Mapping of Ground Water Vulnerability for Landfill Site Selection Assessment at the District Level - A Case Study at the Tarkwa Nsuaem Municipality of Ghana*

[1]E. A. A. Kwesi, [1]K. N. Asamoah, [2]F. A. Arthur and [3]J. A. Kwofie
[1]University of Mines and Technology, Tarkwa, Ghana.
[2]Missouri University of Science and Technology, Rolla Missouri, USA
[3]University of Manchester, UK, Manchester

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Abstract

Municipal solid waste disposal by landfilling (mostly 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 sites. The Tarkwa Nsuaem Municipal Area (TNMA) of Ghana is selected as a case study area. A groundwater vulnerability model has been developed by incorporating the major geological and hydrogeological factors that control the movement and contamination of groundwater, using an overlay and indexed-based DRASTIC method with GIS. These factors were rated, weighted and overlaid to create a vulnerability model showing areas prone to groundwater contamination. Based on the groundwater vulnerability model, landfill sites situated in the northern part of TNMA, within the Tarkwaian system would have high to very high potential of contaminating the groundwater. However, landfill sites situated at the southern part of TNMA, within the Birimian system, would have low potential of contaminating the aquifers. It is recommended that this approach 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, Waste Disposal

1 Introduction

Solid waste volumes are increasing at high rates due to rapid population increase as well as the change in living standards and consumption patterns (Jinhui *et al*., 2019). Consequently, there is the need to expand existing landfill sites and prospect for potential ones. Studies have shown that some existing landfill sites have polluted groundwater (Jaseela *et al*., 2016; Ubavin *et al*., 2015; Aderemi *et al*., 2011). Such landfill sites might have been 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.

1.2 Geographic and Socio-Economic Setting

The study area lies within the Tarkwa Nsuaem Municipal Area (TNMA) of Ghana in West Africa (Fig. 1). It is located between latitudes 5° 00′ N and 5° 25′ N and longitudes 1° 48′ W and 2° 10′ W. Tarkwa, the administrative capital which is the most popular and vibrant mining center in the area, is accessible by both rail and road from Takoradi and Kumasi. The area is host to many of the big mining companies and mining activities in Ghana and thus attracts many people from other parts of the country, Africa and the world, for jobs and other socioeconomic activities (Kwesi *et al.,* 2018; Anon., 2008). It is also an important commercial and transit centre linking the western and coastal towns to other parts of Ghana, and travelers from neighboring countries (Kwesi *et al.,* 2018). These conditions have contributed to rapid urbanisation, high population growth rate (3.0%), high waste generation volumes, disposal problems, illegal mining operations and environmental pollution problems in the area (Kwesi*et al.*, 2018; Anon., 2014; Anon, 2008). Waste collection is at a very low level (about 10%) giving rise to open dumping at inappropriate locations with high sanitation and groundwater pollution problems (Kwesi *et al.,* 2018). In order to control this, the Ghana government has put in policy measures requiring all Municipal Authorities to phase out open dumping and replace them with engineered landfilling and other improved waste disposal methods (Anon., 2010; Kwesi *et al.,* 2018). It is in line with the implementation of this policy that this paper highlights the need for groundwater protection in the search for suitable disposal sites, especially in mining areas where surface water bodies are polluted and many people depend on ground water

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for domestic and other uses (Yankey *et al.,* 2011; Asante, 2011; Kuma and Ewusi, 2010).

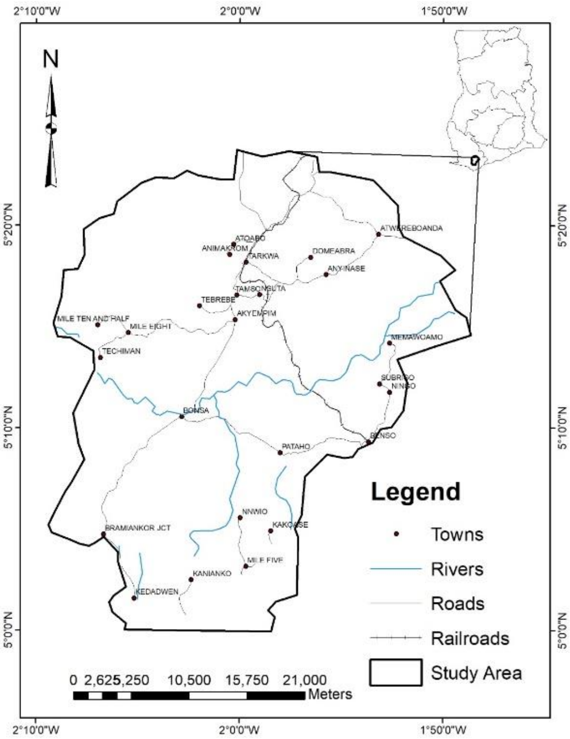

Fig. 1 Map showing the Location of TNMA

1.2 Geologic Setting 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 thus 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).

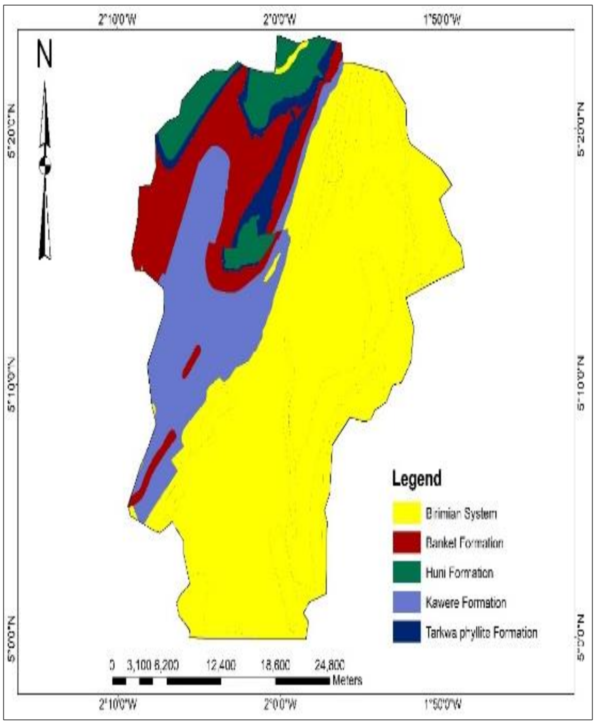

Fig. 2 Map showing the Geology of TNMA

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).

2 Resources 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, 1993), 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; Thapinta and Hudak, 2003). 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 most important seven factors within the hydrogeological settings which control groundwater pollution. Hydrogeological setting is a composite description of all major geologic and hydrogeological factors, which affect the groundwater movement into, through, and out of the area. These factors are: depth to water, net recharge, aquifer media, soil media, topography (slope), impact of vadose zone, and hydraulic conductivity (Fig. 3).

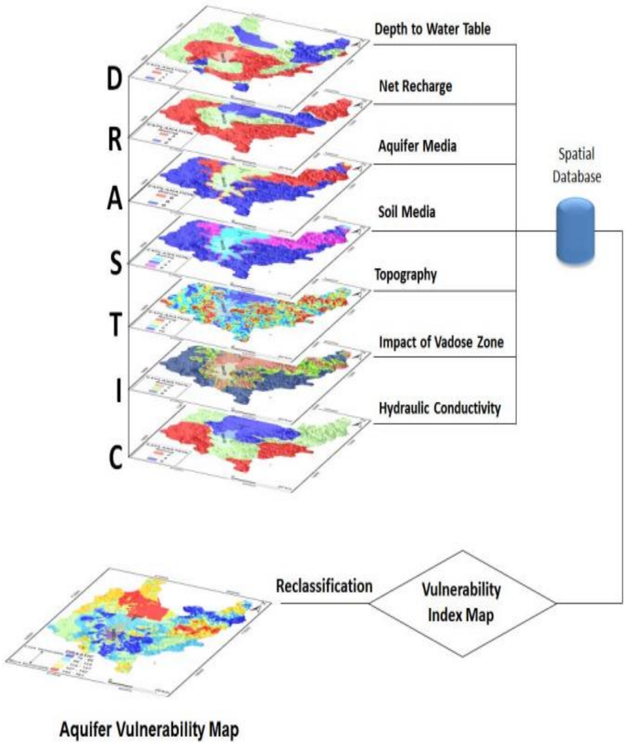

Fig. 3 Flow Chart of the DRASTIC Model (after Alwathaf *et al*., 2011)

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 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 reflecting their relative importance (Table 1). The DRASTIC Index is then computed applying a linear combination of all factors according to the following equation:

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

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.

Table 1 Ratings and Weights for the DRASTIC Parameters (Aller *et al*., 1987, Al-Zabet, 2002)

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, fractured Quartzite, sand	5	
	Silt-sand, fractured Sandstone	6	
Hydraulic Conductivity (m/day)	0.06 - 0.30	1	3
	0.30 - 0.50	2	

3 Results and Discussion

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).

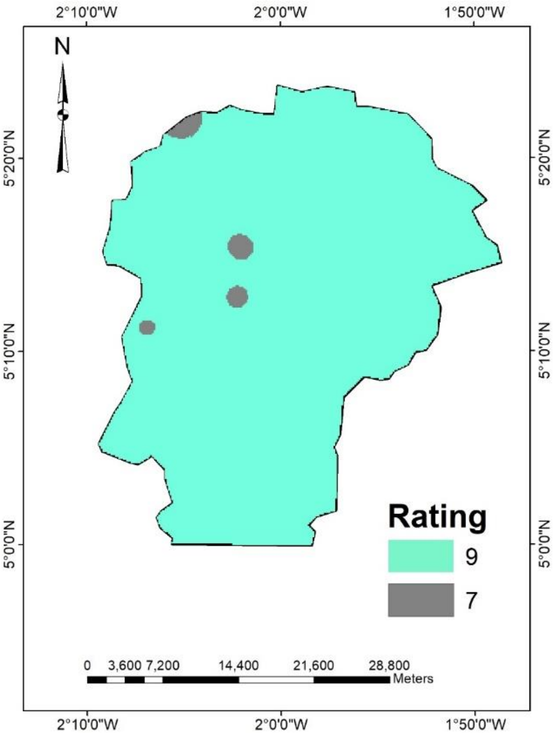

Fig. 4 Groundwater Depth Ratings Map

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.

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.

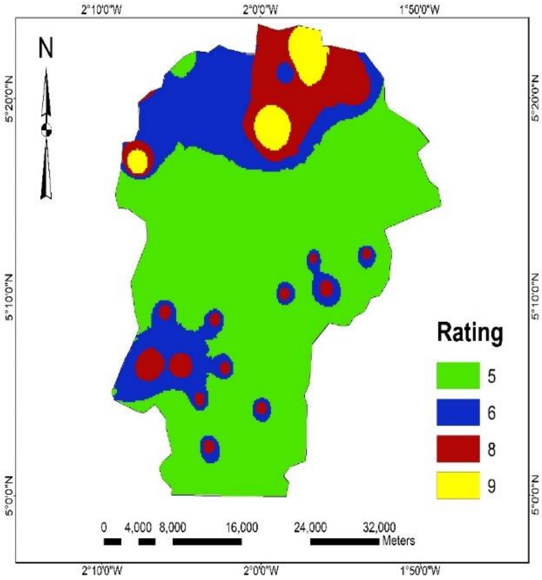

Fig. 5 Net Recharge Ratings Map for TNMA

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 at Fig. 7.

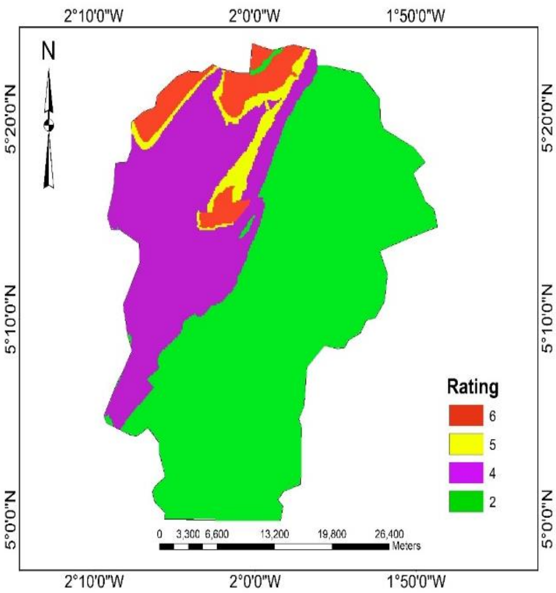

Fig. 6 Aquifer Media Ratings Map for TNMA

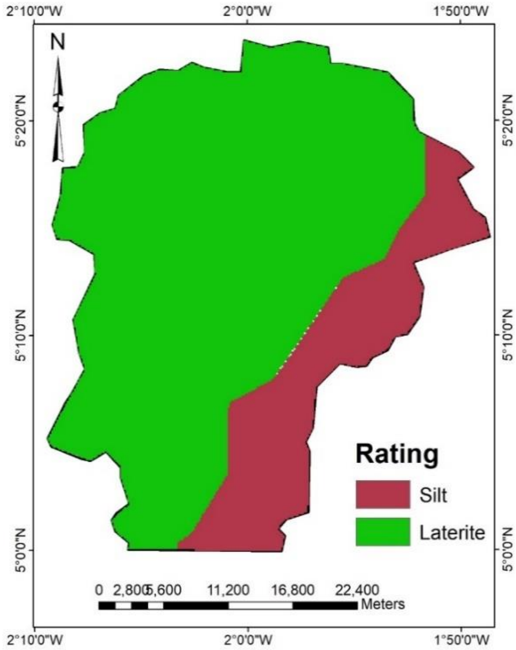

Fig. 7 Soil Media Ratings Map for TNMA

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).

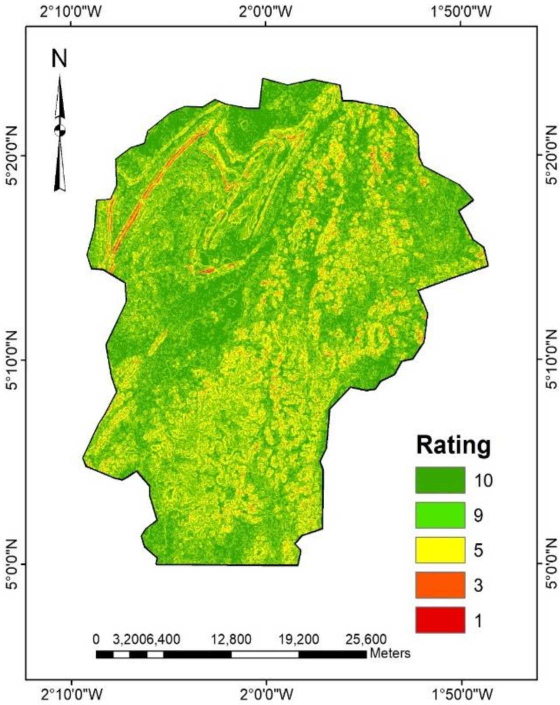

Fig. 8 Topography Ratings Map for TNMA

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.

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 (Fig. 10). The hydraulic conductivities of the shallow aquifers within the study area were reclassified according to the criteria of DRASTIC model using reclassify tool in the spatial analyst extension of ArcGIS environment.

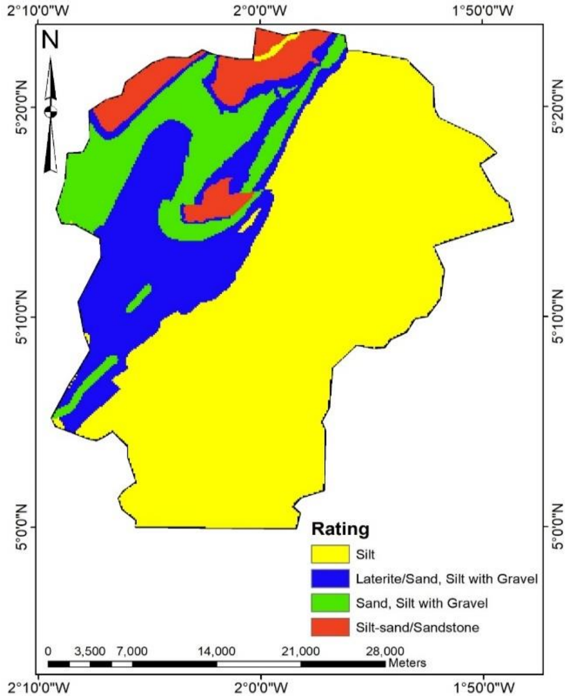

Fig. 9 Vadose Zone Impact Ratings Map for TNMA

3.8 The DRASTIC Index (DI)

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).

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

(After Aller *et al.*, 1987)

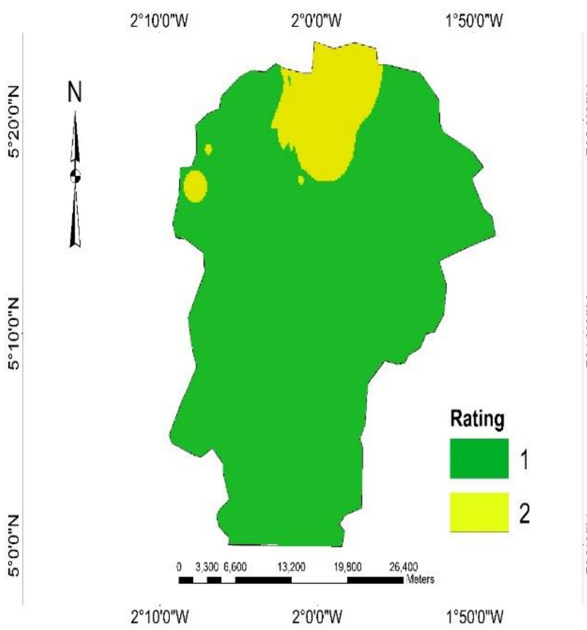

Fig. 10 Hydraulic Conductivity Ratings Map

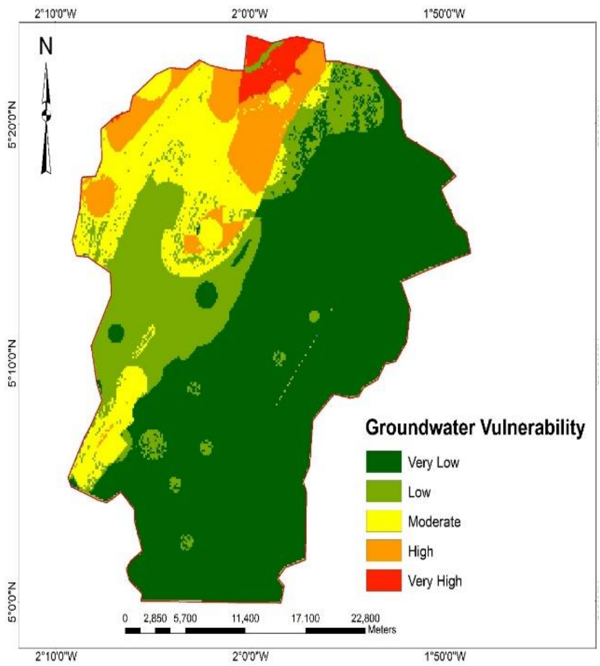

Fig. 11 Groundwater Vulnerability Map of TNMA

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 northwestern part of TNMA is characterised by moderate to very high groundwater vulnerability.

The groundwater vulnerability model (Fig. 11) may be used by site selection analysts to prioritize the number of candidate sites to be presented for final selection after regulatory requirements and other suitability criteria have been met in the initial analyses. Thus, candidate sites that lie within the high and very high groundwater vulnerability areas may be rejected while those lying in the low and moderate vulnerability areas may be considered for final selection (Fig. 11). Decision Makers and Regulatory Agencies may also apply the groundwater vulnerability model as checks on proposed sites presented to them for approval by project proponents or analysts.

The reliability of the methods and results presented in this paper depends on the quality of the data sets used. In the current work, some of the data sets used were generalised regional and district data (for example the geological and soil data) while some were site-specific ones (for example the water levels) but did not cover the entire study area and hence interpolation was applied. The results presented in this paper are therefore useful for the initial selection of alternative sites for developments in which groundwater pollution prevention is a key factor to account for such as in landfill siting. Detailed site-specific groundwater pollution investigation will still be necessary in the final site selection process before development begins.

4 Conclusions and Recommendations

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 resulting 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 categorized into five vulnerability classes; "Very Low", "Low", "Moderate" "High" and "Very High". The high to very high vulnerability potential zones occur at the northern part, with patches at the northwestern part of the study area, which are situated within the Tarkwaian system comprising of sandstones, conglomerates and quartzites. The two classes constitute about 10 % of the total area of TNMA. The very low to moderate classes occur at the northwestern, southern and southeastern part of TNMA, with the majority within the Birimian Supergroup, which comprises of volcanic rocks. Based on the groundwater vulnerability model, any landfill site situated in the northern part of TNMA, within the Tarkwaian system would have high to very high potential of contaminating the groundwater. Conversely, landfill site situated at the southern part of TNMA, within the Birimian system, would have low potential of contaminating the aquifers. We recommend that DRASTIC groundwater vulnerability assessment be integrated into landfill site selection analysis to help reduce the risk of groundwater pollution in the disposal of waste.

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Authors

E. A. A. Kwesi is currently a Lecturer at the Geomatic Engineering Department of the University of Mines and Technology (UMaT), Tarkwa, Ghana. He holds MPhil. Degree in Mining Engineering from UMaT and BSc Degree in Geomatic Engineering from the Kwame Nkrumah University of Science and Technology (KNUST), Ghana. He is a member of Ghana Iinstitue of Surveyors (GhIS), Ghana Iinstitute of Geosciences (GhIG), Federation of International Geomaticians (FIG), Society of Mining, Metallurgy, and Exploration (SME) and Global Land Programme (GPL). His research and consultacy works cover Surveying and Mapping, Community Involvement and Multicriteria Decision Making and their applications in Sustainable Management of Land, Agriculture, Solid Waste and Community Development in Mining Areas.

K. N. Asamoah currently working as a Graduate Teacher and pursuing his MPhil. Degree in Geology at the University of Mines and Technology (UMaT), Tarkwa, Ghana. He holds a BSc in Geological Engineering from the Kwame Nkrumah University of Science and Technology (KNUST), Ghana. He is a member of Ghana Institution of Geoscientist. His research areas include geophysics, geostatistics, GIS and remote sensing and their applications in Mining, Waste Management and related fields.

F. A. Arthur is currently working as a Geomechanic Engineer at Freeport McMoRan Inc., USA. He holds a PhD degree in Mining and MSc Degree in Geology and Mining from the Missouri University Science and Technology, in the USA, and a BSc Degree in Mining from the University of Mines and Technology, Tarkwa, Ghana. He is a member of the Society of Mining, Metallurgy, and Exploration (SME) and American Rock Mechanics Association (ARMA), Canadian Institute of Mining, Metallurgy, and Petroleum (CIM). His research works cover Mine Design and Environmental Safety through monitoring and assessment of stability of underground pillars and roofs, mine geology, rock formation and soil characteristics and their applications for fracking in oil and gas exploration and other areas in mining and geological engineering.

J. A. Kofi is currently a lecturer at the Akrokerri College of Education in Ghana. He holds MPhil Degree, BSc Degree, Postgraduate Diploma and Diploma Certificates in Astronomy and Astrophysics, Physics, Education and Telecommunications respectively from the University of Manchester in UK, University of Cape Coast, Ghana, University of Education, Winneba, Ghana and Ghana Telecommunications School in Accra, Ghana. His research interest includes Climate Change and Environmental Safety and their relationships with Astronomy, Astro-Physics and Telecommunication Networks, Engineering Education and Community Development.