Mapping of Land Subsidence Vulnerability - A Case Study at the Tarkwa Nsuaem Municipality of Ghana

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Abstract

Land subsidence is a serious geo-environmental event that can occur in mining areas and cause disastrous consequences. To minimize its occurrence and negative impacts on humans and the environment, appropriate preventive and mitigation measures must be put in place and these require knowledge and understanding of the risk factors involved and the vulnerable areas within a given geographical region. This paper discusses the combined use of the 'DRASTIC' ground vulnerability modelling technique, the analytical hierarchy process (AHP), Geographic Information System (GIS), GPS and Remote Sensing to collect, process, analyse and evaluate the relative and combined influences of the risk factors involved and to map the susceptible areas of land subsidence in the Tarkwa-Nsuaem Municipality of Ghana. The relevant risk factors identified in the study area include high rainfall, drainage density, elevation and slope, soil, land use/land cover (LULC), depth to ground water, proximity to mine sites, geology and hydrogeology. The relative influence of each of the factors were estimated and combined to generate land subsidence vulnerability maps for the study area with five different classes, namely very low, low, moderate, high and very high vulnerability zones. The vulnerability map indicates that a significant proportion (about 17%) of TNMA lies within the high and very high vulnerability zones and these occur mainly at the north-western parts of the area. The results of the current studies may be used as preliminary references or criteria to check the suitability of proposed land uses or development projects in terms of subsidence risk in the study area. It is recommended that land subsidence vulnerability analysis should be integrated in existing land use and resource development planning and approval processes in TNMA and similar mining areas as discussed and demonstrated in the study.

Keywords: Land subsidence, Vulnerability Mapping, Mining Areas, Land use/development Planning, AHP

1 Introduction

Land subsidence may be caused by multiple factors of both natural and anthropogenic sources. Inappropriate and uncontrolled location and development of land-based projects and activities (such as mining, quarries, sand winning, lumber and sawmill operations, residential and commercial developments and waste disposal) can disrupt natural topographic, hydrogeological, biological and climatic settings and increase the frequency or potential of environmental disasters like flooding, fires, earth tremors, land subsidence and collapse of structures with serious consequences on humans and the environment (degradation or destruction of vegetation, land, soil, water bodies and atmospheric elements) (Kwesi *et al.*, 2020; Asante, 2011; Kim *et al*, 2006; Sun *et al*, 1999). There is a strong perception that the natural ability of the topography and underlying geology of most mining areas to withstand land subsidence is reduced or compromised due to the long and widespread operations of mining activities like blasting, excavations and piling of loose waste materials on the land surface (Ghorbanzadeh *et al.*, 2020; Kim *et al*, 2006; Sun *et al*, 1999). This is especially necessary in mining areas like Tarkwa, Ghana, where underground and surface mining activities have been in operations for over a century, with little or no reliable reclamation of the sites, and rising urbanisation has necessitated the need for other major land uses and developments within mining enclaves (Kwesi *et al.*, 2020; Anon., 2014). It is thus necessary to evaluate the subsidence risk at various sites and apply them to assess the suitabilities of proposed land uses as a way to reduce the potential occurrence and consequences of land subsidence in mining areas. The focus of this paper is thus to discuss and demonstrate the production and use of land subsidence vulnerability maps for assessing the suitability of proposed land uses and locations of developmental projects in the mining areas of Ghana. A case study approach is adopted, using the Tarkwa Nsuaem Municipality as the study area.

1.1 Geographical Background of Study Area

Geographically, the study area, Tarkwa Nsuaem Municipal Area (TNMA), is located between latitudes 5° 00′ N and 5° 25′ N and longitudes 1° 48′ W and 2° 10′ W (Fig. 1). Tarkwa, the administrative capital which is the most popular and vibrant mining centre 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, trading and other socioeconomic activities (Kwesi *et al.*, 2020). 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*., 2020; Anon., 2014). As a result of increasing surface water pollution, many people are now depending on ground water for domestic and other uses, which in turn has the potential to increase ground subsidence occurrence among other contributing factors like uncontrolled blasting, excavations and land development at inappropriate locations in the area. (Kwesi *et al*., 2020; Ewusi *et al*., 2017).

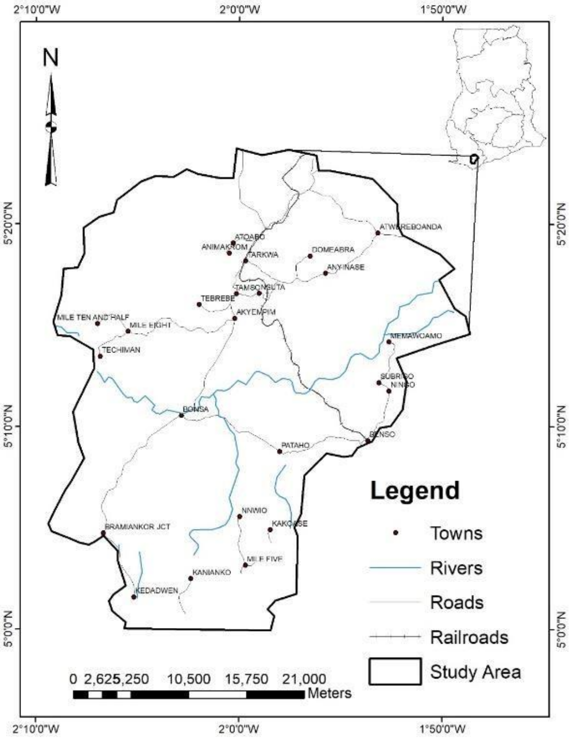

Fig. 1 Map showing the Location of TNMA

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).

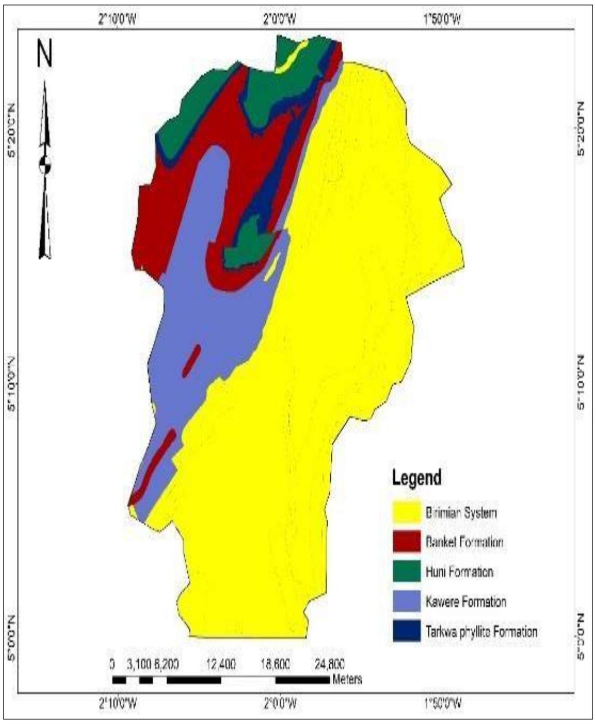

Fig. 2 Map showing the Geology of TNMA

Groundwater in the Tarkwa area occurs in two distinct hydraulically connected aquifer systems; an upper weathered zone aquifer and a deeper unweathered 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 with estimated groundwater recharge and evapotranspiration values averaging about 14 % and 54 % respectively (Kuma, 2007; Kortatsi, 2002).

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. Proximity to mining site data was estimated from google earth. For the Land Use/Land Cover (LULC) model, Landsat 8 Image (March 29, 2020 scene; path: 194, row: 56) was downloaded from US Geological Survey's website (earthexplorer.usgs.gov). It was downloaded from the Landsat Level 1 Collection. The data in geotiff format was projected onto UTM zone 30 N and then extracted by mask to the study area. It was then converted from digital numbers (DN) to Top of Atmosphere (TOA) Planetary Spectral Reflectance. The TOA Reflectance data (bands 2, 3, 4, 5, 6 and 7) was composited and classified using the unsupervised classification technique in ESRI ArcMap 10.3 software. The methods adopted for this research work are summarized in the flow chart in Fig. 3. And discussed is the next sections.

2.2 Land Subsidence Vulnerability Analysis Method(s) Considered and Applied

Similar to groundwater vulnerability assessment, a number of approaches have been developed for assessing and mapping land subsidence vulnerability (Ghorbanzadeh *et al*, 2020; Bui *et al*, 2018; Dehghani *et al*, 2014; Dehghani *et al*, 2014; Kim *et al*, 2006; Saraf and Choudhury, 1998; Kalani *et al*, 2017; Rahman *et al*, 2013; Anane *et al.*, 2008; Longdill, et *al*, 2008). These may be classified into three main groups—overly and index methods; methods employing process-based simulation models, and statistical methods. In overly and index methods, the main contributing factors to vulnerability are mapped based on available primary and/or derived data. Subjective numerical values (ratings and/or weights) are then assigned to the factors based on their relative contributions towards ground vulnerability. The rated and/or weighted maps are then combined by linear functions to produce resultant vulnerability maps of the study area. The ground vulnerabilities evaluated by such methods are qualitative and relative. The main advantage of such methods is that some of the controlling factors (e.g., lithology and depth to groundwater table) can be evaluated over large areas, making them suitable for regional scale assessment (Kwesi *et al*, 2020; Jaseela *et a*l., 2016).

With the advent of remote sensing (RS), global positioning system (GPS) and GIS, adoption of such methods for creating vulnerability databases, maps and assessments are no longer so difficult. Several overly and index methods have been developed for groundwater vulnerability and these may be applied in land subsidence analysis. The common ones include 'DRASTIC' (Aller *et al.*, 1987), 'AVI' (Van Stempvoort *et al.*, 1993), 'SINTACS' (Civita, 1993) and 'EPIK' (Doerfliger and Zwahlen, 1997). The DRASTIC method which is the most popular overlay and index method was adopted, modified and integrated with the analytical hierarchy process (AHP) for this study. Details of the DRASTIC method and its application are well discussed in earlier publications (Kwesi *et al*, 2020; Al-Abadi *et al.*, 2014; Rundquist *et al.*, 1991) and thus not presented in this paper. It is an overlay and index method designed to produce vulnerability scores by combining several thematic maps. Its principles of using the most intrinsic influential factors of ground vulnerability within a given geographical setting was applied in selecting the factors for this study which include depth to water table, elevation, slope, lithology, LULC, soil and proximity to mining sites (Table 1). These factors were not limited in number and in substance to the original seven (7) DRASTIC factors. Also, the weighting method in DRASTIC was replaced by the AHP method to improve its reliability (Kalani *et al.*, 2017; Al-shabeeb, 2016; Saaty and Vargas, 2012). Fig. 3 shows the method, data and processing flow chart used.

2.3 Weighting by AHP Method

AHP has been applied in a number of site selection and suitability studies (Kalani et al., 2017; Al-shabeeb, 2016; Saaty and Vargas, 2012; Anane et al., 2008; Saaty, 2000; Saaty, 1980). It employs Pairwise Comparison Matrices (PCMs) to compare the relative importance among a set of criteria and then determine their relative weights in a consistent manner. Saaty (1980) suggests a scale from 1 to 9 (Table 1) for PCM elements, where the value of 1 indicates that the criteria are equally important and a value of 9 indicates that the criterion under consideration is extremely important compared to the other criteria. PCM includes a consistency check where judgement errors are identified and a consistency ratio is calculated by the following formulae:

$$\lambda_{max} = \frac{1}{n}\left[\sum_{i}^{n}(Aw_I)/w_i\right] \qquad \ldots 1$$

$$C.I = (\lambda_{max} - n).(n-1) \qquad \ldots 2$$

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \qquad \ldots 3$$

Where,

λmax is the eigenvalue vector; **n** is the total number of factors being compared; **CI** is the consistency index; **CR** is the consistency ratio and **RI** is the random consistency index.

There are tables that show values of **RI** against **n** (Saaty, 1980). From such tables, **RI** = 0.41 for using 8 factors in this study. The consistency index rule of thumb is that a Consistency Ratio (**CR**) less than or equal to 0.1 indicates an acceptable reciprocal matrix, while a value over 0.1 indicates that the matrix should be revised (Saaty 1980).

The weight for each parameter was computed using the AHP method described above and the results (Table 1) were assigned to their corresponding data layers. The various consistency checks were done using equations 1, 2, and 3, and a **CR** value of 0.09 was obtained to establish acceptable consistency for the pairwise value judgements and weight estimation for the subsidence factors.

2.4 Subsidence Vulnerability Index

The adopted DRASTIC method has a numerical ranking system that contains three major parts—weights, ranges and ratings. For this study, the main parameters were assigned weights computed from AHP method to reflect their relative influence on land subsidence. The significant variations or classes within each parameter or data layer were rated from 1 to 10 based on their relative effect on subsidence vulnerability (Table 1). The method employs a numerical subsidence index that is derived from the ratings and weights assigned to the main parameters. This index is computed by a linear combination of all the rated and weighted factors using functions like equation (4):

$$\text{Subsidence Index} = \sum_{i=1}^{n} w_i r_i \qquad \ldots 4$$

Where;

w and **r** are the weight and rating of a given parameter, **i**, at a given cell within each data layer of the study area (and i =1, 2, 3, …n).

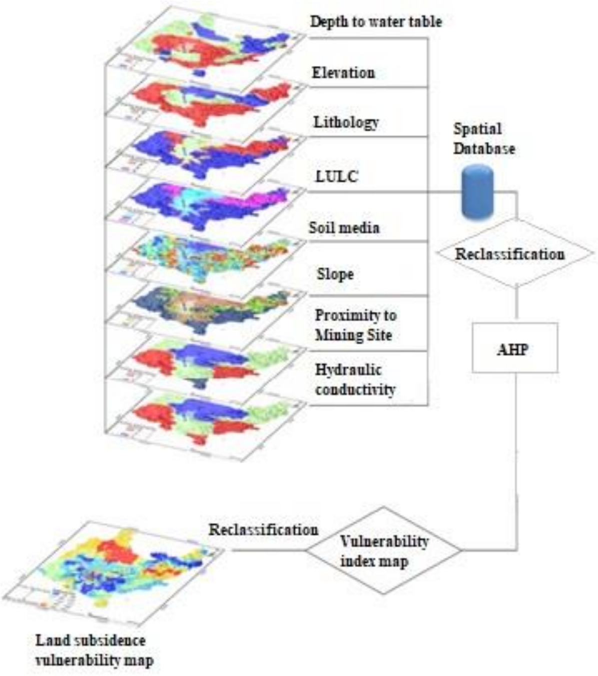

Fig. 3 Flow Chart of the Method

3 Results and Discussion

3.1 Depth to Groundwater

The groundwater or water table depth in this study the estimated vertical distance or height from the ground surface to the water table in unconfined aquifer and to the bottom of the confining layer in confined aquifer.. The smaller the water table depth, the more vulnerable the land is to subsidence and vice versa. The depth to groundwater data was interpolated across the study area using the Inverse Distance Weighting (IDW) method. The raster output result was reclassified and rated as shown at Table 1 and Fig. 4.

Table 1 Ratings and Weights for the Subsidence Vulnerability Parameters

S.N	Parameter	Range	Rating	AHP Weight
1	Depth to Water table (m)	3.50 - 5.34	9	0.317
		5.35 - 8.00	7	
2	Elevation	4– 62	10	0.182
		63 – 92	8	
		93 – 125	6	
		126 – 171	4	
		172 – 332	1	
3	Lithology	Volcanic rocks	2	0.044
		Quartzite/ Conglomerate	4	
		Phyllite	5	
		Sandstone	6	
4	LULC	Forest	3	0.032
		Sparse vegetation /Farmland	5	
		Built-up /Mine Sites	9	
5	Soil Media	Silt	5	0.207
		Laterite	3	
6	Slope (%)	0 – 7	10	0.124
		8 – 13	9	
		14 – 20	5	
		21 – 31	3	
		32 – 73	1	
7	Proximity to Mining Site	0 – 400	8	0.024
		401 – 800	6	
		801 – 1200	4	
		1201 – 1600	2	
		1601 – 2000	1	
8	Hydraulic Conductivity (m/day)	0.06 - 0.30	1	0.071
		0.31 - 0.43	2	

3.3 Elevation

Higher elevations generally have lower moisture while lower elevations generally have higher soil moisture. This is because water flows flow downhill due to gravity. Thus, chemical weathering is higher at lower elevations than at higher elevations. As a result, land subsidence is higher at lower elevations and vice versa. Therefore, higher ratings were given to lower elevations than higher elevations. Fig. 5 is a map showing the elevation ratings map.

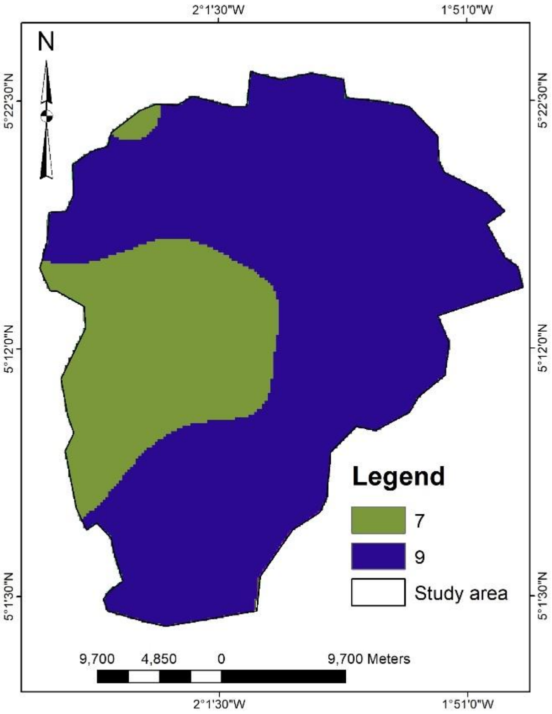

Fig. 4 Groundwater Depth Ratings Map

3.2 Geology/Lithology

Lithology refers to the composition and type of rocks in the study area. Based on the geological description of the study area (Kesse 1985), the underlying rocks in the area include volcanic rocks, Phyllites, quartzites, sandstones and conglomerates. The harder the rock, the more resistant it is to chemical weathering and the less susceptible it is to land subsidence. The hardest rock type in the area are the volcanic rocks, followed by Quartzite/Conglomerate, Phyllite and Sandstone. Fig. 6 is a map showing the ratings of for the classes of rock types or lithology (Table 1).

3.3 LULC Model

The LULC model for the study area is shown in Fig. 7. It is categorised into Forest, Sparse vegetation/farmland and built-up/mining sites. Rates of aquifer drawdown at built-up/mining site is high, as people draw water for wells on daily basis for domestic and mining purposes. Water is also drawn from wells for irrigation purposes. Drawdown is known to be one of the major factors for land subsidence. Hence the higher the drawdown, the higher the risk of land subsidence. Thus built-up/mining site category was assigned the highest rate followed by farmland and forest, as shown in Fig. 7.

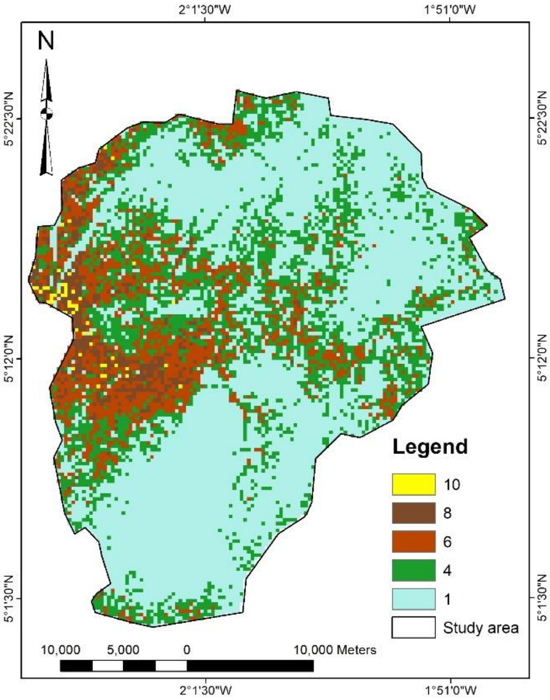

Fig. 5 Elevation Ratings Map

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 lower the risk of land subsidence. In addition, cohesive soils such as silt are more susceptible to land subsidence since they shrink and swell depending on their moisture content. Consequently, the silt was assigned a rate of 5 whereas the laterite, a rate of 3 (Table 3). The vector layer of the soil map was first converted to a raster grid and reclassified by the rating factors (Table 3) to produce the map presented in Fig. 8.

3.5 Slope

Slope refers to the rise or fall of the land surface. Where slopes are low, there is little runoff, and the potential for water to seep through the ground to cause chemical weathering is high. The higher the rate of chemical weathering, the higher the risk of land subsidence. 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.9).

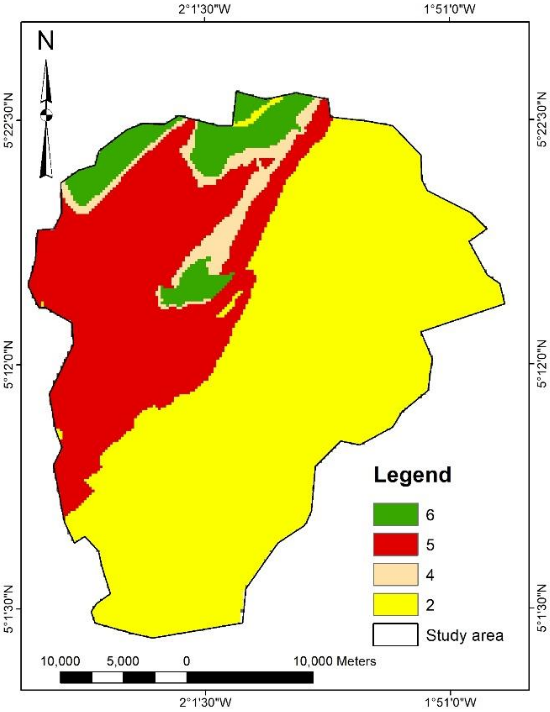

Fig. 6 Map Showing the Lithology Ratings

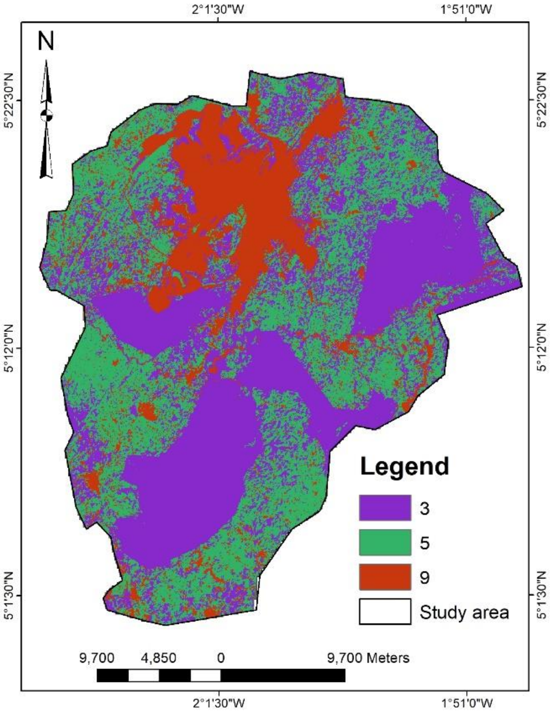

Fig. 7 LULC Ratings Map

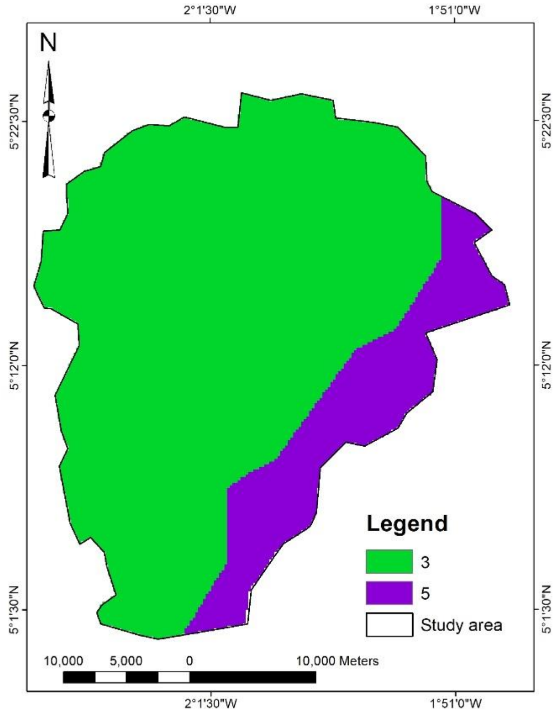

Fig. 8 Soil Media Ratings

3.6 Proximity to Mining Sites

Areas closer to mining site are usually subject to ground vibrations due to the blasting activities of the mines. Land subsidence can occur during ground vibrations due to offset along fault lines. It also occurs because of settling and compaction of unconsolidated sediments from the vibration of the ground. Consequently, areas closer to the mines were given higher ratings and vice versa. The ratings map for the proximity to mining sites layer is shown in Fig. 10.

3.7 Hydraulic Conductivity

Hydraulic conductivity is a measure of how easy the water can flow through the soil or rock. The higher the hydraulic conductivity, the less susceptible the land is to subsidence. 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 and rated as shown at Table 1 and Fig. 11.

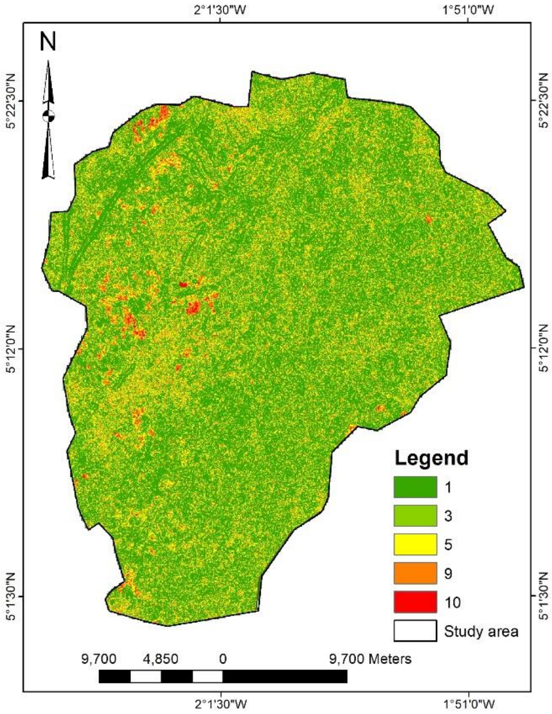

Fig. 9 Slope Ratings

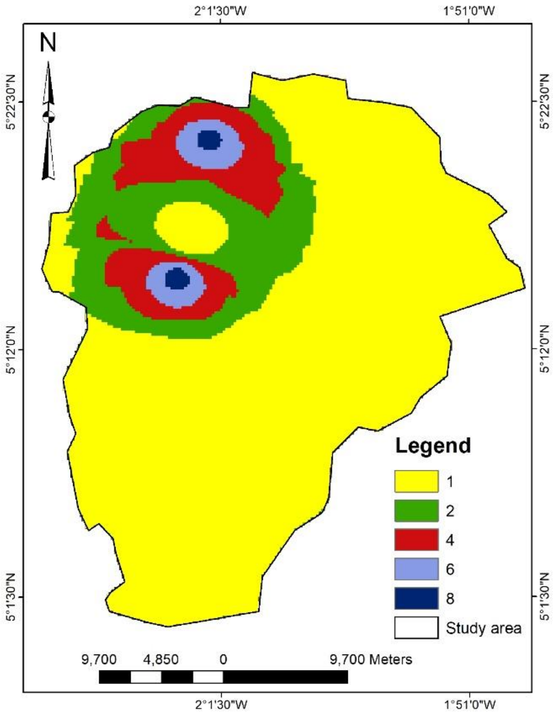

Fig. 10 Proximity to Mining Sites Ratings Map

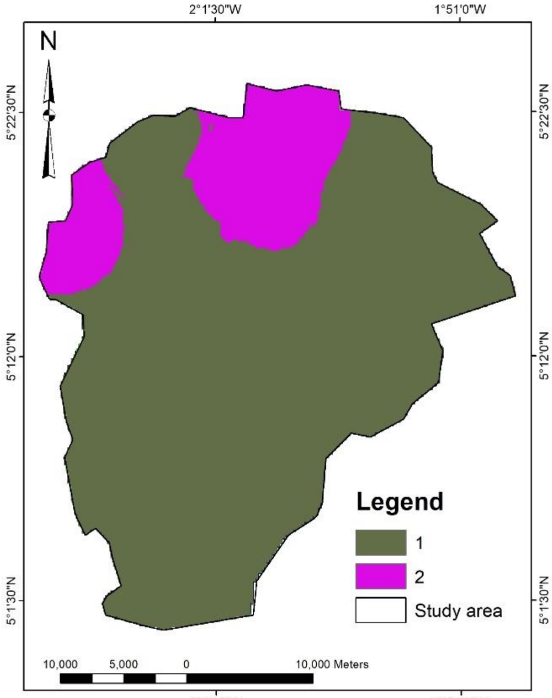

Fig. 11 Hydraulic Conductivity Ratings Map

3.8 Land Subsidence Vulnerability Map

Land subsidence vulnerability index map was generated using the raster calculator in spatial analyst tool in ArcMap 10.3. Equation 4 was used to generate the subsidence vulnerability index (SVI) for each cell within each data layer and aggregated. The SVI range was from 3.5 to 7.5 and its related output index map was reclassified based on Table 2 to produce the final land subsidence vulnerability map (Fig. 12).

Table 2 Criteria for Vulnerability Classes

Class	Vulnerability Potential
< 4.0	Very Low
4.0 – 5.0	Low
5.0 – 6.0	Moderate
6.0 – 7.0	High
> 7.0	Very High

The land subsidence susceptibility map shows that there are five classes within the study area, namely; very, low, moderate, high and very high. The very low-to-low risk zones occur at the southern and eastern part of the study area, and occupy about 64% of the study area. They occur within the volcanic rocks with relatively higher elevations (125 – 332 m).

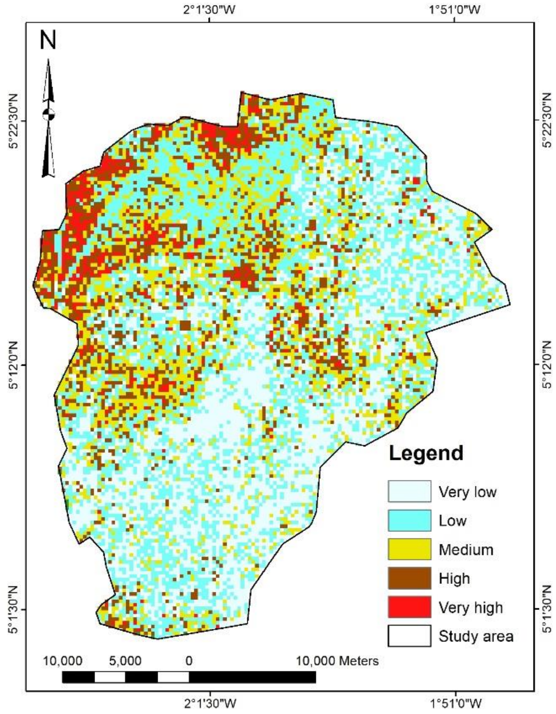

Fig. 12 Land Subsidence Vulnerability Map

From Fig. 12, the moderate vulnerability zones occur at the central parts of the study area and occupies about 19 % of the area. It is located within the conglomerate/quartzite formations. The high to very high vulnerability zones occur at the north-western part of the study area, and occupy about 17 % of the area. They are located predominantly within the Sandstones with relatively lower water tables (3.5 – 4.4 m) and ground elevations (4 – 92 m). Consequently, the zones are susceptible to chemical weathering activities, which increase the risk of land subsidence.

Vulnerability maps such as shown at Fig 12 may be used as references or criteria to check the suitability of proposed land uses or locations of development projects in terms of subsidence risk or potentials. Appropriate decisions can thus be arrived at such as rejecting or disapproving the proposal or requesting more stringent mitigating measures against subsidence potentials and their impacts before allowing or approving the use of such sites.

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 interpolations were applied. The results presented in this paper are therefore useful for the initial screening of proposed developments in which land subsidence prevention is a key factor to account for. Detailed site-specific land subsidence vulnerability investigation will still be necessary in the final site selection process before development begins.

4 Conclusions and Recommendations

This study has demonstrated the combined use of the 'DRASTIC' ground vulnerability modelling technique, the analytical hierarchy process (AHP), Geographic Information System (GIS), GPS and Remote Sensing to collect, process, analyse and evaluate the relative and combined influences of the risk factors involved and to map the susceptible areas of land subsidence in the Tarkwa-Nsuaem Municipality of Ghana. The resulting vulnerability map from this integrated approach indicates areas which must have high priority in terms of protection or monitoring against subsidence vulnerability. The computed land subsidence vulnerability index (SVI) values range from 3.5 to 7.5 leading to five vulnerability classes for the area.

The high and very high subsidence vulnerability zones constitute about 17% of the study area and occur mainly at the north-western parts with patches at the central and eastern parts. They are located predominantly within the sandstones with relatively lower water table depths and ground elevations. These zones were observed to be susceptible to chemical weathering activities which increase the risk of subsidence. They are also close to locations of mining activities. The percentage of high subsidence vulnerability areas was observed to be significant, emphasizing the need to pay more attention to the phenomenon in the study area. It is recommended that the method and results of the current study may be used as preliminary references or criteria to check the suitability of proposed land uses or developments in terms of land subsidence risk in the study area and that land subsidence vulnerability analysis should be integrated in existing land use and resource development planning and approval processes in TNMA and similar mining areas.

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