Flood Vulnerability Mapping and Applications in Waste Management at the District Level - Case Study at the Tarkwa-Prestea Mining Areas of Ghana

Edward A. A. KWESI, Kwame N. ASAMOAH and Alfred K. OFOSU-DJAN; Ghana

Key words: Land flood vulnerability, Landfill site screening, Waste disposal, Environmental pollution, Map overlay, Tarkwa-Prestea mining areas, Ghana.

SUMMARY

Flood vulnerability (FV) is an important factor to consider in the location of appropriate sites for municipal waste disposal and other land uses due to its association with land flood hazards such as inundation, subsidence and collapse of structures; erosion and dispersion of waste materials, soils, contaminants and other loose materials from vulnerable sites into the environment and vice versa; as well as the destruction and loss of properties and life. To reduce these hazards and their negative impacts, 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 to land floods within a given geographical region. This paper discusses the combined use of Remote Sensing, GPS, GIS, the 'DRASTIC' vulnerability modeling technique, the Analytical Hierarchy Process and Multicriteria Decision Analysis, to collect, process, analyze and evaluate the relative and combined influences of the risk factors involved and their application to map the susceptible areas to land floods in the Tarkwa-Prestea Mining Areas (TPMA) of Ghana. The relevant risk factors identified in the study area include rainfall, elevation and slope, soil, land use/cover, ground water depth, proximity to water bodies and hydrogeology. The relative influences of the factors were estimated and combined to generate land flood vulnerability maps (LFVM) which could subsequently be used as inputs in overlay and sieve mapping analysis in site screening and suitability assessment for locating landfills and other facilities. The LFVM show three main distinguished classes, namely, low, moderate and high flood vulnerability zones. Proposed landfill sites lying within the high FV zones are either not recommended for approval and development or flagged out for additional site specific investigations but those occurring within the low and moderate FV zones are recommended for approval and development. This approach is recommended as a further improvement in the landfill site screening exercise to reduce the potential environmental pollutions associated with it through land floods. It can further increase the environmental friendliness and social acceptability of landfilling as a suitable waste disposal method in TPMA and other regions where landfilling and incineration are prevalent practices.

Flood Vulnerability Mapping and Applications in Waste Management at the District Level - Case Study at the Tarkwa-Prestea Mining Areas of Ghana

Edward A. A. KWESI, Kwame N. ASAMOAH and Alfred K. OFOSU-DJAN; Ghana

1. INTRODUCTION

Land floods 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, residential and commercial developments, waste disposal and deforestation) can disrupt natural topographic, hydrogeological and climatic settings and increase the frequency or potential of environmental disasters like flooding, landslides and subsidence, and collapse of structures with serious consequences on humans and the environment (Kwesi *et al*., 2020; Kim *et al,* 2006; Sun *et al*, 1999). There is a strong perception that the natural ability of the land cover, topography or relief, and underlying geology of most mining areas to withstand land floods 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 relevant in the Tarkwa-Prestea mining areas (TPMA) of 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 urbanization and illegal mining are contributing to land floods, changes in local climate patterns and related environmental problems (Kwesi *et al*., 2020; Anon., 2014). It is thus necessary to evaluate the land flood risk at various sites and apply them to assess the suitability of proposed land uses as a way to reduce the potential occurrence and consequences of land floods in mining areas.

The aim of this paper is thus to discuss and demonstrate the production of land flood vulnerability maps for TPMA, and how such maps may be applied to assess the suitability of landfill sites and other land uses or development locations in TPMA and similar areas. Fig. 1 shows one example of the occasions in TPMA where flood waters carry waste materials and other pollutants through residential areas, households and school compounds and dormitories. Such floods, coupled with the prevailing crude waste dumping and management practices in TPMA, can compound and worsen existing environmental and sanitation problems (such as surface and ground water contamination and the spread of diseases), if not properly accounted for (Kwesi *et al*., 2018; Sackey, 2016; Jaseela *et al.,* 2016; Ubavin *et al*., 2015; Aderemi *et al.,* 2011). These reasons highlight the importance of the objectives of this paper.

Fig. 1 An Example of Land Flood Situation in the Tarkwa-Prestea Mining Areas
(with flood waters sweeping through: (a) communities, (b) households, (c) school compounds, (d) school dormitories, and (e) an open waste dump or landfill within the flood plain)

2. BACKGROUND OF STUDY AREA

2.1 Geographical and Socio-economic Setting

The study area is the Tarkwa-Prestea Mining Areas (TPMA) of Ghana which is located generally between latitudes 5º 10′ N and 5º 35′ N and longitudes 1º 52′ W and 2º 14′ W (Fig. 2 (a)). It lies across two administrative districts in Ghana, namely, the Tarkwa-Nsuaem Municipal Area (TNMA) and the Prestea Hunivalley Municipal Area (PHMA). Tarkwa, Bogoso, Prestea, Hunivalley and Damang are among the major vibrant mining centres in the area and these are 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). The combination of uncontrolled illegal mining activities, slum developments, waste dumping and other land uses in the area, especially on the floodplains and ridges, can increase the frequency and severity of land flooding and negative consequences (such as inundations of households, communities, public places like schools and markets drowning in uncovered mine pits, and spreading of diseases and pollution in the environment (see Fig. 1)) (Kwesi *et al*, 2014).

2.2 Geology, Hydrogeology, Topography, and Climate

TPMA is located within the Tarkwaian Group made up of 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(b)). 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). 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 has estimated groundwater recharge and evapotranspiration values averaging about 14 % and 54 % respectively (Kuma, 2007; Kortatsi, 2002). The topography of PHMA is generally undulating with some scarps ranging from 150 - 300 meters above sea level and has long ridges along which miming usually take place (Kwesi, *et al*, 2018). PHMA lies within the South-Western Equatorial Zone and is marked by double maximum rainfall with a mean annual rainfall of about 1878 mm, a temperature range of 26-30 °C, sunshine duration of about 7 hours per day and relative humidity of 70% – 80% (Kwesi *et al*., 2015).

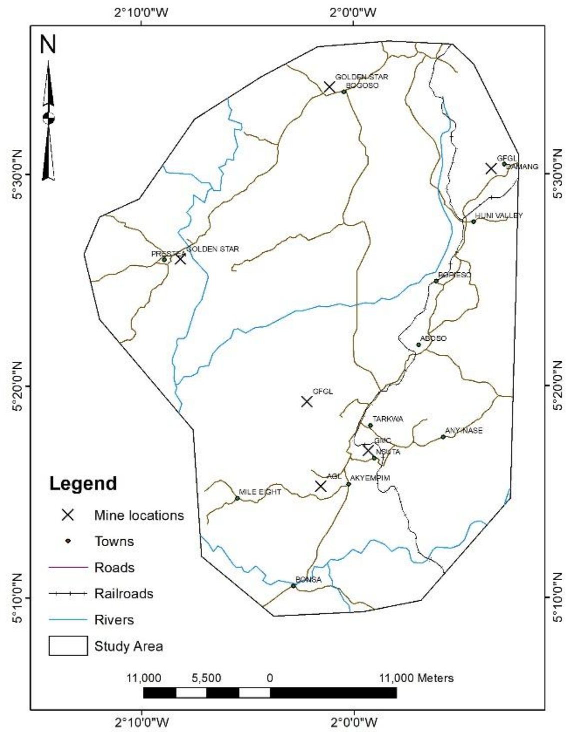


Fig. 2(a) Map of Study Area (TPMA)

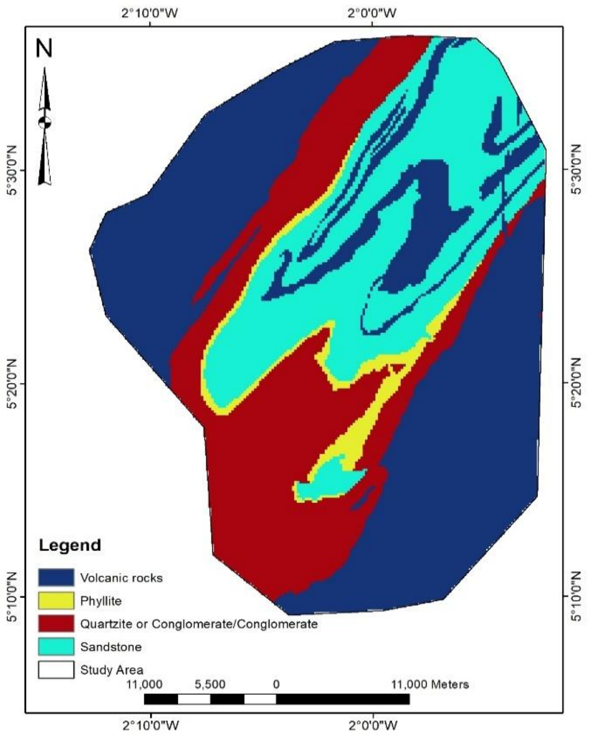


Fig. 2(b) Geological Map of TPMA

3. RESOURCES AND METHODS USED

3.1 Data Sources and Land Use/Cover Classification

Much of the Data used were of secondary sources. The Soil data were obtained from soil maps of Ghana published by FAO ISRIC. Digital Elevation Models (DEM) for slope analysis were obtained from ASTER Global DEM (GDEM). The hydrogeological data were obtained from previous publications and data on mining sites were derived 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. Using ArcGIS 10.3, 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 ISO Cluster unsupervised classification technique. The initial result was then refined by the maximum likelihood supervised classification technique with some few training samples available to obtain the land cover classes shown at Fig.5. This hybrid approach was adopted to account for inadequacies in the training samples used for the classification.

3.2 Land Flood Vulnerability Analysis

Similar to ground water vulnerability assessment, a number of approaches have been developed for assessing and mapping land flood vulnerability (Zhao, *et al*., 2018; Das, 2020; Kourgialas and Karatzas, 2017; Degiorgis *et al*., 2012; Arabameri *et al*., 2019). Examples of these are the frequency-ratio, (FR), rainfall-runoff (RR); soil-water assessment tool (SWAT), analytical hierarchy process (AHP) and digital elevation model (DEM) based approaches (Arabameri *et al* , 2019; Samanta *et al*., 2018, Brodie, 2020; Tan *et al*., 2020; Zhao *et al.,* 2018; Kazakis *et al*., 2015; Das, 2020; Hawker, 2018). These may be classified into three main groups—overly and index based methods; process-based simulation models, and statistical based methods. In the overly and index based 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 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 al*., 2016).

The DRASTIC technique which is one of the most popular overlay and index based methods 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) and thus not presented in this paper. It is designed to produce vulnerability scores by combining several thematic map layers. Its principles of using the most intrinsic influential factors within a given geographical setting was applied in selecting the factors for this study which include rainfall, depth to water table, elevation, slope, lithology, LULC, soil and proximity to water bodies (Table 1). However, the weighting method in DRASTIC was replaced by the AHP method to improve its consistency and reliability; and the factors were not limited in number and in substance to the original seven (7) DRASTIC factors (Kwesi *et al*., 2020; Das, 2020; Al-shabeeb, 2016; Saaty and Vargas, 2012). Fig. 3 shows the method, data and processing flow chart used.

3.3 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; 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 of 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:

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

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

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

where,
λmax is the eigenvalue vector; **n** is the total number of factors being compared; ***A*** *is* the pairwise comparative matrix; **w** is weight or priority vector; **CI** is the consistency index; **CR** is the consistency ratio and **RI** is the random consistency index.

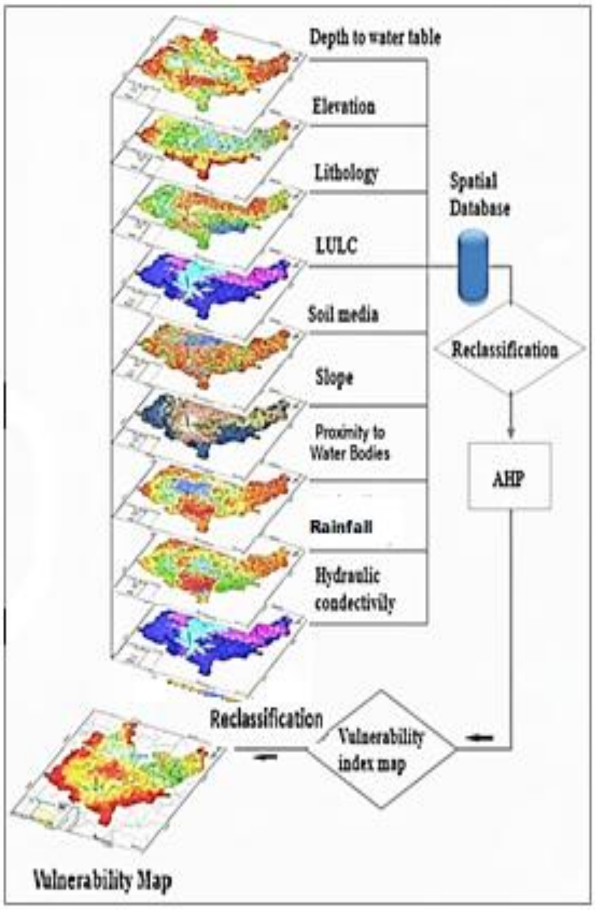


Fig. 3 Flow Chart of the Method

Table 1: Parameter Classification and Rating

SN	Parameter	Class Range	Rating	Weight
1	Rainfall (mm)	< 100	2	0.20
		100-125	3	
		125-175	5	
		175-200	7	
		> 200	9	
2	Elevation (m)	<50	10	0.18
		50-100	8	
		100-150	6	
		150-200	4	
		>200	1	
3	Slope (%)	<10	10	0.13
		10-30	9	
		30-50	5	
		50-70	3	
		> 70	1	
4	LULC	Primary Forest	1	0.11
		Secondary Forest	3	
		Sparse Vegetation and Farmlands	5	
		Built-up Areas	9	
		Mine Sites/areas	9	
5	Soil type	Clay	9	0.09
		Silt-Clay	6	
		Silt-Sand	4	
		Laterite	3	
		Gravel	2	
6	Geology	Volcanic rocks	7	0.04
		Quartzite	6	
		Phyllite	5	
		Conglomerate	4	
		Sandstone	2	
7	Water Table Depth (m)	< 3	9	0.07
		3-4	7	
		4-5	5	
		5-6	3	
		> 6	1	
8	Hydraulic Conductivity (m/day)	<0.05	2	0.02
		0.05-0.15	8	
		0.15-0.25	6	
		0.25-0.35	4	
		> 0.35	3	
9	Proximity to Major Water Bodies (m)	<500	9	0.16
		500-1000	7	
		1000-1500	5	
		1500-2000	3	
		> 2000	2	

There are tables that show values of **RI** against **n** (Saaty, 1980). From such tables, **RI** = 0.45 for using 9 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). Six experts from geological, geomatic, mining, environmental, waste management and town planning fields were involved in evaluating and rating the factors for the weighting, and differences in views were ironed out through consensus to obtain a common set of values. 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 zero was obtained to establish acceptable consistency for the pairwise value judgements and weight estimation for the factors.

3.4 Land Flood Vulnerability Index

The adopted method has a numerical ranking system that contains three major parts—ranges, ratings and weights. For this study, the main parameters were assigned weights computed from AHP method to reflect their relative influence on land flooding. The significant variations or classes within each parameter or data layer were rated from 1 to 10 based on their relative effect on flood vulnerability (Table 1). The method then employs a numerical flood 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 parameters using functions like equation (4):

$$\text{Flood Vulnerability Index} = \sum_{i=1}^{n} w_i r_i \qquad \dots 4$$

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).

4 RESULTS AND DISCUSSION

4.1 Model Parameters

The main contributing factors to flooding in TPMA, identified and prepared as parameters to develop the land flood vulnerable model, is presented at Table 1. These include rainfall, depth to water table, elevation, lithology, land use/land cover model, soil media, water density or proximity and land slope. Ratings were given to subdivisions within each individual criterion and weights were computed for each criterion using the AHP method. As a reference frame for modelling the criterion maps, the information on Table 1 were based on data collected over a broader span of time, geographical area and data sources than those shown on the model maps.

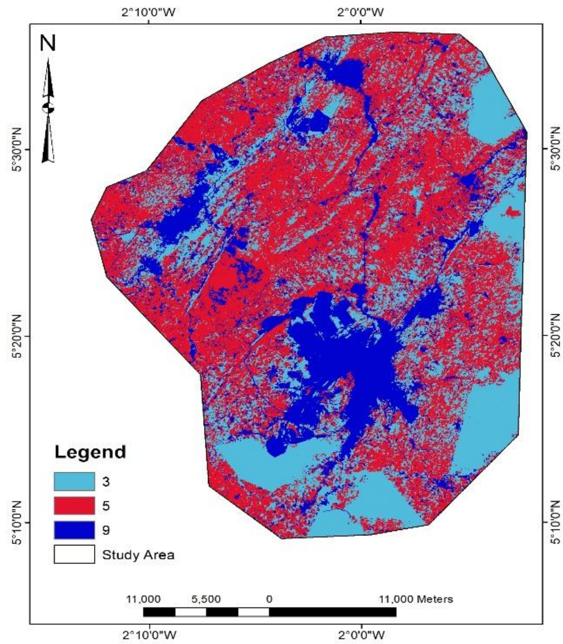


Fig. 4 LULC Ratings Map

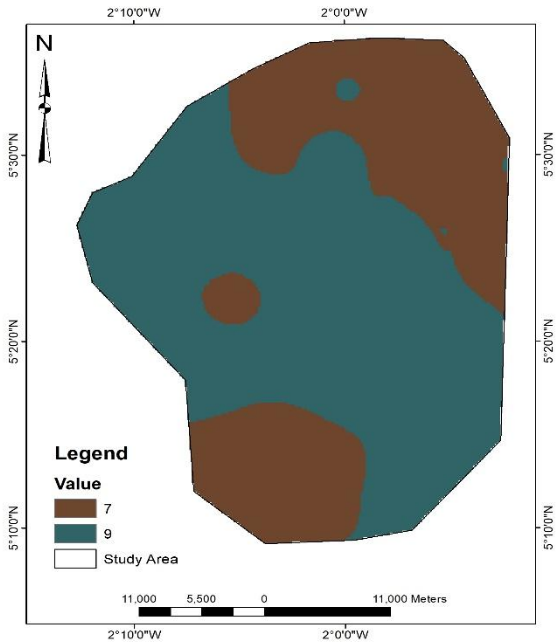


Fig. 5 Groundwater Depth Ratings Map

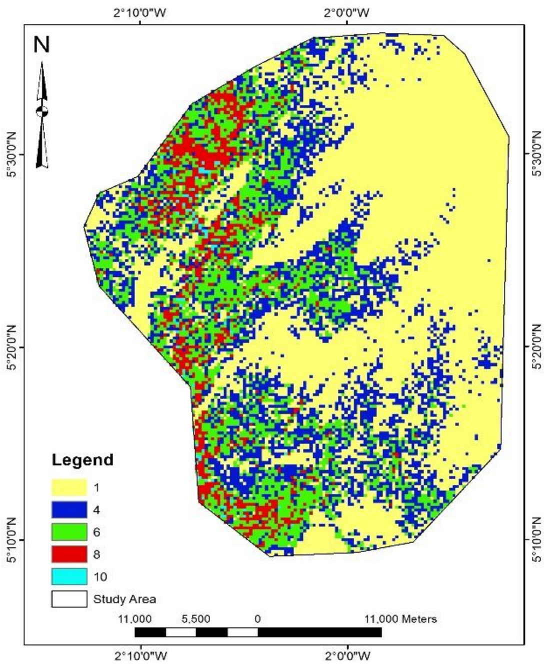


Fig. 6 Elevation Ratings Map

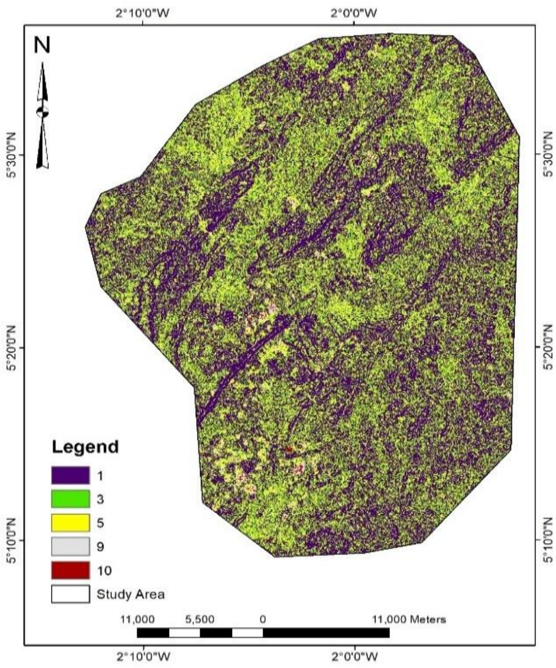


Fig. 7 Slope Ratings Map

4.2 LULC

Fig. 4. Shows the land use and land cover (LULC) classes of the study area and their rating scores. The study area was categorized into forest, sparse vegetation/farmlands and built-up/mining sites. Flood risk is high at built-up/mining areas due to buildings and other human activities that render the natural ground surface more impermeable to water percolation as well as blockage to water courses. Hence the higher the built up situation, the higher the risk of land flood susceptibility. Thus built-up/mining sites category was assigned the highest rate, followed by farmlands and then forest areas (Fig. 4).

4.3 Depth to Groundwater Ratings

Groundwater in this study refers to the distance from the ground surface to the water table in unconfined aquifer and to the bottom of the confining layer in confined aquifer. The shallower this depth, the more vulnerable the land is to flooding and vice versa. The depth to groundwater data was interpolated across the study area using the Inverse Distance Weighting (IDW) method. The resulting raster output was reclassified and rated according to Table 1. The ratings map is shown at Fig. 5.

4.4 Elevation

Fig. 6 shows the elevation classes of the study area and their assigned ratings values. Areas with higher elevations generally have lower moisture and water saturation or density than lower elevations, one reason being the fact that water flows downhill under the influence of gravity. Thus, susceptibility to land flooding is higher at lower elevations than it is at higher elevations. Therefore, higher ratings were given to lower elevations than higher elevations.

4.5 Slope

Slope in this study refers to the amount of rise or fall in elevation per a unit of horizontal distance movement over the terrain or land surface. The lower the slope, the higher the risk of land flood susceptibility and vice versa. 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 shown at Fig.7 for the study area.

4.6 Soil Media

In this study, soil media refers to the upper weathered zone of the earth which averages a depth of about six feet from the ground surface (Alwathaf and Mansouri, 2011). The predominant soil types in the area are silts and laterites. Laterites have larger grain sizes than silt, hence high draining capability than silt. The higher the draining capability, the lower the risk of land flood. Consequently, the silt classes was assigned rates of 4-6 and the laterites were assigned 3. The vector layer of the soil map was first converted to a raster grid and reclassified based on Table 3 to produce Fig. 8.

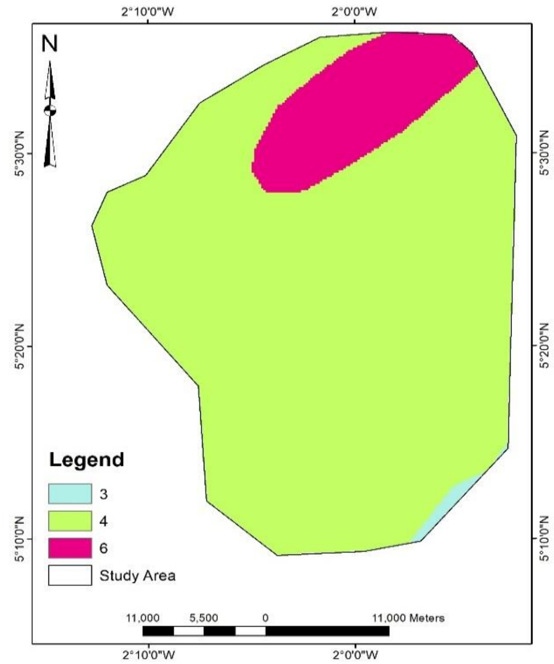


Fig. 8 Soil Media Ratings

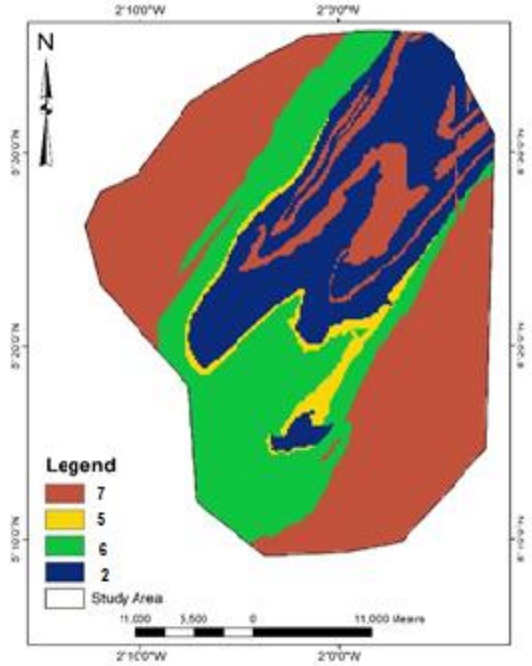


Fig. 9 Lithology Ratings Map

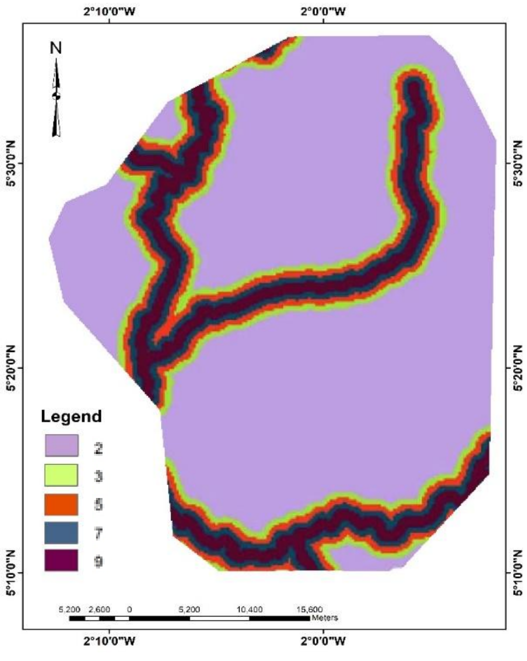


Fig. 10 Water Body Proximity Ratings Map

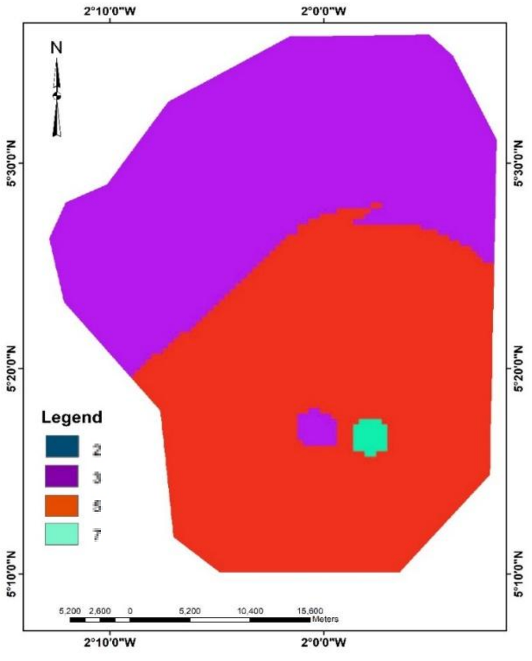


Fig. 11 Rainfall Variation Ratings Map

4.7 Lithology

Based on the geological description of the study area (Kesse 1985), the rocks that underlain the area include volcanic rock, phyllite, quartzite, sandstone and conglomerate. The harder the rock, the more resistant it is to chemical weathering and water percolation but more susceptible to land flooding. The hardest rock in the area is the volcanic rock, followed by Quartzite/Conglomerate, Phyllite and Sandstone. Fig. 9 shows the lithology of the study area and their ratings.

4.8 Water Proximity/ Density

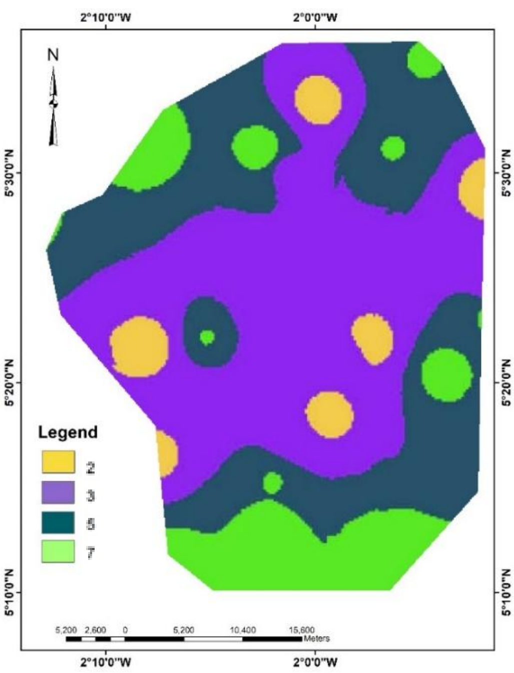
Areas that are close to water body sites are generally prone to flood risk than those that farther way. Land flood can occur during heavy or long rains, storm surges, dam failures and similar events, and when these occur, the natural water bodies usually become full and spill excess water to the immediate surroundings. Consequently, areas closer to the water bodies were given higher ratings and vice versa. Water density is an alternative measure for the water proximity parameter. Areas with more water bodies are more susceptible to flooding than those with less water bodies. The ratings map for the proximity to water bodies is shown at Fig. 10.

4.9 Rainfall Variations

Land flood susceptibility is highly influenced by rainfall distribution within a given geographical area. The greater the intensity, frequency and period of rainfall, the higher the risk of flood occurrence at a given area, if all other things are held equal or constant. Table 1 and Fig. 11 shows the mean monthly rainfall distribution or variations in the study area and their relative rates towards flood susceptibility.

4.10 Hydraulic Conductivity

Hydraulic conductivity is a measure of how easy water can flow through the soil or rock. The higher the hydraulic conductivity, the less susceptible the land is to flooding. 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 Table 5 to produce the ratings map shown at Fig. 12.



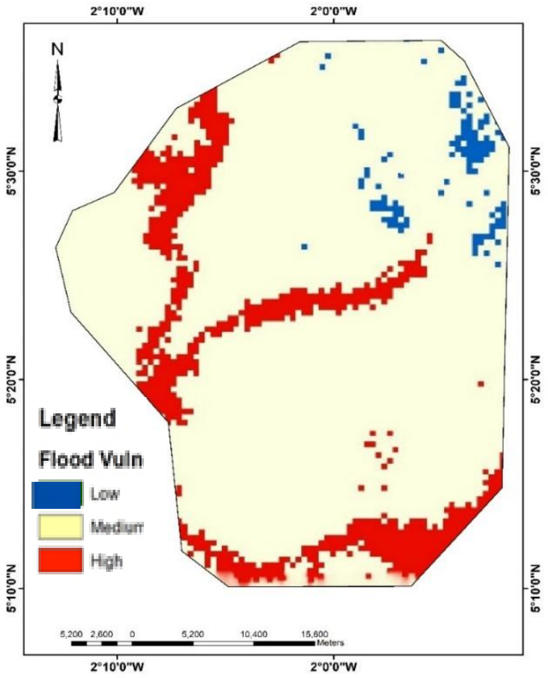


Fig. 12 Hydraulic Conductivity Ratings Map **Fig. 13 Land Flood Vulnerability Map**

4.11 Land Flood Vulnerability Map

Fig. 13 presents the final result of the land flood vulnerability mapping (LFVM) which was created using Equation 4 (section 3.4) and the raster calculator in the spatial analyst tool in ArcMap 10.3. The classification on this output map was based on the information in Table 2. The proportionate sizes of the vulnerability classes over the entire study area, were also computed to assess their relative significance in terms of area coverage, and this is presented at Table 3. The land flood vulnerability map (Fig. 13) and table (Table 3) show three main flood vulnerability classes within the study area, namely; low, moderate and high. The high vulnerability zones occur mainly along the paths of the major water bodies in the area and are concentrated mainly at the south, central, and north-western parts of the study area with few pockets at the eastern area, and in all, occupy about 21.43 % of the study area. The moderate vulnerability zones constitute about 71.43 % of the study area and thus dominate in the region, and occur generally over all the study area except the flood plains and low relief zones. The low risk zones occur generally at north-eastern and northern parts, and occupy about 7.14 % of the study area. The high vulnerability zones are also located mainly in areas closer to water bodies, in the low elevation areas and in some built-up areas, including some mining sites within the study area. Comparing Fig. 13 with the factor maps and Table 1, the high flood vulnerability zones are associated with high rainfall values, low to moderate groundwater depth values, high hydraulic conductivity values, low to moderate elevations and slopes, and lithology dominated by volcanic and quartzite materials that are less permeable.

Table 2 Flood Vulnerability Ratings and

Classification

Class	Degree of Vulnerability
< 2.0	Very Low
2.0 – 4.0	Low
4.0 – 6.0	Moderate
6.0 – 8.0	High
> 8.0	Very High

Table 3 Flood Vulnerability Classes and Sizes

Level of Flood Vulnerability	Area (Km^2)	Percentages (%)
High	300.00	21.43
Moderate	1000.00	71.43
Low	100.00	7.14
Very Low	0.00	0.00
Very High	0.00	0.00
Totals	**1400.00**	**100.00**

4.12 Applications in Waste Management

LFVM can be applied in various aspects of waste management, especially in site selection and site suitability assessment for waste disposal and other related activities. For example, based on the results of the current study, landfill sites situated in the high vulnerability zones, as demonstrated by the real life example in Fig. 1, will have high potentials to cause flood related pollution to the environment and thus require stringent control measures such as closing existing ones, not permitting new ones, and maintaining efficient drainage and flood control systems in place. Site selection Analysts may thus include these flood vulnerability assessments in their work or simply apply the final vulnerability map (Fig. 13) as additional input criterion factor(s) to rule out all sites that fall within high flood vulnerability zones or assign appropriate relative suitability grades to such sites in land screening exercises or evaluation work. Also, such flood vulnerability maps as shown at Fig 13 may be used as references or criteria by those in authority to check the suitability of proposed landfill sites in terms of their association with flood risk potentials to help make appropriate decisions such as rejecting or disapproving the proposal or requesting more stringent mitigating measures against land flood potentials and their impacts before allowing or approving the use of such sites.

3.13 Accuracy Assessment

The reliability of the subjective comparative judgement values for the AHP weight estimation were evaluated by computing the values for the consistency metrics presented in equations 1, 2 and 3 under section 2.3. The values for $\boldsymbol{\lambda_{max}}$ **CI, RI** and **CR** respectively were **9.0, 0.0, 1.45** and **0.0** These values established a perfect and acceptable consistency accuracy for the pairwise judgements, and this could be the result of strict and consistent adherence to the rules of transitivity in assigning numerical values to the pairwise judgement and the associated matrix. The accuracy of the land cover and land use classification was assessed using confusion matrix and related metrics which yielded a kappa coefficient of 0.7115 and overall accuracy of 77.128%, and these were judged to be good for the intended use of the land cover/land use map for the study. The final result map was validated by means of visual inspection and 'sense check' to ensure it met expectation when compared with (1), the impute maps and other thematic maps of TPMA, and (2), expert knowledge and experience of the landscape of the study area.

5. CONCLUSIONS

In this paper, an overlay and index based vulnerability modelling method has been applied in combination with GIS, remote sensing, AHP and MCDA to assess and map land flood vulnerability in the TPMA. The method used the climatic, topographical, land use and land cover, hydrogeological, soil and geological characteristics of the study area to estimate and map the relative vulnerabilities of various locations to land flooding within the study area. The developed vulnerability map from the study shows areas that must have high priority in terms of flood related protection and pollution prevention interventions. The computed flood vulnerability index was categorized into 3 classes, namely low, moderate and high vulnerability zones. The high vulnerability zones constitute about 8.58 % of the study area, and occur mainly at the south-western and north-western parts of the study. They are located mainly in areas closer to water bodies, in low elevations (< 100 m), low slopes (<30%), high rainfalls (175-200 mm per month), shallow groundwater depths, and in lithology dominated by volcanic and quartzite materials that are less permeable in the study area. Based on the results, any landfill site situated in the high vulnerability zones, will have a high potential to cause flood related pollution to the environment. Conversely, landfill sites situated at the low and moderate vulnerability zones, will have low or moderate potential of contaminating the environment through land flooding. It is recommended that the land flood pollution vulnerability assessment used in this study should be integrated into landfill site selection analysis to help reduce the risk of flood related pollutions to the environment in the disposal of waste in TPMA and similar areas. Furthermore, proposed landfill sites lying within high land flood vulnerability zones should either not be recommended for approval and development or flagged out for additional site specific investigations in the study area and similar locations.

REFERENCES

Al-badi, A. M., Al-Shamma, A. M. and Aljabbari, H. M., (2014), “A GIS-Based DRASTIC Model for Assessing Intrinsic Groundwater Vulnerability in North-eastern Missan Governorate, Southern Iraq”, *Springer*, No. 7, pp. 89 - 101.

Aderemi, A. O., Oriaku, A. V., Adewumi, G. A. and Otitoloju, A. A. (2011), “Assessment of Groundwater Contamination by Leachate near a Municipal Solid Waste Landfill”, *African Journal of Environmental Science and Technology*, Vol. 5 No. 11, pp. 933-940

Al-shabeeb, A. R., (2016),”The Use of AHP within GIS in Selecting Potential Sites for Water Harvesting Sites in the Azraq Basin—Jordan”, *Journal of Geographic Information System, Scientific Research Publishing*, Vol. 8, pp. 73-88.

Arabameri, A., Rezaei, K., Cerdà, A., Conoscenti, C., and Kalantari, Z. (2019), "A comparison of Statistical Methods and Multi-Criteria Decision Making to Map Flood Hazard Susceptibility in Northern Iran". *Sci. Total Environ*. 660, pp. 443–458.

Das, S. (2020), "Flood Susceptibility Mapping of the Western Ghat Coastal Belt Using Multi-Source Geospatial Data and Analytical Hierarchy Process (AHP)", *Remote Sens. Appl.: Soc. Enviro*n. Vol. 20, pp. 100379-100389.

Degiorgis, M., Gnecco, G., Gorni, S., Roth, G., Sanguineti, M. and Taramasso, A. C. (2012), "Classifiers for the Detection of Flood-prone Areas Using Remotely Sensed Elevation Data". *J. Hydrol*. Vol. 470, pp. 302–315.

Ewusi, A., Ahenkorah, I., and Kuma, J. S. Y. (2017), "Groundwater Vulnerability Assessment of the Tarkwa Mining Area Using SINTACS Approach and GIS", *Ghana Mining Journal*, Vol. 17, No. 1, pp. 18 - 30.

Hawker, L. , Bates, P. , Neal, J. and Rougier, J. (2018), "Perspectives on Digital Elevation Model (DEM) Simulation for Flood Modeling in the Absence of a High-accuracy Open Access Global DEM", *Front. Earth Sci.* Vol 6, pp. 233-240.

Hirdes W. and Nunoo B. (1994), "The Proterozoic Paleo Placers at Tarkwa Gold Mine, Southwest Ghana", *Geological Journal (Academy of Science of Ukraine*), Vol. 1, pp. 22-24.

Jaseela, C., Prabhakar, K., Sadasivan, P. and Harikumar, P. (2016), "Application of GIS and DRASTIC Modelling for Evaluation of Groundwater Vulnerability near a Solid Waste Disposal Site", *International Journal of Geos-ciences,* Vol. 7, pp. 558-571.

Jinhui, L., Qing, L., Wei, G. and Chen, W. (2019), "The Impact of Consumption Patterns on the Generation of Municipal Solid Waste in China: Evidences from Provincial Data", *International Journal of Environmental Research and Public Health,* Vol.16, pp. 1-19

Karley, N. K. (2009), "Flooding and Physical Planning in Urban Areas in West Africa: Situational Analysis of ACCRA, Ghana", *Theor. Empir. Res. Urban Manag*. Vol. 4 (13), pp. 25–41.

Kazakis, N., Kougias, I. and Patsialis, T. (2015), "Assessment of Flood Hazard Areas at a Regional Scale, Using an Index-based Approach and Analytical Hierarchy Process: Application in Rhodope–evros Region, Greece", *Sci. Total Environ.* Vol. 538, pp. 555–563.

Kesse, G. O. (1985), *The Mineral and Rock Resources of Ghana*, A. A. Balkema Publishers, Rotterdam, 610 pp.

Kortatsi, B. K. (2002), "Hydrochemistry of Groundwater in the Mining Areas of Tarkwa-Prestea, Ghana", *Ph.D. Thesis*, University of Ghana, pp. 70-85.

Kourgialas, N. N. and Karatzas, G. P., (2017), "A National Scale Flood Hazard Mapping Method- ology: The Case of Greece – Protection and Adaptation Policy Approaches", *Sci. Total Environ*., Vol. 601, pp. 441–452.

Kuma, J. S. (2007), "Hydrogeological Studies in the Tarkwa Gold Mining District, Ghana", *Bulletin of Engineering Geology and the Environment, Vol.* 66, pp. 89 - 99.

Kwesi, E. A. A, Asamoah, K. N., Arthur, F. A. and Kwofie, J. A. (2020), "Mapping of Ground Water Vulnerability for Landfill Site Selection Assessment at the District Level – A Case Study at the Prestea Huni Valley Municipality of Ghana*", Ghana Journal of Technology*, Vol. 4, No. 2, pp. 57 - 65.

Kwesi, E. A. A., Horror L. C. and Annan J. K. (2018), "Provision of Sanitation Maps for Improving Waste Management and Sanitation at the District Level: Case Study in the Tarkwa-Nsuaem Municipality of Ghana", *Conference Proceedings,* 5th UMaT Biennial International Mining and Mineral Conference, 1st – 4th August, 2018, UMaT, Tarkwa, Ghana, pp.15-20

Kwesi, E. A. A., Appiah S. T., Borsah, I., Taggoe N. D. and Tinadu K. (2015), 'Impacts of Galamsey on Drainage and Sanitation in the Mining Communities of Tarkwa, Ghana', *Conference Proceedings,* FIG Working Week 2015, on the theme 'From the Wisdom of the Ages to the Challenges of the Modern World', at Sofia, Bulgaria, 17-21 May 2015, pp 1-15

Moazzam, M. F. U., Lee, B. G., Rahman, A. U., Farid, N. and Rahman, G., (2020), "Spatio-statistical Analysis of Flood Susceptibility Assessment Using Bivariate Model in the Floodplain of River Swat, District Charsadda, Pakistan", *J. Geosci. Environ. Protect.* Vol. 8 (05), pp. 159-170

Rolland, A. and Rangarajan, R. (2013), "Runoff Estimation and Potential Recharge Site Delineation Using Analytic Hierarchy Process", *Geocarto International*, Vol. 28, pp. 159-170.

Saaty, T. L. (2000), *Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process*, Analytic Hierarchy Process Series, Vol. 6, RWS Publications, Pittsburgh, pp. 10-20.

Saaty, T .L. and Vargas, L.G. (2012), *Models, Methods, Concepts and Applications of the Analytic Hierarchy Process*, Springer Science & Business Media, New York, pp. 10-18. https://doi.org/10.1007/978-1-4614-3597-6.

Sackey, M. A. (2016), "Groundwater Contamination through Cyanide and Metal Migration from Tailings Dam Operation", *PhD Report*, Department of Civil Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana, pp.134-135.

Samanta, S., Pal, D. K. and Palsamanta, B. (2018), "Flood Susceptibility Analysis through Remote Sensing, GIS and Frequency Ratio Model", *Appl. Water Sci.* vol. 8 (2), pp. 66-74.

Tan, M. L., Gassman, P., Yang, X. and Haywood, J. (2020), "A review of Swat Applications, Performance and Future Needs for Simulation of Hydro-Climatic Extremes", *Adv. Water Res*., pp. 103662 -103672

Ubavin, D., Vujic, B., Vujic, G., Maodus, N., Kovacevic, S., and Djogo, M. (2015), "Groundwater Risk Assessment of Landfills in Province of Vojvodina", *Jornadas Tecnicas Internacionais De Residuos, Portugal*, pp. 1-7

Zhao, G., Pang, B., Xu, Z., Yue, J. and Tu, T. (2018), "Mapping Flood Susceptibility in Mountainous Areas on a National Scale in China",. *Sci. Total Environ*., Vol. 615, pp. 1133–1142.

BIOGRAPHICAL NOTES

Authors

E. A. A. Kwesi is currently a Lecturer at the Geomatic Engineering Department of the University of Mines and Technology (UMaT), Tarkwa, Ghana and a member of GhIS, GhIG, FIG and GPL. His research and consultancy works cover Surveying and Mapping, Community Involvement and Multicriteria Decision Analysis and their applications in Sustainable Management of Land, Agriculture, Waste, and Communities in Mining Areas.

K. N. Asamoah is currently a PhD student at the Kwame Nkrumah University of Science and Technology (KNUST), Ghana, and also working as a Graduate Teacher and holds BSc. and MPhil. Degree in Geology from KNUST and UMaT respectively. His research areas include geophysics, geostatistics, GIS, Remote Sensing, and their applications in Geology, Mining, Environmental Management and related fields.

Alfred K. OFOSU-DJAN is currently working with the Lands Commission of Ghana. He is the regional director of Public and vested lands management division of the lands commission in the central region of Ghana. He has Diploma in Estate management, Bachelor of Science Degree in Land Economy from Kwame Nkrumah University of Science and Technology (KNUST), Ghana and Msc. in Land Policy and Administration from University of Cape Coast-Ghana. He is a professional member of the Ghana Institution of Surveyors and has over 25 years of working experience in land management and related social and environmental.

CONTACTS:

E. A. A. KWESI,
University of Mines and Technology
Tarkwa
GHANA
Email: eaakwesi@umat.edu.gh