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Research paper

Siting a centralised processing centre for artisanal and small-scale mining – A spatial multi-criteria approach

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ABSTRACT

Artisanal and small-scale mining is one of the global phenomena that is a threat to environmental health and safety. There are ambiguities in the manner in which an ore-processing facility operates. These ambiguities can cause environmental problems and hinder the mining capacity of these miners in Ghana. The vast majority of attempts to address these problems through the establishments of centralised processing centres have failed, with only a handful of successes. This research sought to use an established data-driven, geographic information based system to locate a centralised gold processing facility within the Wassa Amenfi-Prestea Mining Area in the Western region of Ghana. The study was designed to first determine the relevant factors that should be considered in the decision-making process for locating a centralised ore-processing facility. Secondly, it sought to implement the identified factors in a case study by identifying specific geospatial techniques that can best be applied to identify potential sites. By adopting in-depth consultations with four stakeholder groups for data collection and content analysis for data analysis, thirteen relevant factors were identified. However, in the case study, due to data unavailability, only seven of the factors were considered. Geoprocessing techniques including buffering and overlay analysis and multi-criteria decision analysis were employed to develop a model to identify the most preferred locations to site a centralised processing facility. Site characterisations and environmental considerations, incorporating identified constraints, to determine an appropriate location were selected. The final map output indicates estimated potential sites identified for the establishment of a centralised processing centre. The results obtained provide areas suitable for consideration.

1. Introduction

Artisanal and small-scale mining (ASM) has been practised in Ghana and several other countries for many decades and serves as an important source of livelihood for many rural people. There is a lack of consensus concerning the definition of ASM in the literature. However, for the purposes of this study, ASM refers to the extraction of mineral deposits by individuals, groups or cooperatives by means of minimal mechanisation or by manual methods, often in the informal sector of the market (Hentschel, Hrushchka, & Priester, 2002). The World Bank (2013) estimates that ASM[2] is practised in over 80 countries, providing a livelihood for over 100 million people worldwide. The sector has been regarded as a significant contributor to global mineral production. For instance, according to the World Bank (2013), 80%, 20% and 20% of the world's sapphire, gold and diamond respectively are produced through ASM activities. Artisanal and small-scale mining (ASM) is and remains a vital part of Ghanaian life and is an intrinsic part of economic growth (Akabzaa, 2009). Existing literature indicates that over a million people are engaged in ASM in Ghana, contributing over 30% of the country's total gold production (Bansah, Dumakor-Dupey, Kansake, Assan, & Bekui, 2018a; Bansah, Dumakor-Dupey, Stemn, & Galecki, 2018b). Several others have equally regarded ASM as a primary source of employment for job seekers from various parts of the country who are relatively disadvantaged in the labour market, including the unskilled, low skilled and women (Aryee, Ntibery, & Atorkui, 2003; Hilson, 2001, 2002; Yakovleva, 2007).

Over the years, the sector has undergone significance changes, from a traditional approach involving the use of rudimentary equipment (e.g.

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[2] In this research, the terms "artisanal and small-scale gold mining" (ASM), "artisanal and small-scale mining (ASM)" and "artisanal mining" (AM) are used with the same meaning. Similarly, the terms "miners" and "artisanal miners" have been used interchangeably.

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hammer, chisel, shovel and pans) to dig for gold to a more unconventional and sophisticated method involving the use of heavy mining equipment like bulldozers, excavators and haulage trucks (Bansah, Yalley, & Dumakor-Dupey, 2016; Hilson & Potter, 2005). These recent developments have exacerbated the many environmental problems associated with ASM in Ghana, such as mercury release, land devastation, visual intrusion, soil degradation, water pollution among others (Minerals Commision, 2015). The recent developments coupled with the influx of Chinese nationals in Ghana's ASM (Bach, 2014; Hilson, Hilson, & Adu-Darko, 2014; Thornton, 2014), together with its associated problems, have led to public outcry for effective management of the sector or a complete ban. However, due to the significant contribution the sector makes to the local and national economy, a complete ban would be disastrous. Instead, an effective solution needs to be found. Thus, the overall aim of this study was to contribute to the process of finding a more sustainable approach for the management of the ASM sector in Ghana by focusing on site selection of a centralised processing facility.

The processing centre should be such so that miners do not have to invest in expensive processing equipment, rather, the ore is taken to a specialised facility where qualified operators extract the gold for a fee (Veiga, Angeloci, Hitch, & Velasquez-Lopez, 2014). Therefore, the implementation of a centralised gold processing facility could be seen as a natural extension and an integral part of a formalised ASM process, in terms of ore recovery. This is because manual techniques of rock extraction, coupled with a lack of technology, as well as opaque transactions of middle-men and brokers, have worsened the living conditions financially and socially of artisanal miners (Bansah et al., 2018b; Hilson, 2003). Beyond insufficient livelihood, due to the use of rudimentary tools for operations, acquiring simple tools for mining activity is limited, due to a lack of funds and the capacity to purchase tools to increase productivity and potentially hire more workers. As a result, ore recovery and yields continue to be low (Hinton, Veiga, & Veiga, 2003; Veiga, Maxson, & Hylander, 2006) and income remains at a subsistence level keeping the artisanal miner in a vicious cycle of poverty (UNECA, 2003). The development of a centralised processing facility could, therefore, improve the current low yields as well as discourage opaque transactions and practices.

The literature on ASM centralised processing centres has largely focused on chronicling and evaluating the success and failure of previous and existing centres (Hilson & Potter, 2005;; Hinton et al., 2003) and evaluating the associated environmental issues (Veiga et al., 2014). For instance, a review by the United Nation Economic Commision for Africa (UNECA) (2003) indicates that various ASM interventions, including centralised processing centres, have contributed to improving productivity, livelihood and reduced localised environmental impacts in some African countries. Hinton et al. (2003) have also emphasised the importance of centralised processing centre by highlighting some significant achievements of some projects, such as the amalgam processing centre in Venezuela, the Shamva Mining Centre in Zimbabwe, the mercury-free artisanal processing plant in Peru and the Experimental Mining Centres in Suriname. They concluded that these processing centres have reduced mercury release as well as created notions of organisation and citizenship within those ASM communities.

However, despite the achievements of such facilities, recent scholarly works indicate that some centralised processing centres have caused more harm than good and were abandoned shortly after their construction. Veiga et al. (2014) evaluated the performance of selected processing centres and identified several environmental issues associated with those facilities, as a result of some poor practices. They observed that the mode of operation used at some centres resulted in more pollution instead of providing the expected pollution reduction that led to their construction. Hilson (2006) regards processing centres as novel in theory, but problematic in practices because of the limited understanding of the ASM communities that those interventions were being targeted. Concerning the Shamva Mining Centre, he notes that though the project was successful in its incipient stage, it quickly became a fiasco because the capacity of the mill installed could not meet the growing needs of the miners. This caused the miners to return to their old ore processing practice that was detrimental to human and environmental health. He also highlights similar problems in centralised processing centres at Tarkwa and Japa in Ghana. In the case of Tarkwa, crushing and assaying centres were abandoned as several of the facilities were located in areas where crushing and assaying were not needed. The case of Japa is similar to the Shamva centre where high demand for service caused miners to wait for extended periods, forcing them to return to their old practices. These shortcomings could have been avoided if extensive research on demand and the location of the centres was carried out. This research seeks to address these gaps by identifying and evaluating the technical requirements for siting a processing centre. At present, there is a lack of literature on the required criteria for selecting an appropriate site for a centralised ore-processing centre. The literature so far only focuses on the technical shortcomings that led to the collapse of some centralised processing centres, as well as the environmental issues posed by such facilities. Thus, this study will be the first to identify and evaluate the criteria for siting an ore-processing centre and implement the selected criteria in a case study.

Presently in Ghana, almost all ASM sites have their own processing centre where excavated materials are processed, using different techniques depending on the nature of the deposit. Bansah et al. (2016) provide a detailed account of how small-scale miners in Ghana process their materials. Recent studies indicate that the current processing techniques face several challenges including low ore recovery and severe environmental and human health effects (Bansah et al., 2018a, 2018b). According to Bansah et al. (2018b), the recovery rate of ASM operators is about 30% due to the inefficiencies in their processing methods. These inefficiencies result in loss of gold to the tailings streams. Due to the gold-rich nature of ASM tailings, large-scale mines (LSM) purchase these tailings and recover the remaining gold using efficient technologies. Bansah et al. (2018b) in their study of the tailings trade between ASM and LSM operators observed that the LSM operators benefit significantly at the expense of the ASM operators, regarding the trade as parasitic to the ASM operators. In that study, the ASM operators complained about the inefficiencies of their processing techniques and equally expressed their displeasure of the tailings trade indicating the purchasing agents often cheated them. Therefore, an establishment of a centralised processing centre with efficient technologies could offer them that opportunity of getting value for their hard work. The literature indicates that the issues that stand out concerning centralised processing centres are the location of the facility, the processing techniques adopted, and the ownership and management of the centres (Hilson, 2006; Hinton et al., 2003; Veiga et al., 2014). According to Simpson (2007), the major challenges that affected the Shamva case in Zimbabwe were its distant location and the inefficient extraction method employed. The major concern for the funders of the project was the avoidance of mercury discharge into water bodies. However, as highlighted by Veiga et al. (2014), the rudimentary processing method adopted by most of these processing centres, actually, contributes to the mercury discharge problem. The method of processing is such that the ore is ground in a mill or copper-amalgamating plates are used to extract a small portion of the gold within a short period, with a large portion of gold in the tailings. This method does not only have a low recovery rate, which has been found to be below 30% (Cordy et al., 2011), it is also highly polluting and unfair for the miners who do all the hard work (Veiga et al., 2014). After the miners have left, the owners of the facility then extract the remaining gold from the tailings left behind using advanced and effective techniques such as cyanidation. In some cases, the miners complain and request to take their tailing away. In such situations, the facility owners would charge the miners the actual cost of the processing. This process has been identified as unfair and parasitic since the facility owners’ benefit at the detriment of the miners (Veiga et al., 2014). Therefore, to maximise the benefit of processing centres it is important that all of these issues be addressed prior to construction.

As highlighted above, the problems of centralised processing centres are diverse and multifaceted, ranging from locational issues to processing techniques and management problems. This study, however, only focuses on the problem of location. This paper demonstrates economical land-use and effective site selection processes incorporating environmental, physical and geological constraints for modelling a centralised processing plant for ASM activities. The research was designed to answer the following question, "what are the primary considerations (criteria) in locating a centralised processing facility?" and "what geospatial techniques can best be applied to identifying potential locations?" The research, therefore, sought to develop criteria for siting an economical processing facility for ASM, whilst considering environmental and physical constraints, and to implement a GIS-based case study to identify potential sites for a processing facility, based on the criteria established. The study addresses some of the factors that led to the failure of some processing centres, such as excessive distance to the facility location, lack of an effective transportation system, limited facility size and capacity.

2. Materials and methods

The method used in the study involved two stages; first, the identification of relevant criteria, followed by the implementation of the established criteria in a real case study. Details of each of the process are provided in subsections 2.1 and 2.2.

2.1. Study area

The study area lies in three administrative districts in the Western Region of Ghana, namely Wassa Amenfi East, Wassa Amenfi West and the Prestea Huni Valley. Due to the unique location of the study area, it shall be referred to as the Wassa Amenfi-Prestea Mining Area (WAPMA). The WAPMA lies approximately between longitude 2°32′W and 1°'57″W and latitude 5°28′N and 6°00′N. It is about 98 km from Sekondi, the capital of the Western Region, and 250 km from the national capital, Accra. The study area occupies a land area of about 2433 km^2. The area was selected due to its unique characteristics. The Western Region is well-endowed with natural resources, with the WAMPA being one of the gold-rich areas. However, illegal mining activities within the gold-rich districts of the region have led to many environmental and health problems, making the sector unacceptable, and a national nuisance. In the WAPMA, activities of artisanal mining are on the increase, with a handful in conformity with regulations and the majority being illegal. Generally, these miners make very little money in spite of unsafe working practices and harsh working conditions. Fig. 1 is a map showing the location of the study area.

2.2. Data collection

2.2.1. Determination of factors for siting a centralised process centre

To determine the required criteria for siting a centralised ASM processing centre, semi-structured individual face-to-face interviews were conducted to gather data from relevant stakeholders and technocrats involving ASM operators, large-scale mine (LSM) operators, university lecturers and researchers and ASM community members. Purposive, snowballing and convenient sampling techniques were used to select and recruit participants for the study. Although the various respondent groups were purposefully selected, only individual participants who consented to participate in the research were interviewed. Therefore, purposive and convenient sampling was used to select the various respondent groups such as ASM operators and individual interviewees respectively. For the ASM operators and the ASM community member group, once the first respondent was recruited, the referral method was used to recruit other respondents. Prior to the fieldwork and data collection, an interview protocol was designed, tested and revised to take into consideration comments and observation made during the pilot testing. Before an interview began, the participants were briefed about the research and given a consent form to sign to indicate their willingness to participate in the research. During the briefing sessions, issues of confidentiality, voluntary participation and anonymity were stressed.

The first author between 19th September 2015 and 5th February 2016 conducted all interviews. Thirty-five respondents participated in the research, consisting of 13 ASM operators, 6 LSM employees, 9 university lecturers and researchers and 7 ASM community members. On average, an interview lasted 25 minutes. The interviews were either audio-taped or handwritten depending on the consent of the interviewee. All audio-recorded interviews were transcribed verbatim and together with the handwritten ones analysed using qualitative content analysis (Schreier, 2012, 2014, pp. 170–183). A purely data-driven approach was used in analysing the interview transcripts since little was known on the topic. Data was analysed by both authors independently and their results compared. Thirteen factors emerged from the analysis and are presented in the results section.

2.2.2. Data for GIS analysis

Several types of datasets at varying scales and from different sources were used for siting the centralised processing centre. These datasets comprised both vector and raster data types. Data was obtained from secondary sources, except the location of ASM and LSM sites that were obtained from field mapping. During the field mapping, Garmin GPS 60C was used to map the location of the sites and to collect other data (such as road intersection and survey controls) to validate the secondary data. Due to the unavailability of data, only 7 out of the 13 identified factors were considered in the GIS analysis. Table 1 is a summary of the data used together with their sources.

2.3. Data analysis for siting the centralised ore processing site

The weighted overlay spatial analysis method was used for locating the centralised processing site. This method was implemented through three stages: (1) selecting and grouping datasets, (2) standardising datasets, (3) weighing, and overlaying datasets to determine suitable areas. Before the process was implemented, the accuracy and reliability of the secondary data were assessed using the geographic data collected during the ground truth surveys (Haining, 2009; Wolf & Brinker, 1994). Additionally, since the secondary data was defined using different coordinates systems, they were rectified and transformed to the UTM WGS Zone 30N coordinate system.

2.3.1. Selecting and grouping criteria

The determination and grouping of criteria in any site selection project is essential because the reliability and trustworthiness of the site are largely dependent on these factors. According to the literature, three groups of criteria (i.e. exclusionary, technical and community-specific) are important for decision-makers for planning, site selection and design projects (Bosompem, Stemn, & Fei-Baffoe, 2016; USEPA, 2002). Exclusionary criteria prevent locating a facility in areas forbidden by local and national laws, such as game and forest reserves. In this study, such criteria refer to the high conservational values (HCVs) and adjacent land-use. According to the USEPA (2002), technical criteria are specific and definite operational and engineering parameters and conditions. Technical criteria outline suitable potential areas, ensuring selected sites are desirable and feasible (Bosompem et al., 2016). The community-specific criteria refer to how the facility will affect the quality of life of surrounding communities. In this study, the technical criteria refer to the selection criteria, whereas the exclusionary and community-specific criteria are the constraint criteria.

The criteria were then grouped based on which datasets can be derived from geoprocessing activities. Table 2 outlines the grouping

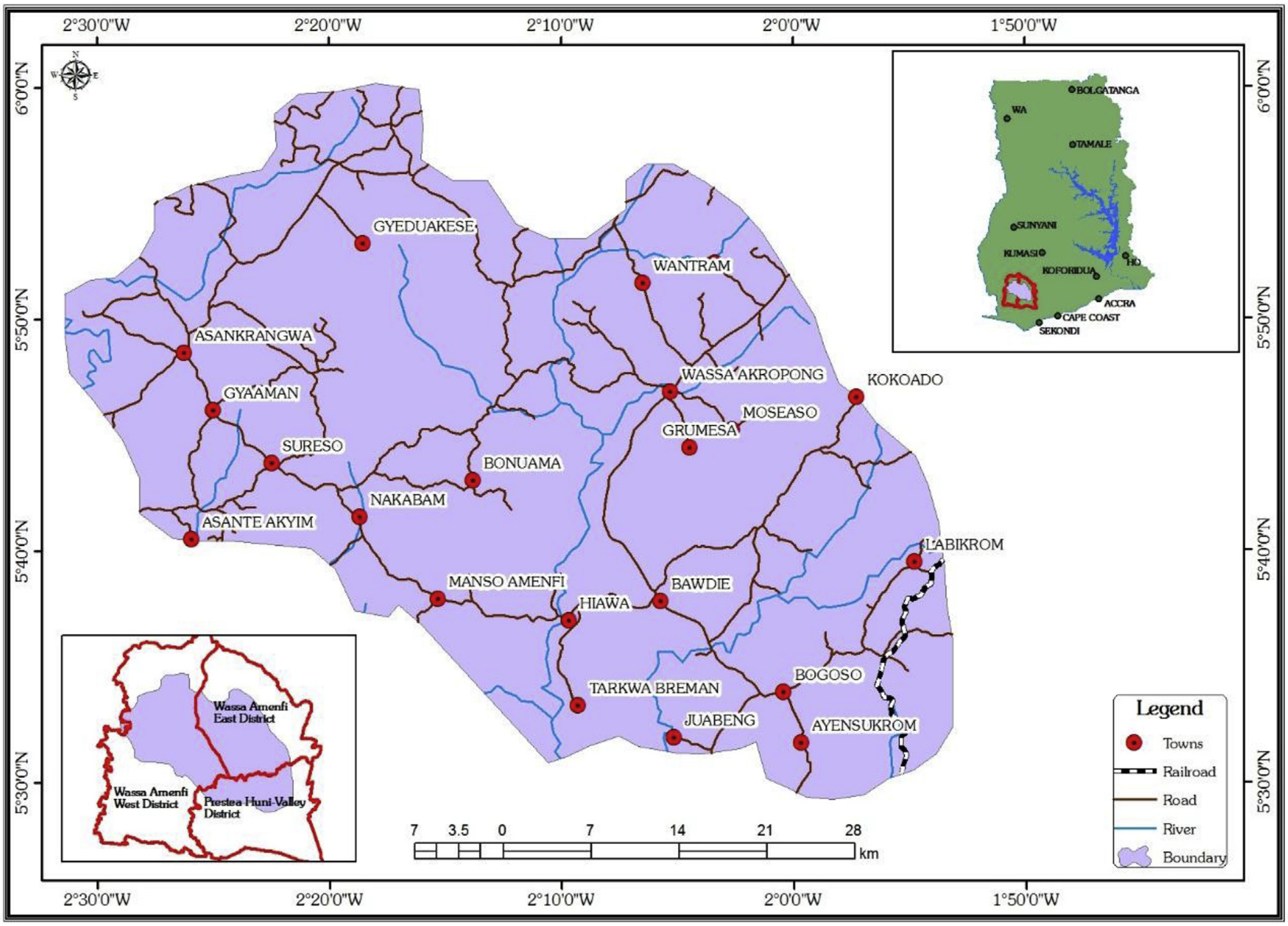

Fig. 1. Map of the study area.

Table 1
Available dataset with their sources.

Dataset	Source
ASM sites	Ground surveys, Google Earth
Road network	Survey and Mapping Division, Land Commission
Waterbodies (streams/rivers)	Survey and Mapping Division, Land Commission
Railway lines	Survey and Mapping Division, Land Commission
Tectonics (faults and fractures)	Ghana Geological Survey
Forest reserve	Forestry Commission of Ghana
LSM sites	Ground surveys, Google Earth
State lands	Land Commission
Urban areas and Settlement	Survey and Mapping Division, Land Commission
Digital Elevation Model (DEM)	US Geological Survey

values of the selection criteria, and Table 3 shows the constraint criteria values. Based on the literature, two types of datasets (namely slope and Euclidean distances) were derived from the criteria grouping in a GIS environment. This was necessary because the preferred location of the facility had to be on a certain slope and certain distance from some of the selection criteria.

2.3.2. Reclassifying and standardising the derived datasets

After generating appropriate distances and slope for the respective selection, each cell in the study area had a value for each input criterion. However, at this stage, it was difficult to practically integrate all the datasets into a single layer that shows suitable areas. Thus, the derived datasets were reclassified and standardised into a common measurement scale to enable data overlay. This measurement scale is what determines how suitable a particular location (each cell) is for siting the processing facility. Higher values indicate locations that are more suitable, while lower values indicate less suitable/unsuitable areas. The reclassification was (0) for unsuitable areas, (1) for less suitable areas (2) for suitable areas and (3) for the most suitable areas, based on Table 2.

2.3.3. Weighting and overlaying the standardised datasets to generate a suitability index

Each of the seven criteria was evaluated on the basis of its relative importance for an effective (best) decision to be made. The derivation of weights within the context of the decision-making objective poses a major challenge in multi-criteria analyses. This is probably due to the high level of inherent characteristics of a sector that spans health and safety, environmental effects and community well-being. The emphasis here is on identifying the appropriate criteria weight to be used based on its significance, sensitivity and influence pertaining to the characteristics of each factor being considered for the proposed project. The pairwise comparison method was used in this study because the method has been proven to produce reliable and consistent results. (Drobne & Lisec, 2009; Dujmović & Tré, 2011; Rafiee et al., 2011; Rikalovic, Cosic, & Lazarevic, 2014).

In this study, experts consisting of 5 university lecturers and researchers, 5 LSM employees and 4 ASM operators were consulted to independently complete a comparison matrix consisting of the criteria shown in Table 2. After completing the matrix, the final weights were determined following three consecutive steps: (1) computing the vector

Table 2
Selection criteria together with their suitability grouping.

Selection Criteria	Suitability Grouping			
	Unsuitable	Less Suitable	Suitable	Most Suitable
Nearness to ASM Sites	> 10000 m	3000–10000 m	1000–3000 m	< 1000 m
Nearness to Roads	> 5000 m	1000–5000 m	500–1000 m	< 500 m
Nearness to Railways	> 5000 m	1000–5000 m	500–1000 m	< 500 m
Distance to Settlement	< 800 m	800–1000 m	1000–5000 m	> 5000 m
Distance from Tectonic Zones	< 750 m	750–1500 m	1500–5000 m	> 5000 m
Distance from Waterbodies	< 250 m	250–500 m	500–1000 m	> 1000 m
Slopes	> 15°	6°–15°	2°–6°	< 2°

Table 3
Constraint criteria.

Constraint Criteria	Buffer (m)
Forest Reserves	500
Large-scale Mines	300
State lands	100
Urban centres	500

of criteria weights, (2) computing the matrix of options scored and (3) ranking the options. To check the consistency of the decision makers and reduce bias in the decision-making process, AHP incorporates a useful technique referred to as consistency ratio (CR) index. According to Saaty (1980), the value of the CR is a determinant of a departure from consistency and recommends that a CR greater than 0.1 (10%) is unacceptable and the comparison matrix ought to be re-evaluated. The final matrix together with the weights for all seven selection criteria is shown in Table 4. After the weights were determined, the individual weighted criteria were combined and overlaid in order to obtain a suitability map.

2.3.4. Selecting optimal sites

In order to determine suitable areas and subsequently select optimal sites, a Boolean constraint map obtained from the constraints criteria was applied on the suitable index map. The resultant product was a map excluding all cells classified as unsuitable (cell value of 0) and cells that fell within the areas of the constraint map. After this, a conditional function was used to select the most suitable areas (areas with cell value of 3). A cluster analysis of the density of ASM sites was performed to improve the optimality of the selected locations. This helped in identifying locations where the processing centres had high clusters of ASM sites so the facility could be located within these clusters.

3. Results

3.1. Factors for siting a centralised ore processing centre

Several factors emerged from the analysis of the interviews as summaries in Table 5. The table indicates that the number of participants commenting on a particular category differ from one stakeholder group to the other.

Table 5
Selection criteria identified by the different participants.

Criteria (Category)	Percentage of participants commenting on categories/criteria			
	ASM Operators (13)	LSM employees (6)	L&R (9)	ASM CM (7)
Nearness to raw material (ASM sites)	100	100	100	71.4
Energy Availability	76.9	100	100	42.9
Transportation Facility	92.3	83.3	100	57.1
Gold Mineralisation	53.8	100	100	28.6
Site Stability	46.2	66.7	77.8	14.3
Climate and Soil	30.8	33.3	66.7	14.3
Hydrology	53.8	66.7	88.9	85.7
Water Supply	69.2	66.7	66.7	42.9
Topography	76.9	50	77.8	42.9
HCVs (forest reserves, sanctuary, shrine, cemetery)	84.6	83.3	77.8	100
Adjacent land-use	30.8	50	66.7	85.7
Site capacity	61.5	66.7	100	57.1
Fire and flood protection	46.2	50	88.9	57.1

L&R = university lecturers and researchers, CM = community members.

3.1.1. Nearness to raw material (ASM sites)

The participants identified this as an essential and fundamental factor in siting a processing facility. They indicated that it is preferable to locate a processing site near the source of an ore feed (mining site) as that will be the main input for production as well as an economic factor that will help realise potential returns in terms of location and allocation of resources. Resource proximity has an economic bearing on productivity; as the distance from the source to the site of ore processing is reduced, costs decrease, as does the risk to the overall production efficiencies and effectiveness. Distance to ASM sites was identified as playing a significant role in achieving overall operational effectiveness in terms of material handling. A centralised processing centre in close proximity to ASM sites will not only minimise the time and cost of moving material from a mine site to its final destination for processing but will also result in savings on equipment health, including wear and tear of haulage facilities.

Table 4
Weight of each selection criteria (CR = 0.072).

Criteria	A	B	C	D	E	F	G	AHP	Weights
Distance to ASM sites (A)	1	2	3	5	6	7	9	0.406	40.60%
Distance to Roads (B)	1/2	1	3	4	5	7	8	0.251	25.10%
Distance to Railroads (C)	1/3	1/3	1	2	4	5	6	0.129	12.90%
Distance to Settlements (D)	1/5	1/4	1/2	1	3	5	6	0.085	8.50%
Distance to Waterbodies (E)	1/6	1/5	1/4	1/3	1	2	4	0.055	5.50%
Slopes (F)	1/7	1/7	1/5	1/5	1/2	1	3	0.043	4.30%
Distance to Fault zones (G)	1/9	1/8	1/6	1/6	1/4	1/3	1	0.032	3.20%

Table 6
Areal extent of suitability index for each selection criteria.

Selection Criteria	Unsuitable (0)		Less Suitable (1)		Suitable (2)		Most Suitable (3)	
	Km^2	%	Km^2	%	Km^2	%	Km^2	%
Distance to ASM Sites	326.5	13.4	1376.9	56.6	531.5	21.8	198.3	8.1
Distance to roads	23.3	1.0	1318.8	54.2	486.9	20.0	604.2	24.8
Distance to railroads	2249.7	92.5	140.4	5.8	20.7	0.9	22.3	0.9
Distance to settlements	96.6	4.0	27.6	1.1	868.4	35.7	1440.6	59.2
Distance to tectonic zones	553.7	22.8	407.4	16.7	907.7	37.3	564.3	23.2
Distance to water bodies	149.3	6.1	127.1	5.2	250.3	10.3	1906.4	78.4
Slopes	33.6	1.4	459.0	18.9	1353.9	55.6	586.6	24.1

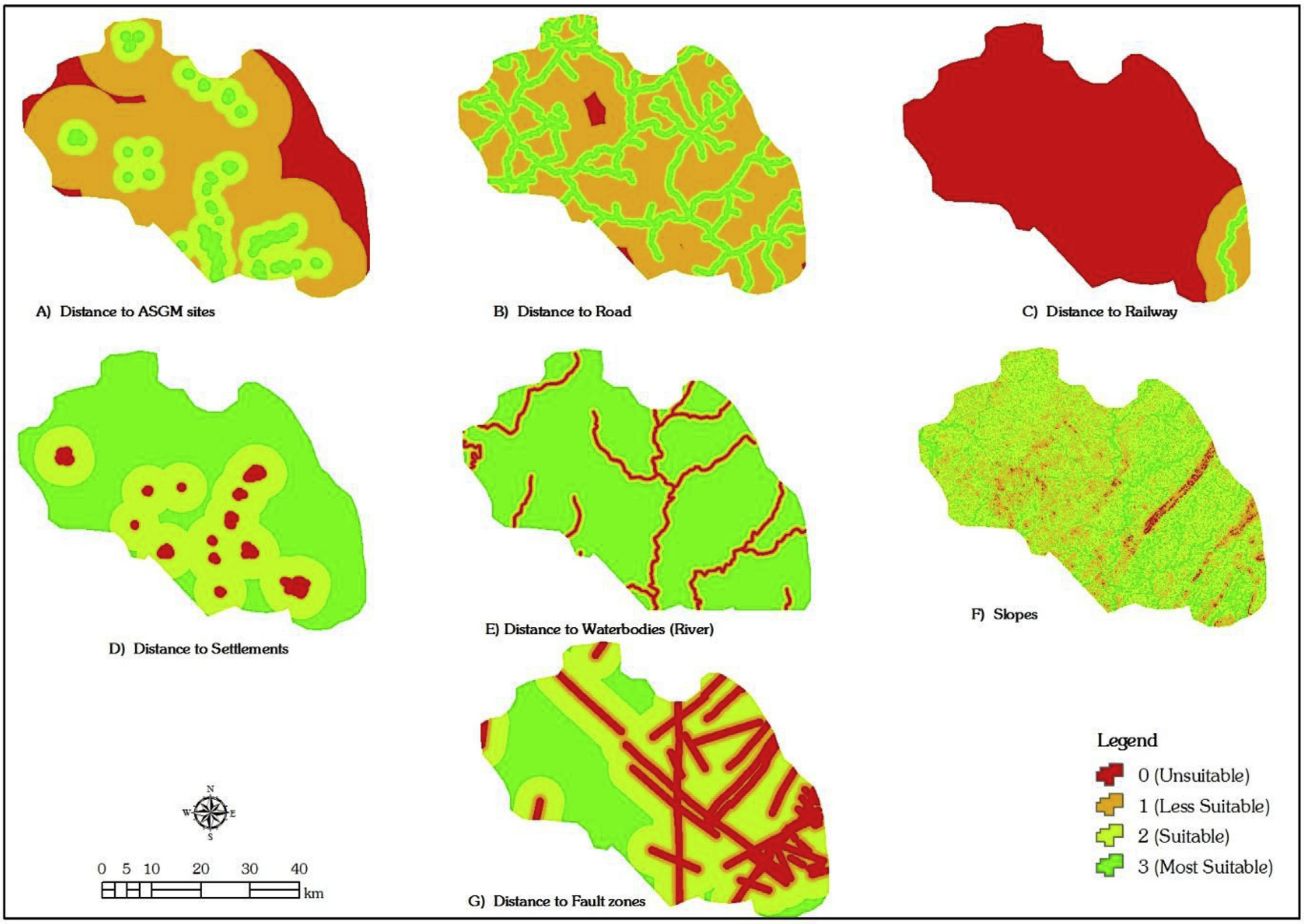

Fig. 2. Maps depicting the suitability index of the evaluated selection criteria.

3.1.2. *Energy availability*

The participants identified that the site should be close to a power source for effective productivity, as power is one of the major constituents of production. Reliable and accessible energy is important in the mining and processing cycle, and therefore its availability and cost have a bearing on project viability (Patsa, Van Zyl, Zarrouk & Arianpoo, 2015). Essentially locating the site near a cost-effective source of reliable energy would effectively contribute to the success of a project. Unavailability of a reliable energy supply would potentially cause the project to fail. Specific mention was made of the recent energy crisis in Ghana that negatively affected operating costs of businesses. The technocrat group recommended an extensive feasibility study be conducted on energy supply prior to siting the processing facility.

3.1.3. *Transportation facility*

Participants identified the selection of an economical transportation facility for the haulage of ore materials from the existing ASM sites to the proposed facility as essential for the success of the project. Transportation networks could include airways, roads, waterways and railways. However, the interviewees only considered the existing ground transportation option, such as roads and railways, within the study area. Since roads and railways exist within the study, it would be economical to access and utilise these facilities. However, in the case of non-existent transportation infrastructure, there will be a need to construct infrastructure to connect the source of raw materials to the processing site. Again, the technocrats emphasised that the determination of an optimum site for the processing centre must be carefully considered so that the location minimises the extent of material transport and overall cost.

3.1.4. *Gold mineralisation*

Geological characteristics of a proposed facility location must be

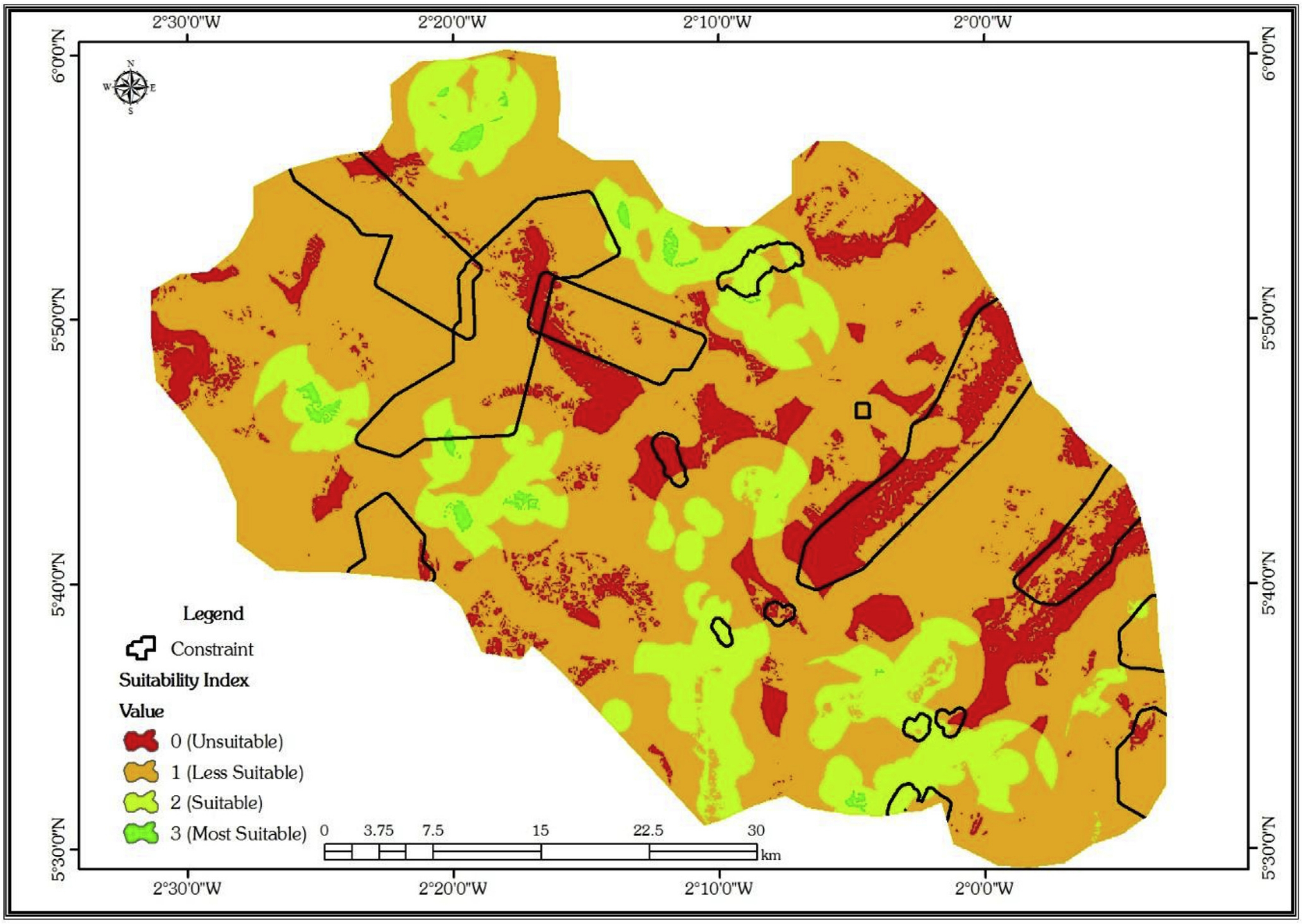

Fig. 3. Map showing the suitability index of the overlay analysis.

adequately distinguished to aid in assessing the economics of the project. Site geologic data and information that define the physical and chemical characteristics of a deposit from which ore will be obtained must be readily available to aid in siting the facility. This was particularly emphasised by the L&R and LSM groups. They indicated that the facility must not be located in an ore mineralised zone. Instead, it should be located in waste bearing areas with a substantial emphasis on rock type and strength. According to them, the aim is to prevent any future possibility of relocation, considering the economic implications of having to construct another facility in the event of the discovery of further resources within the location of the processing facility. Due to data unavailability, the GIS analysis did not include gold mineralisation.

3.1.5. Site stability

The L&R and LSM employees indicated that natural occurring hazards, such as landslides, floods and tectonic activities are dangerous phenomena that run through the cycle of mining operations, from extraction to the transportation of ore to the market. These hazards are somehow interrelated as one occurrence potentially triggers others that in turn affects project operations. According to Legg (1994), the majority of rock or terrain stability issues are associated with active fault zones, fractures, as well as geological tectonic movement. One interviewee stated that "site stability has a direct bearing on the economics of a project and needs to be factored into the initial process to help prevent project failure due to the presence of existing faults". It is therefore important to investigate the stability of terrain or rock masses to assess the probability of the occurrence of failure or collapse prior to establishing a facility irrespective of its proximity and economic gains, as safety to property and workers cannot be compromised.

3.1.6. Climate and soil

Climate and soil information of an area of interest for the facility location was incorporated to aid in identifying the risk of future production impacts. The L&R group indicated that clay soil would not be appropriate for such a facility during rainy seasons, due to its potential hazard for the road transportation system, resulting in slips, accidents and delays in production due to the slowing down or restriction of vehicles transporting ore to the facility. Information on climate and soil will, therefore, assist in the analysis of a suitable location.

3.1.7. Hydrology

The pollution of surface water by wastewater was one of the principal concerns of the ASM community members in relation to the location of the processing facility. The ASM operators even indicated that if the processing site is located in close proximity to waterways there is an increased risk of water pollution. The potential impact of water pollution is greater in waterways that are used for drinking water or aquaculture. It is essential to consider hydrological analysis to locate an appropriate fit within the context of the work, considering the physical and chemical characteristics of the terrain.

3.1.8. Water supply

Water availability was considered integral for an ore processing facility and, therefore, its proximity to processing activities is essential to a project's success. However, locating a facility within the parameters of a water source could present a daunting situation considering the extent of the potential harm (water pollution) to neighbouring

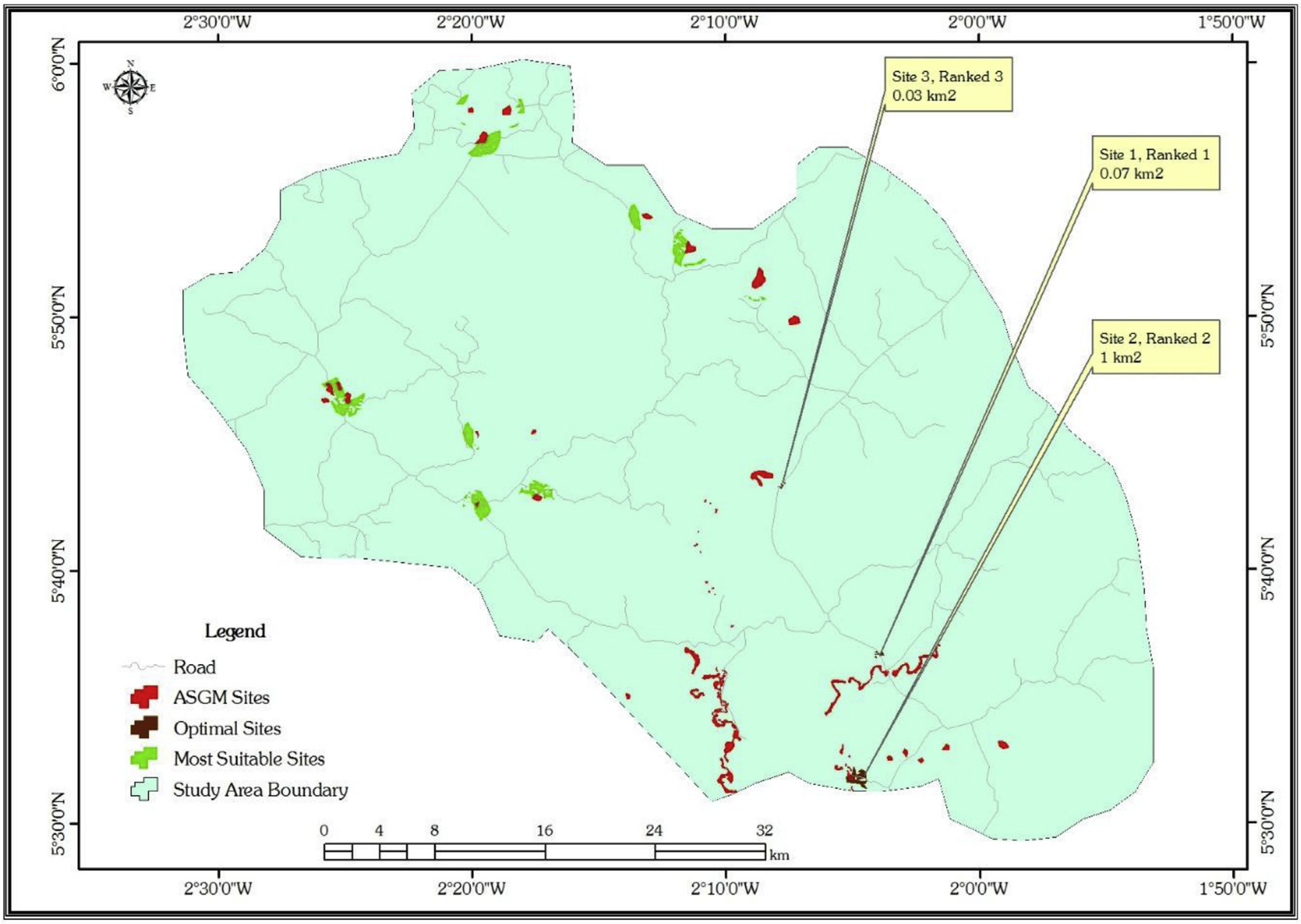

Fig. 4. Map of potential optimal centralised ASM ore processing centres.

communities and users. The direction of flow of nearby water resources is an important factor that must be considered when siting a processing centre to prevent environmental liability and social issues and, hence, to save costs.

3.1.9. *Topography*

According to the interviewees, careful consideration needs to be given to the landforms during the site selection process. However, this is dependent on the characteristics of the topography. Two interviewees who are Geomatic Engineers noted that slopes and aspects on which terrains are modelled determine topographical characteristics. Flat terrain would be ideal for economical facility establishment, due to the technical, safety and financial certainty involved in implementation. They particularly emphasised that terrain with steeper slopes will result in constraints of ore movement from a mining site to a facility, which increases operating cost.

3.1.10. *High conservational values/areas*

All the stakeholders reached a consensus that the site should not be located in areas of high environmental value, or in areas subject to considerable environmental constraints and high environmental risks. Such areas include forest/game reserves, national parks, and local aquatic ecosystems. Contaminants from the processing centre have an environmental liability that might affect regulated areas through the potential release of effluent from the processed residue into nearby water reservoirs, thereby polluting them. The ASM community members specifically mentioned shrines, cemeteries and grottos as sensitive areas that needed to be protected.

3.1.11. *Adjacent land-use*

Adjacent existing and future land-use should be investigated to identify sensitive areas and other protected areas that are likely to be adversely impacted. This criterion is part of environmental impact assessment and, consideration of this will result in economic analysis, as indicated by Goodland (1995). Whereas the ASM community members indicated that the facility should be far from settlements, the LSM employees emphasised that the facility should be far from existing LSM sites to prevent possible encroachment.

3.1.12. *Site capacity*

The life of a processing plant and the demand for future space was considered to be an important factor. The literature on centralised ore processing centres strongly supports this. Particularly in the case of the Shamva and Japa centres (Hilson, 2006), as these facilities were abandoned because the capacity of the installed mill could not meet the growing demands of the miners. It is important to locate the facility in an area that will allow future expansion and the capacity of the facility itself should meet the needs of the miners.

3.1.13. *Fire and flood protection*

Fire and flood potential will often require some higher degree of analysis since the location of the proposed site near flood and fire sensitive areas was considered as a matter of prime concern. Fire hazards in the immediate surrounding area of the plant site must not be overlooked since, as the event of a fire outbreak will lead to a loss of assets and potentially workers, which will, in turn, be realised as a financial loss. The L&R group further stated that fire protection measures, such as fire berms be built around the facility to prevent the spread of fire in the event of an outbreak. They stated that the facility must not only be located with knowledge of technical site characteristics but also with the use of community-based knowledge.

3.2. GIS analysis for siting a centralised ore processing centre

The GIS analysis resulted in the generation of suitability maps for each of the selected criteria, suitability index for the overlay analysis and selected optimal sites for the processing facility. These results are presented below.

3.2.1. Suitability index for the selected criteria

Table 6 and Fig. 2 shows the areal extent and suitability maps for each selection criterion. As stated earlier, all the criteria values were set to a common scale to make comparisons possible and feasible. Thus, the datasets were classified into four levels of suitability as shown in Fig. 2.

3.2.2. Suitability index for the overlay analysis

Weighting and overlaying all the evaluated criteria resulted in an overall suitable index map for siting the processing centres in the study area. An area of 332.1 km^2 (13.7%) was classified as unsuitable, 1655.7 km^2 (68%) as less suitable; 429.7 km^2 (17.7%) as suitable; and 15.6 km^2 (0.6%) of the total area as most suitable. Fig. 3 shows the overall suitability index.

3.2.3. Selected potential optimal sites for the processing centres

Applying the conditional function (areas with a cell value of 3) on the suitable index led to the selection of 44 individual locations representing 15.6 km^2 (0.6%) of the study area as most suitable. However, applying the constraint map and performing the cluster analysis, reduced the number to 3 sites, representing 1.1 km^2 of the study area. These selected sites are shown in Fig. 4 and were ranked according to the cluster of ASM sites around them and proximity to the ASM sites. A site visit took place from January to March 2017 to check the validity and reliability of the selected sites. Two of the sites had vegetated land cover, whereas one was bare land.

4. Discussion

In this study, thirteen factors were identified by four stakeholder groups as relevant for the selection of a suitable centralised ASM ore processing centre site. However, due to data unavailability, only seven criteria were selected for establishing the suitability of locations for a facility in this case study. Factors such as mineralisation, energy availability, fire and flood protection, climate and soil and water supply could not be included since there was no existing data. Due to a lack of information in these areas, suitability modelling was done without considering these aforementioned factors, hence limiting the effectiveness of the modelling. Even when considering these limitations, the study offers valuable contributions which will now be discussed.

This study aimed at utilising geospatial tools in locating a centralised ASM ore processing facility, thus, offering an alternative to other existing widely used approaches for mitigating issues of ASM. The integration of multi-criteria decision and GIS analysis proved to be effective in identifying suitable locations for siting centralised processing centres for ASG miners. A complex phenomenon like ASM requires the evaluation of many criteria to test possible adoption and mitigation factors in their operations. An approach such as spatial analysis has succinctly aided the search for suitable sites through suitability modelling in the designated study area. By interviewing relevant stakeholders to identify the selection criteria and applying the criteria through multi-criteria decision analysis in a GIS environment, this research addresses some of the factors that led to the failure of previous ASM centralised processing centres such as the Shamva mining centre of Zimbabwe and the Tarkwa, crushing and assaying centres of Ghana. Specifically, in the case of the Shamva project, the facility was underutilised and eventually abandoned due to long travel distance and lack of an effective transportation system, among other reasons (Hilson, 2006). In the interviews, the participants regarded the nearness of the centralised processing centre to ASM sites and transportation facility to be among the vital factors. Similarly, in the suitability analysis, these two factors had the greater influence further indicating how important they are in the selection of suitable sites. Therefore, the three optimal sites selected were those that were closest to existing roads and ASM sites in order to ensure that the miners would not travel excessive distance to process their materials. Again, the selected sites are large enough (0.03 km^2–1 km^2) to support the installation of a plant that could meet the growing needs of miners and accommodates future expansion.

The success of a centralised ore processing facility depends on the location as well the design, management, method of processing and effective utilisation by its operators. Therefore, prior to building the facility, considerations must be given to all these factors. For instance, it is important to address the needs of the miners, in terms of considering the current equipment used as well as the production capacity to size the facility. It is, therefore, recommended that prior to construction, there should be an extensive consultation with all relevant stakeholders, particularly the miners, to determine the general operation of the facility and the terms for using the facility. The facility should be run such that it generates equal and mutual benefits for the miners and the facility operators. In Ghana, the miners themselves could form co-operatives to take advantage of the current government's "one district, one factory" policy (JoyBusiness, 2017; One District, 2017; Owuraku, 2017). Within this policy, the government of Ghana seeks to undertake a massive industrialisation campaign throughout the country. The objective is to empower communities to turn their local resources into finished goods. In most mining communities, mineral resources are in abundance, therefore, the communities could come together to take advantage of this opportunity to own the processing centre themselves. Also, the government can equally begin a process of bringing miners together and equipping them with the resources needed to enable them to process the ore themselves in a more effective and environmentally friendly manner.

Successful implementation would also be based on the coexistence and engagement of stakeholders, such as the government, regulators, technocrats, LSM operators, ASM operators and community members, addressing the need for the registration and formalisation of ASM business. Further exploration of orebodies equally remains important to the sustainability of a centralised processing centre. It is important also not to ignore the concerns of society as well as its inputs for the facility operations. Without the understanding of ASM operators, this could lead to failure, as it could lead to the misunderstanding of the conceptions of the facility (UNECA, 2003). Hentschel et al. (2002) reviewed the practices of ASM in developing countries and made recommendations for improving the sector's economic potentials for the benefit of its stakeholders, including the community. In lieu of a sophisticated facility, adequate training should be given to the miners to disseminate best practice of the facility. Again, the facility must be technically robust to withstand the in-situ characteristics of the identified location, given the nature of ASM sites. Moreover, the facility must be easily accessible, flexible, simple, and cheap with improved ASM policies and legal support to attract more miners. The centralised processing centre could potentially affect the livelihood of some people such as those working at existing processing centres. Therefore, this livelihood implication should be considered before actual implications.

Since this research is the first of its kind, it is recommended that the approach described here be tested in other studies, particularly on a large-scale using sufficient data to ascertain the validity and reliability of the method. Other data sources such as national grid service/power providers for energy data and detailed geological data from seismic studies should be explored in future studies. Additionally, future research on the economic potentials of using GIS and spatial analysis in the area of plant capacity is recommended. More research is underway to consider the management of ASM centralised ore processing centres to ensure it provided both economic and environmental benefits.

5. Conclusions

The selection of sites for the construction of centralised ore processing centres for ASM is a complex and multifaceted process requiring the involvement of various stakeholders and the careful consideration of exclusionary, technical and community-specific factors. This study demonstrates how stakeholder consultation is effective in identifying relevant factors and how multi-criteria decision analysis and GIS can integrate several factors to select a suitable site. Interviews were conducted with stakeholders to determine the factors for siting a centralised ore processing centres for artisanal and small-scale mining. The interview data, which was analysed through content analysis, led to the identification of 13 factors that the stakeholder considered important for locating a centralised processing centre. Out of the 13 thirteen factors, the participants considered nearness to ASM sites and transportation as the most important. The integration of GIS and multi-criteria decision analysis proved effective in identifying suitable areas for use as centralised processing centres within the Wassa Amenfi-Prestea Mining Area. The suitability analysis yielded three sites as optimal for siting the centralised processing centre. The three sites were the closest to most existing ASM sites and transportation networks. The sites were equally sizable between 0.03 km^2 and 1 km^2 to support the installation of a plant that could meet the growing needs of miners and accommodates future expansion. For effective and detailed analysis of suitable site locations for a potential centralised processing centre, the cost of construction, management, facility sizing and capacity should be taken into account in the decision-making process. Economic factors such as the costs of land acquisition, land development and ore transportation should also be considered for such a project. This study was done without detailed economic and technical analysis, such as plant sizing and capacity analysis due to data and analytical limitations beyond the scope of the analysis. Therefore, further research could focus on these areas.

Conflict of interest

None.

Funding body

None.

Ethical statement

Authors state that the research was conducted according to ethical standards.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsm.2018.10.001.

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