UTILIZATION OF GIS AND SPATIAL ANALYSIS TECHNIQUES IN ARTISANAL AND SMALL SCALE MINING TO LOCATE A CENTRALIZED PROCESSING CENTRE

by

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Abstract

One of the global phenomena with threats to environmental health and safety is artisanal mining. There are ambiguities in the manner in which an ore-processing facility operates which hinders the mining capacity of these miners in Ghana. These problems are reviewed on the basis of current socio-economic, health and safety, environmental, and use of rudimentary technologies which limits fair-trade deals to miners.

This research sought to use an established data-driven, geographic information (GIS)-based system employing the spatial analysis approach for locating a centralized processing facility within the Wassan Amenfi-Prestea Mining Area (WAPMA) in the Western region of Ghana. A spatial analysis technique that utilizes ModelBuilder within the ArcGIS geoprocessing environment through suitability modeling will systematically and simultaneously analyze a geographical dataset of selected criteria. The spatial overlay analysis methodology and the multi-criteria decision analysis approach were selected to identify the most preferred locations to site a processing facility.

For an optimal site selection, seven major criteria including proximity to settlements, water resources, artisanal mining sites, roads, railways, tectonic zones, and slopes were considered to establish a suitable location for a processing facility. Site characterizations and environmental considerations, incorporating identified constraints such as proximity to large scale mines, forest reserves and state lands to site an appropriate position were selected. The analysis was limited to criteria that were selected and relevant to the area under investigation.

Saaty’s analytical hierarchy process was utilized to derive relative importance weights of the criteria and then a weighted linear combination technique was applied to combine the factors for determination of the degree of potential site suitability. The final map output indicates estimated potential sites identified for the establishment of a facility centre. The results obtained provide intuitive areas suitable for consideration.
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<tr>
<td>ASM</td>
<td>Artisanal and Small-scale Mining</td>
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<tr>
<td>ASM-PACE</td>
<td>Artisanal and Small-scale Mining in Protected Areas and Critical Ecosystems</td>
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<td>AGL</td>
<td>Abosso Gold Fields Limited</td>
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<td>CCD</td>
<td>Charge-Coupled Device</td>
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<td>GIS</td>
<td>Geographical Information Systems</td>
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<td>GDP</td>
<td>Gross Domestic Product</td>
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<td>ID</td>
<td>Identification</td>
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<td>ILO</td>
<td>International Labour Organization</td>
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<td>IFC</td>
<td>International Financial Cooperation</td>
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<tr>
<td>LP</td>
<td>Linear Programming</td>
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<tr>
<td>SDSS</td>
<td>Spatial Decision Support Systems</td>
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<tr>
<td>SEMLUC</td>
<td>Socio-Economic Metabolism and Land use change</td>
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<tr>
<td>WAPMA</td>
<td>Wassa Amenfi Prestea Mining Area</td>
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<tr>
<td>WGS</td>
<td>World Geodetic Systems</td>
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<tr>
<td>UNIDO</td>
<td>United Nation Industrial Development Organization</td>
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<tr>
<td>UNCTAD</td>
<td>United Nations Conference on Trade and Development</td>
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<tr>
<td>UNDESA</td>
<td>United Nation Department of Economic and Social Affairs</td>
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<tr>
<td>USEPA</td>
<td>United States Environmental Protection Agency</td>
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<tr>
<td>UTM</td>
<td>Universal Traverse Mercator</td>
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In this research the terms “artisanal and small-scale mining” (ASM) and “artisanal mining” (AM) are used with the same meaning. Similarly, the terms “miners”, “artisanal miners” and “galamsey” have been used interchangeably.
Chapter 1

Introduction

This thesis aims to establish one location for a centralized processing facility for use by Artisanal and Small-scale Mining (ASM) in the Wassa West District of Ghana. This thesis will employ established spatial analysis techniques to support this aim. The particular focus lies on the Wassa Amenfi-Prestea Mining Area (WAPMA) which comprises three districts namely Amenfi West, Amenfi East, and the Prestea-Huni Valley.

1.1 Artisanal and Small-Scale Mining

There is no single accepted definition of Artisanal and Small-scale Mining (ASM). For the purpose of this thesis, ASM is defined as the extraction of mineral deposits by individuals, groups or cooperatives by means of minimal mechanization or manual methods outside of established law structures. The establishment of this definition will be explored further in the literature review section. The literature identifies a number of problems and challenges of ASM.

Generally, the mining techniques associated with ASM are simple in technology but complex and uncertain in terms of mode of operations from the extraction of the mineral through to the ore recoveries. These complexities are inherent ranging from environmental, technical, health and safety, social and economic. The key challenges associated with ASM are the poor and unsafe working conditions as well as the exploitation by privately owned facility centres that result in wrecking the livelihood of the miners involved (Veiga, 2015).

This thesis considers the current mining process of the sector with emphasis on the technical aspect of potentially utilizing a spatial analysis tool for siting an ore processing facility for ASM. The inherent complexities and uncertainties within this sector are elaborated in Chapter 2.
1.2 Processing Facilities for ASM

ASM processing facility centres over the years have been the sources of economic recoveries for artisanal miners for most developing and third world countries where mineral resources remain an integral part of their geographical domain. However, there has been relatively little investigation conducted into the methods used in the recovery process by some privately owned operators. This includes the safety considerations, mining mechanisms and antiquated technologies used which run in isolation from established laws.

Existing literature addresses the social, economic, safety and environmental features of ASM extensively (Andrew, 2002; Agbesinyale, 2003; Hilson, 2003; Akabzaa, 2009) but little has been reviewed technicality in terms of potentially establishing a centralized facility as an alternative to help mitigate the rudimentary recovery process that is used by these miners. As Hilson (2004) points out: “More research is needed to help evaluate the impact that mining has had on Ghana’s indigenous communities.” The processing facilities and their locations for ASM for decades have required critical and extensive research to establish an end to all issues identified by researchers.

The study area in this thesis involves three districts with potential for establishing a location for a centralized processing centre through the selection of an optimal location, in terms of resource proximity and economic suitability without compromising human safety and environmental harm. Selection of factors and criteria needed to establish the facility location has been addressed and analyzed in Chapter 4.

1.3 Geographic Information Systems (GIS) and Spatial Analysis

The advent of spatial science and information technology over the years has seen many benefits in institutions for planning, designing, impact assessment, predictive modeling, and many other applications. Geographic Information Systems (GISs) are very useful tools for managing, checking, and organizing spatial information from many sources and of many types in thematic layers. One of the most important
applications of a Geographical Information System (GIS) is for site selection for various problems (Legg, 1992). In this study, tools and techniques for proximity and suitability analysis are extensively analyzed and tested for authenticity.

One of the essentials in selecting and assessing land-use for a proposed processing facility centre is the accurate information about the geographical and geological characteristics of the proposed location. This information requires simulation and modeling to conceptualize geographic features to provide authentication for potential consideration. Factors for site selection have been modeled and processed within the GIS environment to justify their suitability.

1.4 Research Goals

This research demonstrates economic land-use and effective site selectivity processes incorporating environmental, physical and geological constraints for modeling a conceptual processing plant for ASM activities utilizing established GIS and spatial analysis tools. The study was carried out in the Wassa Amenfi-Prestea Mining Area (WAPMA) in western Ghana to demonstrate how a spatial decision-supporting tool could effectively resolve economic and environmental tension among mining communities and neighboring large-scale companies through establishment of a centralized processing center for ore recoveries of artisanal miners. This is potentially achieved by building a model within the geoprocessing environment of the GIS spatial analysis tool with the focus being to determine site suitability.

The objectives of the research are to:

- develop and identify criteria for siting an economic processing facility considering environmental and physical constraints,
- complete GIS-based work to identify potential sites for a processing facility, based on the criteria established, and
- produce a spatial model to establish the benefits of a central processing facility.
1.4.1 Gaps in the Literature

There are numerous research areas related to ASM including environmental, health and safety economic, and socio-economic etc. Nevertheless, little or no attention has been drawn to its technical uncertainties particularly in the processing mechanisms employed for ore recoveries in this mining sector. It is hypothesized that a stakeholder approach through corporate coexistence with ASM will mitigate and ease some of the tensions associated with ASM. However, this has been refuted by authors such as Seidu (2015), and Jenkins (2004) who challenge actual positive impacts to resolving conflict and improving the livelihoods the people involved.

Potential application of GIS alternatively could hopefully be a mitigating factor through suitability analysis for site selection for locating a facility centre for miners involved.

The main research questions are:

- What are the primary considerations in locating a centralized processing facility?
- What geospatial techniques can best be applied to identify potential locations?

1.5 Data Collection and Data Analysis Procedures

Data collection and a site visit were conducted to assess operational conditions for hypothetical analysis purposes, ranging from:

- Existing topographical and geological maps of the study area, including precision survey orientation data of ASM sites consisting of all abandoned ASM or disturbed sites within the WAMPA.
- Locations of existing features such as roads, railways, and settlements.
1.6 Potential Impact of the Project

This spatial intelligence system for site location will be an extension of an already established formalized ASM process in Ghana through the fair trade gold market and will hopefully improve the current mineral resource evaluation of the country.

1.7 Thesis Organization

The contents of this thesis are organized according to the following structure.

Chapter One – This chapter provides an overview of the general practices and issues of ASM and potential applications of GIS to test hypotheses for mitigating problems associated within the sector.

Chapter Two – This chapter presents a review of the key drivers of the sector (environmental, health and safety, social, economic and policies) and the gaps, merits, and demerits to its stakeholders.

Chapter Three – This chapter presents a detailed review of the application of GIS tools and their capabilities to justify potential engineering proposals. Spatial analysis tools such as best path, overlay, weights and proximity analysis were investigated to assess the concept of spatial techniques and methodology in the GIS environment.

Chapter Four – This chapter presents a detailed data simulation process and selection of multi-criteria evaluation for the design of the proposed processing facility. The ArcGIS ModelBuilder tool was utilized to process the selected factors for the most suitable site.

Chapter Five – This chapter presents the results and discussions of the project impact.

Chapter Six – This chapter presents the conclusions reached during the study and provides recommendations for future consideration of spatial intelligence analysis in ASM.
Chapter 2

Artisanal and Small-scale Mining (ASM)

In this chapter, Artisanal and Small-scale Mining (ASM) is analyzed not only in the broader space but also in detail to establish the missing links ranging from lack of technical approaches to operations including inadequate systematic and support resources rendering the sector unattractive to investment. Researchers and academia over the decades have yet to agree and accept a common universal definition of ASM although several attempts have been devised. Some regard these types of mining practices as the same while others completely draw a substantial difference between them. According to Hentschel et al. (2003) artisanal and small-scale mining is mining by individuals, groups, families or cooperatives with minimal or no mechanization, often in the informal (illegal) sector of the market.

The World Bank Group (2001) defines artisanal or small-scale mining as a largely poverty driven activity, typically practiced in the poorest and most remote rural areas of a country by a largely itinerant, poorly educated populace with little other employment alternatives. Others describe an artisanal or small-scale miner as a subsistence miner who is not officially employed by a mining company but who would rather work independently using his or her own resources.

According to Hollaway (1997), the United Nations in the 1980’s spent considerable effort and time to devise a common definition and questioned “At what point does artisanal mining become small-scale mining? When does a small-scale mine become a medium scale mine?” For decades these questions have yet to receive an answer. The ASM sector is well known to be associated with various terms depicted in Appendix A-1.1. However, Veiga (2015) distinctly clarified artisanal and small-scale mining as two different entities, with artisanal being one with rudimentary technology employed. In other words, artisanal mining encompasses all small, medium, informal, legal and illegal miners who use rudimentary processes to extract minerals from secondary and primary sites while small-scale mining defines just the size of operations which are legal and mechanized.
There are two groups of ASM gold miners in Ghana, namely the licensed small-scale gold mining firms and unlicensed or illegal artisanal gold mining units, also called “galamsey”. However, Hilson and Potter (2005) observed that there is little difference either organizationally or technologically between legal and illegal mining activities except that the licensed operators have the security of tenure on a demarcated mineralized concession for a given period of time.

For the purpose of this research, a definition of artisanal mining will be adapted since the term “galamsey” in Ghana describes more narrowly illegal and rudimentary mining (Veiga, 2015). Intrinsic complexities and ambiguities within the sector run through its mining cycle, which over the decades has resulted in issues of environmental, economic, social, and safety concern (Seidu, 2015). This will be explored in detail in the subsequent chapters.

2.1 Artisanal Mining in Ghana

Artisanal mining is a part of Ghanaian history; it has been practiced for centuries and has a long tradition. Appendix A-1 describes briefly artisanal gold mining in Ghana.

According to Hilson (2003), about one-sixth of the country contains extractable gold, and certain regions hold rich mineral reserves which provides thousands of indigenous people with a principal source of employment through artisanal mining.

There is an established regulatory framework system for artisanal mining (PNDC Law 218, 1989) that is described in Appendix A-2. It is regulated by the same government department that monitors large-scale mining, however, the two virtually run in isolation. Fundamentally, there are environmental conditions on the leases which make it an important industry here, however, the practices of galamsey run contrary to the established regulations.

The missing link has been a lack of systematic and regular monitoring mechanisms for the existing operational sites of ASM of the mining industry in Ghana to develop quantitative and qualitative data to track reliable and adequate information (Seidu, 2015). Inaccurate information on existing sites is mainly
due to less attention being paid to the sector’s activities due to perceived uneconomic returns realized from artisanal mining, as compared to the large-scale mining industry.

### 2.1.1 Galamsey in Western Ghana

The Western Region is a well-endowed region for natural resources in Ghana (UNCTAD, 2003) with the WAMPA dominating. However, illegal mining activities within the rich districts of the region have led to many environmental and health problems, making the whole sector unacceptable and a national nuisance (Seidu, 2015). In the WAPMA, activities of artisanal mining are on the increase, with a handful of operations in conformity with government regulations and the majority making use of illegal mining. Generally, these miners make very little money in spite of the unsafe working practices and harsh working conditions.

Technical uncertainty in terms of ore crushing and grinding for recoveries, lack of mechanization and adoption of outmoded technology have led to impoverished circumstances of the sector for decades and have led to capitalization by some private processing facility operators. These circumstances have driven artisanal miners into more vulnerable and poverty-driven conditions than sustainable livelihood, causing them to blame other stakeholders, such as the large-scale mining companies operating under legal jurisdiction, for their misfortune and economic calamity by having legally acquired large parcels of claimed customary land. This agitation is not only prevalent among the artisanal miners but also among some non-governmental and anti-mining activists, as well as researchers.

Reisenberger (2010) describes how large-scale mining companies have caused economic displacement of communities and scarcity of land in developing countries where they are located. This author noted how communities located on land hosting ores are attractive for commercial exploitation and, as a result, suffer from a “gold curse”. Having investigated that, he further reiterated how most mineral-rich communities where mining activities are on production peak, rather lack economic growth, and hence find themselves in extreme poverty rather than showing an improved livelihood and general welfare.
Artisanal mining operations more often run into issues with stakeholders, such as the government and large-scale mining companies, due to unclear policies and delineation of concession boundaries. Typically, conflicts between artisanal miners and neighboring Large-Scale Mining companies’ (LSM) span from encroachment of boundaries to economic displacement of resource rich communities. This is as a result of the policy flaws where mineral rights and land rights are not distinctly addressed. According to Andrew (2002), a lack of policies and mechanisms of land management by government results in conflicts between ASM and LSM and creates ripple effects on local communities and the environment. The author argues that there exists a missing link approach used by the government and LSM to potentially reconcile the differences and interests of the AM. Hilson (2002), noted that a lack of effective communication among mining stakeholders contributes to a lack of peaceful coexistence which subsequently results in land conflicts.

For decades, an attempt to mitigate issues of artisanal mining has yet to reach its potential outcome. Corporate Social Responsibility (CSR) is an integral part of every responsible mining company for dealing with community-company relations to insure coexistence as a means of conflict mitigation. Jenkins (2004), however, argues that there is little evidence of fundamentally positive and real impact of CSR to communities.

Researchers and practitioneres have focused on social, environmental, economic and technical issues as methods of resolving impacts in the sector, but have little touched or investigated the sector of processing facility operations. It is important to note that sources of conflict and livelihood setbacks among communities where LSM is practiced go a step beyond that which has been perceived globally. As Hilson (2004) points out, there is a need for adequate investigation to help evaluate the impact of artisanal mining within communities. This drove the motivation of this current research work. Some facts about ASM have been described in Appendix A-1.2.
2.1.2 Environmental Impacts of ASM

Environmental issues are the harmful effects of human activity on the biophysical environment (Millennium Ecosystem Assessment, 2005). The impact of ASM activities generates waste in the form of gases and liquids caused by rock extraction and processing of ore. Generally, these wastes are disposed of within the environment causing various degrees of pollution including river siltation, soil erosion, pollution of waterbodies, destruction of riverbeds and margins, particularly in alluvial mining, acid mine drainage, harmful gaseous emissions such as carbon dioxide, and mercury pollution. Hentschel et al. (2003), and Spitz & Trudinger (2008), have extensively reviewed the negative effects by ASM on the environment. Of these, mercury pollution by small-scale gold mining is considered as one of the greatest environmental and health problems (UNECA, 2003; Veiga, 2015). These negative toxic substance impacts have diverse consequences on all forms of life and include effects on climate change, health and remediation process costs. Impacts of ASM require attention and sustainable approaches to the ecosystem during environmental assessment and planning. Environmental sustainability in terms of maintenance, and use of natural and capital resources, have been briefly reviewed from the (Environmental Protection Agency Act 490, 1994) Ghana perspective in Appendix A-3.

2.1.2.1 Application of Mercury in ASM

Mercury is the only metal that exists as a liquid at normal conditions of temperature and pressure, evaporates easily into the air, and is recognized as a chemical of global concern due to its long-range transport impacts in the atmosphere. The UNIDO (2013) estimates that mercury amalgamation from gold mining results in the release of an estimated 1000 tons of mercury per year, and 100% of all mercury used in artisanal gold mining is released into the environment, constituting a danger on all fronts – economic, environmental and human health (USEPA, 2015).

In spite of all environmental concerns, utilization of mercury is responsible for 40-50% of recoveries of throughput. It is important to note that mercury, added during amalgamation for ore recovery, is lost to
the environment and is always washed out by AM along with the unwanted tailings or sediments and is released mostly into water bodies and the surrounding environment (Veiga, 2015).

2.1.2.2 Gaps in the ASM Gold Processing Environment

According to Veiga (2015) private processing centres within the small-scale mining sector are the worst environmental degradation contributors due to the outmoded technologies used by these operators, and to their negative effects on the environment. This was evident in a presentation on some projects in Ecuador and Peru where processing chemicals such as mercury and cyanide were discharged into drainages, which flow from Ecuador to Peru (Veiga, 2015). In whatever way, the actual perpetrators have not been properly investigated or perhaps ignored.

In the WAMPA, Ghana, the ore processing technique used presents a daunting phenomenon, which is unattractive in returns and ore recoveries as well as for producing damaging environmental and health impacts. There is absolutely no mechanization used in ore recoveries. Ore brought into facilities by AM is crushed manually to an acceptable rock size before being allowed into the crusher. The private facility dealers only provide assistance to a point where the rocks could be turned into particles fine enough to go through the process of gold recovery. Conversely, due to ignorance on the part of these miners, processing plant operators act unscrupulously and unsafely.

There is no adherence to regulation and safety standards and there are constant injuries as personal protective equipment is hardly used by workers. Meanwhile, per the agreed terms for getting hard rocks sized into fine particles at a facility, these facilities are not liable for any eventuality such as accidents or loss of property including ore theft. On the other hand, the tailings residue remains the property of the facility centre for offering services or help at low and sometimes no cost to the miner. The services rendered by these facilities are much more fraudulent and abusive than good as perceived.
2.1.3 Health

Studies have pointed to a persistent rise in the prevalence of respiratory diseases among mineworkers and within local mining communities. This may be due to high levels of dust pollution from surface mining operations as well as from constant exposure to industrial gases (Donoghue, 2004; Hilson, 2002).

In ASM, excessive exposure to unregulated and misused chemicals for ore extraction have been the prime causes of kidney problems, psychotic reactions, respiratory failure, neurological damage, and developmental problems in children in ASM environments (World's Worst Pollution Problems, 2008). Examples of cases are presented in Appendix A-3.1.2. The ASM sector is well known to be linked with sexually transmitted diseases such as HIV and Aids mainly due to the influx of aliens and foreigners for greener pastures (AngloGold Ashanti, 2006).

2.1.4 Safety

Occupational safety in the mining industry is perhaps the number one priority in recent times for most large-scale mining (LSM) firms, if not all. The LSM industry has been made safer with the development of improved safety systems and technology to reduce the prevalence of accidents in the mining industry (Gold Fields Ltd., n.d; Anglogold Ashanti, n.d).

There is no doubt that the ASM sector runs contrary to the current safety practices of large-scale mines globally. The adoption of zero harm in the ASM sector and best practices used in maintaining it in its operations is perhaps nonexistent or minimal. On the rise in the ASM sector are mine injuries and deaths from mine accidents in Ghana, particularly for pit collapses, cave-ins and landslides (Kyeremateng-Amoah & Clarke, 2015).

Artisanal mining is heavily labour-intensive, which clearly presents risk factors in a number of operational areas (Jennings, 2003). From a safety standpoint, all the selected sites visited in the WAPMA showed evidence that miners seemed not to be aware of detrimental operational practices. A random
interview of some miners extensively revealed a level of ignorance of standard operational procedures for mine safety. Lack of safety, ignorance and improper training methods and procedures for mining results in severe injuries and sometimes death from mine accidents. Accidents such as pit collapses occur regularly in Ghana’s ASM and are estimated to have killed over 300 people in 2011 and 2012 alone, according to a government estimate (Human Rights Watch, 2015). An example of a safety breach case is presented in Appendix A-3.1.2 as well as descriptions of some ASM sites visited in the WAMPA in Appendix Figure A-3.

2.1.5 Economic Facts and Analysis about ASM

In spite of multifaceted challenges facing the sector, ASM provides employment and economic freedom for people engaged in the sector. ILO (1999) estimates that the number of artisanal miners is currently around 13 million in 55 countries with an estimated 11.5 to 13 million people engaged in small-scale mining worldwide. It has further been extrapolated that 80 to 100 million people worldwide are directly and indirectly dependent on this activity for their livelihood.

Artisanal mining is and remains a vital part of Ghanaian life and is an intrinsic part of economic growth (Akabzaa, 2009). In Ghana, the number of ASM participants is between 500,000 and 1 million (Human Rights Watch, 2015; Ghana National Commission for UNESCO, n.d), which is one of the most complex economic sectors in the country (Ghana Ministry of Finance, 2014).

According to Seidu (2015), artisanal mining in the WAPMA has proved to be 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. The Minerals Commission and the Ghana Chamber of Mines estimates that 60% of the country’s total mining labour force is employed in small-scale mines (Hilson, 2001). See Appendix A-4 for facts and figures.

Statistics in the sector are probably not accurately captured or are inconsistent due to a lack of resources and the dispersed nature of the sector in terms of accurate records, opaque nature of involvement
in ASM activities and the fact that a large percentage of activities is carried out illegally and in a covert manner, for which there are few if any statistics available.

2.1.6 Social Impact of ASM

The ASM sector is an important part of societal livelihood where mining is an integral part of local culture given the closely linked economic sustainability and benefits in resource rich environments such as the WAMPA. Its activity is increasingly gaining momentum in Africa (Economic Commission for Africa, 2002). ASM in Ghana has grown enormously over the past decades (Seidu, 2015). However, the sector is often known to be characterized by daunting traits including social vices such as prostitution, health issues, drug running, child labor, human abuse and environmental degradation that have attracted international organizations, including the United Nations, ILO, and the World Bank over decades for consideration of potential control or possible mitigation.

According to Jennings (2003), ASM is labeled as dirty, dangerous and damaging, yet discouraging or perhaps eliminating it (risk) has been unsuccessful due to its economic importance to the involved societies. It has been the main source of income particularly by artisans who lack the requisite education, training, and skills to manage resources and business (Economic Commission for Africa, 2002; Hentschel et al., 2003). This makes it difficult for the predominant stakeholder, the government, to completely eliminate its activity and that of ASM to accept stringent policies to redraw or minimize its activities.

Beyond the sector’s role as a source of livelihood, ASM is a vital sustainable phenomenon given the extent of benefits, serving as the foundation to the quality of lives of the people involved. ASM can play a pivotal role in implementation of moderate and quality needs of dependents, including providing education, and basic necessities. This contribution by the sector signals the relative importance of galamsey in the prevalent societal economy. However, competition for accessibility of resources, coupled with an influx of foreign miners resulting in socio-cultural change, and to some extent STD’s, has been a main setback for AM.
2.1.7 Conflict

Conflicts in ASM stem from land to resource accessibility which is mainly due to lack of cadastral boundary barriers and policies to establish the distinction between land ownership and mineral rights ownership. Hilson (2001) described how constantly ASM and LSM of Ghana are in competition over the plots of land overlying the country's rich deposits of gold and diamonds.

Generalizations about customary land tenure and “ownership” of land in Ghana are notoriously difficult and imprecise, both because the boundaries between the customary and statutory land sectors are not always clear and because the customary law itself recognizes a multiplicity of overlapping interests. The alodial title is the highest interest in land known in customary law, above which there can theoretically be no other interest (Woodman, 1996).

The unclear distinctions of ownership of land have resulted in disputes over decades (Reisenberger, 2010). These disputes stem mainly from the competing interests of the various stakeholders with respect to land use or mineral resources, as observed by authors such as (Davidson, 1998; Hilson, 2004; Nyame & Blocher, 2009). Communities in the WAMPA, where LSM is alleged to have caused economic displacement and vulnerability, believe their rights of land ownership are denied and therefore, in their quest for better living conditions, sustainability and equal benefit of the good fortune (gold) that the land holds, devise all means to have access to the mine concession to mine (Artisanal Miners, 2015).

This perhaps has been the main source of riots over decades as many local farmers have been denied access to their farm lands due to operation of mining projects. These people have deep connection to their land, are well aware of the importance of land for their livelihood, and therefore, in the absence of livelihood, this can spark conflict. (Example Appendix A-5.1).

This situation has been little addressed and not properly established to distinguish between the two institutions governing land ownership. Adequate attention and research in the area of tenure system ownership has the great potential of mitigating conflict between local community people who are mostly galamsey miners and large-scale miners (Nyame & Blocher, 2009).
2.1.7.1 Opportunity for Coexistence

Stakeholder engagements to projects in communities are intrinsic for project developmental success. It is therefore important for a better approach to be adapted to help in the process of establishment. Importantly, expertise with an in-depth skill is required for this to be successful, especially in the case of the local community, in which the majority of people are illiterate or semi-literate. Usually, these indigenous communities have misperception of LSM activities and their impacts to their society. This includes the fear of potential influence on lifestyle and culture between the local population and newcomers, social disruption due to population influx, changes in their traditional livelihood and physical displacement.

‘Soft skill’ (personal attributes that indicate a high level of emotional intelligence) is of paramount importance in relation to stakeholder partnership for co-existence and community development (Davidson, 2014). Effective communication in clear language must be understood by the locals in order to build confidence and trust in partnership without diminishing the community way of doing business in terms of mining, as well as the culture and lifestyle. These values when respected or properly managed would insure the community ‘sweat equity’ in the success of the project (Davidson, 1998). The fear of loss of access to traditional resources, dependency, loss of identity, breakdown of traditional codes of conduct and ultimately spiritual and physical breakdown are the major concerns of the locals with LSM development (Spitz & Trudinger, 2008).

Developing a centralized processing facility through proper communication and potential positive impact of the AM, as well as the community, will engage these stakeholders which will potentially ‘sweat their asset’ to ensure the implementation of such a facility. Potential benefits may include training, development of special skills, improved infrastructure, and transparent transactions of resources and market prices of final product.
2.1.8 Central Gold Buying

Ghana has reasonably well developed markets for precious minerals, including gold. The Precious Minerals Marketing Corporation Law (PNDCL 219) (1989) PMMC created a central purchasing centre to allow private exporter transactions in the mid-1990s with the aim of creating avenues for AS miners to sell product. The law granted the organization authority to buy and sell gold in addition to diamonds. Its mission is to buy from small-scale miners, and to sell precious minerals profitably in order to enhance foreign-exchange earnings from the sector. This means that the sector has a potential for economically contributing to the development of the state as well as for improving the well-being of locals.

Facilitating the creation of a common platform for ore processing among the WAPMA artisanal miners and communities by stakeholders such as the government or LSM could motivate AM to embrace the engagement of such a project, given the assurance of maintaining the socio-cultural beliefs and rights through dialogue and consultations. These would be achieved through the chiefs and elders of the society, as well as effective communication on the benefits of the facility to society and its livelihood for the project success.

This could be an extension to the already existing trade by PMMC, although this trade will be dealt with internally within the boundaries of the society where the processing centre would be sited. The policies and practices of the PMMC would be adapted for fair trade of gold produced by the AM processing centre. Generally, the established facility would be formalized and guided by regulations which would ensure proper conformity, in terms of health and safety, payment of taxes and royalties, and transparency in trading in gold price.

2.1.9 Centralized Processing Facility

Implementation of a centralized facility could be seen as a natural extension and an integral part of a formalized artisanal mining process, in terms of ore recovery. This is due to the fact that manual techniques of rock extraction, coupled with lack of technology, as well as opaque transactions of middle-men and
brokers, have worsened the living conditions financially and socially of AM involved (UNDP, 1999; Hilson, 2003).

Beyond insufficient livelihood due to use of rudimentary tools for operations, acquiring simple tools for mining activity is limited, due to 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 and income remains at a subsistence level keeping the AM in a vicious cycle of poverty (UNECA, 2003).

Development of a centralized processing facility could complement the current low yields as well as discourage opaque transactions and practices. UNECA (2003) reviewed various notable technologies and programs for small-scale mining in several parts of Africa which have contributed to improving productivity, livelihood and reduced localized impacts to the environment. However, this technology is still in its infancy considering the inadequate capacity of programs designed to accommodate their performance.

For example, the Shamva Gold Mining Centre in Zimbabwe was established to address the needs of AM by improving access to its processing facility, with the primary aim being to provide appropriate technologies and skills in the mining and processing of gold, to improve health and safety, the environment and community sustainable development (Svotwa & Bugnosen, 1993). Initial stages of operations attracted more ASM who utilized the facility effectively with the centre operating at full processing capacity.

However, the facility centre’s ability to support the growing demand of ore from AM was inadequate which resulted in increased processing time and consequently limitations on the amount of ore to be processed to unlock the potential of AM to run a viable operation (Drechsler, 2001). Moreover, poor decisions by authorities contributed to unresponsive operation of the facility due to lack of managerial experience and societal and techno-economic problems (UNECA, 2003).
2.1.9.1 Justification of a Centralized Processing Facility in the WAPMA

The success of a centralized processing facility is dependent on its design and implementation as well as effective utilization by its operators. The processing facility at the Shamva Gold Mining Centre was reviewed Practical Action (n.d), Svotwa & Bugnosen (1993), and Drechsler (2001), in terms of success and the challenges from its operation and its capacity for sustainability. It is important to adapt a strategy to address the necessary needs of AM in terms of techniques to the current operational capabilities, considering the current equipment used as well as the production capacity to size the facility. Factors that led to the failure of the Shamva Mining Centre UNECA (2003), including excessive distance to the facility location, lack of effective transportation system, trust factors and, above all, poor facility size and capacity, left many AM ores in a queue to be processed, thus they must be properly investigated to design this facility.

It must be mentioned that, for the purpose of this research work, capacity sizing was not considered as it is beyond the scope of the analytical work. However, it is very important to note that processing plant capacity is integral for success in ore throughput and hence profits, and, considering the amount of ores produced by AM, plant size can be designed which would go a long way towards evaluating mineral resources within the ASM sector. Future research on economic potentials of using GIS and spatial analysis in the area of ASM could be utilized in the area of plant capacity.

Thriving implementation would be based on the coexistence and engagement of stakeholders such as the Government of Ghana or LSM firms with AM, addressing the need for registration and formalization of ASM business, as well as further exploration of orebodies with emphasis on the technical processing involved for the benefit of society. It is important, however, not to ignore the concerns of society as well as its inputs for the facility operations, as it is a very technically oriented facility in nature. Without the understanding of AM, this could lead to failure, as it could lead to misconnection of conceptions of the facility (UNECA, 2003;Practical Action, n.d). Hentschel et al. (2003) 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 AM 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, easy accessibility of the facility must be flexible, simple, and cheap with improved ASM policies and legal support to attract more AM. A “Compendium on Best Practices in Small-scale mining in Africa”, Economic Commission for Africa (2002) was however adapted for a justification of a potential facility centre in the WAPMA.

2.2 Legislation in the Area of ASM

Ghana has reasonably well developed regulations and policies governing ASM operations, such as the Small-Scale Gold Mining Law (PNDCL 218) (1989). Established under the Minerals Commission Law of 1986, the law regularized artisanal mining activities by providing registration, granting of gold-mining licenses to individuals or groups, licensing of buyers to purchase product, and the establishment of district-assistance centers. This provided the sector an enormous potential and made it an important part of the country’s economic growth in terms of GDP, as well as providing employment for its citizen. Appendix A-2 illustrates permitted and non-permitted activities with issues associated with the current legislation.

2.3 Selected Factors – Siting a Central Gold Processing Plant

The selection process is relatively important as it can strongly influence the success of an investment venture (Stemn, 2015). The site should be critically selected and located in proximity to the proposed facility where the cost of production and access to raw materials is minimal, and the selection process should also factor in environmental and social impact analysis to the proposed site. Additionally, site selection for the facility should provide for future expansion and not necessarily relocation as the cost involved for relocation could affect the project economics. In this project, the affecting criteria have been categorized into two, namely primary or fundamental, and secondary factors.
2.4 Fundamental Factors

2.4.1 Nearness to Artisanal Mining Sites

The artisanal mining sites should be considered as a primary factor during the modeling process. It is preferable to locate a processing site near the source of ore feed (mining site) as that will be the main input for production as well as an economic factor to realize 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, this in turn decreases the cost, as well as the risk, of the overall production efficiencies and effectiveness. Distance plays a significant role in achieving overall operational effectiveness in terms of material handling (Stemn, 2015).

An ideal processing centre in close proximity to ASM will not only minimize the time and cost of moving material from an AM site to its final destination for processing but will also result in savings on equipment health including wear and tear of haulage facilities. It is important to extensively consider factors that might account for potential project cost in implementation (Thorley, 2015).

Factors such as inaccessible or poor road networks obstruct flexible productivity due to the existence of poor terrain characteristics. This includes barriers in hilly sites and areas prone to natural hazards such as landslide and fracture zones, which are potential cost drivers. It is empirically necessary to weigh the cost and benefit hypothetically and to test the project economics in order to proceed or not.

2.4.2 Energy Availability

The site should be close to a power source for effective productivity. Power is one of the major constituents of production and, therefore, considering an effective energy option for a project is significant to production success. 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 et al., 2015). Essentially locating the site near a power source or an alternative cost effective source of reliable energy would efficiently contribute to the success of a project. Lack of availability of reliable energy supply would potentially cause
the failure of a project. Therefore, operations must essentially provide a reliable energy source for power. For example the energy crisis of hydroelectric power generated from the Akosombo power station by the Volta River Authority in Ghana has negatively impacted operating costs of business.

This has limited production capacity particularly in the manufacturing and the mining sector and has resulted in loss of profit to companies and revenue to the state, as well as unemployment due to shut downs and production reduction (Centre for Policy Analysis, 2007). In spite of the loss of revenue and the collapse of industry due to unreliable and unavailable energy, it is quite expensive to create and implement a power generating facility and, therefore, the economics of cost and benefit must be thoroughly investigated to establish project viability to decide on project implementation. Having experienced the current energy crisis in the country, it is known that this could potentially be a factor for immense impact not only on the project, but also on the economics of scale to the investor and society where the project would be implemented (The Ghanaian Times, 2015; The Chronicle, 2015).

An extensive feasibility study needs to be conducted on energy supply prior to project commencement. Conversely, an alternative source of energy must be considered should there be a break or loss of energy supply due to technical issues. A project is likely to be unsuccessful due to lack of sufficient supply of power and, therefore, consideration of energy is essential in locating a processing facility.

2.4.3 Transportation Facility

Selectivity of an economic transportation facility for haulage of ore materials from the existing artisanal mining sites to the proposed facility is essential for the success of the project. It is considered as a key driver of economic development (Asian Development Bank, 2008). Transportation networks could include airways, roads, waterways and railways. According to Legg (1992), it is economic to utilize air transportation for a high-value commodity such as gold into the market, however, this project will not consider this option as this study is considering only the existing ground transportation option such as roads and railways within the study area.
Roads and railways exist within the boundary area of study and, therefore, it would be economic to potentially access and utilize these facilities over air transportation proposed by Legg (1992). Therefore, an ideal case would be for the site to be close to an existing road or railroad. It is worth noting that, in the case of non-existing transportation infrastructure, there will be a need to construct infrastructure to connect the source of raw materials to the processing site. The determination of an optimum site for the processing centre must be carefully considered, such that the location should minimize the extent of material transport and overall cost (Modular Mining Systems, Inc, n.d).

However, since this project is associated with an area of several artisanal sites, the preparation of the plant must best be located in a manner such that the total input-output material handling system is minimized. This will not only minimize the extent of the hauling transportation system but will also minimize the extent of other factors such as reduction in fleet breakdowns, wear and tear, and reduction in fuel consumption.

This will directly minimize operational cost which can yield substantial immediate and long-term savings on capital cost by minimizing haulage distances. Combined techniques such as intuitive and analytical approaches must be carefully utilized to account for the multiple tasks (criteria) needed to achieve a unique objective which would be analyzed with the GIS and spatial analysis tools in this project.

### 2.4.4 Gold Mineralization

Geological characteristics of a proposed facility location must be 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 the siting of the facility. The facility must not be located in an ore mineralized zone, but instead must be located in waste bearing areas with substantial emphasis on rock type and strength. The aim is to prevent any future possibility of relocation considering the economic implications of having to construct another facility in
the event of discovery of further resources or mineralised zones within the location of the processing facility.

Economically, determination of a facility sited in a non-mineralization zone has the potential of realizing attractive investment return, given adequate geological analysis from exploration to find available mineral resources, hence further preventing facility re-location. One of the essentials in assessment of mineralization is to ascertain the accurate resource information within an area identified as a suitable site for project establishment (Yakubu, 2014). However, due to the issue of data unavailability associated with the geological mineralization of the study area, the work was conducted without mineralization information being available.

It is worth noting that a simulated data approach could be incorporated as a conceptual hypothesis to further test a potential suitable site. It is hoped that (mineralization) data availability will actualize the work in order for stakeholders to hypothetically test this phenomenon and generate proof of concept to establish the benefit of the proposed established GIS tool in the future.

2.5 Secondary Factors

2.5.1 Site Stability

Site stability should be considered from both short and long-term perspectives. Natural occurring hazards such as landslides, floods and tectonic activities are dangerous phenomena that run through the cycle of mining operations including extraction to transportation of ore to the market (Jones, 1997). These hazards are somehow interrelated as one occurrence potentially triggers others which in turn affects project operations.

Typically, the majority of rock or terrain stability issues are associated with active fault zones, fractures, as well as geological tectonic movement (Legg, 1992). Such features can result in displacement of geomorphological features which makes it essential to investigate movement and displacement to know the rock and the terrain strength in order to make judgments for siting a facility.
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 potential faults. It is therefore important to investigate the stability of terrain or rock masses to assess the probability of 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. Tectonic data acquired from the Ghana Geological Survey (GGS) was of particular concern, in terms of the fault layers that lie in the area of study.

It is important to note that siting this facility in an area subjected to instability will have safety and economic impacts on the project and therefore requires the services of experts in the field of seismic risk analysis. Data of the study area acquired from the GGS is based on structural studies which were quantified in reference to historical data and records to help in risk identification and assessment. These were processed in the GIS environment to help in the site selection simulation.

2.5.2 Climate and Soil

Climate and soil information of an area of interest for a facility location must be incorporated to aid in identifying the risk of future production impacts. The study area is a tropical rainforest zone with canopies making the forest floor nearly invisible from the areal point of view to assess the soil texture for the proposed site.

Clay soil will not be appropriate for such a facility during rainy seasons due to its potential hazards to the road transportation system resulting in slips, accidents and delays in production due to slowing down or restriction of vehicles transporting ore to the facility. Information on climate and soil will assist in analysis for a suitable location.

2.5.3 Hydrology

The pollution of surface water by wastewater is one of the principal concerns in relation to processing facility factor location. If a 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. Project success greatly relies on community support as indicated by Davidson (1998). This includes the ‘sweat equity’ contribution of a community to a project with a company operating under the jurisdiction of the law without compromising the environment.

It is essential to factor the hydrological analysis to locate the appropriate fit within the context of the work, considering the physical and chemical characteristics of the terrain. Detailed planning will contribute to the project viability in terms of chemical characteristics to simulate and create a buffer zone to mitigate the impact of the facility operations on the neighboring community.

Ground surface water depends upon the use of terrain models which, when created to sufficient accuracy, can be used to model surface water flow and hence determine drainage basin impacts and predict runoff and flooding under various conditions of weather and climate (Hogg et al., 1993). Detailed planning for the facility location will involve a ground survey of water bodies that have potential of being polluted due to the impact of the processing activities.

2.5.4 Water Supply

Water availability is an integral part of an ore processing facility, and therefore, its proximity to processing activities is essential to a project success. However, siting a facility within the parameters of a water source could present a daunting phenomenon considering the extent of harm (water pollution) that might potentially be created to neighbouring communities and users. This is particular for the direction of flow of a waterbody from a facility to downstream with potential contaminants.

The direction of flow of nearby water resources, including ground surface water within the proximity of the proposed site, is an important factor that must be considered in siting a processing centre to prevent environmental liability and, social issues, and hence to save costs. Ore processing must be strategized such that operations would be economically executed without compromising environmental traits, standards and regulations (Environmental Protection Agency Act 490, 1994). The hydrological characteristics and
existing ecological features of the area of interest must be well assessed and investigated before an attempt is made to commerce a project.

2.5.5 Topography

Careful consideration needs to be given to the landforms during the site selection process, however, this is dependent on the characteristics of the topography. Topographical characteristics are determined by slopes and aspects on which surfaces or terrain are modeled. Flat terrain would be ideal for economic facility establishment, due to the technical, safety and financial certainty involved in implementation. For instance, terrain with steeper slopes will result in constraints of ore movement from a mining site to a facility centre which increases operating cost. A certain degree of slope sets within the study area must be classified to reject or accept suitability for the facility establishment.

2.5.6 Environmentally Sensitive Areas

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 reserves, national parks, local aquatic ecosystems and game reserves among others. Contaminants from the processing center have an environmental liability which might affect regulated areas Environmental Protection Agency Act 490 (1994), through potential release of effluent from the processed residue into nearby water reservoirs thereby polluting them. This may include an exceedance of supernatant water, and exceedance of standards for selenium, and sulfates for human consumption, thereby introducing contamination, and bioaccumulation, which might pose risks to local communities.
2.5.7 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 criteria is an input to environmental impact assessment and, therefore, consideration of this will result in economic analysis, as indicated by (Gooland, 1995). There is a need to ensure the protection of amenities associated with residential, commercial or rural zones from nuisances associated with noise, dust, and visual effects.

Typically, areas of non-existing farm lands and with available drinking water are more favourable for the facility location, while areas prone to high erosion might be unfavorably impacted due to the cost associated with remediation and mitigation in the case of a breach (Yakubu, 2014). The operational impact of construction of access roads from ASM locations to the proposed allocation facility might lead to some degree of farm crop, natural vegetation and drinking water destruction which in effect might present the project as a liability not only to the environment but financially through the need for remediation.

Having identified the potential of the project for creating this liability, detailed information of the site location must be mapped and geographically referenced to represent this information as a means of providing a buffer for planning purposes.

2.5.8 Site Capacity

The life of a processing plant and the demand for future space should be considered during the site selection process. It is important to locate this facility in a location where future activities of the facility would not impact the surroundings or its operation for relocation due to the costs involved in its construction. Land litigation due to the nature of the tenure system in Ghana can easily result in this phenomenon. Site suitability that falls within the jurisdiction constraints such as state reserves, and community sacred and spiritual lands must be avoided.
2.5.9 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 is a matter of prime concern. A regional history of natural events like floods must be conducted if a site is to be located near large bodies of water such as rivers. Fire hazards in the immediate surrounding area of the plant site must not be overlooked since, in the event of a fire outbreak, it will lead to a loss in assets and sometimes workers which will in turn be realized as a financial loss. It is important to factor all environmental and climatic conditions with respect to land use for effective selectivity. Fire protection measures, such as fire berms, must be built around the facility to protect against fire spread in the advent of an outbreak. The facility must not only be located with knowledge of technical site characteristics but also using community based knowledge and ideas of the site.

For instance, flat land along rivers and stream courses must be restricted to pasture land as tracts of natural grassland along river courses are often good indications of regular flooding and, therefore, such sites should be avoided. A project site should not be liable to flooding and should be easily accessible during all seasons (Legg, 1992). These factors could be easily incorporated and processed in the GIS environment specifically in the spatial analysis tool to produced models and maps to aid in site selectivity. A summary of data considered in the research is illustrated in Table 1. The analytical techniques used in the final work will be discussed extensively in Chapter 3.
Table 1 Analytical Data on the Basis of Availability and Non-availability

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<thead>
<tr>
<th>Available Data</th>
<th>Non-available Data</th>
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<tbody>
<tr>
<td>Small Scale/Artisanal Mining Sites</td>
<td>Mineralization</td>
</tr>
<tr>
<td>Road Networks</td>
<td>Energy Availability</td>
</tr>
<tr>
<td>Water Bodies (Streams/Rivers)</td>
<td>Hydrology</td>
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<tr>
<td>Railway Lines</td>
<td>Water supply</td>
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<td>Tectonics</td>
<td>Fire and Flood Protection Area</td>
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<td>Forest Reserve</td>
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<td>Large Scale Mines</td>
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<td>State Lands</td>
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<td>Urban Areas/Settlement</td>
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<td>Digital Elevation Model (DEM)</td>
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</table>

It is important to note that energy availability in this analysis presents a critical impact issue for which little data availability exists. Lack of power availability is a major siting constraint for this work, thus limiting the effectiveness of the analysis and restricting the potential for detailed analysis. Therefore, energy availability with respect to projects must be a future priority in any similar analysis process.

It must be noted that power availability needs to be rated as very important in project implementations such as a processing facility and therefore determination of energy supply by whatever means possible should be undertaken to ensure project success. Acquiring requisite data for power production and usage presented a daunting effort in this analysis, as there are limited records readily available in the public domain, thus, making reliability poor. However, alternative methods for assessing sources of power generation could be feasible. For example looking at nighttime satellite imagery to see if local or regional centres of bright lights (power generation zones) actually exist that might indicate the actual occurrence of good existing power sources and, therefore, should be highly considered.
Chapter 3

GIS and Spatial Analysis Techniques

This chapter presents methods and techniques for determining site selection among candidate sites. In this research, tools necessary to analyze land suitability will be evaluated to economically locate a processing facility for artisanal miners in the WAPMA. These techniques incorporate multi-criteria evaluation to select an optimal site by integrating a geographic information system (GIS) for determining effective results. (Carver, 1991).

GIS is a computer-based system designed for capturing, storing, manipulating, analyzing, managing, and presenting all types of spatial or geographical reference data (Eastman, 2001; ESRI, 2014). This system enables visualization, questioning, analysis, and interpretation of data to understand relationships, patterns, and trends. GIS benefits organizations of all sizes and in almost every industry, including the public health, transportation, disaster management (such as an earthquake or hurricane), exploration, mineral prediction, and population resource industries among others.

GIS is the go-to technology for making better decisions about location analysis (ESRI, 2014). Common examples include site selection, route selection, evacuation planning, conservation, mineral exploration, and pollution etc. With GIS technology, people can compare the locations of different features in order to discover how they relate to each other, a technique known as autocorrelation. There are many providers of GIS software and this thesis will employ ArcGIS by ESRI (Steiniger & Weibe, 2009). ArcGIS by ESRI was used for the research analysis due to the extent of multifaceted issues in the area of the research as well as the software with hands-on exposure and knowledge. The benefits of GIS technology span all aspects of application from analysis through to management.

However, the artisanal mining sector has little or no benefit from this technology due to its operational nature (Hilson, 2001) as well as lack of global perception of the sector. The fact is, locations of
ASM present a daunting problem due to inaccurate or lack of records from authorities that control the natural resources in Ghana. GIS technology based on the spatial analysis technique could be utilized on ASM through derivation of data sets of physical and geographical characteristics of existing activities to analyze their sensitivity on economics for decision-making. However, the success of implementing this technique will be dependent on professionals in many different disciplines such as computer science, geography, surveying, engineering and others for development and analysis (Wolf & Brinker, 1994).

It must be noted that GIS can use any information that includes locations of points of interest to hypothesize scenarios, before implementation of a concept for profit or benefit. Authors such as Goodchild (1987), Eastman (2003), and Rhoma et al. (2011) applied GIS analysis in different fields of modeling. The subject of modeling is addressed in detail in the sub-chapters of this thesis section. There is no limit to the kind of information that can be analyzed using GIS technology. Some benefits of GIS are discussed in Appendix A-6.4.

3.1 Sources of Data

There are two main sources of data for GIS. These are Primary Data and Secondary Data sources. (see Appendix A-6.2 and A-6.3).

3.2 GIS and Data Model

A data model in GIS is a mathematical construct for representing geographic objects or surfaces as data. There are two data classifications used in GIS (Wolf & Brinker, 1994).

- Spatial data
- Non-spatial data

3.3 Spatial Data

These are graphical data that digitally represent features in the form of lines or symbols on maps or images on photographs in a spatial (geographical) location, which are represented by vector and raster
data models (formats). These data models describe the spatial representation of attributes and features of objects and fields which provides a flexible approach to layer manipulations and implementation of map algebra (Jones, 1997). Vector and raster models are the basic structures for storing and manipulating geospatial data and research analysis from a conceptual stand point.

3.3.1 Vector Data

Vector data comes in the form of points, lines and areas that are geometrically and mathematically associated. These are spatially located in coordinates, commonly in plane or Universal Transverse Mercator (UTM) systems. Points are stored using coordinates, for example, with a two-dimensional point being stored as (x, y) which can be encoded in coordinate systems such as latitude/longitude or Universal Transverse Mercator (UTM) grid coordinates.

Vector data is easier to handle on a computer because it has fewer data items and it is more flexible to be adjusted for different scales (Eastman, 2003). For example, vector data is a projection system in a mapping application that has the flexibility to attach attribute information to a feature such as a particular criterion name, exact location ID or its evaluation.

3.3.2 Raster Data

Raster or grid processing consists of a matrix of cells or pixels organized in rows and columns or a grid where each cell contains a value representing information (ESRI, 2008). Images come in the form of individual pixels, and each spatial location or resolution element has a pixel associated where the pixel value indicates the attribute, such as color, elevation, or an ID number. Raster images are normally acquired by an optical scanner, digital CCD camera or other raster imaging devices. Rasters are digital aerial photographs, imagery from satellites, digital pictures, or even scanned maps. Cells with the same values are regions, while all regions with the same value are called zones (Jones, 1997).
A raster image has to have pixels for all spatial locations, and it is strictly limited by how large a spatial area it can represent. Each pixel is given a numeric value which represents either a feature identifier, a qualitative attribute code or a quantitative attribute value (Eastman, 2001).

### 3.3.3 Coordinate Systems

Coordinate systems are fundamental to surveying and map-making for precision purposes (Jones, 1997). The location of a subject will be expressed in the coordinate systems through detailed surveying, as well as geo-referencing data into a common projection system. This means that locations of features such as waterbodies, vegetation, farms, and artisanal mining sites could be geographically referenced for information acquisition and map production and modeling, hence project implementation.

Data in many different forms, such as raster and vector models, can be entered into a GIS program for simulation purposes. DeMers (2009) illustrated numerous examples of how GIS stores information about the world as a collection of layers that can be linked at specific locations on the earth together by a common locational component such as latitude and longitude, census tract name, or road name. This is known as geographical referencing as shown as a set of geographical reference lines Figure 1.

### 3.4 Non-spatial Data

These data describe characteristics of spatial features within geographical regions without definite locations in space. They are usually alphanumeric and provide information such as color, texture, quality, quantity and values of features. Non-spatial data are often derived from sources such as documents, files, and tables (Wolf & Brinker, 1994). Non-spatial data are attribute data or tabular data linked to spatial data to achieve a common identifier that is stored in both graphic and non-graphic data locations.
3.4.1 Data Model Conversions

Relative merits of raster and vector models have their own advantages and neither can be expected to displace the other. The ArcGIS software accommodates the processing and conversion of both model types to aid in analysis and interpretations. It must be noted that the great majority of vector-oriented GIS models employ graphic display devices such as scanners which are based on raster technology (Jones, 1997). This implies that data acquired in the form of raster information must be converted to vector model data to produce unique identifiers in final maps.

According to Eastman (2001), raster systems are typically data intensive since they must record data at every cell location regardless of whether that cell holds information that is of interest or not. On the other hand, vectors models are simple and produce thematic maps of queries and, as well, are efficient in feature manipulation. Compared to their vector models, raster system models provide substantive analytical techniques compared to vector systems due to their unique and simple geographical data pattern analysis in continuous space and are therefore unique in evaluating models. A combination of both models is shown in Figure 2 for the spatial analysis tool that was used.

Figure 1: Geographical Referencing Source: (DeMers, 2009).
3.4.1.1 Data Simulation

In this work, data simulation in the geoprocessing functionality were analysed in raster models from the data deriving set through to the weight overlay analysis. The process involved initial rasterisation of vector data through the utilization of vector to raster algorithms incorporated in the spatial analysis tool of ArcGIS 10.3 as shown in Figure 2. Finally raster data was converted into a vector model to produce vectorised versions of selected criteria in the form of lines, points and polygons after the data analysis in the final maps in order to attach unique identifiers of classification.

The attachment of class identifiers of selected criteria would aid in providing object recognition and distinguishes between different-shaped criteria such as roads, ASM sites etc. and attribute data, which will help in the interpretation process.

3.4.2 Spatial Overlay Analysis

For the purpose of this work, Boolean overlay was adapted for the selectivity analysis due to the GIS system capacity for incorporating criteria analysis, which accounts for the importance of different layers of an overlay and specifically the identified constraints. Boolean logic can be used to find the combination of layers that is defined by a combination of AND, OR, and NOT operators and is appropriate if selected factors or constraints are of equal importance (Jones, 1997).

Traditionally, conventional (paper) maps for overlay analysis involved the superimposition of series or different maps with cartographic annotations such as labels, legends and scales to achieve the best fit or objectivity of purpose. However, there are issues and gaps such as accurate positioning of geographic projection in making changes and adjustment in executing this technique as well as the time involved (Maling, 1991).

The map overlay concept is one of the essential tools used in GIS spatial analysis (Wolf & Brinker, 1994). Essentially, using the manual map overly method in the past assisted in immense contributions in
developments. For example Makhdoom (1993) utilised this approach to evaluate the ecological capability of Guilan and Mazandaran provinces in Iran for urban, industrial, rural and tourism developments. One approach is provided by Lotfi & Koohsari (2009), who introduced a stepwise map overlay methodology for measuring accessibility to public spaces at the neighborhood scale to investigate the distribution of such spaces by examining the socio-economic status of citizens in Iran. Though not necessarily of interest to the study, it was known to be correlated to the principle of multi-criteria evaluation of a concept incorporating the society that is of interest to this work.

To all extents and purposes, this method of map overlay produces less effective and flexible results. Again, this traditional method is random and somehow produces vague results due to the un-biasness of the Boolean concept, as there is no room for prioritzation given assignment of equal values to selected factors (Hajehforooshnia et al., 2011). Therefore, the setback in this traditional application outweighs its advantages given the potential issues that might arise during implementation and interpretation of outcomes.

With the array of GIS technology, features on conventional maps are captured, adjusted and transformed to extract data in digital format and are processed in GIS with spatial objects and attributes recorded in spatial database files. GIS technology is a straightforward approach for customizing, analyzing and modeling maps, which can be current and contain the latest revisions to a database (Bonham-Carter, 1994).

Spatial analysis technology by far has a significant level of accuracy compared to the traditional manual map overlay method given the elimination of human error and time in processing as well as the cost involved in training technical labour. As an example, Yakubu (2012) accounted for geological uncertainty and risk in land evaluation through mapping of features utilizing the spatial overlay technique to identify high-risk areas. In this analysis, all selected criteria were combined using logical operations OR and AND within the weighted constraints, such that the resultant image simply has two classes indicating the unsuitable and suitable areas in the GIS environment. See Table 10.
The idea is that the combined factors must satisfy all functions of a single objective, including vector and raster-based systems, which fall within the region of interest for further criteria discrimination. As noted by Jones (1997), not all factors may be of equal importance and in practice certain factors may be more important than others and, therefore, the relative importance of factors must be determined by attaching weights within overlay analysis.

3.4.2.1 Overlay Analysis Weights

Assignment of weight in an overlay analysis validates and justifies the relative importance of candidates (factors) in project analysis which aids in effective decision-making. The selection of weights is one of the crucial decisions and an integral part necessary in design and analysis (Yakubu, 2014).

However, it is not uncommon for weight assignment to be decided arbitrarily since the determination is solely based on the decision maker (or makers) or analyst or sometimes on consultations with other stakeholders. The assumption of facts (weights) usually results in a probability of errors in findings and hence creates problems in results. Jones (1997) noted the effects and problems associated with inappropriate selection of weight assignments on overlay analytical operations. This is discussed in the next chapter.
3.5 Spatial Analysis and Statistics

Spatial statistics is an analytical technique which studies geographical entities in space directly into mathematics (ESRI, 2012). In a more restricted sense, spatial analysis is the technique applied to structures at the human scale, most notably in the analysis of geographic data. However, classification of the technique of spatial analysis is difficult because of the large number of different fields of research involved, including the different fundamental approaches involved in selection of methodology. Complex issues also arise in the technique analysis, many of which are neither clearly defined nor completely resolved, but which form the basis for current research.

According to Goodchild (1987) appropriation of scale including model input, storage, analysis and output limits the capacity of GIS, emphasizing the data model representation with respect to raster and vector systems of analysis of spatial models. Fundamentally, this taxonomy of data model constituents is the problem of spatial statistics and statistical analysis. Haining (2009) demonstrated how spatial data are qualitatively and quantitatively modeled to avoid data bias in an indistinctive data structure, thus involving
non-spatial data. One of the main purposes of undertaking spatial statistical analysis is to make inferences based on data collected.

Spatially referenced information is an essential requirement for a large proportion of tasks expected of local, regional and national governments (Jones, 1997). Planning the location of an economic processing facility center for a trade-off between ASM and neighboring companies requires the collection of geographical data and information in a spatially referenced datum. An ASM site subjected to a planning application should be identified with its corresponding activities for ease of accessibility and interpretation of features and attributes for planning purposes for siting the facility centre. This includes the proximity analysis of constraint features that might potentially have a negative impact on the environment, such as the destruction of natural habitat and pollution of water bodies, upon the proposed development through spatial searches of neighboring land. The combination of spatial data in a single system integrates the information needed for capacity and resource planning which serves as a decision support tool.

GIS in a spatial database offers a great deal of flexibility in generating maps which are closely tailored to specific user requirements relating to routes, site characteristics, and types of information displayed. GIS in the context of planning depends on the ability to view information at different levels of detail and generalization to generate a solution to planning problems and to perform analyses of the relative merits of alternative solutions. Explanatory spatial data analysis as well as the geovisualization to support geographic data and information analysis is explained in Appendix A-6.0 and Appendix A-6.1 respectively.

3.6 ModelBuilder Tool

ModelBuilder is a visual programming language for building geoprocessing workflows. Geoprocessing models automate and document spatial analysis and data management processes. The capacity of ModelBuilder integrates and accounts for the creation and modification of geoprocessing models in the form of representation and processing models. These models are represented as diagrams in
Figure 3 that interconnect the processes, and procedures as well as the geoprocessing tools. In ModelBuilder, the output of one process is the input to another process (ESRI, 2015).

Modeling capabilities of ModelBuilder within the ArcGIS software automates and builds workflow to conduct spatial and temporal analysis through interactive geospatial relationships as well as processes. Lee, et al. (2008) utilized the ArcGIS ModelBuilder to develop the SEMLUC model to simulate the interrelationship between land-use change and socio-economic metabolism from a biophysical perspective. The use of the network analysis and conditional tools within the geoprocessing tool by utilizing ModelBuilder of the spatial analysis tool will automatically generate results to potential issues for the proposed site. For instance, in this project constraints such as forest reserves and LSM and state lands within close proximity to the identified proposed processing center would be delineated (avoided) having specified the limitation (range) factors to cater for potential financial and environmental risk.

Figure 3: ModelBuilder Tool

3.7 Network Analysis

Many applications in GIS are characterized by data network analysis representing different features under analysis and investigation. The fields where these types of analysis are used are different, such as roads networks, and hydrographic networks and so on. A line from a network is characterized by length, direction, connectivity and information about the outflow for crossing the network (Nemes, 2012). The ways of representation that can include all these features are shown in Figure 4.
When constructing a road between two points, the most logical pathway is the one that minimizes the travel distance or, in some cases such as in mountainous terrain, the one that requires the least travel time or least effort. Determining how a particular proposed route would affect travel distances and travel times is not always simple, but an understanding of its effect could be valuable in transportation planning (Stemn, 2015).

ArcGIS has the capabilities of performing advanced network analysis in locating optimal routes to areas of interest economically. In this work, a road network was analyzed with the best path algorithms in the Euclidean distance tool in the spatial analysis.

3.8 Spatial Decision Support Systems (SDSS)

Geological complexities, as well as spatial problems due to lack of technical resources governing the practices within the small-scale mining sector, require analytical techniques to model and develop an economical project such as a processing centre. This implies that data collection must be as accurate and precise as possible to perform analysis, and conceptually test its hypothesis before development. It must be stressed, however, that sometimes field and geological information captured are redundant and fuzzy.
mainly due to lack of experience of field personnel or instrumental error thereby producing a myriad of inherent inefficiencies in output, particularly paper maps and map-related tabular data (Yakubu, 2014). This, however, introduces error into the process and therefore the allocation decision-making process under the varying levels of trade-off may appear daunting due to the existence of potential multiple objectives with error involved.

Spatial Decision Support Systems (SDSS) help in efficient decision making by taking existing spatial data and a variety of mathematical models to make projections into the future in order to aid in robust project planning. Rhoma et al. (2011), and Rafiee et al. (2011) applied SDSS utilizing mathematical programming of linear mixed integer and spatial multi-criteria analysis approaches respectively to resolve problems of solid waste management infrastructure under environmental and geographical uncertainty.

The ArcGIS spatial analysis tool uses a mathematical model and statistical analysis for decision making employing algebra operators and functions within the geoprocessing framework, through ModelBuilder. This technique allows analysts, mine planners, and decision makers to evaluate and test the hypothesis to make an informed decision prior to implementation.

3.9 Proximity Analysis

Planning and implementing a processing facility for ASM in an environment where miners have less understanding of the negative effects of their activities on the environment and its surrounding adjacent communities could be a daunting effort considering the amount of capital investment in its set up. It is therefore necessary to evaluate an intervention to any breach that might cause a project to fail through a spatial proximity technique process. Proximity analysis provides an accurate description of an activity in distance within an area of influence and identifies the effects on its surroundings or entities for an intervention or mitigation.

Bilintoh & Stemn (2015), Rafiee, et al. (2011), and Ghribi (n.d) applied proximity analysis as an analytical technique to determine the relationship between a selected point of interest and its neighbors for
effective modeling. This provides a measure of ‘nearness or farness’ of an interested entity using distance or some relative measure of distance such as travel time. Development of realistic economic objectives for a potential siting of a processing facility is an important factor, necessary to locate and establish a facility, incorporating constrains as well as meeting the needs of the stakeholder involved, in this case the ASM.

Integrating a spatial decision tool by providing the baseline of measure for an intervention in an event of an uncertainty such as environmental or geographical breach would remediate the consequences of its negative effect on a project. Proximity analysis is usually conducted to evaluate the influence of objects with respect to other surrounding objects through buffering techniques. Buffering is a common form of proximity analysis.

### 3.9.1 Buffer Analysis

Buffering is a spatial analytical function for creating new polygons that are geographically related to nodes, chains, or existing polygons (Wolf & Brinker, 1994). In buffering, zones of influence are drawn around features of influence represented by points, lines, polygons and the extent of the zone (effects) is determined by the distance or time the user or analyst provides.

This zone of influence can be used to either include or exclude objects that fall within it, to generate new data with information. This includes generation of pollution zones, environmental protection zones and governmental protection zones including no-go areas to aid in analysis. Buffering analysis is a function of a query tool, which simply delineates features from or to an analysis through a simple combination of factors and conditions pertaining to a structure or an area under investigation. Mahamid & Thawab (2010) utilized a buffer analysis technique to create a vulnerability map around sensitive areas to site an appropriate landfill in Palestine. In this work, representation of each identified ASM site on the map as a point with coded information indicates the extent of operations within the area of study.

Having established this, constraints, such as sensitive areas in LSM, state lands and forest reserves in the form of line buffers and polygons as well as adjacency analysis in close proximity within a specific
radius to the ASM site and the proposed processing facility, were delineated. Delineation factors applied to this work established the link between forbidden boundaries beyond which, under no circumstances, should a facility be located.

GIS provides the tools to construct buffer zones within the sensitive areas identified within a specific distance of a designated target of the processing facility and therefore makes it quick in acquiring pertinent information to support management and decision-making.

3.10 Multi-Criteria Decision Analysis (MCDA)

Identification of land-use and sites that meet particular criteria is one of the main geospatial analytical applications of GIS (Jones, 1997). It is important to utilize multiple decisions in order to meet the required objectives of a project. The use of Multi-Criteria Decision Analysis (MCDA) methodologies in site selection is good practice in uncertainty classifications such as ASM. According to Neste & Karjalainen (2013) GIS and spatial multi-criteria evaluation can be effective ways to evaluate alternatives. Thus, the integration of GIS–MCDA has the objective of favoring decision-makers, providing them with ways to evaluate several alternatives, based on multiple, conflictive criteria.

MCDA is a technique and process for structuring decision problems, and designing, evaluating and prioritizing alternative decisions (Estoque, 2011). According to Malczewski (1999) decision analysis is a set of systematic procedures for analyzing complex decision problems. These procedures include dividing the decision problems into smaller more understandable parts; analyzing each part; and integrating the parts in a logical manner to produce a meaningful solution. Malczewski (1999) classified decision analysis as a goal preference-structure which is dependent on individuals or groups of decision-makers. The structure of the MCDA in the context of visualizing, analyzing and providing alternative to problems makes it an important component of a decision support system (Roudgarmi et al., 2008).

It must be mentioned that factors under consideration for the ASM processing facility exhibit inherent uncertainties and complexities which requires a better understanding of decision analysis. Eastman
(1993) classified decision under uncertainty into fuzzy and probabilistic decision-making. The probabilistic decisions are handled by probability theory and statistics and the outcome of a stochastic event is either true or false. However, if the situation is ambiguous, the problem is structured as the degree of how much an event belongs to a class. This type of problems is handled by fuzzy set theory (Zimmermann, 1985).

Zeinhom et al. (2009) used an integration of GIS and Multi-Criteria Decision Making (MCDM) to locate a landfill site in Mansoura City, Egypt. Suleman (2016) utilized Multi-Criteria Decision Analysis to select suitable sites for mine waste dumps. The steps involved in the workflow of Multi-Criteria Decision Analysis (MCDA) are briefly described in Subsection 3.10.1.1 with Figure 5 showing the flow chart of the process.

The criteria selected for suitability of sites require effective simulation for decision analysis. There are quite a number of mathematical approaches and techniques, such as Integer Programming, Bayesian statistics, Rule-based systems and Linear Programming (LP), for finding optimum solutions for several factors to achieve a single objective (Jones, 1997). Bonham-Carter (1994) applied fuzzy logic and Bayesian statistics to select the best location for landfills and rank mineral potential areas.

For instance, the LP technique has played a very sensitive role in resolving multiple objective problems such as in operations research and optimization of land-use including economic, social, and environmental aspects as well as mining load and haul activities. Geographical problems such as land-usage as described by Killen (1979) demonstrated the benefit of LP applications in land optimization. Wright et al. (1983), and Chuvieco (1993) described the use of LP for allocating land-use in an optimal manner. This approach is, however, complicated as Jones (1997) explained and addressed the equal capability of the MCE in accounting for multiple objectives and constraints with flexibility and versatility.
3.10.1 Multi-Criteria Evaluation

A multi-criteria evaluation model for suitability assessment of sites requires effective simulation by building a topology. This would help enhance decision-making by combining a set of criteria to achieve a single composite for a specific objective. One approach is provided by Carver (1991) to demonstrate a system approach to site selection by incorporating multi-criteria evaluation (MCE) within GIS to help decision-makers distinguish between options for effective selection. This decision is dependent on factors with respective levels of importance according to their influence to create an appropriate model.

For the purpose of flexibility and the degree of uncertainty of the selected factors, the (MCE) was employed in the ASM processing site selection. It is, therefore, essential to consider an appropriate technique when dealing with a project of multiple objectives as this has a potential influence on project success or failure given the sensitivity of the geographical characteristics within the selected area. The MCE, by incorporating spatial analysis techniques within the GIS environment, will effectively aid in the site selection process for the suitability map of the facility.

It is therefore important to approach a multifaceted phenomenon such as ASM heuristically with the MCE technique to help in site selectivity for a centralized processing facility and proper data management. Ghribi (n.d) selected multifaceted geographical characteristics to produce a single objective suitability map by the MCE and the Multiple Objective Land Allocation (MOLA). The MOLA model by IDRISI Eastman (2003) produced alternative final resource allocations which can be modified and adjusted should there be future alteration. It is worth noting that MOLA and MCE have the same principle of aiming at enhancing decision making among multiple factors for a specific single objective.
Rafiee, et al. (2011) applied spatial MCE and analysis to site a transfer station for waste disposal. Though waste disposal is not necessarily of interest to the study, it correlated to a concept that was of interest to this work. As an example, the authors utilized the MCE to optimize and develop land suitability for solid waste transfer stations. GIS-based MCDA and particularly MCE has a great potential to support interaction and dialogue between stakeholders for complex scenarios. However, the big question is how to do weight elicitation in an understandable and theoretically sound way with people who are not familiar with MCDA (Neste & Karjalainen, 2013). The nature of being “participatory” raises subjectivity particularly in choosing the criteria and defining the weights of each factor (Estoque, 2011).

![Figure 5: Framework for Spatial Multi-criteria Decision Analysis (Malczewski, 1999).](image)

### 3.10.1.1 Steps for Multi-criteria Decision Analysis (MCDA)

The steps for effectively implementing a Multi-criteria Decision Analysis are briefly explained as follows:
3.10.1.1 Problem Definition

A decision problem is the difference between the desired and existing state of the real world (Suleman, 2016). Problem definition is one of the most difficult aspects of the modeling process as the key components to overall objective must be identified (ESRI, 2014). It is a gap that may be complimentary or competitive which needs to be recognized by a decision-maker. However, a clear definition of each component and how they interact must be established to identify what the problem is, after which a clear understanding needs to be developed to define when the problem is solved, or when the phenomenon is satisfied.

Any decision-making process begins with the recognition and the definition of the problem in which specific measures should be established to identify the success of the outcome from the model. This stage is in the intelligence phase of decision-making and it involves searching the decision environment for conditions, and obtaining, processing and examining the raw data to identify the problems. The GIS capabilities for storage, management, manipulation and analysis are used in this stage which provides major support (Malczewski, 1999).

3.10.1.1.2 Evaluation Criteria

This stage involves specifying a comprehensive set of objectives that reflects all concerns relevant to the decision problem and measures for achieving those objectives which are defined as attributes. These criteria are broken down into submodels for clarification, organization thoughts, and to more effectively solve the overlay decision problem. Because the evaluation criteria are related to geographical entities and the relationships between them, they can be represented in the form of maps which are referred to as attribute maps. GIS data handling and analyzing capabilities are used to generate inputs to spatial decision-making analysis (Malczewski, 1999).
3.10.1.1.3 Criterion Weights

A weight can be defined as a value assigned to an evaluation criterion which indicates its importance relative to other criteria under consideration. Certain factors may be more important to the overall goal than others, which implies factors must be evaluated based on their importance (ESRI, 2014).

Assigning weights of importance to evaluation criteria accounts for: (i) the changes in the range of variation for each evaluation criterion, and (ii) the different degrees of importance being attached to these ranges of variation (Kirkwood, 1997). Malczewski (1999) has extensively reviewed techniques in assigning weights including Ranking, Rating, Pairwise Comparison and Trade off Analysis Methods. These methods are explained in Chapter 4 of which the Pairwise Comparison will be adapted.

3.10.1.1.4 Decision Rules

The criterion map layers and weightings must be integrated to provide an overall assessment. This is accomplished by an appropriate decision rule or aggregation function (Suleman, 2016). Since a decision rule provides an ordering of all alternatives according to their performance with respect to the set of evaluation criteria, the decision problem depends on the selection of best outcome. The Analytical Hierarchy Process decision rule is widely used.

3.10.1.1.5 Sensitivity Analysis

Sensitivity analysis aims to identify the effects of changes in the inputs which are geographical data and the decision maker’s preferences on the outputs, in other words, on the ranking of alternatives. If the changes do not significantly affect the outputs, then the ranking is assumed as robust and satisfactory. If the result is unsatisfactory, it should be returned to the problem formulation step (Malczewski, 1999; Belton & Stewart, 2002). In line with the objectives of this thesis, the set of constraints and criteria were identified, assessed and assigned weights once they have varying degrees of influence on the best site to be selected and used. The weights were assigned using pairwise comparison.
3.11 Suitability Analysis

GIS is a tool that supports in facilitating the search for optimum locations and suitable paths needed for the establishment of facilities in a cost effective and environmentally friendly manner as in the case of ASM. This technique employs the combination of field survey and analysis as well as geospatial data to find sites that satisfy the criteria and constraints of land usage and terrain characteristics.

According to Jones (1997), suitability analysis through feature-based search and overlay processing had been performed in the past by overlaying thematically specific maps representing individual factors of interest such as elevation, slope and land subject to particular planning purposes. This technique, by far, involved a lot of time and may be subjected to catastrophic errors through human errors, which obviously cannot perform the kinds of precise, rapid manipulations of data that computers are clearly good at. The computer program and system seemed much better at the kinds of rigorous and logical analysis demanded by the scientific method than by imperfect mortals (Goodchild, 2000).

Automation of suitability techniques through the application of GIS easily permits the analysis of both vector and raster data models as discussed in Chapter 3.3, as well as overlay analysis. The principle guided by this operation is the map algebra tool, which uses math-like expressions containing operators and functions within the geoprocessing functionality to discriminate the target and constraint features for consideration. This will be used to compute suitable locations, taking into account the selected criteria needed for the establishment of an economic processing facility.

The principle of Boolean and logical operations within the spatial analysis tool were considered for the purpose of this project, as well as weights to rank the relative importance of factors considered and finally to make strategic decisions to select a potential location for the centralized processing centre. The benefit of this functionality is exhibited in Chapter 4.
Chapter 4

Material and Methods

4.1 Study Area

4.1.1 Size and Location

The study area lies in three administrative districts in the Western Region of Ghana. These three districts are 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. It occupies a land area of about 2,430 km². Figure 6 is a map that shows the location of the study area.

Figure 6: Map of Study Area
It must be noted, however, that to ascertain the sites of mining activities within the WAMPA was impossible due to the geographically-scattered nature of these activities within the study area. Unlike Large-scale mines, there exists no published physical information available on ASM, and therefore, any accurate map of the ASM in the study area is unavailable. In consequence of the fact that little actual ASM site data is available, it could be considered that ASM activity is uniformly distributed across the WAPMA for the purpose of the model evaluation.

However, a centralized processing facility should serve most of the intensive ASM sites in this area to be effective. For this purpose, a hypothetical data collection approach was utilized to illustrate this concept.

4.2 Materials

In this research, several materials such as datasets, software and equipment were used to execute it. These materials are described in detail in the following subsections.

4.2.1 Type and Source of Data Used

Several types of datasets at varying scale and from different sources were used for this research. These datasets comprised both vector and raster data types. A spatial resolution of 30m×30m was set for all the raster datasets in the analysis. This was imported from a vector data format. The map of various sources and scales acquired were imported into the GIS environment and geo-referenced. Table 2 summarizes the datasets together with their sources and scales that were acquired and used for this research.
Table 2: Dataset Used for the Research

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Scale/ Resolution</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Scale/Artisanal Mining Site</td>
<td>1:250000</td>
<td>Goldfields Ghana Limited, Google Earth</td>
</tr>
<tr>
<td>Road Network</td>
<td>1:400000</td>
<td>Survey and Mapping Division, Land Commission</td>
</tr>
<tr>
<td>Water Bodies (Streams/Rivers)</td>
<td>1:400000</td>
<td>Survey and Mapping Division, Land Commission</td>
</tr>
<tr>
<td>Railway Lines</td>
<td>1:400000</td>
<td>Survey and Mapping Division, Land Commission</td>
</tr>
<tr>
<td>Soil Types</td>
<td>1:400000</td>
<td>Survey and Mapping Division, Land Commission</td>
</tr>
<tr>
<td>Tectonics</td>
<td>1:400000</td>
<td>Ghana Geological Survey</td>
</tr>
<tr>
<td>Forest Reserve</td>
<td>1:400000</td>
<td>Forestry Commission</td>
</tr>
<tr>
<td>Large Scale Mines</td>
<td>1:250000</td>
<td>Goldfields Ghana Limited, Google Earth</td>
</tr>
<tr>
<td>State Lands</td>
<td>1:400000</td>
<td>Land Commission</td>
</tr>
<tr>
<td>Urban Areas/Settlement</td>
<td>1:400000</td>
<td>Survey and Mapping Division, Land Commission</td>
</tr>
<tr>
<td>Slopes-Digital Elevation Model</td>
<td>30m×30m</td>
<td>US Geological Survey</td>
</tr>
</tbody>
</table>

4.2.1 Software Used

In this research, ArcGIS 10.3 was used to carry out all spatial analysis and map production. Various tools in the Spatial Analyst Toolbox of ArcGIS 10.3 utilizing ModelBuilder visual programming were used for siting the potential centralized processing site. All the spatial datasets used both vector and raster data types and were projected onto a common WGS 1984 UTM Zone 30 N coordinate system.

4.2.2 Equipment Used

The Garmin GPS 60C (handheld Global Positioning System unit) was used to collect geographic data during the ground truth survey. This was done to validate the other geographic datasets that were
obtained from other secondary data sources, which is required to validate attributes, locations at points of interest and to verify the given spatial reference datum.

4.3 Method Used for Siting the Central Processing Site

In this research, the weighted overlay spatial analysis method was adopted for the siting of the centralized processing site. This method was implemented using three main methods of deriving datasets, standardizing datasets and finally weighing and overlaying datasets to determine the suitable area for the central processing facility. However, before these three methods were implemented, there was a need to determine the criteria as well as the constraints that would be used for the study. The methodology used is explained in detail in the following subsections.

4.3.1 Data Capture and Validation

Data quality can be assessed in terms of four characteristics: accuracy, completeness, consistency and resolution (Haining, 2009). This implies that data acquisition and authentication of acquired information requires the application of technical skills and specialized knowledge in the field of study for effective analysis as noted by Wolf & Brinker (1994). Geographic data was collected during ground truth surveys of some selected areas of study, to validate the secondary datasets that were available and collected for the project analysis. What is of interest here, however, is how measurement problems might introduce certain inaccuracies into the data (Guptill & Morrison, 1995).

Prior to the ground truth survey, about 50 features consisting of road intersections, survey controls and some permanent monuments were identified and marked on a base map. The positions of these 50 features were subsequently surveyed. The positions of these features were placed onto a base map to show the study area boundary, roads, railroads, and rivers. The result of the validation process was a stack of consistent data or map files whose geographic positions have been rectified, verified and validated in Chapter 5.1.1.
The secondary datasets that were obtained were defined using different coordinates systems, therefore there was a need to rectify and transform all systems to a common UTM WGS Zone 30N coordinate system and plot them. As noted by Maling (1991) there is an effect of inherent inaccuracies from secondary derived dataset sources. Conversely, the spherical assumption of the earth makes data quite often appropriate which is not always the case due to the degree of distortion introduced during the conversion.

During the rectification, positions of 12 features were identified in both local and UTM coordinate systems. The positions of these features were plotted in both coordinate systems, and then the spatial adjustment tool (the Transformation – Affine Adjustment Method was used) in ArcGIS 10.3 was used to rectify and transform all the datasets from their respectively coordinate systems onto the UTM WGS Zone 30N coordinate system.

4.3.2 Selection of Criteria

The determination of criteria in any site selection project is essential due to the fact that the reliability and trustworthiness of the site to a large extent is dependent on these factors. These are sets of guidelines or requirements used as a basis for decisions and therefore require in depth technical skills and knowledge of the site characteristics.

As pointed out by Rafiee, et al. (2011), the selectivity of sites is dependent on several criteria that require sophisticated spatial analysis. Various site criteria selection factors published by USEPA (2004) are mainly grouped into three criteria namely exclusionary, technical and community-specific which ideally form the basis of reference for decision makers for planning, site selection, and design projects. In whatever way, this approach requires specialized knowledge of the terrain and its characteristics for technically robust output. Rafiee, et al. (2011) selected criteria such as soils, geology, slope, residential areas, waste generation centers, streams, faults, and highways.

Bilintoh & Stemm (2015) selected four criteria, namely properties, water bodies, roads and slopes to evaluate the suitability of land for a landfill site. Nilchiyan (2002) selected sites for waste transfer stations
in Tehran City using several criteria, including accessibility, waste generation centers, disposal site, land use, geology, topography, wind direction, aesthetic characteristics, health centers, land area, and costs. In this research, the selected criteria were determined after an in-depth literature review given carefully consideration to all details and aspects of the research. Although the authors work was on waste management it correlates with ASM with the aim of location optimization.

Apart from these criteria, constraints such as 500m offsets from reserve forest and protected areas, 300m offsets from large-scale companies and 100m offsets from state lands were also used in the suitability evaluation process (Bilintoh & Stemn, 2015; Rafiee, et al., 2011; USEPA, 2004; Nilchiyan, 2002).

The criteria were not only selected based on literature review but also after a thorough discussion with experts and practitioners (Dapaah, 2016; Yakubu, 2014; Stemn, 2015). Thus, the criteria were selected based on a combined approach of expert opinion and literature review. During this stage several criteria were determined, however, due to lack of data, only a few of those criteria were selected.

The first criterion that was considered was the location of the artisanal mining sites relative to the proposed processing site. It is preferable to locate the processing site near these mining sites, as they will be the main input sources for the production. It is also economic to locate the processing site near the source of the mineral extraction product. This will reduce transportation costs as well as the risk of low productivity.

Since both the ore material and the processed ore will be transported, there is a need to consider transportation facilities for bringing in raw materials and distributing finished products. This is also required for the transportation of the workforce. In this particular research, road and railroad transport were considered. Therefore, the site should be accessible from the source of ore feed to the proposed processing facility. However, in an event where a transportation facility is non-existing, then there will be the need to construct one to connect the processing site to the source of ore feed. The processing plant should not be sited near areas subject to instability, except where the instability is of a shallow or surface nature that can be overcome, in perpetuity, by engineering works (Stemn, 2015).
The pollution of water bodies by wastewater produced by the processing facility is one of the principal concerns in relation to the processing facility location. Nonetheless, if a 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.

The presence of existing or potential future land use activity should be investigated to identify sensitive areas and other protected areas that are likely to be adversely impacted by the processing facility. There is the need to ensure the protection of amenities associated with residential, commercial or community zones from nuisances associated with noise, dust, odour and visual effects. Therefore, nearness to major settlements was also considered as a criterion. Additionally, careful consideration needs to be given to the landforms in the vicinity of the processing site, thus the topography of any potential site was considered. To reduce constructional cost, the site should preferably be located on relatively flat terrain.

Finally, the criteria that were selected were grouped into three categories of suitability or desirability, namely unsuitable, suitable and most suitable. Tables 3 and 4 show the suitability grouping of the selected criteria and the constraints used.

4.3.2.1 Criteria Grouping Rationale

Criteria grouping is an integral part of a suitability modeling process. Ideally, criteria grouping must sensibly meet the objective of selecting the suitable sites for clarification and for simplification of information in a raster model (Chen, 2016). Thus, all aspects of criteria grouping of the modeling process must contribute to this overall objective of an economic processing facility without compromising health and safety, as well as risk, to any nearby community and the environment. It is important to balance the key potential project cost drivers in criteria grouping modeling, thus keeping construction costs down and minimizing risks to the environment and community safety.

In this work, all criteria grouping and constraints were derived using literature review and recommendations of practitioners in the fields of environmental, surveying and mining engineering to
illustrate the grouping principle. It must be mentioned that no previous background research in these areas has been documented for Ghana thus, values used are based largely on published literature. Jones (1997) illustrated criteria groupings in various degrees to establish layer-based GIS for suitability analysis.

Intuitively, the facility location should be primarily composed of land with shallow slope, because steep terrain will increase the cost of construction. Therefore identifying locations with a wide variety of favorable terrain needs to be considered. According to Makhdoom (1993), areas with slopes measuring between 0 to 6 degrees are considered suitable for siting a facility, and with slopes of 0 to 5 degrees being generally ideal for site selection purposes (ESRI, 2014). In this work, sites with slopes less than 2 degrees were selected as being most suitable to minimize the cost for building a facility.

Choosing the site for a facility development means assessing the proximity of the location of the ore feed (ASM) to the processing facility. Distance between the source and destination of the ore for processing must be short as it is an integral cost factor for a project. Thus, the longer the path, the higher the construction costs, hence the higher the operating cost. For this purpose a minimum distance with a proximity of 1000m from the source of ore feed (ASM sites) to the facility was selected as being the most suitable. According to Dapaah (2016) locations between 500m to 1000m from accessible road networks are suitable for siting an economic mine waste dump. Locations beyond 5000m are unsuitable, although applicable within LSM, its could be utilized in the ASM. Railway paths were also grouped and rated the same fashion as the road networks.

The processing facility should be located at distance far away from communities or settlements, as there are risks of water and air pollution. To these groups construction within an acceptable distance must be considered to possibly avoid conflict with a community which could potentially maximize costly delays. For environmental, health and societal reasons, siting distances close to a potential facility centre should be avoided, thus distance away from a community less than 800m would be unsuitable, even if it represents an economical site. Distances further away from the community, greater than 5000m, would be most suitable.
The data on tectonic zones were grouped to ascertain the displacement of potential movement of the terrain stability in the model process. Data values that were selected as favourable are those distances far away from potential tectonic zones. According to Rafiee, et al. (2011) areas within 1,000 m of fault zones should be considered as unsuitable for siting of a waste transfer facility, while locations located beyond 5,000 m from fault zones should be considered as most suitable. Areas between 1,000 to 5,000 m from faults zones are therefore deemed moderately suitable for siting a facility. In this work, distance less than 1500m within a potential rock instability zone to the proposed facility were considered as unsuitable. Thus, distances of 3000m far away from potential tectonic zones were considered as most suitable.

Water is an important part of a processing facility hence release of effluent water must be included in a suitability process to ascertain the best location of a facility. It also represents an integral part to the success of ore throughput of a processing plant. However, mismanagement of wastewater into the environment could be detrimental to a project. The cost of remediation as well as potential project shut down requirements could present daunting problems to facility success. Water bodies that lies within 500m of a processing facility have a potential risk of being polluted and, therefore, must be considered unsuitable. Thus, on a scale of profitability, it is practical to incur a minimum cost to be in a continuous operation rather than to risk operation shut downs due to potential pollution by the processing activities. For this reason water bodies more than 1000m distant away from a facility were considered most suitable.

It must be noted, however, that the capability to group ranges of values for criteria becomes more critical when reclassifying continuous data (ESRI, 2014). For example, reclassifying a continuous surface such as ASM sites location into common ranges of scale values. Therefore, grouping a range of values requires the knowledge of lower and upper bounds of existing values on the input raster and an alternative value to assign to the range of values.

All values that fall within a specified range of values will receive the alternative value assigned to that range. That is, if two ranges are specified, such as 1000 to 3000m equals to 2 and 3000 to 10000m
equals to 1, the value of 3000m will usually be assigned a value of 2 and 3001.53 will be assigned a value of 1 as output values. Contributing factors and constraint data for the work were generated in the form of vectors and rasters, with cells containing the target features such as lines, polygons and points which, in this case, are assigned to roads, rails, waterbodies, etc. Table 3 shows the criteria used with their respective grouping.

**Table 3: Criteria Used with their Respective Groupings**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Unsuitable (m)</th>
<th>Less Suitable (m)</th>
<th>Suitable (m)</th>
<th>Most Suitable (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nearness to ASM Sites</td>
<td>&gt;10000</td>
<td>3000-10000</td>
<td>1000-3000</td>
<td>&lt; 1000</td>
</tr>
<tr>
<td>Nearness to Roads</td>
<td>&gt; 5000</td>
<td>1000-5000</td>
<td>500-1000</td>
<td>&lt; 500</td>
</tr>
<tr>
<td>Nearness to Railways</td>
<td>&gt; 5000</td>
<td>1000-5000</td>
<td>500-1000</td>
<td>&lt; 500</td>
</tr>
<tr>
<td>Distance to Settlement</td>
<td>&lt; 800</td>
<td>800-1000</td>
<td>1000-5000</td>
<td>&gt;5000</td>
</tr>
<tr>
<td>Distance from Tectonic Zones</td>
<td>&lt; 750</td>
<td>750-1500</td>
<td>1500-5000</td>
<td>&gt;5000</td>
</tr>
<tr>
<td>Distance from Water bodies</td>
<td>&lt; 250</td>
<td>250-500</td>
<td>500-1000</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>Slopes</td>
<td>&gt;15°</td>
<td>6° - 15°</td>
<td>2° - 6°</td>
<td>&lt; 2°</td>
</tr>
</tbody>
</table>

Constraint criteria (Table 4) in this work indicate factors or areas where certain kinds of development are forbidden by local and governmental laws. In this case, offset distances from forests, large-scale mines and state lands were considered and analyzed as constraints. It is important however, to clearly delineate such areas and remove them from participating in the analysis through buffer analytical techniques discussed in the previous chapter. The factor criteria are those factors that enable the selection of the required site. Apart from these criteria, others, such as energy availability, gold mineralization, climate and
fire and flood protection, were considered but could not be assessed because of non-availability of data as earlier mentioned.

**Table 4: Constraints Used**

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Away from (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest Reserves</td>
<td>500</td>
</tr>
<tr>
<td>Large-scale Mines</td>
<td>300</td>
</tr>
<tr>
<td>State Lands</td>
<td>100</td>
</tr>
</tbody>
</table>

4.3.3 Deriving Datasets

To implement this site selection project in a GIS environment, a model was created within the Arc toolbox. The creation of the model, ModelBuilder, which is a visual programming language for building geoprocessing workflows, was necessary as it allows easy updates, changes and manipulations. Various properties were defined for this model such as the current and the scratch workspace, the processing extent of all processes, the cell size of all rasters and a boundary to mask the results of all processes.

Essentially, derivation of the datasets from the raw datasets was acquired after the creation of the model shown in Figure 7. Two main datasets were created, namely slope and distance to assist in the proximity analysis.

There was a need to find areas where the terrain was relatively flat to potentially establish the facility as the study area is characterized mainly by undulating and hilly geography and therefore the topography (slope of the terrain) was factored and considered. Using the digital elevation model (DEM) as input, a slope dataset was derived using the slope angle as the measurement output. Apart from the DEM (slope) data, distances were created for the datasets shown in Figure 7. This was necessary for the fact that the new site should be of a certain distance from those datasets.
In deriving these datasets, the Euclidean distance tool, which is a straight line distance, was applied on each of the selected datasets. Thus, distances were calculated from the location of the artisanal mining sites, roads, railroads, settlements, waterbodies and tectonic zones to create a map. During the process of deriving the various datasets, all the input data were defined as model parameters. Doing this assists other users of the model to easily distinguish input datasets (which can be changed) from output dataset.

**Figure 7:** Deriving Dataset Model

### 4.3.4 Best Path Selection

#### 4.3.4.1 Straight Line Distance

Project planning, such as for mining, requires effective optimization strategies to achieve set targets for corporate and investment decisions goals. It is anticipated that, for planned production targets to be achieved, close proximity of available resources to their final destination (processed or to the market) plays a significant role (Thorley, 2015). Emphasis in achieving this must be based on how well characterized the
study area is, in terms of analytical or empirical study performed on the terrain characteristics. This is necessary to prove the project viability without compromising safety, the environment and community health.

Essentially, the closer the distance that a resource to be processed is to the market, the less operating cost and intrinsically the more return on an investment will occur. The Euclidian distance or simply straight line distance functions in ArcGIS 10.3 measures the shortest distance between every cell until the closest source point is determined. This implies that determination of proximity will be a relatively straightforward approach taking into account that this incorporates GIS program functionality.

For instance, if the coordinate of a start-end point of a line is known, then a simple Pythagoras theorem can be applied to find the length of the line. This theorem is the algorithm underlying the best path analysis tool incorporated within the spatial analysis tool. It is worth noting that all acquired data needed for the analysis must be in the projected coordinate system to avoid map distortions as well as to ensure reliability and technical robustness of spatial data measurement and plans as well. In this way, determination of allocation, distance, and direction towards the closest source point is easily computed and adjusted if need be.

4.3.4.2 Cost Distance

As uncertain as mining projects are, mainly due to technical constraints such as terrain characteristics and the environment, it requires technical and complex approaches to understand the nature and the extent of a project in order not to incur losses during and after implementation. AM does not present straight line projects mainly due to inherent complexities with various project liability drivers, such as communities, geographic barriers and the environment. These cannot be easily measured economically using the straight line distance algorithm, but by weighting methods through the cost-distance approach. These barriers and
frictional effects involved in the distance calculation are referred to as cost-distance functions (Eastman, 2001).

Technical measuring skills of terrain characteristics would be required in an event where straight line distance measurement is impossible due to barrier effects. For instance, the distance to a destination point could be shorter by climbing a mountain, but movement between could be made faster by going around the mountain. It is important to utilize the cost-distance function specifically to the cost allocation factor to identify the source cell for which a minimum cost will be determined based on the accumulated cost of geographical displacement.

This function creates a map of the routes identifying the necessary route from any cell to the closest source point. It also can create a raster representing the distance and the direction, and can as well calculate the minimum cost or the shortest route from a source point to a destination point. The cost-distance evaluation function modifies the Euclidian distance by adding a variable (weight) associated with the displacement between any two given cells (ESRI, 2014). This technique of weight assignment is well examined and implemented in the work-study.

### 4.3.5 Reclassification and Standardization of Datasets

Deriving datasets, such as distance to ASM sites from a potential processing facility, is the first step when building a suitable model. Each of the cells in the study area now has a value for each input criteria. At this stage it was practically impossible to combine the derived datasets, hence the need for reclassification of each of the individual datasets. Different number systems cannot be directly combined effectively (ESRI, 2014). For instance, combining a cell value in which slope is 2° with a cell value in which distance to ASM sites is 1,000 m, to get a meaningful answer that can be compared to other locations, is impossible. However, standardizing them in a common measurement system that represents a relative weighting scale permits analysis to be completed freely between the datasets. Figure A-7.1 in Appendix A shows the suitability levels for each of the standardized criteria.
To combine datasets, there is a need to standardize or transform all the individual datasets into a common measurement scale such as 1 to 10. This common 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 or unsuitable areas. The application of fuzzy set membership function approaches by authors such as Ghribi (n.d), Eastman (2001) and Rafiee, et al. (2011) has been well documented and used in criteria standardization. However, a continuous scale map (function) which produces regular boundaries characterizes this approach (Bilintoh & Stemn, 2015).

For this particular study, all the datasets were reclassified into four classes: (0) for unsuitable areas, (1) for less suitable areas (2) for suitable areas and (3) for most suitable areas as shown in Table 3. The model for the reclassification process is shown in Figure 8. The values in the datasets that were derived using the previous method were all floating-point, continuous datasets, categorized into ranges and needed to be classified so that each range of values was assigned one discrete integer value such as 0, 1, 2 and 3 according to the measurement scale. This is because the inputs of the weighted overlay, which would be used in the next step, must contain discrete integer values.
4.3.6 Overlaying and Weighting Datasets

Seven criteria, as listed in Table 3, with varied importance, were used to determine the location of a processing facility in this research. The order of importance for these selected criteria was ranked to enable feasible and reliable selectivity of a site, to establish location optimization in order to reduce cost, and, to mitigate issues involving stakeholders. It was necessary, however, to ensure that each of the seven identified criteria for the purpose of the study, was evaluated on the basis of its relative significance for an effective (best) decision to be made.

It might reasonably be acknowledged and accepted that derivation of weights within the context of the decision-making objective poses a major challenge in multiple criteria analysis. 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 as a whole. The emphasis here is in identifying the appropriate criteria weight to be used on the basis of its significance, sensitivity and influence pertaining to the characteristics of each factor.
being considered for the proposed project. Essentially, a project like this involves understanding of the principles and techniques governing its established activity, which is based on theory, empirical research or common sense. Wang et al. (2011) used the ideas and principles of theoretical and empirical work to establish various degrees of land-use simulation in an integrated ecosystem.

However, relatively little information and understanding of the area of ASM requires an extra input to generally understand its mode of operation in order to select an appropriate criteria weight to properly discriminate selected factors. When compared with a developed and well established GIS application for a facility, such as public health care, progress in the field of ASM has been remarkably daunting and therefore derivation and selection of criteria weights must be treated in a manner which will establish and retain the integrity of the analysis. Criteria and weight identification can be done using the participatory approach by groups of experts from various disciplines (Hajehforooshnia et al., 2011).

The need for adequate consultation and team cooperation such as by decision-makers, experts with different technical skills, as in engineering and scientific backgrounds, as well as by the local communities, including ASM, are required. In addition, considerations of reliable and successful engineering work, and empirical literature review on previous successful work, is needed before selection could potentially assist in tackling these challenges of weight determinations.

It is important to note that, since some of the criteria could be contrasting, a daunting theory could probably be presented that the best option would be the one which optimizes each single criterion, rather than the one which achieves the most suitable trade-off among the different criteria (Mocenni, n.d). Therefore, multiple criteria simulation is required to achieve a single objective to help in decision-making (Jones, 1997).

Many operations researchers and analysts utilize decision analysis to help decide among alternative factors to aid in maximizing output. However, issues arise when priorities or methodologies are somehow being misplaced or misappropriated (selection) in order of ranks (weights). Mathematical approaches such as functions, logic and matrices are well-established procedures for assigning weights to a set of factors in order of importance. However, improper use of such approaches often results in maximizing single
evaluations, and in effect, leads to a trajectory of subjective evaluation rather than the objective function for suitability.

### 4.3.7 Weight Determination Approaches

Analytical strategies and processes are required in the selection of weights to avoid subjective approaches by a user task on a project feasibility study in terms of spatial reasoning. A strategic approach or method is intrinsically necessary to guide in the selection of weights to minimize risk due to subjectivity opinion analysis and to maximize the potential upside of the intended project as a trade-off among stakeholders. Using equal weights on selected criteria analysis and evaluating them (weights) will result in a single indiscriminate phenomenon (Yakubu, 2014), while stakeholders in projects have diverse unique preferences and interests in terms of resource allocation. Weights are essentially employed to criteria to aid in discrimination to rank required levels of importance to each criterion, due to inequality of (criteria) significance (Bilintoh & Stemm, 2015; Jones, 1997). With the myriad complexities involved in ASM operations, multi-weight selection could be the most important approach for the identified factors to establish location optimization.

It must be noted that finding the best method of allocating weight to multiple criteria itself is a generic problem of suitability. Methods such as binary logic, rough set and functional set operators for reasoning are identified approaches for defining weights, however these methods or functions are associated with deviations of classical sets, making crisp or stochastic approaches unpredictable. Again, the described characteristics of these methods have uncertainty in modelling and the treatment of qualitative magnitudes and distributions are not described by these concepts. As well the effects pose interpretation problems (Albertos & Sala, 1998).

An attempt to find an appropriate weighting method often results in a generic algorithm search which in some cases results in uncertainty expectation due to assumptions that most concepts and applications exhibit. There has been some application of developing methods for determining and allocating criteria
weights such as the ranking method, the rating method, pairwise comparison and the trade-off analysis method (Malczewski, 1999). These methods are associated with advantages and disadvantages which need to be well analyzed for consideration.

4.3.7.1 Ranking Methods

This is the simplest method for evaluating the importance of weights which requires that every criterion under consideration is ranked in the order of a decision maker’s preferences. Due to its simplicity, the method is very attractive. However, the larger the number of criteria used, the less appropriate is the method. Another disadvantage is lack of theoretical foundation.

4.3.7.2 Rating Methods

The method requires the decision maker to estimate weights on the basis of a predetermined scale. One of the simplest rating methods is the point allocation approach. It is based on allocating points ranging from 0 to 100, where 0 indicates that the criterion can be ignored, and 100 represents the situation where only one criterion needs to be considered. Another method is the ratio estimation procedure that is a modification of the point allocation method. A score of 100 is assigned to the most important criterion and proportionally smaller weights are given to criteria lower in the order. The score assigned for the least important attribute is used to calculate the ratios. The pitfall of this method, like the ranking method, is the lack of theoretical foundation and also the assigned weights might be difficult to justify (Saaty, 1980).

4.3.7.3 Pairwise Comparison Method

The method involves pairwise comparisons to create a ratio matrix. It takes pairwise comparisons as input and produces relative weights as output. The pairwise comparison method involves three steps:

- Development of a pairwise comparison matrix: The method uses a scale with values ranging from 1 to 9.
• Computation of the weights: The computation of weights involves three steps. The first step is the summation of the values in each column of the matrix. Then, each element in the matrix should be divided by its column total (the resulting matrix is referred to as the normalized pairwise comparison matrix). Then, computation of the average of the elements in each row of the normalized matrix should be made which includes dividing the sum of normalized scores for each row by the number of criteria. These averages provide an estimate of the relative weights of the criteria being compared (Saaty, 1980).

• Ranking the criteria options: The option ranking is accomplished by ordering the global score in decreasing order of importance.

4.3.7.4 Trade-off Analysis Method

In this method, the decision maker is required to compare two alternatives with respect to two criteria at a time and assess which alternative is preferred. Trade-offs define a unique set of weights that will allow all of the equally preferred alternatives in the trade-offs to get the same overall value. There is an assumption in this method that the trade-offs that the decision maker is willing to make between any two criteria do not depend on the levels of other criteria (Malczewski, 1999).

The weakness of this method is that the decision maker is presumed to obey the axioms and can make fine-grained indifference judgments. On the other hand, the method can be implemented within the spreadsheet environment (Kirkwood, 1997).

4.3.7.4.1 Justification of Appropriate Weight Method

The pairwise comparison method has been proved by literature and existing projects to produce reliable and consistent results since it provides an alternative for a check (Bilintoh & Stemn, 2015; Rafiee, et al., 2011; Teknomo, 2006).
Rao, et al. (1991) suggested that a logical process for the development of such weights is the procedure of pairwise comparisons developed by Saaty (1980). The pairwise comparison method was used to derive the relative importance of each criterion, as it is an effective method for determining order of importance.

This method has an added advantage of providing an organized structure for group discussions and helping the decision-making group focus on areas of agreement and disagreement when setting criterion weights (Saaty, 1980; Drobne & Lisec, 2009). In implementing this pairwise comparison, the methodology developed by Saaty (1980), which is applied in the context of the Analytical Hierarchy Process (AHP), was used. Wang & Chin (2009) have reviewed approaches such as various Least-Square Methods, the Fuzzy Programming Method (FPM), the gradient method (GEM) and the (AHP) for weight assignment. In the field of design, AHP is the one that is widely used in reducing bias in a decision-making process. This is described in detail in Subsection 4.3.9.

4.3.8 Assignment of Evaluated Criteria Weights

For the purpose of this work, decision analysis techniques by Kirkwood (1997), as described in Chapter 3.10.1.1.3 for multiple objective decisions, were adopted to understand and appreciate the effects of multiple objective evaluations on project output as well as the perspectives of involved stakeholders to decision making. The author applied two approaches for criteria evaluation to rank relative importance.

The first approach was to select the same numerical range, such as from 0 to 255, for each criterion (standardization), assign each criterion a score based on its relative importance (weight), and multiply each standardized criterion by the value assigned to its relative weight to calculate its suitability index. Rafiee, et al. (2011), and Bilintoh & Stemn (2015) applied this technique to assign and rank criteria to select suitable sites for waste management.
The second approach is to use a variable numeric range for the various criteria depending upon the relative importance of each criterion. The second approach was critically analyzed and utilized in the context of AHP pairwise comparison in this research.

4.3.9 The Analytic Hierarchy Process (AHP)

The AHP, introduced by Saaty (1980), is an effective tool for dealing with complex decision-making, and may aid the decision maker to set priorities and make best decisions (Mocenni, n.d; Jones, 1997; Rafiee, et al., 2011; Teknomo, 2006). By reducing complex decisions to a series of pairwise comparisons, and then synthesizing the results, the AHP helps to capture both subjective and objective aspects of a decision. Again, both benefits and risks can be weighed, assigning a number value to each criterion (benefit or risk factor under consideration), with more important benefits receiving a higher number on the scale to determine which projects have the highest overall value, or the most valued benefits and least risks.

According to the Saaty (1980) the AHP is an appropriate approach for the determination of relative importance of each factor with each other factor, as it accounts for weighted decision criteria which are useful for complex decisions involving multivariate selection criteria. The approach uses a ratio matrix known as the Eigenvector Method to compare one criterion with another. Additionally, it uses a numerical scale with values ranging from 1 to 9, where 1 means the that two factors are equally important and 9 means that the one factor is absolutely more important than the other as shown in Table 5. AHP is the most widely used multi-criteria method. If a factor is less important than another then this is indicated by reciprocals of the 1 to 9 values (1/1 to 1/9).
Table 5: Relative Importance in Pairwise Comparison

<table>
<thead>
<tr>
<th>Criteria / (Value $a_{jk}$)</th>
<th>Degree of Importance / Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equally important (j and k)</td>
</tr>
<tr>
<td>2</td>
<td>Equal to moderately important</td>
</tr>
<tr>
<td>3</td>
<td>Moderately important (j is slightly more important than k)</td>
</tr>
<tr>
<td>5</td>
<td>Strongly important (j is more important than k)</td>
</tr>
<tr>
<td>6</td>
<td>Strongly to very strongly important</td>
</tr>
<tr>
<td>7</td>
<td>Very strongly important (j is strongly more important than k)</td>
</tr>
<tr>
<td>9</td>
<td>Extremely important (j is absolutely more important than k)</td>
</tr>
</tbody>
</table>

Source (Saaty, 1980, Mocenni, n.d)

4.3.10 Implementation of the AHP

The AHP can be implemented in three simple consecutive steps according to (Mocenni, n.d). These are:

- Computing the vector of criteria weights.
- Computing the matrix of options scores.
- Ranking the options.

From Table 5, seven (7) criteria that represent seven options (matrix) considered were evaluated as well as seven (7) numbers of options were evaluated. A useful technique for checking the reliability of the results will be also tested with the Random Consistency Index in Table 6.

4.3.10.1 Computing the Vector of Criteria Weights

In order to compute the weights for the different criteria, the AHP starts by creating a pairwise comparison matrix $A$. The matrix represents a real matrix ($m \times m$), where $m$ is the number of evaluation
criteria (factors) considered. In this work, seven (7) criteria were analyzed, and therefore, a \((7 \times 7)\) real matrix was evaluated as matrix \(A\). Each entry factor of the \((7 \times 7)\) matrix represents the degrees of importance of the criterion relative to other criteria. If factors of the matrix are \(> 1\), then the selected criterion is more important than the other criteria, while if a factor is \(< 1\), then the criterion is less important than the other criteria.

On the other hand, if two criteria have the same importance, then the entry factor is 1. The entries of the real matrix and its reciprocals satisfy the constraint if they are equal to 1. Noticeably, the value of the importance criterion is 1 among criteria. The relative importance between two criteria is measured according to a numerical scale from 1 to 9, as shown in Table 5, where it is assumed that the \(j\)th criterion is equal to or more important than the \(k\)th criterion. The phrases in the “Interpretation” column of Table 5 are only suggestive, and may be used to translate the decision maker’s qualitative evaluations of the relative importance between two criteria into numbers. It is also possible to assign intermediate values which do not correspond to a precise interpretation (Mocenni, n.d). The values in the \((7 \times 7)\) matrix are, by construction, pairwise consistent (see Appendix A-7.1.1). On the other hand, the ratings may, in general, show slight inconsistencies. However, these do not cause serious difficulties for the AHP.

Once the \((7 \times 7)\) matrix is built, it is possible to derive from the matrix the normalized pairwise comparison matrix by making equal to 1 the sum of the entries on each column. That is, each entry of the normalized matrix is computed from Mocenni (n.d) Equation (1):

\[
\bar{a}_{jk} = \frac{a_{jk}}{\sum_{l=1}^{m} a_{lk}}
\]

See Appendix A-7.1.2 for the normalized weight derivations.

Finally, the criteria weight vector \(w\) (a \(m\)-dimensional column vector) is built by averaging the entries on each row of the normalized matrix \(A_{\text{norm}}\). This is shown in Equation (2) and in Appendix A-7.1.3.
4.3.10.2 Computing the Matrix of Option Scores

The matrix of option scores is a row and column real \((n \times m)\) matrix \(S\), and in this work is a \((7\times7)\) matrix. Each criteria entry of the matrix represents the score of the option with respect to the criterion. In order to derive such scores, a pairwise comparison matrix is first built for each of the criteria similar to computing the vector criteria weights. Second, the AHP applies to each matrix the same two-step procedure described for the pairwise comparison \((7\times7)\) matrix, i.e. it divides each entry by the sum of the entries in the same column, and then it averages the entries on each row, thus obtaining the score vectors, \(s^{(j)}\) \(j=1,...,m\). The vector \(s^{(j)}\) contains the scores of the evaluated options with respect to the criterion. Finally, the score matrix \(S\) is obtained as shown by Equation (3):

\[
S = [s^{(1)} ... s^{(m)}]
\]  

(3)

4.3.10.3 Ranking the Options

Once the weight vector \(w\) and the score matrix \(S\) have been computed, the AHP obtains a vector \(\lambda\) of global scores by multiplying \(S\) and \(w\), as given by Equation (4):

\[
\lambda = S \cdot w
\]  

(4)

As the final step, the option ranking is accomplished by ordering the global scores in decreasing order (see Appendix A-7.1.4).

4.3.11 Consistency

The AHP incorporates a useful technique for checking the consistency of the decision maker’s evaluations, thus reducing the bias in the decision-making process. As noted by Mocenni (n.d), the
inconsistencies in comparing many pairwise matrices (algorithms) are mainly due to errors in the decision maker’s judgement and therefore there is a need to check the reliability of results. A robust technique developed by Saaty (1980) can complement inconsistencies by filtering and searching the capability biasness in a matrix of pairwise comparison between criteria to assist in evaluation of weight. This is known as the Consistency Ratio.

With Saaty’s method, the weights are derived by normalizing the eigenvector of the square reciprocal matrix of pairwise comparison between criteria. (Rafiee, et al., 2011). For a consistent reciprocal matrix, the largest Eigenvalue is equal to the size of comparison matrix, given by Equation (5):

\[ \lambda_{max} = \eta \]  

(5)

where \( \eta \) is the number of criteria (size) of the comparison matrix, and \( \lambda \) is the largest eigenvalue. A measure of consistency, known as the Consistency Index, is determined as a deviation or degree of consistency value using the formula of Equation (6):

\[ CI = \frac{\lambda_{max} - \eta}{\eta - 1} \]  

(6)

Knowing the deviation or consistency \( CI \) calls for using this index to compare with the appropriate index, known as the Random Index, \( RI \) from Table 6. This is randomly generated by a reciprocal matrix using a scale of the selected weights to get the random consistency index to test for appropriate weight reliability. Saaty (1980) further proposed that the Consistency Ratio, \( CR \), is the comparison between the Consistency Index and the Random Index, \( RI \), which is a measure that provides a departure from consistency (Equation 7) given as:

\[ CR = \frac{CI}{RI} \]  

(7)

If the value of the Consistency Ratio is smaller than or equal to 10%, the inconsistency is acceptable. However, if the Consistency Ratio is greater than 10%, the matrix or the subjective judgement needs to be revised or re-evaluated (Teknomo, 2006).
Pairwise comparisons between all contributing factors in columns and rows (of ASM, roads etc.) were completed in a matrix. Using this procedure, the weights for all the seven criteria determined are as shown in Table 7 with detailed calculations for these being shown in Appendix A-7.1. Following the calculation of the weight vector $w$ from Equations 1 and 2, the $CI$ was obtained from Equation 6 as computed in Equation 8. The random index from Table 6 (Equation 9) shows the number of criteria $\eta$ with their corresponding consistencies $RI$ under consideration. From Table 6, the seven (7) criteria correspond to a $RI$ of 1.32. Therefore, CR was computed and found to be 7.2% from Equation 7 and is shown in Equation (10) which is less than 10% as proposed by Saaty (1980), and Teknomo (2006) and, therefore, was found to be accepted.

Table 6: Random Consistency Index

<table>
<thead>
<tr>
<th>$\eta$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$RI$</td>
<td>0</td>
<td>0</td>
<td>0.58</td>
<td>0.9</td>
<td>1.12</td>
<td>1.24</td>
<td><strong>1.32</strong></td>
<td>1.41</td>
<td>1.45</td>
</tr>
</tbody>
</table>

Source (Teknomo, 2006)

\[
CI = \frac{7.57 - 7}{7 - 1} = 0.095 \quad (8)
\]

\[
RI = \eta = 7 = 1.32 \quad (9)
\]

Therefore,

\[
CR = \frac{0.095}{1.32} \quad (10)
\]

\[= 7.2\% \]
Table 7: Weight Determined and Assigned (CR = 0.072)

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Distance to ASM sites</th>
<th>Distance to Roads</th>
<th>Distance to Railroads</th>
<th>Distance from Settlements</th>
<th>Distance to Water bodies</th>
<th>Slopes</th>
<th>Distance from Fault Zones</th>
<th>AHP</th>
<th>Weights</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance to ASM sites</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>9</td>
<td>0.406</td>
<td>40.60%</td>
</tr>
<tr>
<td>Distance to Roads</td>
<td>1/2</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>7</td>
<td>8</td>
<td>0.251</td>
<td>25.10%</td>
</tr>
<tr>
<td>Distance to Railroads</td>
<td>1/3</td>
<td>1/3</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>0.129</td>
<td>12.90%</td>
</tr>
<tr>
<td>Distance to Settlements</td>
<td>1/5</td>
<td>1/4</td>
<td>1/2</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>6</td>
<td>0.085</td>
<td>8.50%</td>
</tr>
<tr>
<td>Distance to Waterbodies</td>
<td>1/6</td>
<td>1/5</td>
<td>1/4</td>
<td>1/3</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>0.055</td>
<td>5.50%</td>
</tr>
<tr>
<td>Slopes</td>
<td>1/7</td>
<td>1/7</td>
<td>1/5</td>
<td>1/5</td>
<td>1/2</td>
<td>1</td>
<td>3</td>
<td>0.043</td>
<td>4.30%</td>
</tr>
<tr>
<td>Distance to Fault zones</td>
<td>1/9</td>
<td>1/8</td>
<td>1/6</td>
<td>1/6</td>
<td>1/4</td>
<td>1/3</td>
<td>1</td>
<td>0.032</td>
<td>3.20%</td>
</tr>
</tbody>
</table>

It is important to note that the weighting criteria factors, such as distance to slopes and fault zones, accounted for about 8% of the overall rating. This resulted in negligible effect on the suitability analysis, hence the general weighting factor rating had no significant impact on the two selected criteria.

What is of interest in determining the criteria weights in this work is that four (4) different iterations of the pairwise matrix were performed to test appropriate weights for the criteria significance level (shown in Appendices A-7.2 through A-7.4). Consistency ratio levels in the order iteration from 1st to 4th of 0.082, 0.052, 0.073, 0.072 respectively were acquired to evaluate the criteria and hence to reduce bias in the process. It must be mentioned that all the weights derived during the iteration could be used in this work since they were all below 10%, hence, 0.72 was used in this analysis. A Pareto chart shown in Figure 9 shows weights derived for individual criteria in descending order. This was necessary to graphically summarize and display the relative importance of the differences between weights applied for effective communication among stakeholders involved.

From the AHP, the distance to ASM exhibited more weight followed by distance to roads as demonstrated from Table 7 and Figure 9, due to proximity and cost effectiveness to a potential processing centre, thus a high probability for economic gains was judged without compromising the community and the environment.
After the weights were determined, the individual weighted criteria were combined and overlaid in order to obtain a suitability map using the Weighted Overlay tool in ArcGIS 10.3. The suitability map was obtained from the suitability values of all the locations on the map. Layers such as slope, distance to ASM sites, distance to roads etc. were combined to create a single ranked map of potential areas to site the processing facility.

This was done to identify the desirable location areas that meet the goal of the model. In this combination approach, it is assumed that the more favorable the factors, the more desirable the location will be (ESRI, 2014). Thus, criteria that were selected were grouped into two main categories of unsuitable and suitable.

In doing this, two of the most common procedures for multi-criteria evaluation that were utilized are Weighted Linear Combination and Concordance-Discordance Analysis (Carver, 1991). Weighted Linear Combination (WLC) was adopted in this study due to the fact that (WLC) is widely used and can be easily executed in the GIS environment. A suitability score or index was determined by obtaining the summation of the product of the weight of each criterion with its standard suitability score according to Equation 11.
\[ SI = \sum w_i x_i \]  \hspace{1cm} (11)

where SI is the suitability index, \( w_i \) is the relative importance (weight) of each criterion \( i \) and \( x_i \) is the standardized score of each criterion \( i \).

Hence a suitability map with the constraints was derived from equation 12:

\[ S = (\sum w_i x_i) \cdot n \cdot C_i \]  \hspace{1cm} (12)

where \( C_i \) are the constraints and \( n \) is the product of constraint.

Suitability levels of the combined layers are compared and assign numeric values to classes within each map layer. The grouped criteria were assigned a suitability score for each of the factors as shown in Table 10 and standardized. Each map layer was ranked by its suitability level to determine the desirable location for the facility. In this analysis, criteria were standardized on a scale of 0 to 3, where 3 is the most suitable.

Throughout the analysis for reliable decision-making, weights were developed by providing a series of pairwise comparisons of the relative importance of factors to the suitability of pixels for the activity being evaluated. It must be reiterated that one of the key limitations to multi-factor analysis for achieving a single decision objective is the derivation of suitable weight.

4.3.12 Selecting the Suitable Sites

Each pixel (candidate) within the result of the weighted overlay was assigned a value which indicated how suitable that pixel was for the siting of the processing facility. Pixels with a value of 3 are most suitable while those with a value of 0 are unsuitable. The first thing that was done in order to determine the suitable areas was to select the pixels with a suitability score of greater than 0. Thus, the output values for each cell are controlled and evaluated as true or false output raster (suitable and unsuitable). The conditional function tool (con) within the raster calculator of ArcGIS was used to execute these numerical values of layers. Thus if the evaluation of the expression is nonzero, it is treated as True. If no input false raster or constant is
specified, NoData will be assigned to those cells that do not result in True from the expression. Figure A-7.5 shows the attribute table of the evaluated suitability criteria.

After this, a constraint map was applied on the selected pixels to reduce their number and further increase the suitability of the pixel. The application of this constraint map was essential because, after a thorough discussion with experts and through literature review, it was observed that the site should not be close to protected sites such as forest reserves and national parks as well as large-scale mines. Thus, the constraint that was used consisted of a 500m offset from forest reserves, 100m offset from state lands and 300m offset from large-scale mines. Areas that fell within the constraint were excluded and this led to the reduction of the number of most suitable sites that were selected.

Finally, cluster analysis (on density of artisanal mining) was used as a criterion to determine and select suitable locations for the new centralized processing facility. It was observed that, after applying the constraint and the selection of suitable areas, the desirability levels reduced as shown in Table 11. It is important to note that the relative importance of location to the ASM sites was considered and factored as the main objective. Figure 10 shows the model process in the Arc ModelBuilder. Thus, the sites which were surrounded by the most ASM locations were selected according to the number of ASM locations around them. Figure 11 is a flowchart that summarizes the research approach that was used.

![Figure 10: Model for the Selection of Suitable Areas.](image)

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**Figure 11:** Flowchart of Research Approach.
Chapter 5

Results and Discussions

5.1 Results

The approach used in this research resulted in the creation of suitability maps for the various criteria used. Maps show unsuitable, suitable and most suitable land areas for each of the evaluation criteria.

5.1.1 Result of Rectification and Validation

During the rectification of the datasets into the UTM WGS 84 Zone 30N coordinate system, residuals and an overall root means square error (RMSE) were computed from Equation 10. The RMSE equation was applied to quantify how much error there is between the two datasets (local and UTM coordinate systems). This was essential because it helps in determining the accuracy as well as the reliability of the spatial adjustment that was performed. In this research, as can be seen in Table 8, an overall RMS error of 0.05 was obtained while the residual errors lie between 0.02 and 0.09. These results are fairly good and therefore show that the rectification was done well.

The RMSE is derived by squaring the differences between the observed and calculated values, adding these residuals together, dividing these values by the total number of values, and taking the square root of the result. RMSE is obtained as shown by Equation 13:

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - y_i)^2}$$  \hspace{1cm} (13)

where $N$ is the total number of values, and $x_i$ and $y_i$ are residuals of observed and calculated values.
Table 8: Result of Map Rectification Showing the Root Mean Square Error

<table>
<thead>
<tr>
<th>ID</th>
<th>X Source</th>
<th>Y Source</th>
<th>X Destination</th>
<th>Y Destination</th>
<th>Residual Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>628636.8811</td>
<td>605177.7081</td>
<td>592812.5168</td>
<td>632523.6569</td>
<td>0.096653</td>
</tr>
<tr>
<td>2</td>
<td>628272.3631</td>
<td>604678.3101</td>
<td>593013.5195</td>
<td>631938.9902</td>
<td>0.088677</td>
</tr>
<tr>
<td>3</td>
<td>627085.2541</td>
<td>604927.2471</td>
<td>592130.1777</td>
<td>631107.8078</td>
<td>0.039497</td>
</tr>
<tr>
<td>4</td>
<td>627019.8991</td>
<td>608736.1091</td>
<td>588969.1373</td>
<td>633233.3451</td>
<td>0.04156</td>
</tr>
<tr>
<td>5</td>
<td>627264.8221</td>
<td>609412.1431</td>
<td>588554.8616</td>
<td>633820.9964</td>
<td>0.05863</td>
</tr>
<tr>
<td>6</td>
<td>629810.3701</td>
<td>604801.8501</td>
<td>593792.1475</td>
<td>633271.0497</td>
<td>0.06966</td>
</tr>
<tr>
<td>7</td>
<td>624958.7001</td>
<td>605147.5141</td>
<td>590732.843</td>
<td>629489.7282</td>
<td>0.050308</td>
</tr>
<tr>
<td>8</td>
<td>623946.0601</td>
<td>606857.3081</td>
<td>588751.2327</td>
<td>629637.4264</td>
<td>0.031015</td>
</tr>
<tr>
<td>9</td>
<td>625571.0751</td>
<td>610115.3151</td>
<td>587009.0974</td>
<td>632834.206</td>
<td>0.026605</td>
</tr>
<tr>
<td>10</td>
<td>627230.6861</td>
<td>611223.8801</td>
<td>587049.5475</td>
<td>634829.563</td>
<td>0.031079</td>
</tr>
<tr>
<td>11</td>
<td>628915.0181</td>
<td>615495.5251</td>
<td>584510.2114</td>
<td>638654.9252</td>
<td>0.027326</td>
</tr>
<tr>
<td>12</td>
<td>633102.8181</td>
<td>613906.7461</td>
<td>588209.2264</td>
<td>641180.3221</td>
<td>0.022712</td>
</tr>
</tbody>
</table>

Root Mean Square Error 0.054169

Spatial Adjustment of Map Coordinates

5.1.2 Result of Deriving Datasets

Proximity analysis performed on the evaluated criteria datasets resulted in maps shown in Figure 12. These maps show the criteria simulation for the centralized processing facility indicating distance proximity to ASM sites, proximity distance to roads, proximity distance to railroads, proximity distance to settlements, proximity distance to water bodies, proximity distance to slopes and proximity distance to faults zones.
Figure 12: Results of Derived Datasets for Each of the Evaluated Criteria
5.1.3 Result of Constraints Dataset

A map showing the constraint areas for the centralized processing facility is shown in Figure 13. Areas that fell within the constraint areas were excluded and this led to the reduction of the number of most suitable sites that were selected. This shows the features such as state lands, forest reserves, and large-scale mines that represent restricted zones. These were considered unsuitable for the facility siting and therefore were delineated prior to the suitability index analysis. This constraint map was produced by applying the Boolean logic (mask) which consists of raster images that excluded certain areas from consideration.

![Map showing constraint areas for centralized processing facility](image)

**Figure 13:** Results of Constraint Areas: State Lands, Forest Reserves, Large Scale Mines.
5.1.4 Result of the Suitability Group Criteria

A map showing the suitability levels of the group criteria for unsuitable and suitable siting is shown in Figure 14. Showing conditional raster images representing the true or false result of the desired condition. For example where the value of the input conditional such as (ASM) raster is less than or equal to 3000m offset, the output value will be 1, and where it is greater than 3000m offset, the output value will be 0.

Figure 14: Suitability Levels Map of the Evaluated Criteria
5.1.5 Results of Reclassified Datasets

The results of the criteria datasets after reclassification of the selected factors are shown in Figure 15. As noted, 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 (0, 1, 2, and 3). The factors are represented as raster images containing the target features from which distances were measured by the Euclidean distance analysis procedure. The target features, such as distance to roads, distance to waterbodies, etc. are vector files.

Figure 15: Results of Reclassified Datasets of Criteria.
Table 9 also shows the areal extent of each of the suitability level zones for each of the evaluated criteria.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>0 (unsuitable)</th>
<th>1 (less suitable)</th>
<th>2 (suitable)</th>
<th>3 (most suitable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>Km²</td>
<td>%</td>
<td>Km²</td>
<td>%</td>
</tr>
<tr>
<td>Distance to ASM</td>
<td>326.5440</td>
<td>13.4208</td>
<td>1376.8720</td>
<td>56.5886</td>
</tr>
<tr>
<td>Distance to Roads</td>
<td>23.3296</td>
<td>0.9588</td>
<td>1318.7610</td>
<td>54.2003</td>
</tr>
<tr>
<td>Distance to Railroads</td>
<td>581.4575</td>
<td>23.8976</td>
<td>1808.6350</td>
<td>74.3339</td>
</tr>
<tr>
<td>Distance to Settlements</td>
<td>18.7139</td>
<td>0.7691</td>
<td>105.4476</td>
<td>4.3338</td>
</tr>
<tr>
<td>Distance to Tectonic zones</td>
<td>40.5887</td>
<td>1.6682</td>
<td>920.5690</td>
<td>37.8349</td>
</tr>
<tr>
<td>Distance to Waterbodies</td>
<td>25.8828</td>
<td>1.0638</td>
<td>250.5724</td>
<td>10.2984</td>
</tr>
<tr>
<td>Slopes</td>
<td>0.0058</td>
<td>0.0002</td>
<td>713.1267</td>
<td>29.3091</td>
</tr>
</tbody>
</table>

**5.1.6 Results of Overlaying and Weighting Datasets**

The combination of all the weighted criteria in an overlay analysis resulted in a suitability index map for facility siting of the study area. A land area of 932.56 km², representing 38.33% of the total land area, was classified as unsuitable, 576.27 km², representing 23.68% of the total land area, was classified as less suitable, 899.56 km², representing 36.97% of the total land area, was classified as suitable, and 24.73 km² representing 1.02% of the total land area was classified as most suitable. Figure 16 and Table 11 show the overlain suitability index map and the area extent of the study areas by suitability index respectively.
Figure 16: Suitability (Level) Index of Overlay

Table 10 shows the suitability scores evaluated as (unsuitable) False or (suitable) True, where False has an index value of 0, representing unsuitable sites, and True has an index value of 1, representing suitable sites.
Table 10: Suitability Scores Evaluated as Unsuitable and Suitable

<table>
<thead>
<tr>
<th>Index</th>
<th>Suitability</th>
<th>Area (Km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Unsuitable (False)</td>
<td>932.56</td>
</tr>
<tr>
<td>1</td>
<td>Suitable (True)</td>
<td>1500.56</td>
</tr>
<tr>
<td>Total Area</td>
<td>2433.12</td>
<td></td>
</tr>
</tbody>
</table>

Table 11 shows the areal extent versus suitability levels of the study area classified from unsuitable to most suitable sites.

Table 11: Areal Extent of Suitability Levels

<table>
<thead>
<tr>
<th>Index</th>
<th>Suitability</th>
<th>Area (Km²)</th>
<th>Land Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Unsuitable</td>
<td>932.56</td>
<td>38.33</td>
</tr>
<tr>
<td>1</td>
<td>Less Suitable</td>
<td>576.27</td>
<td>23.68</td>
</tr>
<tr>
<td>2</td>
<td>Suitable</td>
<td>899.56</td>
<td>36.97</td>
</tr>
<tr>
<td>3</td>
<td>Most Suitable</td>
<td>24.73</td>
<td>1.02</td>
</tr>
<tr>
<td>Total Area</td>
<td>2433.12</td>
<td>100.00</td>
<td></td>
</tr>
</tbody>
</table>

5.1.7 Results of Selected Suitable Sites

Using a simulated analysis from the suitability index, total site areas amounting to 24.73km² were selected as being suitable among all participating and satisfactory candidate sites (cell value of 3) as shown in Table 11.
Cluster analysis was performed on the selected sites from which potential most suitable sites were identified. Acceptable sites with the highest density of desirability for the facility location were identified as 3 among all selected sites. Thus, depicting the most favourable candidates among simulated factors. Locations identified as being unsuitable as shown in the spatial model map, labeled (0) in the legend, must be discarded and not considered in the selection process. From the map, most of the unsuitable sites are located at the northern zone of the study area.

From Equation 14, cluster-neighboring sites among the candidates were identified, as being acceptable sites overlain on the factor maps.

\[
L(d) = \sqrt{\frac{A \sum_{i=1}^{n} \sum_{j=1, j \neq i}^{n} k_{i,j}}{\pi n(n - 1)}}
\]

(14)

where \(d\) is the distance, \(n\) is the number of features, \(A\) is the total area of the features and \(k_{i,j}\) is a weighted criteria.

Spatial locations among these sites suitable for consideration were located as shown in Figure 17 and indicated on the map legend as (3). Thus, indicating the highest candidate that reasonably meet the criteria after the aggregation of the resulting output raster.

Intuitively, the facility should be sited centrally to serve ASM within the WAPMA. Therefore, sites that were centrally located among the candidates would be ideal for the purpose of serving miners. Instinctively, ASM sites nearby the identified facility locations should be considered as the primary decision features for suitability. For instance, if most gold tonnage produced by miners occurs within the southern zone of the study area, it would be intuitive to site the facility within this southern zone, as there is a need to take into account the density of the mining sites with respect to the identified areas for the facility. This would therefore favour locations of densely populated, existing operational mine sites, due to the tonnages that would be needed to economically meet the facility capacity. Other factors such as cost of
development, land use, availability of utilities and operation of the facility must also be considered in order to factor the best sites to develop.

From the suitable potential facility map, areas with high suitability are concentrated in the southern zones adjacent to available road network systems. The proposed facility, as depicted, is sited further away from identified constraint and settlement areas to prevent any social and environmental breaches as well as to establish economic viability of the project. The results of the analysis provide vital reference points for discussions about potentially establishing a facility that would meet the needs of stakeholders and decision-makers.

5.1.8 Results of the Potential Facility Location

The acceptable positions for the location of the centralized processing facility, identified as legend symbol (3) areas, is as shown in Figure 17. Suitability analysis has determined the appropriateness of a given area (land resource) for locating an economic processing facility.

However, it is important to verify acceptable sites from the suitability modeling for accuracy and reliability of selected sites. It may be beneficial not only to explore the best locations identified by the model but also to investigate other suitable candidate sites. The identified sites must be visited to validate their suitability. The identified suitability sites should be visited in the field to validate them on the basis of possible obstructions. Thus, things could have changed since the data for the model was created, and often the achieved results may have unaccounted for something important. For example, there may be farming activities within the identified site that are producing food and livelihood of which decision makers may be unaware of. Again, there is the possibility that the identified area is far from power or energy resources and water supplies which are critical to project operations. If either is the case, there is a need to add this information to the analysis.
Figure 17: Map of Potential Suitable Gold Processing Sites.
5.2 Discussions

GIS techniques and theories have been able to identify suitable locations for siting of a processing centre for artisanal and small-scale miners with limited datasets. A complex phenomenon, as ASM is, requires evaluation of many criteria to test possible adoption and mitigation factors in their operations. An approach such as spatial analysis has succinctly aided in a search for suitable sites through suitability modeling in the designated area of Ghana that has been the focus of this thesis.

In this work, seven criteria were selected to establish the suitability of locations for a facility, however, other factors such as mineralization, energy availability, cost of development, plant capacity and other factors could also be included subject to data availability. Due to lack of information in these topic areas, suitability modeling was done without considering these aforementioned factors hence limiting the effectiveness of the modeling.

Simulation was done based on the available data relevant to the study area to identify potential sites. It must be noted, however, that this may not offer the optimal sites for the proposed facility due to unavailable datasets needed during the modeling process. Inevitably, broad scale models of this analysis necessitate a number of assumptions that limit its potential for detailed plant design and analysis.

However, these limitations are justified in this study, as the aim was to provide a proof of concept for utilizing a geospatial tool in locating a facility with minimal data, thus, creating an alternative to other existing widely used approaches for mitigating issues of ASM. Acquiring nationally available datasets of information for this research presented a major limitation to the analysis. One of the major constraints was unavailability of data on energy production which presents insuperable restrictions to the successful implementation of this project. It must be mentioned that establishing a processing facility without energy availability and technology to generate power for a facility limits the capability and the functionality of an operation.

These limitations have shown the effect of lack of data availability for which the degree of susceptibility in suitability modeling affects the establishment of a facility among selected criteria.
However, widely available datasets, such as satellite imagery of night views of cities could be used as a baseline for energy assessment, notably spatial availability of energy resources. To realize the full potential of GIS applications with respect to suitability study, data availability as well as data integrity must be part of the decision process. With this, a better return on investment would be achieved considering effective data analysis with equal participation of stakeholders as well as decision-makers.
Chapter 6

Conclusions and Recommendations

GIS analysis is usually part of a workflow that includes the spatial data, data analysis and the interrogation and debate process by decision makers to finalize the results in order to improve an existing condition. The work done utilizing the ArcGIS 10.3 software, for a clear understanding and a proof of concept, has been established to define the benefit and usefulness of spatial intelligence for selecting the best sites for siting a centralized processing facility in Ghana. This has facilitated the production of suitability maps generated from the various datasets being used for optimizing the site selection of a centralized processing centre. Stakeholders, as well as decision makers, have been accounted for in selection of an optimal site for positioning a processing centre for artisanal miners, taking into account a corporate coexistence approach.

It is expected that this spatial analysis approach will bring to light the opaque transactions among some private processing centre operators as well as a method to reduce incidences and accidents within the sector due to the rudimentary processing technology and improper training that currently exists for ASM. This spatial intelligence system for site location will alternatively be an extension to an already established formalized artisanal mining process for improving ore processing transactions. The hypothetical centralized processing facility could potentially provide techniques for improving mineral resource evaluation as well as provide the state with necessary information on ASM locations.

Inevitably, geospatial analysis will help provide further assessment of conditions such as flood occurrence, air quality, heat conditions and others that will improve current practices of unsafe and not profitable ASM effort.

It is therefore important to consider this technique as an alternative to technology and policy challenges, with a possibility of having it integrally embedded in the Ghanaian mining institutional structure. It is hopeful that, in the future, stakeholders, such as the government, large-scale mining
companies and investors, will see the benefit that GIS can bring to an already well-established practice within the ASM sector.

There is a need for a national survey, with much emphasis on small-scale mining communities, to ascertain the populations of miners and settlements within all districts. This will provide a baseline census as a means of monitoring the population of miners with respect to utility services and other vital information such as energy supply, as lack of energy supply is synonymous with problematic, in the health and safety conditions sense, and limited to economic production.

Again, the government, in collaboration with Large-scale Mines, could independently develop energy generation plants at suitable sites without relying on the national grid as a means of power supply. This is because a project would likely be unsuccessful due to lack of sufficient supply of power and, therefore, consideration of energy is essential in locating a processing facility. In the future, the state and private institutions should support projects like this by providing the requisite available data necessary to hypothetically test the effectiveness of a siting model, such as the one develop for this thesis.

For effective and detailed analysis of suitable site locations for a potential a centralized processing centre, the cost of facility construction as well detailed facility sizing and capacity analysis should be taken into account and factored into the decision making process. Beyond the periphery of this analysis, economic factors such as the costs of land acquisition, land development and ore transportation should also be taken into an account for such a project.

This research 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 be done in these areas to improve this research work.
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Appendix

A-1 Brief History of Artisanal Gold Mining in Ghana

Gold mining started in Ghana perhaps in the sixth centuries B.C. when the Phoenicians and the Carthaginians most likely reached the Gold Coast, now Ghana. Trans-Saharan caravan trade between West Africa, the Mediterranean coast in North Africa and Europe also involved trade in gold and salt, with much of it coming from the Gold Coast. The Moors of Northern Morocco were active gold trading partners with the Ghanaian Akans with trade across the Sahara and final destination in Arab or Islamic countries in the Middle East, for example in the form of dinars minted by the Almoravids of Morocco. Juan de Santarem and Pedro de Escobar in their search for fortune through gold arrived on the coast of Ghana between the Ankobra River and the Volta River in 1471 and named the region “Mina de Ouro” meaning Goldmine (Agbesinyale, 2003). This was the time when Ghana got its former name: ‘The whole region between Cape Three Points and Cape Coast was so rich in gold that the coast received the name 'the Gold Coast’ (Ward, 1966).

AM is popularly known as galamsey in Ghana, which originated in the early 17th century by the natives through the trade of gold with their colonial masters. The abundance of gold nuggets and easy accessibility of the deposits from gold-bearing gravels in river beds brought about booming trade and economic growth. The pronunciation of ‘Gather them’ and ‘sell’ became ‘Galamsey’ which is still the accepted name in Ghana.

A-1.1 Definition of ASM of Different Countries

The ASM sector is well known to be associated with numerous jargons, ranging from ‘Rathole’ mining in India, ‘Ninja’ mining (Mongolia), ‘Garimpo’ (Brazil), and ‘Galamsey’ (Ghana), just to mention a few. Countries have devised unique definitions of “artisanal” and/or “small-scale mining”, according to a variety of criteria such as the following:
• Level of mechanization (e.g. as in Brazil, Burkina Faso, Ghana and Sri Lanka)
• Size of Concession (e.g. as in Ghana, Zambia, and Zimbabwe)
• Depth of working (e.g. as in Colombia, Senegal, and Ethiopia)
• Capital investment (e.g. as in Argentina, Mexico, South Africa, Pakistan, and Thailand)
• Level of employment (e.g. as in Chile)
• Production levels (e.g. as in the Philippines and Senegal)

Nevertheless, common features in the different definitions are;
• Stakeholders are usually limited to citizens of the country.
• Use of sophisticated equipment is restricted.
• There are set limits on the level of production, the number of miners, and infusion of capital. (DFID, 2000).

A-1.2 Facts About ASM

The ASM process through its rudimentary means of ore crushing and milling for recoveries at an affordable cost, reliable and fast-track by facility centers over the years has little been investigated to establish its authenticity as well as its compliance with mining and environmental regulations. These facility operators earn significant wealth as they trade the residual of artisanal miners to third parties since miners get their crushed ores with virtually little or no fee. As a result, the returns from their ores are insufficient to liberate them from economic dependency.

All in all, these facility operators sometimes lend money to these artisanal miners for their livelihood. This oscillation trend has unable the sector growth. However, these miners have little knowledge on the extent of exploitation by theses facility operators, but rather, accused LSM for their misfortune; by allegedly taking over their allodial and ancestral resource rich lands for large scale production and recoveries of ores (Nyame & Blocher, 2009). It is worth knowing that not all facility centers are unworthy of emulation; obviously some are in compliance with regulations and must be commended.
A-1.3 Anti-mining Activist Perception

Large-scale mining companies over decades have allegedly suffered the consequences of irresponsible environmental violations, which have rendered the industry as unattractive (Seidu, 2015). Not much research has been done or little in-depth investigation has been conducted to attest to this claim by some anti-LSM activists and non-governmental agencies (NGO).

Many mining companies are under enormous environmental pressure by anti-LSM and NGO’s mainly due to unregulated practices by a handful of companies failing to utilise the cutting edge technology to reduce environmental damage. This has been the main source of justification by most anti-LSM and NGO’s to the detriment of the whole industry.

Rather, much emphasis of ASM has been on economic displacement and socio-cultural aspects of the involved society and miners, ignoring the exacerbated environmental dangers caused by ASM. These claims by stakeholders require further work and review of the unknown practices by these ASM.

Appendix A-2 ASM Regulatory Framework

General Mining Laws

- Minerals and Mining Act, 2006 (Act 703) and its amendments.

IV (a) Small-scale Mining Enactments

- Small-Scale Gold Mining Law, 1989 (PNDCL 218)
- Precious Minerals Marketing Corporation Law, 1989 (PNDCL 219)
- Minerals Commission Act, 1993 (Act 450)
- Environmental Protection Agency Act, 1994 (Act 490)
A-2.1 Legislation

Legalization of ASM is a key step toward achieving sustainability and national development, making the law a step in the right direction, for improving the economic state of affairs in Ghana. (Hilson, 2001). However, the legal definition of ASM prevents its recognition and leads to large economic losses, mainly due strict legislation. This has resulted in an unattractive overview and participation of illegal mining practices. Beyond the stringent regulations involved, legislation is also bogged down with excessive needlessly time-consuming procedures and bureaucracy particularly through the licensing process. As noted by Bugnosen (2003), most legislation associated with ASM has the tendency to limit technological development of operations such as workings to be limited to a certain depth. These include prohibition of the use of explosives, prohibited use of mechanized equipment, and non-application of advanced processing technologies resulting in limited conflicts due to upgrading of ASM into LSM operations.

A-2.2 Permitted Activities

The Minerals and Mining Act (2006) Act 703, grants mineral right licenses for ASM at small scale to Ghanaian nationals and are only renewable for a period of no more than three years for two consecutive terms and a period of five years for cooperatives which is renewable for a period no longer than five years for two consecutive terms.

The law permits the buying and selling of gold through the authority of PMMC and sets for payment of taxes, royalties and other local imposts levied by Metropolitan, Municipal and District Assemblies MMDAs and other government agencies.

A-2.3 Non-Permitted Activities

The Minerals and Mining (Amendment) Law, 2014 Act, (Act 703) (2006), criminalizes illegal ASM as well as foreigners and Ghanaians without permit usage. It is also an offense for a Ghanaian to employ or engage a foreigner to undertake or participate in illegal ASM activities.
Trading and marketing of gold without a licence granted or without valid authority commits an offence and is liable to a summary conviction to a fine of not more than 3,000 penalty units or to a term of imprisonment of not more than five years or to both.

100 penalty units are equivalent to GH¢1,200. ($315USD).

A foreigner who undertakes small scale mining operations contrary to the provisions of the law commits an offence and is liable on summary conviction and a fine of not less than 30,000 penalty units and not more than 300,000 penalty units or to a term of imprisonment of not more than 20 years or both.

A Ghanaian who employs or engages a foreigner to illegally undertake or participate in small-scale mining in the country commits an offence and is liable on summary conviction to a fine of not more than 17,000 penalty units or to a term of imprisonment of not more than 10 years or to both. (Graphic Online, 2015)

A-2.4 Issues with current legislation

Although the ASM law is a step in the right direction, implementation has been critical, giving the extent of activities and challenges faced by AM in accordance to the legislation. The legislation appears to be ineffective given the biasness skewing in favor of LSM investment, which is unrealistic and user-unfriendly for ASM.

In fact, as Seidu (2015) argues, that existing policies on ASM have hardly had positive and sustainable impacts in galamsey communities pointing the need for substantive evidence to support its position. Explaining that, policies on the ASM sector has negative impacts on community labour, hence local economy due to structural limitations.

For instance, the legislation limits the potential of AM realized an appreciable returns, in terms of prohibiting the use of sophisticated equipment’s and mechanisms as well as the restricted boundary and size of land. In fact, according to the legislation, issued licenses covers areas not exceeding 25 acres for three to five years (Hilson, 2001).
The issue of transparency in terms of permitting accessibility to land and licensing renewal coupled with stringent and unattended bureaucracies including taxation are working not distinctively working for majority of licensed AM. This situation worsens the attractiveness of the process and thereby illegality is encouraged resulting in deteriorating environmental and economic state of affairs.

**A-3 Environmental Sustainability**

Environmental sustainability (ES) is the rates of renewable resource harvest, pollution creation, and non-renewable resource depletion that can be continued indefinitely (Daly, 1990). According to Gooland (1995), ES is the maintenance of natural capital; It suggests the unaffected preservation of human life support systems. Essentially, sustainable development correlates economic growth through a better environmental management.

In Ghana, the Environmental Protection Agency EPA is the regulatory body that undertakes impacts and assessment of the environment, established in 1994 with (act 490), and aimed at protecting the environment through directing procedures to control wastes discharges, emissions, deposits or other sources of pollutants (Environmental Protection Agency Act 490, 1994).

Under section 2(h) it is the EPA function "to prescribe standards and guidelines relating to air, water, land and other forms of environmental pollution including the discharge of wastes and the control of toxic substances. Typically, best environmental practice supports human life and maintained natural capital. However, the practice within the ASM environment used by AM at WAMPA runs contrary to this extent of human life support, as the techniques and procedure of operations is in divergent to the EPA regulation. These processes have accounted for quasi-environmental issues within the sector. A report by ASM-PACE (2012) program on sustainable development report on Africa region describes how ASM of gold has been a biggest challenge in terms of its negative localized environmental impacts. The reports noted how environmental education for AM has been poorly managed. Rather much emphasis on rehabilitation, increasing throughput and mercury management which suggested the need for further inputs to help ASM operations in a less environmentally damaging phenomenon.
ASM operations involve the common practice of washing of residue into surrounding water as well as uncontrollable disposal of wastes such as sewage into their working area, intrinsically resulting in diverse effect on the downstream where the community relies on this water for a living. Influx and migration of the vulnerable in search of livelihood during gold rush contributes significantly to the destruction of the environment in many ways. This includes hunting, gathering firewood, and timbering for construction for temporal accommodation and preparation of food which subsequently leaves the forestland permanent clearance. Spitz & Trudinger (2008) describes the effect of ASM on surface disturbance and it impacts on health and safety of involved workers and the community.

ES in ASM is still infancy, stemming from its overall inadequate legal and regulatory framework coupled with exacerbated application of rudimentary and inappropriate technology, impact negatively on capacities to generate income (UNECA, 2003).

Consequently, activities of ASM with respect to the environment results in lack of investor confidence both locally and internationally, due to political marginalization and lack of incentives and capacity to support ASM (ASM-PACE, 2012). Improvement in capacity and proper planning of ASM operations can potentially realize a positive return on investment for investors and would help improve the lives of the community and the country through direct (tax) revenue as a whole if properly researched and managed. Figure A-3 typically illustrates some of the negative environmental impacts of the sector of selected site visited.

A-3.1 Ore recovery Process

Utilization of mercury in gold amalgamation makes recoveries easier due to its physical and chemical particle properties. Beyond its physical and chemical property, it is cheap and affordable, easy use, and easily accessible. Artisanal gold miners combine mercury with gold-carrying silt to form a hardened amalgam that picked up most of the gold metal from the silt. The amalgam is later heated with blow torches or over an open flame to evaporate the mercury, leaving small gold pieces.
A-3.1.1 Effects of mercury

The gaseous mercury is inhaled by the miners and often by their immediate family, including children. Mercury that is not inhaled during the burning process settles into the surrounding environment or circulates globally for future deposition far from the site, where it is absorbed and processed by a variety of living organisms. This transforms elemental mercury into Methyl mercury. Mercury contaminates into the environment during smelting to recover the gold metal which involves heating and also the discharging of the residue into the terrestrial and aquatic environment causing toxic and ill-health issues.

The refinery facilities ‘gold shop’ which produces the final product for sale is, perhaps an important part of the production process to the AM, are the major cause of air pollution from mercury which have serious health effects both locally and globally (USEPA, 2015). Exposure to mercury can cause health issue and even death. Conversely, lack of knowledge and the application of mercury for gold recoveries makes its very dangerous and risky to all department of life. Having noticed that, the use of mercury for ore recoveries presents a daunting risk to the miners and the environment as a whole. With no personal protective equipment, particularly the amalgamation of the ore with bare hands.

It is estimated that one or two grams of metallic mercury are lost for every gram of gold produced using the amalgamation process which also constitute at least two grams of mercury emission into the environment (UNIDO, 2013; Veiga, 2015). The International Guidelines on Mercury Management in Artisanal and Small-Scale Gold Mining are proposed for the purpose of assisting governments in the development of policy, legislation and regulation that will lead to improved practices of artisanal and small-scale gold mining (ASM).

However, operations of these miners within the sites visited appear not to be under any law or guidance on the use of mercury. Their mining practices seemed to contradict the principal technical measures on mercury usage. These include the unsafe usage and storage, as well as inefficient and disposal of mercury into the environment.
A-3.1.2 Health Case

This is evident in a mass lead poisoning caused by illegal ore processing operators polluting drinking stream water in Zamfara state, Nigeria that killed 400 kids and left many paralyzed and blind. On May 15th 2015, activities of illegal artisanal miners residuals into neighbouring streams and ore processing at their homes killed at least 28 children and left dozens in critical condition through pollution (Jamasmie, 2015). This obviously despises the purpose of improving living conditions if the end results are death and illness.

A-3.1.3 Safety case

It must be noted that, illegal operations of miners are not only threat to the safety of themselves, but also the surrounding adjacency community of which the operations exist compromising the integrity of neighbouring formal large-scale mining operations.

For example, in open-pit mining operations of some large-scale mines, slope stability may be affected by illegal excavations by neighbouring galamsey activity operating within the boundaries of a mine concession. Consequently, theft of gold-bearing material, equipment, and other assets, as well as, confrontation with mine staffs resulting in various degree of reported injuries (AngloGold Ashanti, 2006). Overall safety practice within the ASM sector presents a daunting and catastrophic phenomenon to the workers themselves and the ecosystem at large, as there are very limited or no technical expertise to assess catastrophic risk and hazard from the engineering perspective for predictions and mitigation. AM base their hazards and risk prediction and control on the hands-on experience in the field of operation and therefore the adoption of zero harm in LSM industries and best practices used in maintaining zero harm in its operations is unknown to their operations.
A-4. Economic facts

It is worth however, noting that, statistics on employment were gathered over decade by ILO (1999), which could be vast underestimated, since there is a probability of an increased. Considering the increased in global population, coupled with declining employments and the soar for economic livelihood and lack of interest in subsistence farming, particularly in developing nations.

Moreover, the entire sectors within the ASM are often not taken into account, particularly in the case of industrial minerals. These include lime in Zambia, salt in Ghana, barytes in India and gypsum in Nigeria as well as construction materials such as, aggregates or brick clay which are often produced for
local consumption and not exported (D'Souza, 2002; ILO, 1999). Weber-Fahr, et al. (n.d), estimate that “there are approximately 60 developing and transition countries as shown in Table A-4.2 where mining is or could become an important economic activity”. This could potentially make the promotion of ASM an appropriate strategy for governments aiming to raise living standards in rural communities.

The (Ghana Minerals Commision, n.d) estimates that, about one-third (34 %) of Ghana’s gold comes from ASM, and nearly all of it is exported which has plays significant role in the Ghanaian economy. This includes balance of the government payment and reduction in tariff barriers as well as an increase in gross domestic product (GDP). In 2013, 40.7 tons of gold from the artisanal and small-scale gold mining sector were exported, at a trade value of US$1.7 billion. (Human Rights Watch, 2015). ASM has contributed impressively to the country’s merchandise export as shown in Table A-4.1 (Ghana Ministry of Finance, 2014).

**Table A-4.1 ASM Contribution to National Exports (US $000)**

<table>
<thead>
<tr>
<th>Item</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Merchandise Export</td>
<td>7,960.09</td>
<td>12,785.4</td>
<td>13,541.4</td>
<td>13,017.8</td>
<td>12,983</td>
</tr>
<tr>
<td>Mineral Export</td>
<td>4,900</td>
<td>5,062.8</td>
<td>5,768.8</td>
<td>5,138.89</td>
<td>4,516</td>
</tr>
<tr>
<td>ASM Export</td>
<td>951.2</td>
<td>1,553.64</td>
<td>2,283.3</td>
<td>1,919.9</td>
<td>1,913.12</td>
</tr>
<tr>
<td>Mining % (B/A)</td>
<td>62</td>
<td>39.5</td>
<td>42.6</td>
<td>39.4</td>
<td>42.3</td>
</tr>
<tr>
<td>ASM % (Mining Sector) (C/B)</td>
<td>19.4</td>
<td>30.6</td>
<td>39.5</td>
<td>37.4</td>
<td>42.3</td>
</tr>
<tr>
<td>ASM % (Total Exports) (C/A)</td>
<td>11.9</td>
<td>12.2</td>
<td>16.9</td>
<td>14.7</td>
<td>14.7</td>
</tr>
</tbody>
</table>

(Ghana Ministry of Finance, 2014)
Table A-4.2 Countries Where the Mineral Sector Could Have an Impact on Poverty

<table>
<thead>
<tr>
<th>Latin America and the Caribbean</th>
<th>Sub-Saharan and North Africa</th>
<th>Europe, Middle East, and Asia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argentina</td>
<td>Botswana</td>
<td>Bhutan</td>
</tr>
<tr>
<td>Bolivia</td>
<td>Central African Republic</td>
<td>Bosnia</td>
</tr>
<tr>
<td>Brazil</td>
<td>Congo</td>
<td>China</td>
</tr>
<tr>
<td>Chile</td>
<td>Eritrea</td>
<td>Fiji</td>
</tr>
<tr>
<td>Colombia</td>
<td>Ethiopia</td>
<td>India</td>
</tr>
<tr>
<td>Ecuador</td>
<td>Ghana</td>
<td>Kazakhstan</td>
</tr>
<tr>
<td>Guyana</td>
<td>Liberia</td>
<td>Jordan</td>
</tr>
<tr>
<td>Jamaica</td>
<td>Madagascar</td>
<td>Indonesia</td>
</tr>
<tr>
<td>Mexico</td>
<td>Mozambique</td>
<td>Malaysia</td>
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<tr>
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<td>Pakistan</td>
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<tr>
<td></td>
<td>Namibia</td>
<td>Papua New Guinea</td>
</tr>
<tr>
<td></td>
<td>Niger</td>
<td>Philippines</td>
</tr>
<tr>
<td></td>
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<td>Romania</td>
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<tr>
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<td>Russia</td>
</tr>
<tr>
<td></td>
<td>Tanzania</td>
<td>Thailand</td>
</tr>
<tr>
<td></td>
<td>Tunisia</td>
<td>Turkey</td>
</tr>
<tr>
<td></td>
<td>Zambia</td>
<td>Sri Lanka</td>
</tr>
<tr>
<td></td>
<td>Zimbabwe</td>
<td>Solomon Islands</td>
</tr>
<tr>
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<td></td>
<td>Ukraine</td>
</tr>
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<td></td>
<td></td>
<td>Uzbekistan</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vietnam</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yugoslavia</td>
</tr>
</tbody>
</table>

(Weber-Fahr, et al., n.d)

A-4.2 Loss of economic factor

Galamsey is important part of Ghana’s economy as noted by Akabzaa (2009), nevertheless, the government’s part to the profit (economic) share seems unrealized, mainly due to the unavailability of stringent and unclear policies governing the sector.

Revenue realization in taxes and royalties are just handful spanning from only 15% registered and licensed AM. Out of the total 2,930,328 ounces of gold produced in Ghana, in 2009, licensed AM produced 18% while LSM companies produced 82% (Ministry of Lands and Natural Resources, 2010). This confirms the low per capita productivity in the ASM subsector. Meanwhile, it is mandatory for AM to obtain license to operate under the Ghanaian law (Minerals and Mining Act, 2006), but majority of AM operates without a valid license (Nyame & Blocher, 2009).
A-5 Conflict

While the government of Ghana efforts to address issues associated with galamsey, its systems to monitor and eliminate illegal operations function poorly. Inspections for galamsey by districts officials are not systematic, and the Mines Inspectorate dealing with these illegalities are weak and underfunded and understaffed (Seidu, 2015). There is the need for fundamental reforms to address the menace by illegal AM.

Formalization and stakeholder partnership and engagement have been the popular remedy for illegal ASM and its degradations (Davidson, 1998). Seidu (2015) describes how social vices and environmental degradation are rare in licensed, formalized mines, working under stringent policies and regulations in Ghanaian mines. The interviewer observed the failure of the country to make formalization of illegal mining attractive to galamsey operators has resulted in the deplorable conditions of AM.

Moreover, formalizing AM would be potentially attractive to investment as well as a strategy to control illegal activities into a formal sector. This would also assist galamsey miners gain access to capital fund for financing their operations which would generate revenue through taxes for national development. However, Veiga (2015) has argue that formalization without effective training of AM on the tools and skills needed for operation is void, referring it as ‘fiasco’. From Veiga’s perspective, adequate training on mining methods and process of ore particularly on chemicals usage should be prioritized.

Again, Hilson & Potter (2005), argue that the logic in the legalization of the small-scale gold mining, in Ghana, lies in its resilience and ability to reduce poverty amidst government crackdown. This implies that better mining policies and their effective implementations are necessary, to improve household income and livelihood as well as the performance of the sector. To all extents and purposes, bridging these recommendations of these expertise’s coupled with proper regulations of land tenure systems through distinctive description of land and mineral rights as well as flexible licensing procedure for AM would make the sector more attractive. AM would be encouraged to operate in a transparent and environmentally clean manner given the clear description of boundaries of operations, mining and
environmental regulations as well as the policies governing mineral resources. This will fundamentally help changed the sector’s known ‘dirty’ practice phenomenon and potentially be attractive for corporate and investors.

Typically, the indigenous people hold an allodial title to the land with designated a traditional ruler, usually the chief who is the custodian and holds title to the lands in trust for the community. He also plays a vital role in the society such as administering farming and mining activities it for the benefit of his subjects. This perhaps gives the traditional rulers and natives usufructuary right and interest to pursue their course for livelihood especially to an inheritance handed by ancestors. However, the chief have little control or authority in terms of property allocation to a third party such as LSM by the government, although the chiefs are the caretakers of the land.

A-5.1 Conflict case

Promotion of foreign investment within the LSM on the part of the Ghanaian government has been the key for an increase in revenue and therefore turns to give much attention to companies rather than the indigenous and therefore less power to the Chiefs.

Hilson (2003), noted how the Ghanaian government has perpetually worsened disrupted the livelihoods of many of the country’s rural inhabitants and indigenous small-scale miners by giving preferential treatment to foreign international mining corporations. LSM according to Seidu (2015) are incentivized with supportive mechanisms by the government, including access to geological data, technical aid as well as tax incentives to attract foreign investment, which is rare in ASM which is perhaps not of prime interest to the state. Beyond this discrimination, accessibility to land for farming and mining activities has been a serious problem imposed by LSM.

The rights for resource accessibility by the local community who owned the land from their ancestors and predecessors have been denied for not holding rights, depriving them from their property. While the LSM possess all the legal title and mineral rights and, therefore, any trespassing and unlawful
transactions is deemed criminal. This multiplicity of overlapping interests has obvious implications for determining who is entitled to rights.

A-5.2 Violence due to Influx

In spite of its internal issues involving stakeholders such as the government, LSM and ASM on rights to resource and land, there are some large number of illegal immigrants that caught the attention of these proliferating policies to operate under covers and some in conspiracy with the locals to engage in illegal mining.

For example, in 2013 large influx of Chinese migrant workers invaded the WAPMA with non-conformance as well as causing damage to farm lands, polluting drinking water and destroying lands. This ignited huge violence and armed attacks between these illegal Chinese AM and Ghanaian natives which resulted in loss of lives. As a result, the Ghana government instituted a special task force to crack down these illegal migrant which resulted in the deportation of over 4,000 Chinese illegal AM. (The Guardian, 2013).

A-6 Explanatory Spatial Data Analysis (ESDA)

Explanatory Spatial Data Analysis (ESDA) comprises a collection of visual and numerically resistant techniques for summarizing data properties, detecting patterns in data, and identifying unusual or interesting features in data including data errors and formulating hypotheses (Haining, 2009). It is important to relate characteristics of a feature with its corresponding geospatial information data to assist in the decision-making process.

Explanatory Spatial Data Analysis (ESDA) utilizes spatial data and map information to identify the spatial relationship of actual features and data to aid in analysis. ArcGIS software is capable of handling spatial index and queries due to spatial referencing of data incorporated which in turn aid in visualization as the production of a thematic map. An essential conduct of the ESDA is that the map produced becomes a visualization tool (Dorling, 1994). However, viewer’s discretion on spatial visualization limits the integrity of map produced by GIS technology particularly in scale unit causing biasness in decision-making.
The focused on this work is to appreciate how GIS technology supports ESDA essentially for analytical purposes.

**A-6.1 Geovisualization**

Geovisualization (GVis) combines scientific visualization with digital cartography to support the exploration and analysis of geographic data and information, including the results of spatial analysis or simulation. GVis leverages the human orientation towards visual information processing in the exploration, analysis and communication of geographic data and information. In contrast with traditional cartography, GVis is typically three- or four-dimensional (the latter including time) and user-interactive.

There is considerable potential in planning to use artificial intelligence techniques to generate solutions to complex problems. Smith et al. (1988) demonstrated this by applying knowledge-based system technology to a planning GIS in order to generate possible land-use classification, given a variety of environmental datasets and constraints. Armstrong et al. (1992) demonstrated the need to integrate spatial analytical tools with interactive user interference to facilitate visualization and cooperative human decision-making. Geographical characteristics of features such as ground and surface water are spatially modeled through phenomena for easy visualization and understanding. This is done through accurate and precision measurement of the feature through a system, which is statistically categorized into nominal, ordinal, interval, and ratio elements, which aid in classification analysis.

Nominal measurement in this work will represent the type of feature (criteria) or category that distinguishes one from another feature, say waterbodies and roads. Ordinal observation utilizes category rankings or ratings in order of candidates which includes the size and the extent of the feature. Interval scales quantify the difference between particular observations, such as the distance between the proposed facility center and existing feature. These techniques were employed in the site selectivity analysis. The increasing ability to capture and handle geographic data means that spatial analysis is occurring within increasingly data-rich environments. GIS provide platforms for managing these data, computing spatial
relationships such as distance, connectivity and directional relationships between spatial units, and visualizing both the raw data and spatial analytic results within a cartographic context.

**A-6.2 Primary Data Sources**

This data is obtained through traditional survey methods such as remote control surveys and, ground surveys and are captured using traditional survey instruments such as Total Stations and Global Position Systems (GPS). With advancements in technology, GPS is most commonly used now for most surveys.

**A-6.3 Secondary Data Sources**

This data involves the transformation of conventional map or photograph data into a digital storage format through the use of scanners and digitizers. GIS incorporates conventional data through the method of digitization and geocoding data into computerized tools with converted information. This includes such information as the location of rivers and roads.

Geo-information data that are already in digital forms, such as images taken by satellites and most tables, can simply be uploaded into GIS and processed. Information sources such as maps are easily accessed and updated with this technology and can be simply added to an existing GIS program for analysis. This skips the traditional process of drawing a map, which can be time-consuming and expensive.

There is largely theoretical and empirical literature on the efficiencies of GIS map applications over traditional (analog) maps. This includes information reliability (Legg, 1992). The author emphatically noted economic benefit and minimum production time requirements of map production using GIS technology. However, as noted by Jones (1997), the bulk of available surveys were stored originally using conventional map documents which poses issues of digital mapping when digital conversion to be processed in GIS.

The importance and benefits of GIS does not imply that the system is 100% reliable with no pitfalls. According to Maling (1991), the effect of inherent inaccuracies of utilizing derived datasets from secondary sources such as digitized maps through GIS applications could result in some degree of errors. This is due to lack of technical skills and spatial intelligence in handling geo-spatial data. Conversely, the spherical
assumption of the earth makes data quite often appropriate. It is important to note that traditional conventional maps can be used in conjunction with GIS information for better interpretation and to supplement field checking for reliable base map features. GIS can also include data in an attribute table form, such as geographical information which is illustrated in Appendix A-7.5

A-6.4 Benefits of GIS

GIS have been applied in virtually every imaginable field of activity from engineering to agriculture and from medical science to flood and wildlife management (Wolf & Brinker, 1994). Goodchild (n.d), extensively reviewed various application of the tool and the potential benefits of the system. Beyond the capability of the system, the author recommends that GIS should be an art of science, noting that, should policies be integrated with the tool, it would provide a positive return ranging from project and policy implementation. The author illustrated how geographic information science enables users and decision makers with limited mathematical tools to perform sophisticated analyses compared to other programs.

To the geologists studying fractures and faults within an area of study, as well as for classifications and prediction of mineralization, this technology has realized numerous benefits (USGS, 2015). Hazard prediction and planning mitigation measures is one particular example utilized by Zulherman et al. (n.d) to predict high-risk geohazards through GIS application. Comparing population growth to resources, such as drinking water or determining a region’s future needs for public services like parking, roads, and electricity, are examples of benefits of the tool.
Appendix A-7 Suitability Levels for Each Standardized Criteria

The suitability levels for each evaluated criteria grouping is shown in Figure A-7.

Figure A-7 Suitability Levels of each of the standardized criteria.
A-7.1 Analytical Hierarchy Process (AHP)

A-7.1.1 Pairwise Comparison Matrix, giving $\eta = 7$ (number of criteria)

<table>
<thead>
<tr>
<th>Scale (Row x Column)</th>
<th>Dist-to-ASM</th>
<th>Dist-to-Roads</th>
<th>Dist-to-Railroads</th>
<th>Dist-from-Settle</th>
<th>Dist-to-Water</th>
<th>Slope</th>
<th>Dist-from-Fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dist-to-ASM</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Dist-to-Roads</td>
<td>1/2</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Dist-to-Railroad</td>
<td>1/3</td>
<td>1/3</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Dist-from-Settlement</td>
<td>1/5</td>
<td>1/4</td>
<td>1/2</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Dist-to-Waterbodies</td>
<td>1/6</td>
<td>1/5</td>
<td>1/4</td>
<td>1/3</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Slope</td>
<td>1/7</td>
<td>1/7</td>
<td>1/5</td>
<td>1/5</td>
<td>1/2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Dist-from-Fault Zone</td>
<td>1/9</td>
<td>1/8</td>
<td>1/6</td>
<td>1/6</td>
<td>1/4</td>
<td>1/3</td>
<td>1</td>
</tr>
<tr>
<td>$\Sigma$</td>
<td>2.45</td>
<td>4.05</td>
<td>8.12</td>
<td>12.70</td>
<td>19.75</td>
<td>27.33</td>
<td>37.00</td>
</tr>
</tbody>
</table>

$$\bar{a}_{kj} = \frac{a_{jk}}{\sum_{l=1}^{m} a_{lk}} \quad \text{Normalized weights} \quad (1)$$

$$w_j = \frac{\sum_{l=1}^{m} \bar{a}_{jl}}{m} \quad \text{Averages of Weights} \quad (2)$$

$$S = [s^{(1)} ... s^{(m)}] \quad (3)$$

$$v = S \cdot w \quad (4)$$

From equation 1,

Appendix A-7.1.2 The normalized weights are derived as:

<table>
<thead>
<tr>
<th>Scale (Row x Column)</th>
<th>Dist-to-ASM</th>
<th>Dist-to-Roads</th>
<th>Dist-to-Railroads</th>
<th>Dist-from-Settle</th>
<th>Dist-to-Water</th>
<th>Slope</th>
<th>Dist-from-Fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dist-to-ASM</td>
<td>0.4080888</td>
<td>0.49369307</td>
<td>0.36960984</td>
<td>0.39370172</td>
<td>0.30379747</td>
<td>0.2569787</td>
<td>0.24224324</td>
</tr>
<tr>
<td>Dist-to-Roads</td>
<td>0.20403441</td>
<td>0.24684554</td>
<td>0.36960984</td>
<td>0.31495317</td>
<td>0.25315456</td>
<td>0.2559787</td>
<td>0.21621622</td>
</tr>
<tr>
<td>Dist-to-Railroad</td>
<td>0.13466271</td>
<td>0.0822395</td>
<td>0.12320328</td>
<td>0.15748069</td>
<td>0.20253165</td>
<td>0.18292705</td>
<td>0.16216216</td>
</tr>
<tr>
<td>Dist-from-Settlement</td>
<td>0.08161377</td>
<td>0.06171163</td>
<td>0.06160164</td>
<td>0.07874034</td>
<td>0.15189687</td>
<td>0.18292705</td>
<td>0.16216216</td>
</tr>
<tr>
<td>Dist-to-Waterbodies</td>
<td>0.06801161</td>
<td>0.04936931</td>
<td>0.03080382</td>
<td>0.02624416</td>
<td>0.0563291</td>
<td>0.07317082</td>
<td>0.10810811</td>
</tr>
<tr>
<td>Slope</td>
<td>0.03527223</td>
<td>0.03524909</td>
<td>0.02464066</td>
<td>0.01574807</td>
<td>0.02531640</td>
<td>0.03058541</td>
<td>0.08108108</td>
</tr>
<tr>
<td>Dist-from-Fault Zone</td>
<td>0.04533645</td>
<td>0.03085582</td>
<td>0.02053392</td>
<td>0.01312365</td>
<td>0.01265823</td>
<td>0.01219392</td>
<td>0.02702703</td>
</tr>
<tr>
<td>$\Sigma$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Appendix A-7.1.3 Averaging the entries on each row of the normalized matrix equation 2

<p>| | |</p>
<table>
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<tr>
<th></th>
<th></th>
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</thead>
<tbody>
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<td>Dist-to-ASM</td>
<td>2.47</td>
</tr>
<tr>
<td>Dist-to-Roads</td>
<td>1.86</td>
</tr>
<tr>
<td>Dist-to-Railroad</td>
<td>1.05</td>
</tr>
<tr>
<td>Dist-from-Settlement</td>
<td>0.78</td>
</tr>
<tr>
<td>Dist-to-Waterbodies</td>
<td>0.41</td>
</tr>
<tr>
<td>Slope</td>
<td>0.28</td>
</tr>
<tr>
<td>Dist-from-Fault Zone</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Appendix A-7.1.4 Combine equation 3 and 4 for global score = lambda \( \lambda \)

<table>
<thead>
<tr>
<th>Sum of Weights(S)</th>
<th>Average of Weight (w)</th>
<th>( \lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.45</td>
<td>0.35</td>
<td>0.86</td>
</tr>
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<td>4.05</td>
<td>0.27</td>
<td>1.08</td>
</tr>
<tr>
<td>8.12</td>
<td>0.15</td>
<td>1.21</td>
</tr>
<tr>
<td>12.70</td>
<td>0.11</td>
<td>1.42</td>
</tr>
<tr>
<td>19.75</td>
<td>0.06</td>
<td>1.15</td>
</tr>
<tr>
<td>27.33</td>
<td>0.04</td>
<td>1.08</td>
</tr>
<tr>
<td>37.00</td>
<td>0.02</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Total lambda \( \lambda = 7.65 \)

From equation 7

\[
CI = \frac{\lambda_{max} - \eta}{\eta - 1}
\]

\[
7.65 - 7 \quad \frac{7 - 1}{\eta - 1} = 0.108
\]

Appendix A-7.2

2nd Iteration

<table>
<thead>
<tr>
<th>Scale (Row v Column)</th>
<th>Dist-to-ASM</th>
<th>Dist-to-Road</th>
<th>Dist-to-Railroad</th>
<th>Dist-from-Settle</th>
<th>Dist-to-Water</th>
<th>Slope</th>
<th>Dist-from-Fault Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dist-to-ASM</td>
<td>0.39549534</td>
<td>0.40927018</td>
<td>0.423539077</td>
<td>0.420329978</td>
<td>0.408386252</td>
<td>0.40499</td>
<td>0.389826355</td>
</tr>
<tr>
<td>Dist-to-Roads</td>
<td>0.25109168</td>
<td>0.239567359</td>
<td>0.250030568</td>
<td>0.254483957</td>
<td>0.269129792</td>
<td>0.27115</td>
<td>0.267921156</td>
</tr>
<tr>
<td>Dist-to-Railroad</td>
<td>0.13342453</td>
<td>0.12867724</td>
<td>0.119572855</td>
<td>0.121519941</td>
<td>0.127908752</td>
<td>0.13069</td>
<td>0.137457386</td>
</tr>
<tr>
<td>Dist-from-Settlement</td>
<td>0.08387832</td>
<td>0.084348759</td>
<td>0.0778807</td>
<td>0.076419922</td>
<td>0.079194172</td>
<td>0.08213</td>
<td>0.09156152</td>
</tr>
<tr>
<td>Dist-to-Waterbodies</td>
<td>0.05665166</td>
<td>0.058285152</td>
<td>0.054343835</td>
<td>0.053105276</td>
<td>0.049140912</td>
<td>0.04817</td>
<td>0.050773991</td>
</tr>
<tr>
<td>Slope</td>
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<td>0.045484893</td>
<td>0.041902377</td>
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<td>0.037292885</td>
<td>0.03551</td>
<td>0.03622897</td>
</tr>
<tr>
<td>Dist-from-Fault Zone</td>
<td>0.03138992</td>
<td>0.034357568</td>
<td>0.032723217</td>
<td>0.032690178</td>
<td>0.029010765</td>
<td>0.02736</td>
<td>0.026230622</td>
</tr>
<tr>
<td>( \Sigma = )</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Appendix A-7.2.1

<table>
<thead>
<tr>
<th>Sum of Weights($)</th>
<th>Average of Weight (w)</th>
<th>$\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.45</td>
<td>0.41</td>
<td>1.00</td>
</tr>
<tr>
<td>4.05</td>
<td>0.25</td>
<td>1.05</td>
</tr>
<tr>
<td>8.12</td>
<td>0.13</td>
<td>1.04</td>
</tr>
<tr>
<td>12.70</td>
<td>0.08</td>
<td>1.05</td>
</tr>
<tr>
<td>19.75</td>
<td>0.05</td>
<td>1.05</td>
</tr>
<tr>
<td>27.33</td>
<td>0.04</td>
<td>1.09</td>
</tr>
<tr>
<td>37.00</td>
<td>0.03</td>
<td>1.15</td>
</tr>
</tbody>
</table>

Appendix A-7.3

3rd Iteration

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight (w)</th>
<th>$\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dist-to-ASM</td>
<td>0.41</td>
<td>1.00</td>
</tr>
<tr>
<td>Dist-to-Roads</td>
<td>0.25</td>
<td>1.01</td>
</tr>
<tr>
<td>Dist-to-Railroad</td>
<td>0.13</td>
<td>1.05</td>
</tr>
<tr>
<td>Dist-from-Settlement</td>
<td>0.09</td>
<td>1.07</td>
</tr>
<tr>
<td>Dist-to-Waterbodies</td>
<td>0.06</td>
<td>1.10</td>
</tr>
<tr>
<td>Slope</td>
<td>0.04</td>
<td>1.16</td>
</tr>
<tr>
<td>Dist-from-Fault Zone</td>
<td>0.03</td>
<td>1.18</td>
</tr>
</tbody>
</table>

Appendix A-7.4

4th Iteration

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight (w)</th>
<th>$\lambda$</th>
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</thead>
<tbody>
<tr>
<td>Dist-to-ASM</td>
<td>0.400</td>
<td>1.00</td>
</tr>
<tr>
<td>Dist-to-Roads</td>
<td>0.251</td>
<td>1.02</td>
</tr>
<tr>
<td>Dist-to-Railroad</td>
<td>0.129</td>
<td>1.05</td>
</tr>
<tr>
<td>Dist-from-Settlement</td>
<td>0.085</td>
<td>1.07</td>
</tr>
<tr>
<td>Dist-to-Waterbodies</td>
<td>0.055</td>
<td>1.10</td>
</tr>
<tr>
<td>Slope</td>
<td>0.043</td>
<td>1.16</td>
</tr>
<tr>
<td>Dist-from-Fault Zone</td>
<td>0.032</td>
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</tr>
</tbody>
</table>
Appendix A-7.5 Attribute Data of Evaluated Suitable Sites (Unsuitable and Suitable)

<table>
<thead>
<tr>
<th>OBJECTID</th>
<th>VALUE</th>
<th>AREA</th>
<th>PERIMETER</th>
<th>THICKNESS</th>
<th>XCENTROID</th>
<th>YCENTROID</th>
<th>MAJORAXIS</th>
<th>MINORAXIS</th>
<th>ORIENTATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>932553800</td>
<td>1557328</td>
<td>6457.178</td>
<td>562844</td>
<td>641458.2</td>
<td>26496.84</td>
<td>11203.09</td>
<td>164.5813</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1500650000</td>
<td>1491745</td>
<td>6366.656</td>
<td>595045.6</td>
<td>630467.7</td>
<td>27128.23</td>
<td>17508.66</td>
<td>135.4044</td>
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</tbody>
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