Integration of Groundwater Vulnerability Assessment in Landfill Site Screening at the Local Level: Case Study in the Prestea Huni-Valley Municipality of Ghana

Key words: waste management, groundwater vulnerability assessment, landfill site screening, multi-criteria decision modelling, constraint mapping.

SUMMARY

This paper presents the steps and results of a GIS-based site selection method that explicitly accounts for groundwater protection in the selection of landfill sites for municipal solid waste (MSW) management by integrating groundwater vulnerability assessment as a criteria in addition to meeting existing regulatory requirements and local conditions. This is especially important for urban mining areas in Ghana and other developing countries where there are rising urbanization, waste generation and disposal problems, environmental pollution and health hazards from mining operation and waste dumping at inappropriate locations. A case study approach is adopted with the Prestea Huni-Valley Municipal Area (PHMA) as the study area. Equipment used include a desktop computer, ArcGIS and Microsoft Office Software, Google earth, GPS receiver and field cameras. With the waste management needs of the study area and the regulatory requirement as bases, the necessary data sets were gathered and organised into a spatial database suitable for site selection analysis. The factors considered included proximity to rivers, roads, railways and settlements; land-cover type; slope; hydrogeology; and groundwater. The ArcGIS was vital for the preparation of the spatial database, processing models and the generation of criterion and output maps and other analytical steps and results. The analysis was done in a 2-stage constraint mapping fashion using tools and methods like buffering, overlays, raster-vector conversion, boolean algebra and “model-builder”. The initial constraint mapping produced a number of sites that met the regulatory requirements but these were reduced to a few suitable ones in the second stage where ground water vulnerability analysis was applied to exclude areas of high groundwater contamination risk from the candidate sites. The methods and final results which indicate both the prohibited and suitable sites are available to support improved waste disposal efforts in the study area. The paper recommends the method for use by waste management departments in PHMA and other similar areas and that groundwater vulnerability analysis should be included in the site selection process as demonstrated in this paper.

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1. INTRODUCTION

Municipal solid waste (MSW) management continues to present difficult challenges for urban areas in Ghana and other developing countries. Such challenges include increasing volumes of waste generation, low levels of waste collection, crude waste disposal practices, high environmental sanitation problems and inadequate acceptable final disposal sites and facilities (Kwesi *et al*, 2019; Anon. 2002,). There has therefore been increasing concerns and demands for sustainable solutions to the rising municipal waste management problems. Based on an estimated population of about 31 million and an average daily waste production per capita of 0.45 kg, Ghana generates about 5.1 million tons of solid waste annually (Anon, 2002; Anon. 2010; Anon, 2014; Miezah *et al*., 2015). These quantities may double by the next decade. A high percentage of these volumes of waste are being disposed without adequate protection from the nuisance and harm caused to the environment and public health. One area that has been identified as having the potential for improving waste disposal in developing countries, is the use of engineered landfilling. This was a major reason that necessitated the development of the Landfill Guidelines (LG) by the Environmental Protection Agency (EPA) of Ghana and other countries (Anon., 2002). Amongst other functions, the guideline was to provide the basis upon which Environmental Permits and Certificates for land operations would be issued and renewed by the EPA and other related Local Authorities like the Metropolitan, Municipal and District Assemblies (MMDAs) in the country. Meeting these permit requirements start with the identification of candidate sites that meet regulatory requirements for locating landfills and other waste disposal facilities. The guidelines entreat all MMDAs to identify, acquire and secure such sites for current and future use so as to eliminate or reduce the perennial lack of appropriate final disposal sites for effective waste management (Anon., 2002, Kwesi, *et al*, 2019).

Previous papers have discussed and demonstrated scientific and practical methods for carrying out the complex site screening and selection exercise to meet regulatory requirements and guidelines (Kwesi, *et al*, 2019; Khan and Samadder, 2014; Nishanth *et al.,* 2010; Onuigbo and Bello, 2014). There is however a rising concern for ground water protection in mining areas like Tarkwa and Prestea in Ghana where surface waters have been heavily polluted (Kwesi and Asamoah, 2020; Asante, 2011; Yankey *et al.,* 2011; Kusimi and Kusimi, 2012; Sackey, 2016; Miezah *et al.,* 2015). Previous research have also shown that some groundwater have been polluted by existing landfill sites (Jaseela *et al.* 2016; Ubavin *et al.* 2015; Aderemi *et al,* 2011).Thus the aim of this paper is to discuss and demonstrate the integration of ground water vulnerability assessment in landfill sites screening to reduce the risk of ground water contamination.

1.1 Geographic, Economic and Geological Background of Study Area

Fig. 1 shows the study area which is located in the Western Region of Ghana within latitudes 5º 15′ N and 5º 40′ N and longitudes 1º 40′ W and 2º 15′ W. It is the Prestea Huni-Valley Municipal Area (PHMA) of Ghana with Bogoso as the administrative capital. PHMA has an area of about 1200 km^2 and a population of about 159, 304 with with Prestia, Aboso, Huni-Valley, Bogoso, and Damang as the major urban centres. (Kwesi *et al*., 2020; Anon, 2014). The area is one of the major mining centres in Ghana that attracts many people from other parts of the country, Africa and the world. Many of the big mining operations in the country are located in PHMA (Kwesi *et al*., 2020; Kuma and Ewusi, 2009). Thus the economy of the area centers on mining and agriculture and related commerce and services. The administrative capital, Bogoso also serves as an important commercial and transit centre connecting the western and coastal towns to the northern parts of Ghana, and travelers from southern Cote d'Ivoire to Burkina Faso (Kwesi, *et al*, 2019). These factors attract migrants to the area for jobs and business which in turn contributes to the rapid urbanization and increasing waste disposal and sanitation problems observed in the area (Kwesi, *et al*, 2020; Anon., 2014). Geologically, the area forms part of the Birimian and Tarkwain formations. Aquifers in the area are considered possessing dual and variable porosity and limited storage capabilities (Kuma and Ewusi, 2009; Kortatsi, 2004; Kesse, 1985). Figure 2 shows the geological formations of the study area. Topographically the area is generally undulating with some scarps ranging from 150 - 300 meters above sea level, and small scale mining operations frequently take place along these ridges and valleys, contributing to frequent flooding, sanitation and water pollution problems (Kwesi *et al.*, 2019; Asante, 2011; 2012; Kusi-Ampofo and Boachie-Yiadom, 2012).

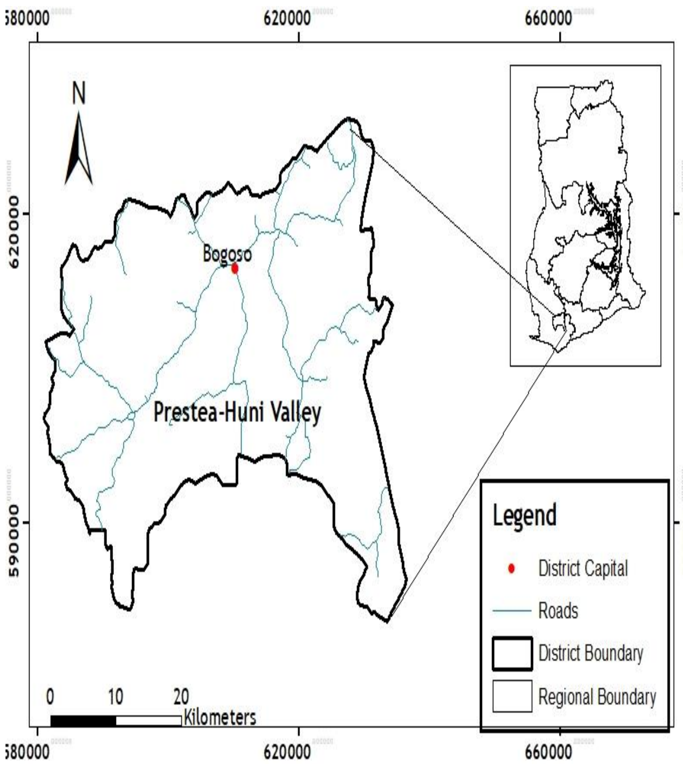

Fig. 1 Map of Study Area (PHMA) within

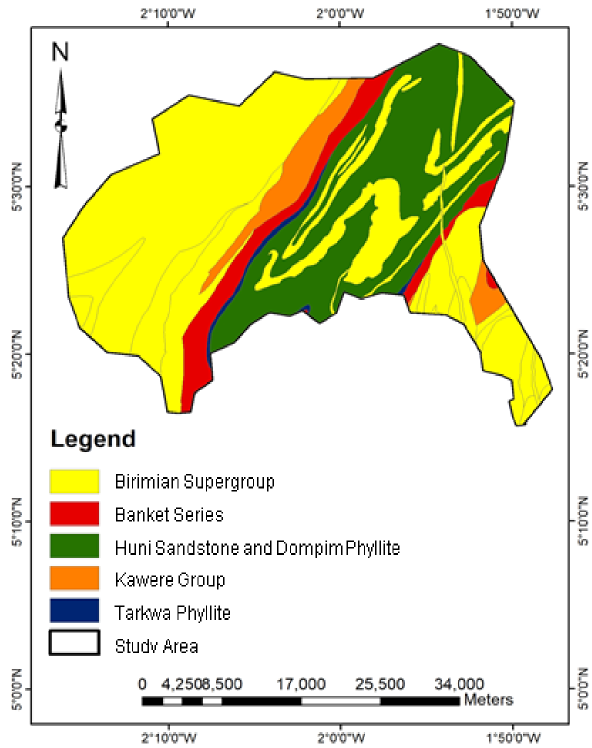

Fig. 2 Simplified Geological Map of Study

2. MATERIALS AND METHODS USED

2.1 Materials

The materials used for the study include relevant information from literature; secondary data comprising criteria information, maps on soil, topography, geology, hydrogeology, land cover/use, utility and communication lines, climate, administrative and property boundaries; primary data comprising field coordinates, photographs, observations and interviews; and data capturing, processing and analyses equipment like GPS receivers, cameras, scanners, computers and their associated software and accessories. The data sources include Landsat ETM+ images of 2015, the US Geological Surveys (USGS.com), ASTER Global DEM (GDEM), Google Earth, government agencies like EPA, MMDAs, TCPD, Land, Forestry and Minerals Commissions, Geological Survey and Meteorological Service Departments; and private data vendors and experts. The soil data was obtained from maps published by FAO ISRIC. Software used include ArcGIS (10.4 and 10.5) and Microsoft Office Suite (2013/2016).

2.2 Methods

The methods used include literature review on waste disposal and site selection for municipal waste management, including the criteria that must be met; collection of relevant data (such as remote sensing images (USGS.com), land use maps, legal requirements and criteria for landfill site selection, land-cover information; geology, soil, drainage and topographic maps); processing of data into spatial database; and spatial analysis for the site selection and evaluations using ArcGIS tools such as “Model Builder” and ‘map overlays’. The criteria considered were based on established regulations and guidelines and literature. Table 1 gives examples of the criteria, and details of the methodological steps are discussed in the subsequent sections.

2.2.1 Modeling

The selection of suitable waste disposal sites was carried out through a model building process employed to facilitate the multi-criteria decision analysis (MCDA) involved (Fig. 3). To facilitate easy understanding of the processing analysis, the modelling was fashioned separately according to the feature classes within the database, namely point, linear and areal features. Also to meet the last segment of multi-criteria decision making process where the individual decision layers have to be aggregated into a resultant outcome, an integrated model was also employed for the combination of individual feature-based models into aggregation units. These decision models (Fig. 3) were then applied to process and evaluate the decision variables based the various criteria employed in a step-by-step manner (feature by feature, feature-class by feature-class, and aggregate by aggregate) to yield the results presented and discussed in this paper. The simple additive weighting method of MCDA was used for the aggregation.

2.2.2 Data Conversion, Processing and Analysis

The data available for the work were of different formats and sources. Thus those in vector formats were converted into to raster formats in line with the demands of the analysis models and software used for the work. Reclassification of the layer's value were done into (1's) and (0's) scoring system, where "0" represented unsuitable and "1" signified suitable outcome.

Table 1 Sample of the Site Selection Criteria and Buffer Zones Used

Criterion Factors/Elements	Restrictions Related to Criterion Element Based on Regulatory Requirements	Criteria Applied
Land Use (Residential Areas, Active Mining Sites, Cemeteries, etc)	Areas within 500 m of residential and other sensitive land-uses	500 m buffer for residential, 200 m buffer for cemeteries and 300 m for active mining areas.
Land-cover (cash crops/farms, forests/game reserves, etc.)	Areas within 300-500 m of reserves and other properties	300 m buffer
Surface Water Bodies	Areas within 90-360 m of rivers, lakes, ponds, dams, wells, and springs	400 m buffer was used for wells important and 500 m buffer around other important water bodies
Roads, Railways and Utility Lines (water, gas, power and telecom lines)	Areas within 100-200 m of public transport and import utility lines	200 m buffer
Airport Runways and landing strips	Areas within 3000 m from the end of airport runways and landing strips in direct flight paths and areas within 500 m of airport or airfield boundaries	3000 m buffer and 500 m buffer
Slope	Areas with slopes ≤ 2% and ≥ 10%	slopes ≤ 2% and ≥ 10%
Soil	Areas with shallow bedrock and little soil cover	Based on the geology and soil information of the study area, locations characterized by the Fluvisols soil groups were rated as unsafe and thus restricted for use.
Geology	Subsidence, fault, seismic, mining and other unstable areas	Based on the geological information of the study area, locations having the Banket Series (Phyllite, Quartzite and Conglomerate hosting gold mineralisation), as well as the Huni Sandstone Formations within the Tarkwaian system were rated as unsuitable and thus restricted for use.

Ground water	Areas with high ground water vulnerability	Ground water vulnerability map of area

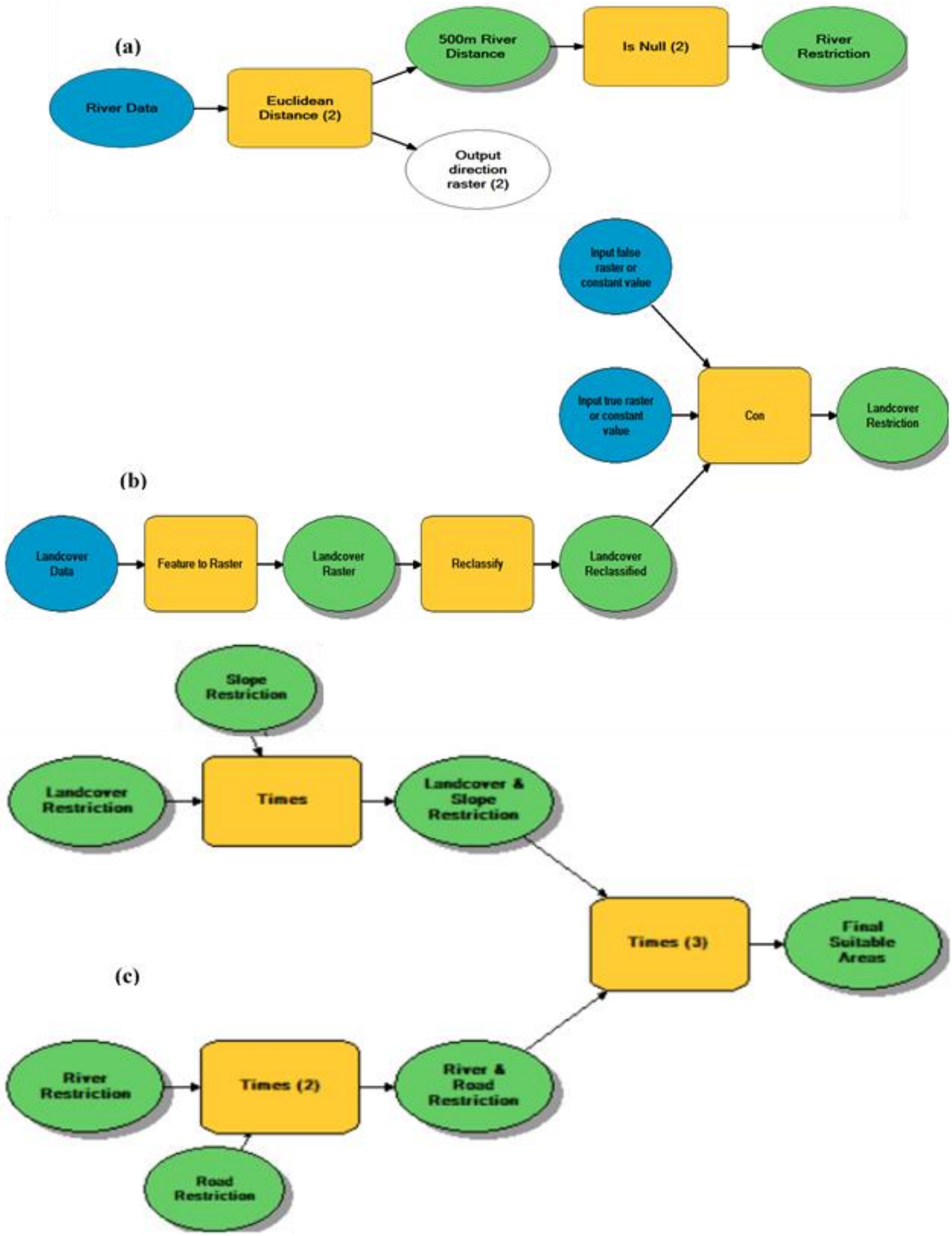

Fig. 3 Example of the Decision Processing Models Applied in the Site Screening Analysis for (a) Linear features, (b) Polygon features, and (c) Combined features

Buffering was done on various layers to determine values to assign suitable or unsuitable, for example, river was buffered by 300 m and areas within the buffer were assigned a value of 0, while areas outside were assigned the value of 1. Overlay of generated buffer maps were done in order to identify sites that were Suitable and sites that were not suitable for landfill. ArcGIS (10.4 and 10.5) was used for the processing. All the data layers were then entered into the model builder and thereafter converted to raster (grid) format from where buffering for the constraint mapping were carried out. After this, classification and union of all the buffered layers were done within the model builder. The model builder utilizes the weighted overlay procedure. In this process output maps are produced from various combinations of the multiple input data layers. The cells in the input map layers are assigned relevant weights to reflect the relatives importance of the criteria imposed before the layers are overlaid to produce the output maps. Figures 4 to 10 show examples of the output results from the data processing described in this section.

3. RESULTS AND DISCUSSIONS

Figures (Fig.) 4 to 10 show maps of analysis results based on the criteria applied for identifying suitable sites for municipal solid waste disposal in the study area. These are discussed in details in the subsequent sections under this.

3.1 Suitable Areas based on Surface Water Restrictions

According to Ghana Landfill guidelines (2002), a landfill site should not be situated near water bodies such as rivers and streams, lakes, ponds and dams. A range of 90 m - 300 m is suggested in the guidelines depending on the type of water body and its relative importance. The location is a mining area where the effects of both legal and illegal surface mining activities on water bodies are already of a great concern to the general public with increasing threats of deteriorating water quality and subsequent health implications in the future. Fears of such threats will be heightened when waste disposal facilities are located in close proximities to the few major water bodies in the area. River Bonsa and its tributaries constitute the main water body in the area. Accordingly, 500 m buffer was used for the restriction. Using the ArcGIS (10.4 and 10.5) and its model builder function, the entire study area was segregated into two broad regions, those within the buffer zones classified as not Suitable or unsuitable for waste disposal, and those outside the buffer zones classified as Suitable for locating waste disposal sites. Within the Suitable zones, areas lying between 500 m to 700 m from water bodies were classified as suitable and those beyond 700 m as most suitable use (Fig. 4).

3.2 Suitable Areas based on Roads, Railways and Utility Lines Restrictions

Landfills should not be located within 300 m of any roads so as to avoid the nuisance caused by birds and other scavenging animals crossing the roads. However, it is not advisable to site landfills too far from existing roads, so as to avoid or reduce the cost of constructing and maintaining new access roads and haulage time. Frequent break down of haulage trucks has been attributed to the poor nature of haul roads and hence the need to give more preference to sites within reasonable proximity to the major access ways (Anon, 2012). Thus areas lying within 300 m of main roads were classified as unsuitable, areas between 300 m to 500 m as suitable and areas beyond 500 m as most suitable for siting landfills as shown in Fig. 5.

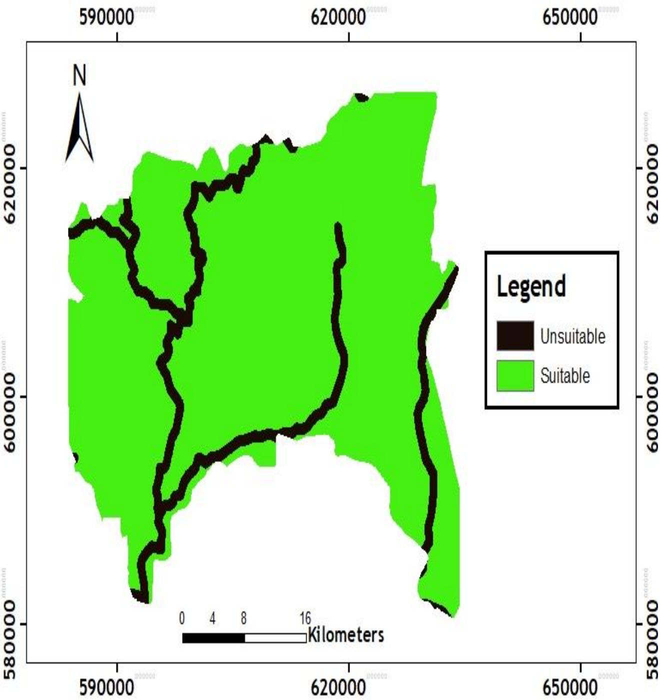

Fig. 4 Suitable Areas based on Criteria for Water Bodies.

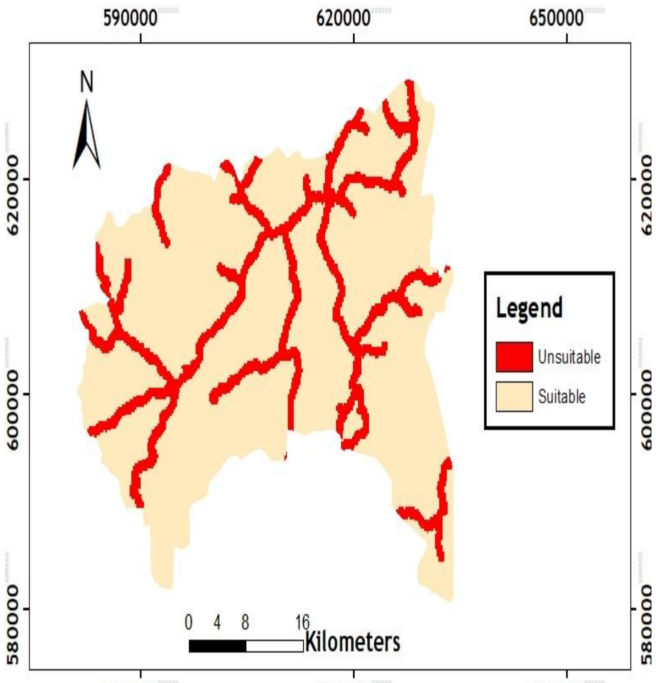

Fig. 5 Suitable Areas based on Criteria for Road/Railroad/ Utility Lines

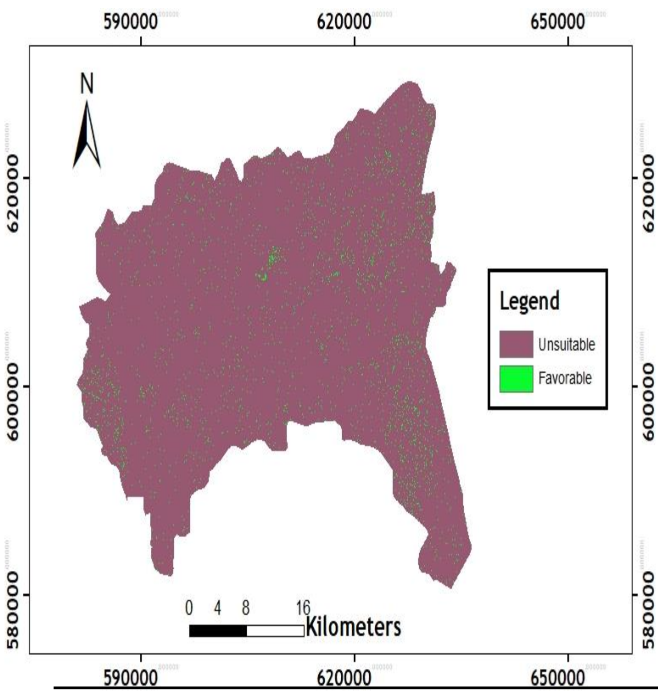

Fig. 6 Suitable Areas based on Slope Criteria

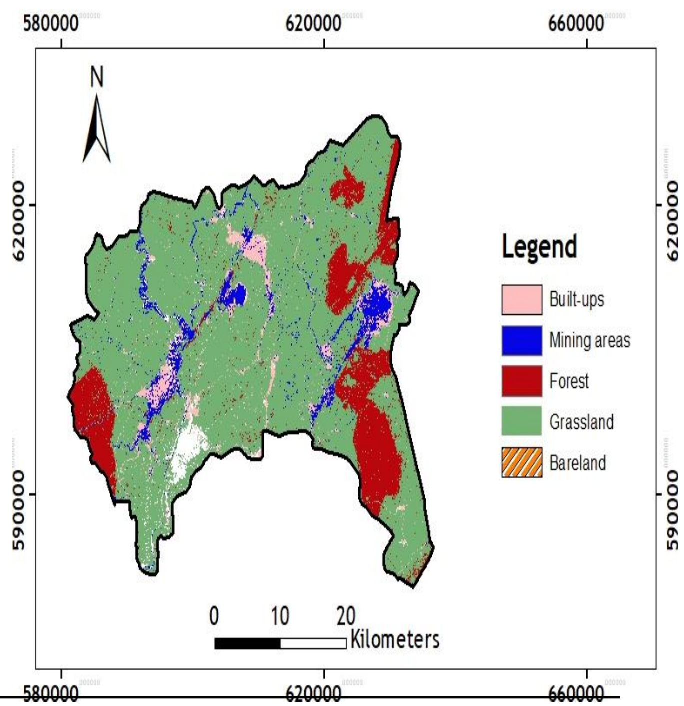

Fig. 7a Land-cover/Land-use Categories

3.3 Suitable Areas based on Slope Restrictions

Slope is one of the basic parameters considered when deciding on potential landfill sites. Areas having gradients greater than 10%, where stability of slopes cannot be guaranteed are not suitable for landfill. Areas with steep slopes (>10%) will also have high runoff rates any time it rains. A higher runoff rate will lead to a decrease in infiltration thereby carrying contaminants as far as the runoff water can travel. The environment is then prone to contamination from the leachate and other toxic chemicals that will be carried away from the containment area by the runoff from the landfill, most especially, surface waters. In this study, areas with slopes between 2% and 10% were considered most suitable for the construction of a landfill and ranked 3; slopes between 10% and 15% were considered suitable and ranked 2, and areas with slopes less than 2% and greater than 15% were considered unsuitable and ranked 1. Fig. 6 shows the site classification of the area based on the slope criteria and analysis.

3.4 Suitable Areas based on Land-cover and Land-use Restrictions

Fig. 7a shows a map of the various land-cover/land-use classes considered for this work. Due to the presence of natural mineral reserves within the municipality, the population influx and growth is very high. The rate of expansion and development in the urban centres of PHMA municipality is spreading very fast, so a reasonable buffer has to be determined for a landfill site so that it does not interfere with the developmental plans of the city. It is not permitted to site landfills in close proximity to land cover/use areas such as forest reserves, residential areas and mining sites so as to avoid adverse effects on the current and future uses of such lands. In this study, areas within 500 m from forest reserves were considered unsuitable and areas within 1000 m from villages/hamlets were also considered as unsuitable. Areas that were 2000 m away from settlements were considered most suitable for landfill as shown in Fig. 7b. Protection of surface water bodies were considered separately in section 3.1.

3.5 Suitable areas Based on Geology and Soil

Geologically (see Fig. 2), only a small part of the study area have locations considered to be unsafe and thus rated as restricted zones. These consist of Phyllite, Quartzite and Conglomerates hosting gold mineralization in the area. Fig. 8 shows the results of the application of the restriction criteria on soil based on information from available literature, Table 1 and Fig 2. The soil information of the study area is generally okay requiring no restrictions for most parts of the area except the western, north-western and south-western parts of the area. These are made up of Fluvisols, comprising mainly of sandy and silt materials which together with the underlining geology make them unfavourable and thus rated as restricted zone. The remaining areas are dominated by acrisols and ferralsols consisting mainly of laterite and silt materials respectively rated as suitable and very suitable for use.

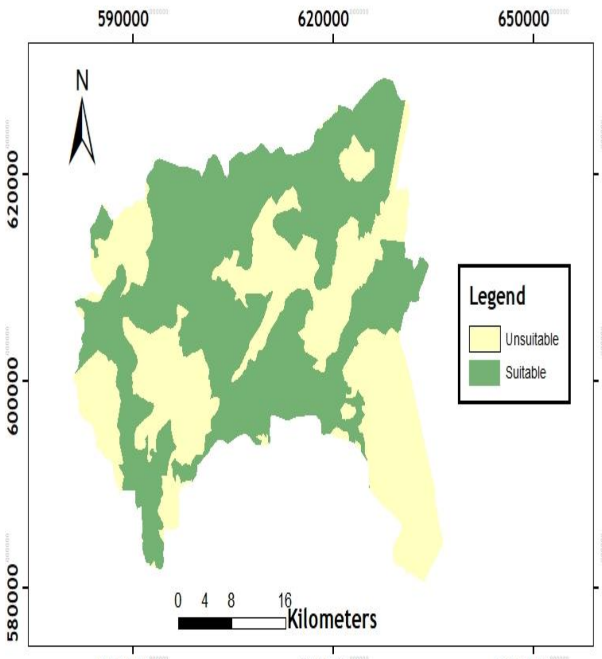

Fig. 7b Map Showing Suitable Areas Based on Land cover/use Criteria

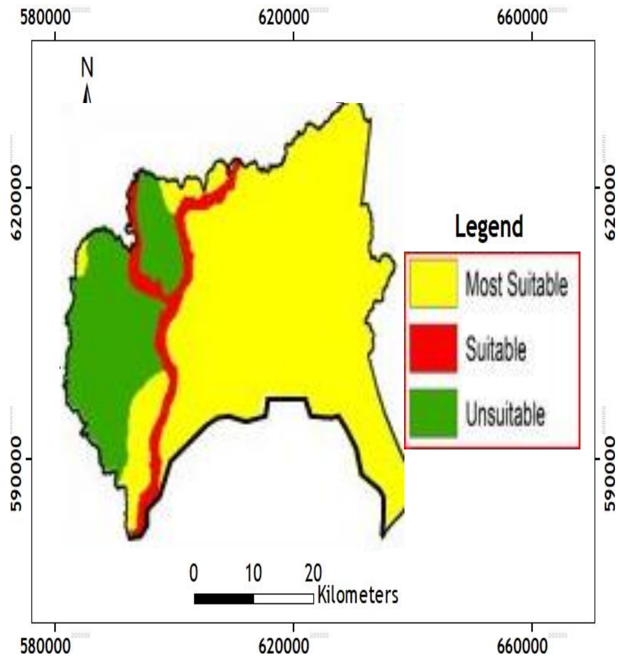

Fig. 8 Map Showing Suitable Area Categories Based Soil Types

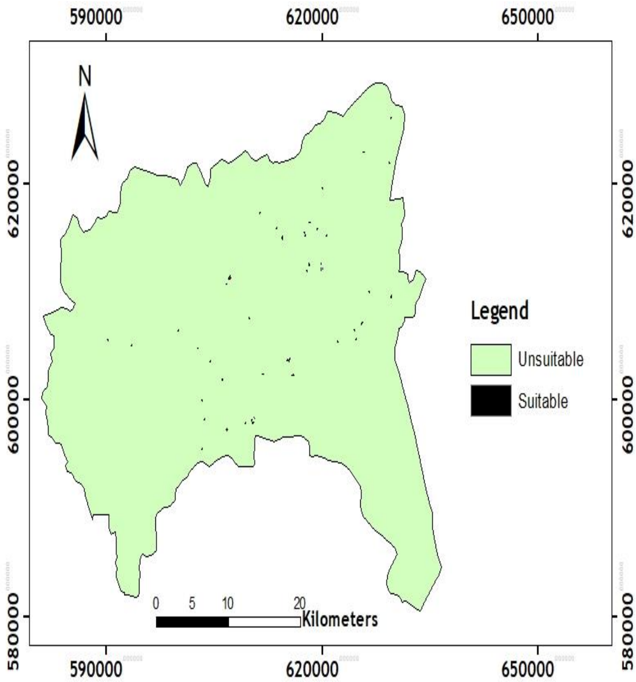

Fig. 9 Map Showing Suitable Areas Based on all Restrictions

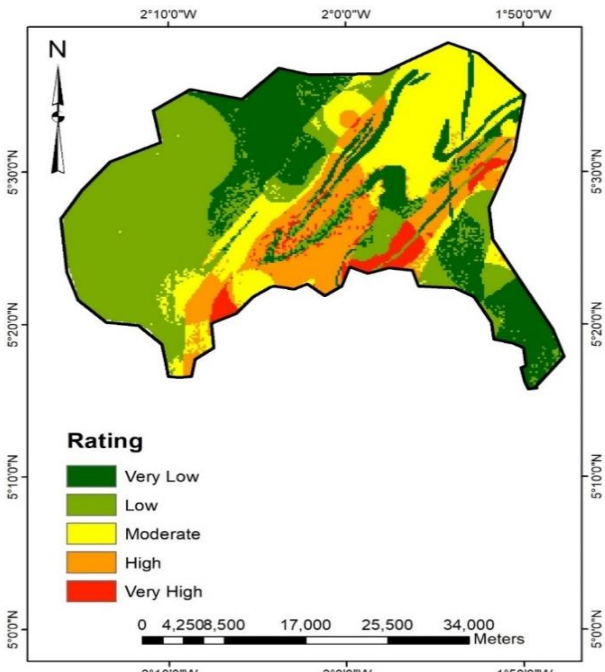

Fig. 10 Groundwater Vulnerability Distribution and Ratings for Study Area

3.6 Suitable Areas from All Restrictions

Fig. 9 shows the result of the composite mapping indicating the suitable areas from all the restriction criteria imposed on the search analysis according to the regulatory requirements and the related available data used for the work. This composite suitability map was derived by running all the constraint maps based on all the criteria employed (Table 1) using the Times tool in ArcGIS Spatial Analyst module. This constraint mapping produced about 50 suitable sites that meet the regulatory and other desirable requirements and these covered about 0.67% of the study area. Some of these sites however have high potential of contaminating groundwater at some locations due to local conditions. Groundwater vulnerability analysis was thus applied to address this need (section 3.7).

3.7 Integration of Groundwater Vulnerability Assessment

To improve the reliability of protecting groundwater from contamination, ground water vulnerability assessment was done and applied in the site identification analysis, though this is not explicitly stated in the regulatory requirements or guidelines. This is especially necessary for mining areas like PHMA where surface water bodies are already polluted and there is greater need to protect ground water for domestic and other uses (Kwesi *et al.*, 2020). The "DRASTIC" method of groundwater vulnerability analysis was employed and this was based on the seven major geologic and hydrogeological factors that control groundwater movement and pollution in the study area (Rundquist *et al.,* 1991; Al-Abadi *et al*., 2014; Ewusi *et al.,* 2017; Kwesi *et al.,* 2020). Details of this analysis can be found in Kwesi *et al.,* 2020. Fig. 10 shows the results of the groundwater vulnerability mapping indicating various classes of the risks of groundwater contamination. The final map of suitable areas at Fig. 9 was overlaid with the groundwater vulnerability map (Fig. 10) of the area to rule out all areas that have high risk of groundwater contamination if used for waste disposal. Figure 11 shows the results for this analysis, which reduces the number of suitable sites to about 20, and that constitutes about 0.27% of the entire area.

The groundwater vulnerability map shows that the high to very high vulnerability classes occur mainly at the central part of the PHMA with some extensions at the southwestern and eastern parts of the area. These classes occupy about 17 % of the study area. The moderate to very low vulnerability classes, constituting about 83% of the entire region, occupy mainly the western, northern, eastern and south-eastern parts of the region. Based on this information (Fig. 10), landfill sites situated in most parts of the central portions of the study area, will have high to very high potential of contaminating the groundwater, and thus expected to be rated unsuitable. On the other hand, landfill sites situated in the other parts of the study area will have moderate to low potential of contaminating the groundwater and thus expected to be rated suitable in most of the cases. These expectations are correctly reflected in the final site screening map at Fig. 11, proving the reliability of the simple but practical approach used for this exercise.

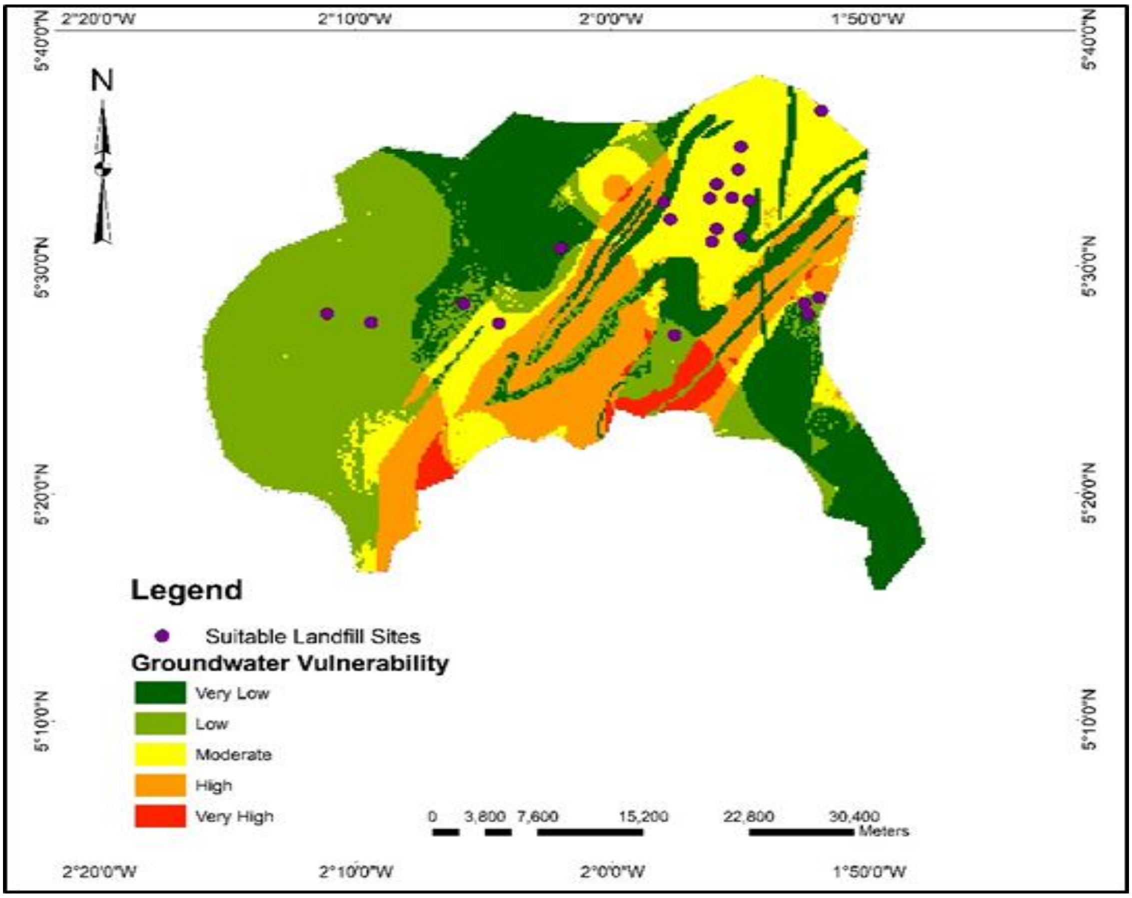

Fig. 11 Final Map of Suitable Sites Based on Groundwater Vulnerability Criteria

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

This study used Geographic Information System and spatial-based decision making models to identify suitable sites for landfill developments in the Prestea-Huni Valley Municipality that meet regulatory requirements and explicitly accounts for groundwater vulnerability. The criteria used for the work was based on the regulatory requirements and guidelines from the EPA, MMDAs, and other Public and private bodies. The final composite map shows areas that are suitable and areas that are not suitable for landfill and other waste disposal development. The percentage of the total suitable areas over the entire area was estimated to be 0.67% and this was further reduced to 0.27% by the application of groundwater vulnerability maps as additional criteria. The inclusion of groundwater vulnerability in the analysis is an important innovation to help reduce the risk of groundwater contamination. This is especially necessary for areas like PHMA and its environs where protection of ground water for domestic uses is increasingly becoming necessary since existing surface water bodies are being polluted by surface mining and related activities. The approach presented in this paper can help meet regulatory requirements and local needs in landfill site selection which is an important but elaborate process that requires systematic analysis and evaluation of numerous factors, criteria and data to be able to achieve the engineering, economic, environmental, and socio-cultural objectives involved.

4.2 Recommendation

It is recommended that groundwater vulnerability should be incorporated in the early stages of the site selection process to help reduce the risk of water contamination as demonstrated in this study. Also, due to constraints with data availability, not all the legal requirements were applied in this study. Further work incorporating all the requirements is recommended. The results also indicate that available suitable sites for landfilling in the study area may be scarce and thus need to be protected.

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BIOGRAPHICAL NOTES

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