Suitability analysis for siting oil and gas filling stations using multi-criteria decision analysis and GIS approach – A case study in Tarkwa and its environs

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Abstract: Oil and gas stations are indispensable in the current technological society, however explosions from such fuel stations often cause loss of lives and properties within the surrounding communities thereby posing great concern to government and the citizenry. This condition calls for research that would provide meaningful solutions to mitigate this menace. Unlawful siting of oil and gas stations, non-consideration of environment impact on growing human population, competition for customers and lack of enforcement of standards are some of the causes of these explosions. This study investigated the level of compliance to standards set by the Ministry of Energy, and the Town and Country Planning Department by existing oil and gas stations in the study area. Primary and secondary data were used for the study. The primary data consist of locations of oil and gas filling stations picked with the Garmin handheld GPS whilst the secondary data comprise of topographic and soil maps from which soil types, roads, water bodies, terrain slope and land-use features of the area were extracted and used. The dataset was reclassified and Analytical Hierarchy Process was used to assign weights to the selection criteria. Spatial analyses were carried out using ArcGIS software to show areas suitable or otherwise for siting stations in the study area. The results showed 75% of oil and gas operators in the study area were compliant with the required standards while 25% were not. The integration of GIS techniques with multi criteria decision analyses has proved to be an effective tool for selecting suitable sites for filling stations and very useful in determining places of high fire risk for proper planning of the area. It is recommended that the authorities put measures in place to combine education and enforcement of the set standards through prosecution of offenders to bring sanity in the oil and gas filling station business.

Keywords: Analytical Hierarchy Process, Fire Risk, GIS, Oil and Gas Filling Stations

1. Introduction

The frequent reports of oil and gas explosions in the Republic of Ghana and its associated loss of lives, properties and national assets is an issue of concern receiving much attention by geospatial professionals (Saraei and Ghanei, 2011; Aslani and Alesheikh, 2011). The growing number of oil and gas stations operating along main roads, and settlement areas in some developing countries, especially Ghana calls for the need to control and manage the operations of such activities in the country (Uzochukwu *et al*., 2018). It is therefore imperative that government with the support of non-governmental agencies enforce set of rules and standards to manage the operations of oil and gas stations in the country (Tah, 2017).

As human population increases, there is commensurate surge in the number of automobiles working on the road leading to increasing demand for oil and gas (Njoku and Alagbe, 2015). This creates the need for filling station services and consequently the establishment of oil and gas stations within the communities. The permit required to operate oil and gas filling stations in Ghana is usually obtained from the Ministry of Energy and the Town and Country Planning Department. Some operators however, ignore seeking licenses from these bodies prior to establishing their businesses, perhaps to avoid payment of the required fees. Hence, some of these stations find themselves operating in unsuitable areas (Uzochukwu *et al*., 2018). The siting of environmentally sensitive commercial and service activities in rural or urban areas are guided by rules and standards (Tah, 2017). Accessibility for maneuvering in times of danger is key to safe operations of oil and gas stations.

In recent years, there have been several concerns regarding provision of licenses and indiscriminate siting of oil and gas stations (Aslani and Alesheikh, 2011). These fuels can give off flammable vapour at very low temperatures and can result in high risks of explosions if an ignition source is close (Njoku and Alagbe, 2015). In the Republic of Ghana, there have been several cases of wildfires and explosions of oil and gas filling stations as presented in literature with thousands of lives and millions of dollars lost each year (Norman *et al*., 2015; Kusimi and Appati, 2012; Addai *et al*., 2016; Amissah *et al*., 2010). As the health, safety and protection of people is a major concern to all, hence, the need to assess a site suitability for operating these activities in spatial contest of the study area concerned.

Geographic Information Systems (GIS) has proven to be very relevant in solving spatially related problems (Guler and Yomralioglu, 2017; Njoku and Alagbe, 2015). GIS has been applied in solving majority of problems in geoscientific discipline. Notably among them are; siting oil and gas stations (Tah, 2017; Njoku and Alagbe, 2015; Aslani and Alesheikh, 2011), forest risk mapping (Akay and Erdogan, 2017), selection of suitable sites for growing rice (Kihoro *et al*., 2013), landfill site selection (Guler and Yomralioglu, 2017), and planning of primer transportation of forest products (Akay and Yilmaz, 2017). Multi-criteria Decision Analysis (MCDA) and GIS are very useful tools for solving problems in spatial context because various decision variables can be evaluated and weighted according to their relative importance to attain the final optimal decision (Broekhuizen *et al*., 2015; Kihoro *et al*., 2013). Also, MCDA has the ability to judge qualitative criteria along with quantitative criteria (Boroushaki and Malczewski, 2008). Moreover, it is simple to understand, easy to implement, modify, and suitable for problems which have a hierarchical framework (Aslani and Alesheikh, 2011). Hence, MCDA and GIS techniques were adopted in the present study. This study aims at finding out whether or not oil and gas operators in Tarkwa and its environs comply with the standard rules and regulations set by the Ministry of Energy and Town and Country Planning Department in Ghana. Furthermore, a propose map for siting oil and gas stations for future development and planning in suitable areas has been produced.

2. Study area

The study area (see Figure 1) is a mining community situated in the southwestern part of the Republic of Ghana. It is located on latitude 5º 18´ 00″ N and longitude 1º 59´ 00″ W with topographic elevation of about 78 m above mean sea level (Peprah *et al*., 2017). It is a semi urban area with high demand of oil and gas products for their daily operations. Some of the renowned mining companies include AngloGold Ashanti Iduapriem, Goldfields Ghana Limited, Ghana Manganese Company Limited and several mining services companies such as BCM Limited, Liebherr Limited, Africa Mining Services, Mantrac Company, Volvo Company, Hyundai Company Limited, Maxam Limited, Geodrilling Limited, Maxmass Limited, African Resource Management, SGS Geochemical Laboratory Limited and Cummins Limited. Most homes, offices, factories, hospitals and schools in the study area have power plants that provide alternative source of electric power due to the power fluctuations in the country's national grid. Moreover, other minor business services depend on private power produce by oil and gas products.

3. Resources and methods used

3.1. Resources

The data used for the study comprise primary and secondary data. The primary data consist of the location of some of the oil and gas filling stations in the study area picked with the Garmin Handheld GPS while the secondary data consist of topographic maps containing features such as contours, land use, vegetation, roads, soil types, and water bodies of the study area. Table 1 is a sample location of the oil and gas filling stations.

3.2. Methods used

3.2.1 Field data collection

A reconnaissance survey was carried out to inspect the vicinity of the stations and to determine appropriate methods to adopt for the survey. The locations of the oil and gas filling stations in the study area were captured using the Garmin Handheld GPS receivers. Geographic features within the surroundings of each station was measured and recorded. The measurements made included distance from green areas, distance of pump station to road, size of the filling stations, distance to neighbouring stations, and distance to any public facility (such as schools, banks, churches, hospitals, lorry stations, market, *etc*.).

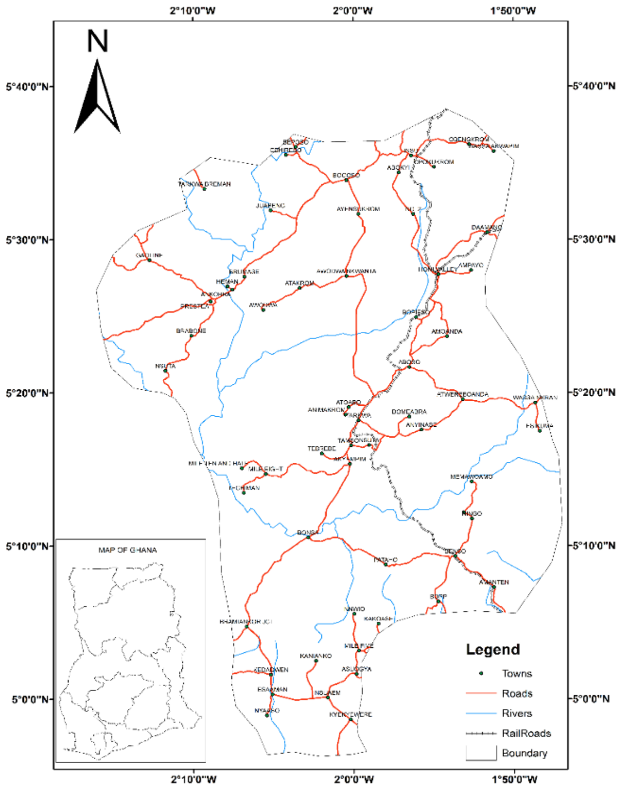

Figure 1: Study area

Table 1: Sample of oil and gas filling stations (units in meters)

ID	Northings (m)	Eastings (m)	Filling Stations	Location
1	580793.600	610277.400	Total 2	Akyempim
2	580836.500	610340.800	Star oil	Akyempim
3	581597.900	610299.700	Crown	Bankyim
4	584067.900	610525.900	Champion	Tamso
5	589204.300	613030.500	Shell	Tarkwa
6	588994.700	612859.600	Goil	Tarkwa
7	587577.600	611941.400	Allied	Tarkwa
8	586873.600	611533.400	Total 1	Tarkwa

3.2.2. Proximity analysis

Buffer analyses of fuel pumps distance to road, distance between neighbouring stations, distances between stations to any public facilities were done in ArcGIS environment. This was to assess the stations' compliance to the set standards by the Ministry of Energy, and Town and Country Planning Department. Filling stations that fell within the specified buffer distances complied with the set standards and are more likely to pose less hazard to the environment while those that fell outside the buffer zone are expected to pose hazards to the surroundings. The set standard of pump stations to roads is to be at least 15 m, and hence a buffer of 15 m was generated in ArcGIS environment. Again using set standard distance of at least 100 m and 400 m from any public facility and water bodies respectively, buffers were generated for each of the oil and gas stations to assess the level of compliance.

Buffer analyses were also performed to assess the proximity of oil and gas stations to populated areas and firefighting stations. Proximity analysis was carried out to determine the spatial relationship between the selected stations and their neighbouring features with regards to distances (Sara *et al*., 2011). It also allowed the spatial feature to be reclassified based on distance that meet the set criteria (Njoku and Alagbe, 2015; Tah, 2017; Aslani and Alesheikh, 2011).

3.2.3. Selection of suitable site for oil and gas stations

The suitable sites were selected based on spatial analyses of the following dataset: slope, land use, vegetation, roads, soil type and water bodies. As the dataset are of varying relative importance, Analytic Hierarchy Process (AHP) based on pairwise comparisons was used to generate weights for each criterion. The relative importance between two criteria was measured based on a numerical scale from 1 to 9 (Saaty, 1980). Figure 2 shows the flowchart of the MCDA. The AHP, which was first developed by Myers and Alpert (1968) and remodified by Saaty (1977), was used because the technique assesses a set of evaluation criteria and search for the optimal solution among a set of alternative options (Akay and Erdogan, 2017; Akay and Yilmaz, 2017). In the solution process of AHP, the study area was classified into low, moderate, and high.

3.2.4 Model generation

The suitability and restriction model was created in ArcGIS environment according to Equation 1 given as:

$$S = \sum_{i=1}^{n} w_i * c_i \prod_{j=1}^{m} r_j \qquad (1)$$

Where; S is suitability site for oil and gas; w_i is weight for criteria; c_i is criteria for suitability; r_j is restriction. Most restriction will include a minimum and maximum buffer distances for suitable selection of a site. Table 2 is the standards set for suitability selection and Table 3 is the relative importance values. The following procedure was adopted for creating the final raster map:

- Buffer creation for the criteria (slope, land use, roads and water bodies).
- Conversion of vector layers to raster.
- A restriction is created using the null tool so as to show areas viable for siting the oil stations.
- The various restrictions are combined to give the final restriction.
- The Restriction model and the suitability model are combined to give the final suitability of locations appropriate for siting the oil stations.

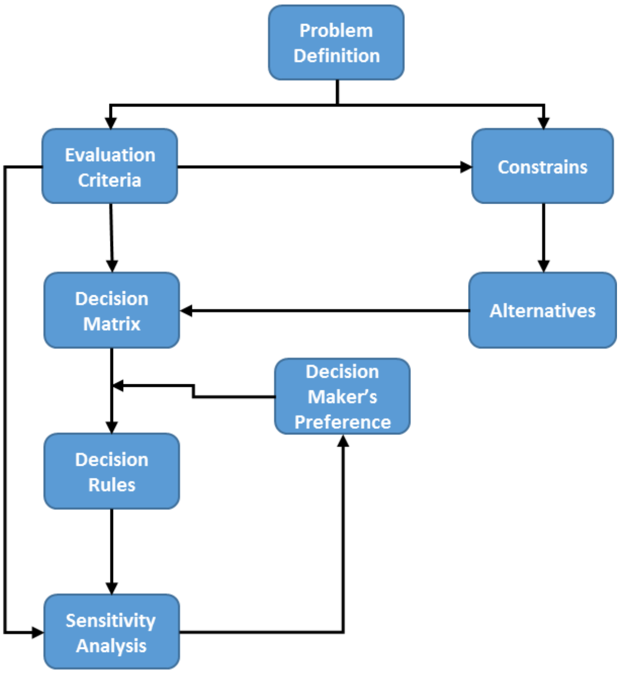

Figure 2: Flowchart of the MCDA process (Malczewski, 1999)

Figure 3 and 4 show the suitability and restriction model generated respectively for the suitable site selection. The combined model for the final output raster map is shown by Figure 5.

From Table 3, the values assigned to the sub-criteria were evaluated with regards to suitable site selection. Higher score was given when the criterion was more important (Akay and Yilmaz, 2017). The derived matrix was normalized to obtain the Eigen vectors (weights) which were assigned to the selection criteria.

Table 2: Restriction standards for suitability selection

Restriction source	Minimum buffer distances / degree	Maximum buffer distances / degree	Analysis buffer distances / degree
Slope	0°	20°	≤ 20°
Built-up areas	500 m	1000 m	500 m
Roads	100 m	500 m	100 m
Surface water	100 m	500 m	100 m

Table 3: The relative importance values (Saaty, 1980)

Importance Scale	Definitions of Scale
1	Equal Importance
3	Weak importance of one over another
5	Essential or strong importance
7	Demonstrated importance
9	Absolute importance
2, 4, 6, 8	Intermediate values between the two adjacent judgements

Each entry $a_{ji} = 1/a_{ij}$ of the matrix represents the importance of the *i*th criterion relative to the *j*th criterion. If $a_{ji} > 1$, the *j*th criterion is more important than the *i*th criterion. The column vector was produced by using Equation 2 given as (Gulci, 2014; Akay and Erdogan, 2017):

$$x_{ji} = \frac{a_{ji}}{\sum_{j=1}^{n} a_{ji}} \qquad (2)$$

Where x_{ji} is each entry at the column, and *n* is the number of criteria. The weighted averages of the criteria w_{ji} were computed by averaging the entries (c_{ji}) on each row using Equation 3 given as (Aslani and Alesheikh, 2011):

$$w_{ji} = \frac{\sum_{i=1}^{n} c_{ji}}{n} \qquad (3)$$

The ratio of consistency index (CI) and random index (RI) were also computed to check the consistency of the evaluations made for the pairwise comparison matrices. The smaller value of this ratio (< 0.1) the better the assigned weights (Kihoro *et al*., 2013; Broekhuizen *et al*., 2015). This was done to prevent bias through criteria weighting according to Equation 4 and Equation 5 given as:

$$CI = \lambda_{\max}/n \qquad (4)$$

$$CR = CI/RI \qquad (5)$$

Where $\lambda_{\max}$ is the maximum Eigen value, *CI* is the consistency index, *CR* is the consistency ratio, *RI* is the random index, and *n* is the number of criteria or sub-criteria in each pairwise comparison matrix.

After consistency analysis, spatial analyst extension in the ArcGIS environment was used to assign weighted values (w_{ji}) to the corresponding criteria. Finally, a weighted overlay operation was carried out to sum up the weighed criteria together according to their relative importance to produce a weighted overlay map.

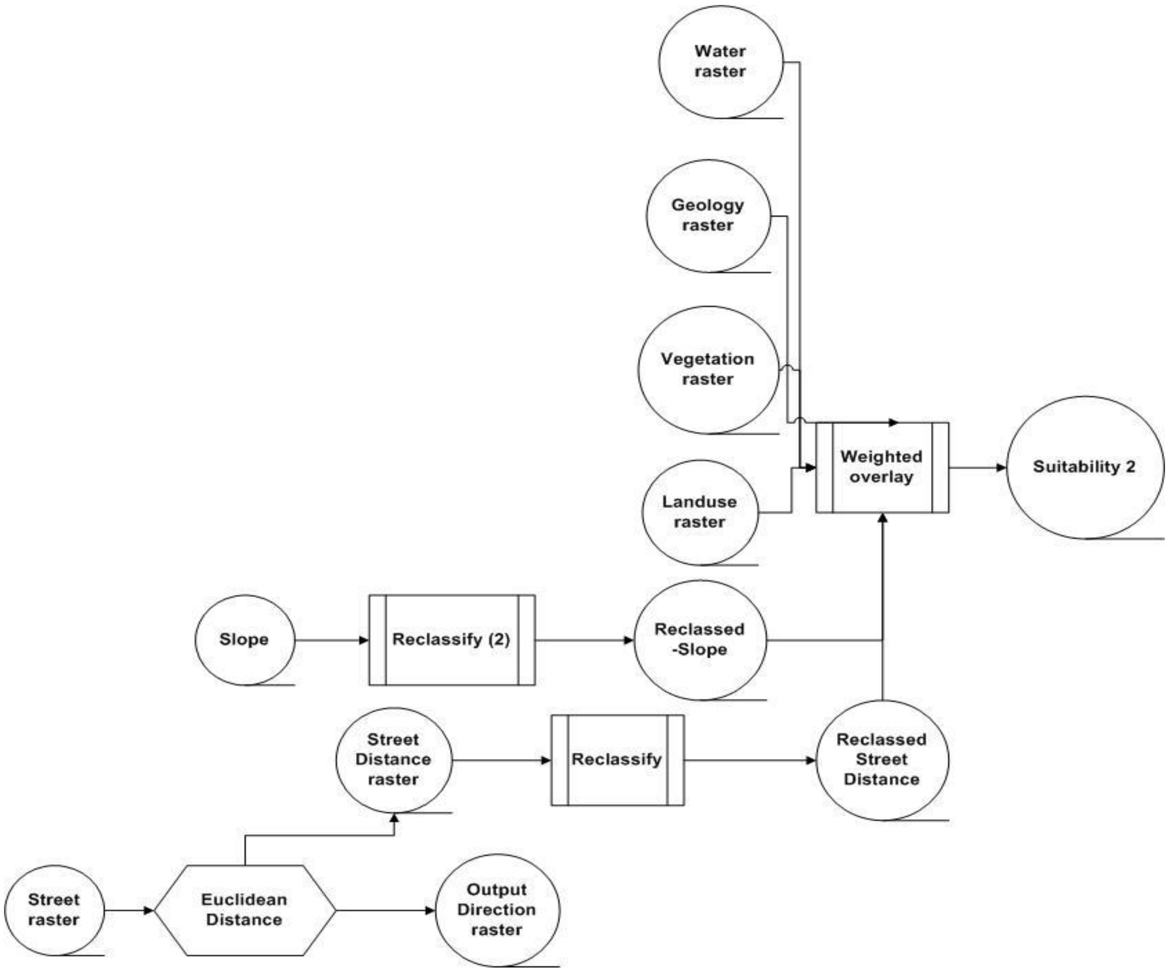

Figure 3: Suitability model of criteria used

Figure 4: Restriction model

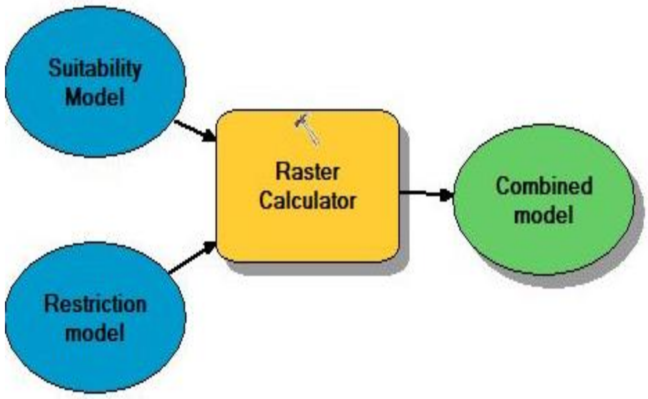

Figure 5: Combined model

4. Results and Discussion

4.1. Results

The outcome of the buffer analyses is presented in Figure 6, 7, 8 and 9 show the land use analyses. Table 4 and 5 are the suitability description and search distance to neighbouring stations. The required size of any station should be of a minimum area of 1080 m^2.

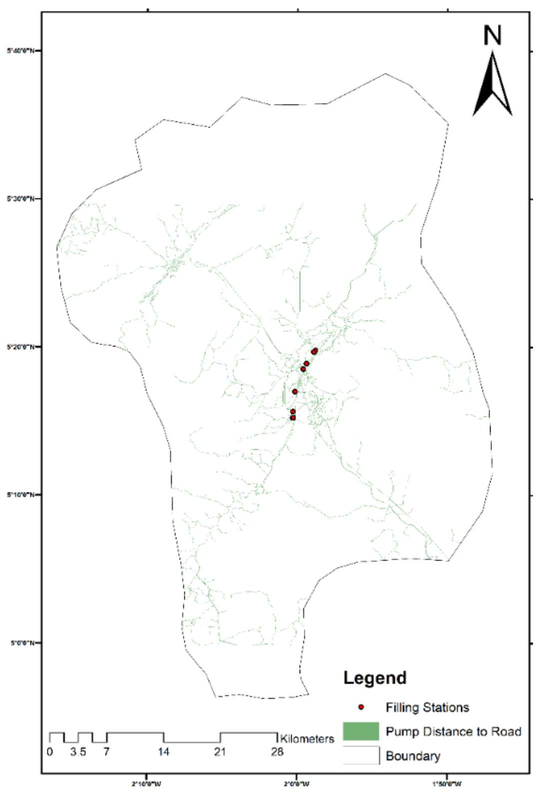

Figure 6: Distance of pump station to road buffer analysis

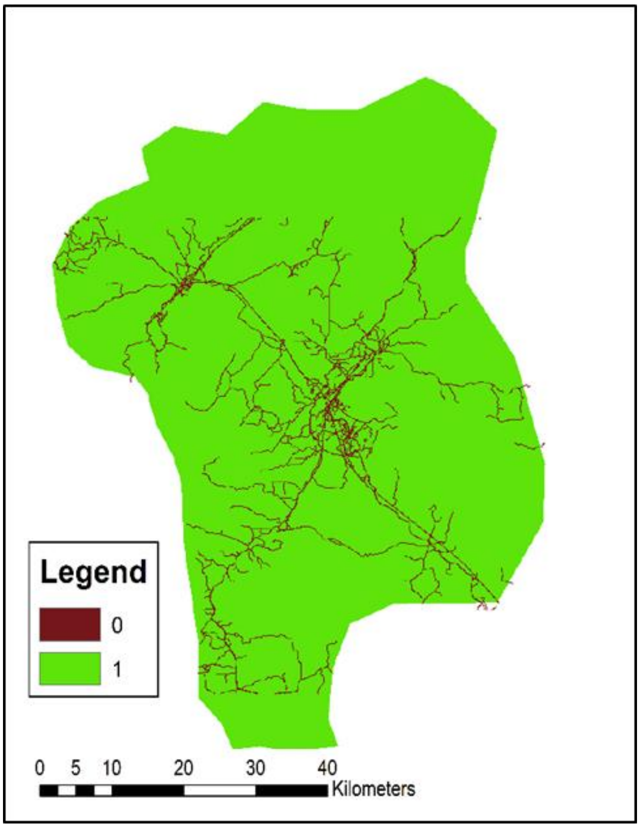

Figure 7: Map of street restriction

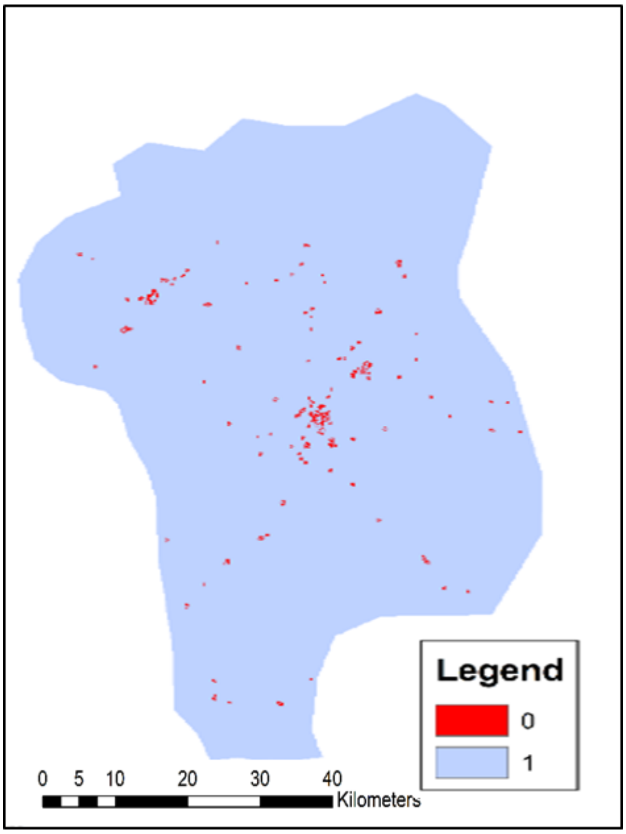

Figure 9: Map of land use restrictions

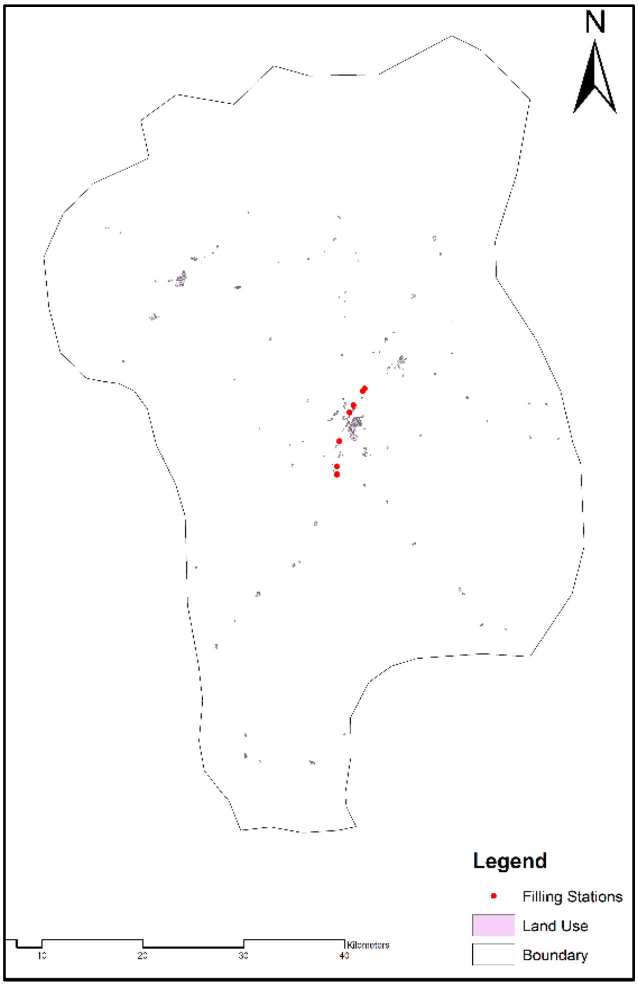

Figure 8: Distance to public facilities analysis

Table 4: Suitability description

Range of Value	Colour Code	Description
0.0 – 1.0	Red	Not Suitable
1.1 – 2.0	Yellow	Moderate Suitability
2.1 – 4.0	Green	Most Suitable

Table 5: Distance to neighbouring stations (units in meters)

From	To	Linear Distance (m)
Total 2	Star Oil	76.4921
Star Oil	Crown	762.6709
Crown	Champion	2480.6839
Champion	Total 1	2981.5189
Total 1	Allied	813.8200
Allied	Goil	1688.8023
Goil	Shell	270.4306

Figure 10 is the water restriction map. Figure11 is the slope analysis. From the restriction results (see Figure 7 and 9), the 0 represents the restricted region and 1 represents a viable region

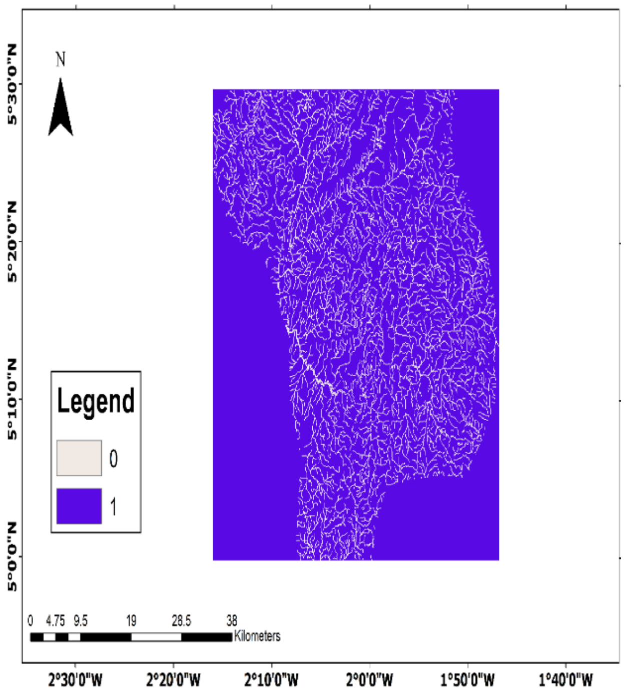

Figure 10: Map of water restriction

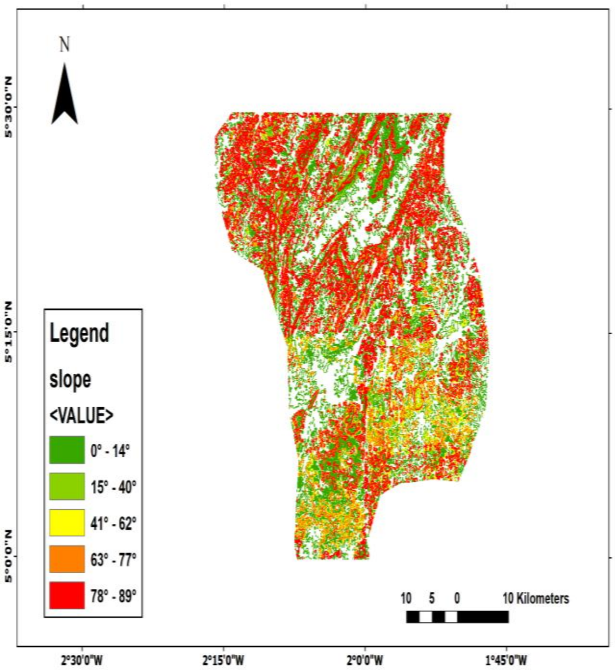

Figure 11: Slope analysis

The outcome of the pairwise comparison from which the weight for the criteria and their sub-criteria were generated is shown in Table 6. Also, Table 7 presents the normalized matrix and the computed weights from AHP. The calculated CI and CR were found to be less than 0.105, which implies there was consistency in the assigned weights. The suitability map for siting oil and gas stations is represented by Figure 12 and 13 shows the map of the combined model thus, suitability and restriction model for siting oil and gas stations including all the various criteria (slope, Land use, water bodies, forest, roads, and soil type). Figure 14 is also a map of the existing stations on the combined model map to check whether or not they are within acceptable region.

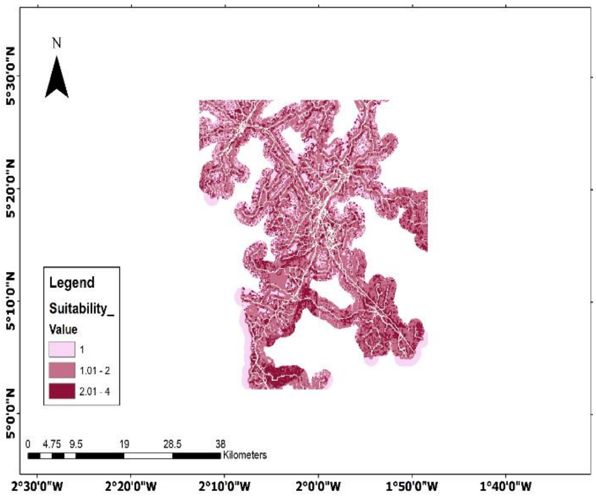

Figure 12: Suitability map

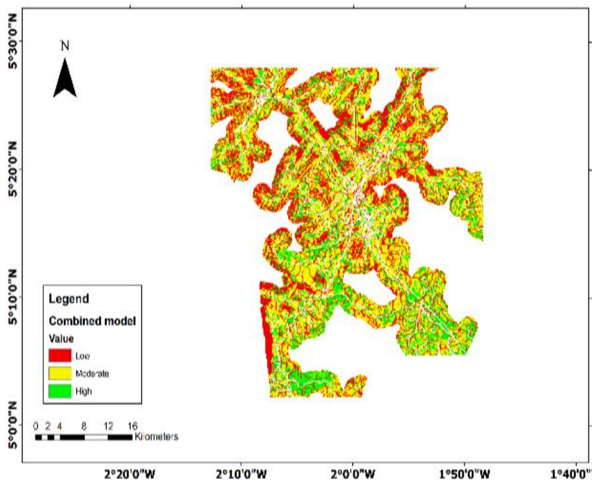

Figure 13: Map of combined model

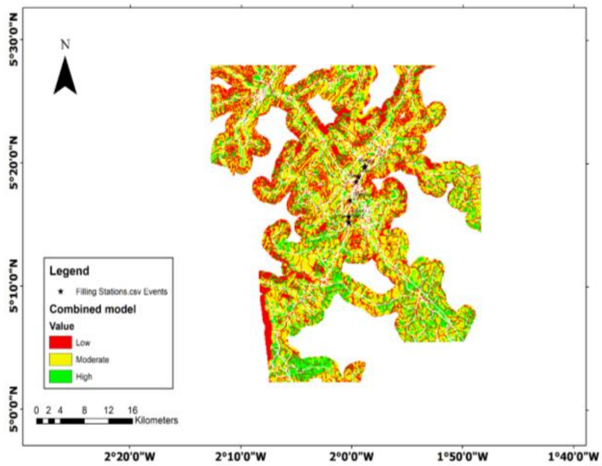

Figure 14: Map of combined model and existing filling stations

4.2. Discussion

All the oil and gas stations were found to be sited along the main highway in the study area. Some were also found close to settlements and public facilities (see Figure 8). 75% of the oil and gas filling stations in the study area meet the set standard while 25% do not. In terms of the pump distance to road analysis (see Figure 6), Star oil pump station does not meet the 15 m to major road criteria.

Table 6: A pairwise comparison

Criteria(n)	Land use	Slope	Soil types	Forest	Roads	Waterbodies
Land use	1	0.33	3	3	0.33	0.33
Slope	3	1	3	5	3	3
Soil types	0.33	0.33	1	0.33	0.33	0.33
Forest	0.33	0.2	3	1	0.33	0.33
Roads	3	0.33	3	3	1	0.33
Waterbodies	3	0.33	3	3	3	1

Table 7: Normalized data with weights

Criteria(n)	Land use	Slope	Soil type	Forest	Roads	Waterbodies	Weights
Land use	0.0938	0.1310	0.1875	0.1957	0.0413	0.0620	0.11855
Slope	0.2814	0.3968	0.1875	0.3262	0.3755	0.5639	0.3552
Soil types	0.0310	0.1310	0.0625	0.0215	0.0413	0.0620	0.0582
Forests	0.0310	0.0794	0.1875	0.0652	0.0413	0.0620	0.0777
Streets	0.2814	0.1310	0.1875	0.1957	0.1252	0.0620	0.1638
Waterbodies	0.2814	0.1310	0.1875	0.1957	0.3755	0.1880	0.2265

The major road within the vicinity of this station happens to have heavy traffic for most parts of the day making it difficult for vehicles to enter and exit the station. From Table 5, it was observed that, although a distance of 400 m is required between any two stations, longer distances were found between one station and the next with a distance of 2981.52 m being the longest distance found between Champion and the next filling station (*i.e.* Total 1). Only 25% of the filling stations were located at a distance of at least 400 m away from water body criteria. This can be attributed to the fact that management of some stations did not comply with the set standards before the establishment of the station as a result of improper planning. The study also revealed that all the filling stations in the study area were far away from firefighting stations, and some were not having all the required firefighting equipment. Some stations were also found to be located few meters from churches, lorry parks, and gas operating stations. Again, it was found that some filling stations had large land area for vehicles to enter and exit the station whiles others did not meet the set criteria. From Fig. 14, it was obvious that some of the existing filling stations are operating in an uncongenial environment and as such require much attention to prevent any future casualties.

It was furthermore observed that, the general topography of the study area is undulating with steep sloping terrains which make most portions unsuitable for operating oil and gas filling stations as previous studies have shown that, fire risk is relatively higher on steep terrains (Akay and Erdogan, 2017; Jaiswal *et al*., 2002). Moreover, some soil types and their engineering properties are not suitable for construction purposes (Aysen, 2003; Budhu, 2011; Frost and Frost, 2014), this is particularly true for sites close to the hilly part of the study area. This serves as a limitation as most oil filling stations store their oil in deep drenches.

5. Conclusions and Recommendations

From the study, it has been found that, 75% of the filling stations in the study area comply with the laid down standards set by the Ministry of energy and Town and Country Planning Department of Ghana. The study has revealed the spatial distribution of oil and gas stations along the main road of the study area for future planning purposes. The proximity analyses point to the fact that, some of the existing stations are sited in an uncongenial environment and therefore poses threat to the lives and properties within their vicinity. It was also realized that, there were no firefighting stations close to the locality of these stations. The study has again demonstrated the usefulness of multi-criteria decision analysis and GIS tools in solving spatially related pertinent problem.

It is recommended that the suitability map produced for the study area should be used and further environment impact assessment should be carried out by the authorities to assess the significant impacts the sited stations have on the environment. It is also recommended that site suitability analyses be incorporated in the Town and Country Department's planning scheme for future development and policy formulation. Measures should be put in place to enforce the set standards and prosecute offenders to bring sanity in the oil and gas filling station business. Finally, it is recommended that this study be replicated in other parts of the country or be adopted for future redevelopment of the study area.

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