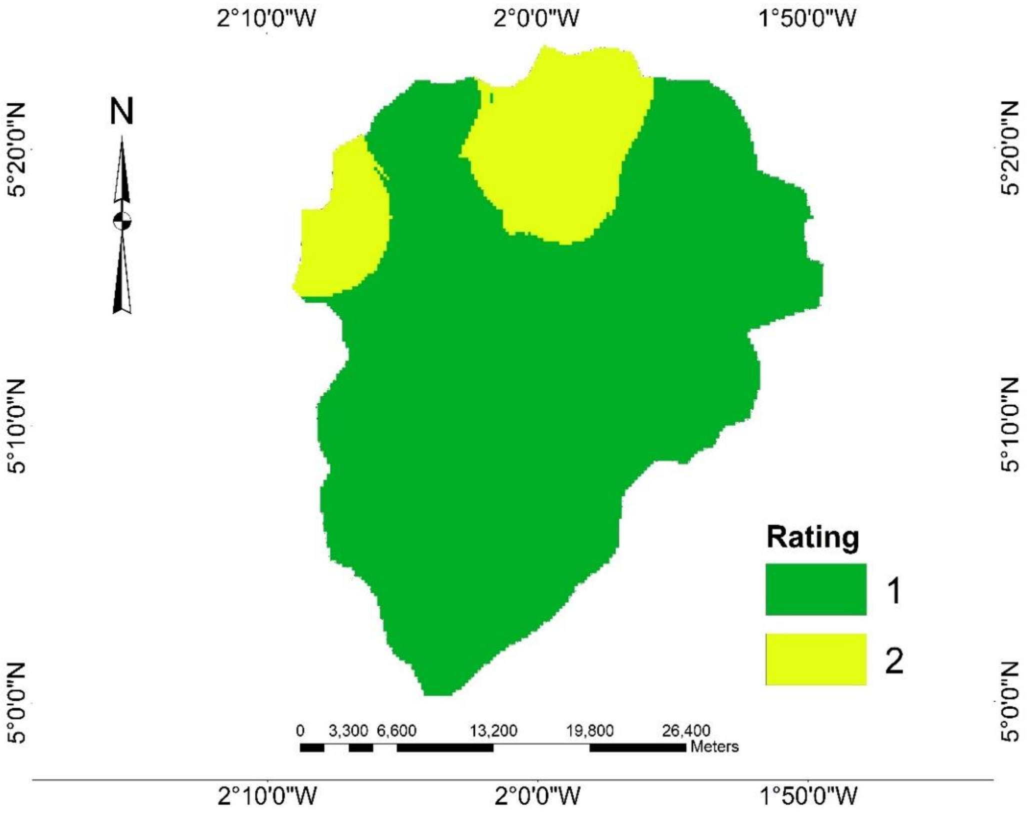

Fig. 10 Hydraulic Conductivity Ratings Map for TNMA

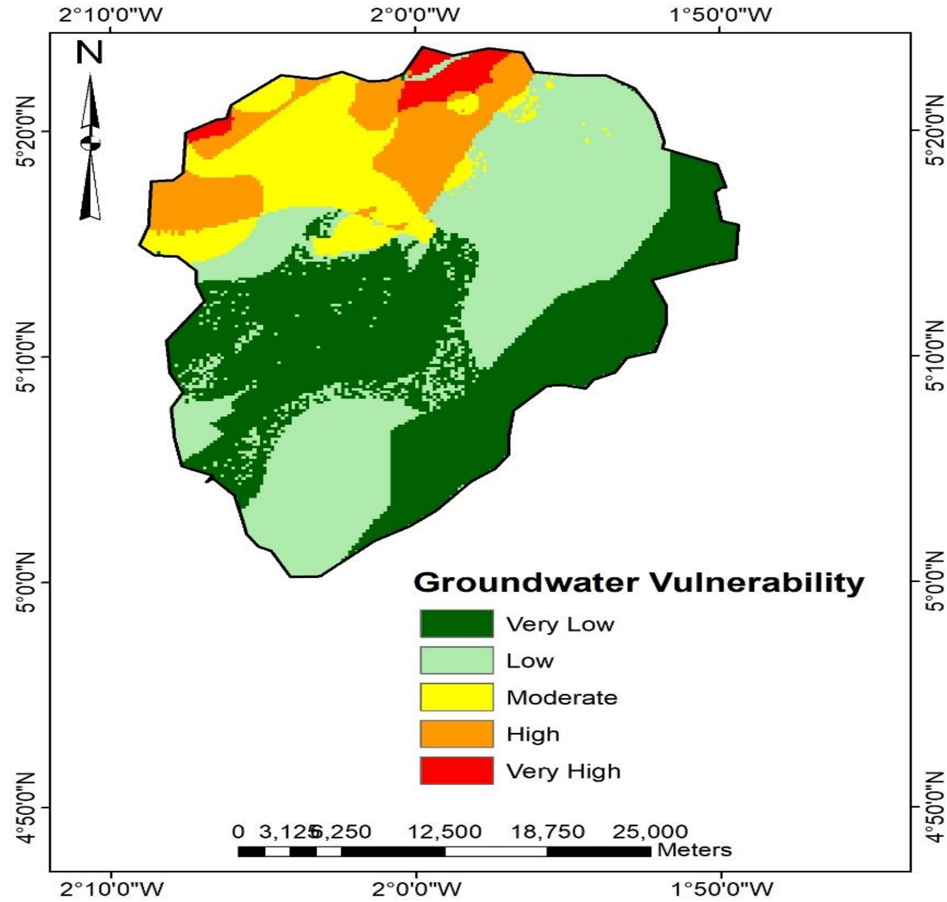

Fig. 11 Groundwater Vulnerability Map of TNMA

4. CONCLUSION

The overlay and index DRASTIC model was deployed into GIS to assess the intrinsic vulnerability and risk for groundwater contamination at Tarkwa Nsuaem Municipality. The method uses the hydrogeological and topographical characteristics to determine the natural vulnerability of the groundwater resources. The obtained vulnerability map from the DRASTIC method gives location, which must have high priority in terms of protection and pollution prevention. The computed DRASTIC Index (DI) ranges between 93 and 154. The DI was categorised into five vulnerability classes; "Very Low", "Low", "Moderate", "High" and "Very High". The moderate to very high vulnerability potential zones occur at the northwestern part of the study, which are situated within the Tarkwaian system comprising of sandstones, conglomerates and quartzites. The three classes constitute 33.52 % of the total area of TNMA. The very low to low classes occur at the southern part of TNMA, within the Birimian Supergroup, which comprises of volcanic rocks. Based on these DRASTIC results, landfill sites in the high and very high vulnerability areas are not recommended for development unless special provisions are available to guarantee ground water protection. Conversely, landfill sites situated at the southern part of TNMA, within the Birimian system, would have low potential of contaminating the aquifers and hence may be recommended for development. It is further recommended that the DRASTIC groundwater vulnerability assessment be integrated into landfill site selection analysis to help reduce the risk of groundwater pollution in the disposal of waste in the study area and similar locations.

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BIOGRAPHICAL NOTES

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