A GIS-AHP Based Approach for Optimal Quarry Site Location Around Harer and Dire-Dawa Towns, Eastern Ethiopia

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Keywords: Aggregate quarry, Analytic Hierarchy Process (AHP), Suitability analysis, weighted overlay

Posted Date: August 27th, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-58834/v1>

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Abstract

The scarcity of lands for suitable quarry sites is rapidly becoming a critical growing problem in most developing countries of the world. Therefore, selection of optimal quarry sites for crushed aggregates is a prerequisite for safe operation and economic viability. The present study was carried out around Harer and Dire-Dawa towns located about 520 km from Addis Ababa. The main objective of the study was to identify optimal location of quarry sites for crushed aggregates by using integrated Analytic Hierarch Process (AHP) and GIS approach. Selection was carried out by considering factors such as lithology, land-use and land-cover, distance to built-up areas, distance to water bodies, distance to roads, relative relief, and slope angle. For each of the factors appropriate classifications and criteria were formulated based on its suitability. Finally, by utilizing all factors, weighted overlay analysis was applied to produce the quarry site suitability map. The resulted suitability map shows about 136km² of the area is highly suitable, 1,587km² is moderately suitable, and 2,166km² has low suitability for quarry site development. The findings of the study will be helpful in narrowing down the area to the suitable areas that may further be studied through detailed field investigation. This result will also greatly serve as guide in quarry site selection in other states and/or other developing countries.

1. Introduction

The menace of environmental degradation and pollution resulting from quarry operation has been a threat to the inhabitants of most developing countries and its harmful effects on the major roads, power lines, built ups, and water environment are considered to be frightening. As a result of quarrying natural habitats and features such as; hedgerows and trees can be removed (Saha and Padhy 2011). Quarrying activities have the potential to impact an area of valuable habitat, particularly when it is located in the vicinity of such habitats. Habitats outside the quarry site can be impacted indirectly by dust deposition, alteration of the water supplies, or as a result of run-off or siltation (Ogbonna et al. 2019). The archaeological heritage is a non-renewable resource therefore; the presence of known archaeological sites must be an essential consideration during the selection of quarry sites (Akanwa et al. 2017; Kindiga 2017; Barakat et al. 2016; Regessa et al. 2015; Zaruba and Mencl 1976). Similar considerations apply in the case of protected structures. Blasting at quarries can give rise to vibration, noise, fly rock, and dust. Noise can cause annoyance; nuisance, and sleep disturbance. Residential, schools, hospitals, churches, etc. are noise-sensitive receptors. Thus, for the extraction of dimension stones, aggregates for concrete pavement, railway ballast and other construction materials, selection of suitable quarry site is essential. A quarry is an open pit used for mining of rock or minerals for various purposes. Most communities all over the world are often faced with task of making a suitable decision when finding the most appropriate sites for new quarry as process of making choice is a complex procedure since social, environmental and technical factors must be considered together (Ming'ate and Mohamed 2016). In most of the African nations, the selection of quarry sites and its operations and management do not take into account the environmental sustainability (Darwish et al. 2011). Generally, the methods followed for resource extraction are poor and the site selection for quarrying are not made through systematic methods. Very often this leads to land collapse, land conversion, environmental pollution and may also affect the people residing in the nearby localities (Pal and Mandal 2019; Ethirajan and Mariappan 2018). Thus, need for proper site selection, quarrying planning and management is essential not only for successful quarry operations but also it is equally important for quality control and sustainable environmental management (Egesi and Nwosu 2018).

Rocks for aggregates are quarried through blasting using explosives and/ or mechanical excavation by using machineries. The aggregate production from the rock involves mechanical crushing, screening, loading, and transportation processes (Langer et al. 2004). The quarry excavation may cause land conversion of previous land use and possibly lead to environmental degradation, if quarrying is not well planned and managed (Ming'ate and Mohamed 2016). The primary sources of crushed aggregate are the alluvial deposits and various types of rocks such as; basalt, gneiss, dolomite and limestone etc (Barakat et al. 2016).

For suitable quarry site selection various factors can be considered such as; lithology, land-use and land-cover, distance to built-up area, distance to streams/ water bodies, distance to roads, relative relief and slope angle. These factors may possibly influence quarry site with respect to its geotechnical, economic and environmental suitability during its operational and decommissioning phases of materials extraction. In order to apply these factors to identify suitable quarry sites, systematic framework through Analytical Hierarch Process (AHP) can be applied. AHP is a technique which can be applied in a GIS environment that provides a flexible and easily understandable way of analyzing complicated problems that allows subjective as well as objective factors to be considered in a decision-making process (Kou et al. 2016; Vaidya and Kumar 2006; Dey and Ramcharan 2008).

For natural aggregate production tremendous time and money is spent in locating potential aggregate resources and in determining their quantity and quality (Langer et al. 2004; Langer and Tucker 2003). Besides, efforts are also made to determine the feasibility of production, environmental impact assessment, fulfillment of the norms set as mining laws, in procurement of permit for mining operation, processing and transportation. The first step in aggregate exploration is a preliminary geological, geotechnical, environmental and economic evaluation. The preliminary investigations are followed by detailed studies that involve satellite image interpretation and field reconnaissance studies of target areas to define the limits of the potential sources of aggregate. According to Barakat et al. (2016), rocks exposed at higher elevations are less desirable for quarrying operations because of poor accessibility and high transportation costs. Similarly, rocks forming steep slopes are susceptible for instability (Raghuvanshi 2019; Barakat et al. 2016; Raghuvanshi et al 2014; Anbalagan 1992; Tan 1984) therefore such steep slopes may not be feasible for quarrying operation and may further pose problems in accessibility and developing roads on steep slopes may incur additional cost to the project.

According to Akanwa et al. (2017) quarry operations may leads to loss of vegetation cover. Moreover, Subhasis et al. (2018); SOPAC (2005) indicated that quarry operations have impact on environment through air, noise pollution and vibrations. According to Langer et al. (2004), changing a landscape from agricultural lands to a quarry is also an obvious impact of quarrying. Further, it is required to assess the potential impacts of quarrying activities on soil and water resources, and on the populated areas so that anticipated risks due to potential quarry sites may be minimized (Pal and Mandal 2019; Regessa et al. 2015; Darwish et al. 2011). Further, Barakat et al. (2016); Regessa et al. (2015); Tan (1984) has identified prominent parameters such as; slope angle, elevation difference, land-use and land-cover and rock type have significant effect on the suitability and feasibility of quarry site.

Integrated Analytic Hierarch Process (AHP) with GIS has been adopted in previous works for selection of groundwater recharge site (Rajasekhar et al. 2019), land fill site (Akanwa et al. 2017; Dimopoulou et al. 2013; Ebistu and Minale 2013; Zelenović et al. 2012; Yoxas et al. 2011; Ketema 1982), and for selection of mining methods (Mandal and Mondal 2016; Ataei et al. 2008). In Ethiopia not much previous studies were carried out to identify suitable quarry sites by following systematic criteria based expert judgment. A study carried out by Regessa et al. (2015) followed the criteria based quarry sites selection procedure to select potential quarry sites for ballast aggregate. For selection of suitable quarry sites in the study area they formulated selection criteria and applied it in GIS environment. Another study was carried out by Getahun (2010) in which multi-criteria approach was used to select the appropriate quarry sites by using GIS and Remote Sensing approach. To prepare the suitability map weighted linear combination method was used and a pair-wise comparison matrix was developed for the selected parameters. However, integrated AHP and GIS approach has not been adopted in aggregate quarry site selection, particularly in Ethiopia. Therefore, the main objective of the present study was to identify suitable potential quarry sites for crushed aggregates by using integrated Analytic Hierarch Process (AHP) and GIS approach.

2. Description Of The Study Area

The study area is located in the Eastern part of Ethiopia, about 520 km from Addis Ababa. The area is bounded by UTM coordinates of 746247-886247E and 994861-1084861N (Fig. 1). Harer town is accessible from Addis Ababa through asphalt road, where as Dire-Dawa town can be accessed either by road, by air or by train. Topography of the area is characterized as rugged with elevation ranging from 976 to 3378 masl. Ahmar mountain chain which runs from east to west along the margin of the eastern plateau is a distinct physiographic highland feature in the study area. The northern part of the study area forms the valley whereas; southern area is characterized by gently undulating surfaces and occasionally cliffs.

The present study area is situated in “kola” agro-climatic region. The temperature is hot throughout the year with minor seasonal variations and progressively increasing temperatures towards northward. The rainy seasons are from March to September, with an irregular rainfall during February to May and a regular maximum rainfall from July to September. The mean annual rainfall is 850 mm and the mean annual temperature is 25°. June is the warmest month in the year while December and January are the coldest.

3. Geology Of The Study Area

The regional geology of Harer and Dire-Dawa area ranges from Precambrian basement rocks up to recent sediments (Fig. 2). The Precambrian rocks include Archean high-grade gneisses and migmatites, Archean amphibolite rock and Proterozoic rocks (low-grade quartz-mica schist: schistose fine-grained rock, pelitic and psammitic biotite schist, amphibole schist, quartzites, and marbles). In the study area, Precambrian-Proterozoic massive granite is exposed on elevated portions and is underlying the lower sandstone. The rocks belonging to upper Paleozoic, Soka Group, includes phyllite, greenstone, chert, serpentinites, and talc schist is also exposed in the study area. The Mesozoic succession of Dire-Dawa and Harar province consists of lower fluvialite sandstone, carbonate, and upper fluvialite sandstone (Bosellini et al. 2001). Cenozoic volcanic rocks (oligocene) Alaji basalt, and (middle Miocene) Tarmaber basalts are exposed at plateau. The rift plain and parts of major eroded valleys on the plateau contain Quaternary alluvial sediments of lacustrine origin. Further, re-deposited valley sediments occur on gentle slopes, interfluvies and wide valley floors both on the plateau and the rift zones (GSE 2010).

The local geology of the study area is dominantly covered by the Antalo limestone (Fig. 2). Gildessa limestone, exposed in northeast of Dire-Dawa town consists of massive grainstone, oolitic coarse grainstone, parallel and cross lamination with marine coral fragments. It also consists of Dire-Dawa Formation which is black micritic limestone and marls rich in belemnites, ammonites and Gryphaea and marly limestone. The Antalo limestone overlies the lower Adigrat sandstone unit. The topmost part of the limestone is weathered and the limestone in the Dire-Dawa area mostly covers the escarpment zone (Ketema 1982). Well sorted upper sandstone of the Mesozoic Era is also exposed around Dire-Dawa town and overlies the Antalo limestone.

The main geologic structures present in the limestone unit are joints, solution cavities, and karstification. These structures are developed along the bedding planes and along the major tectonic directions. The limestone beds around Dire-Dawa town dip towards south and southwest and strike east-west and NW-SE direction. The limestone beds have usually a horizontal orientation (dips below 10°). Major joints run in N-S direction along with the Ethiopian rift system while minor joint sets are perpendicular to the major joints (Ketema 1982).

4. Materials And Methods

Materials

The supporting materials and analytical tools used in the present study are: topographic map at a scale of 1:50,000, Landsat 8 images, Google Earth images and Digital Elevation Model (DEM) extracted from ASTER data set and Geological map of Dire Dawa and Harer sheets (scale of 1:250,000) prepared by GSE in 2010. Further, Arc GIS, ERDAS Imagine and Global Mapper software were used for the preparation of various maps used in the present study. Besides, IDRISI was also used for the computation of pair-wise comparison matrix for the factors. The geological map of the area was firstly georeferenced and subsequently digitized to show criteria features considered for selecting quarry site in the GIS environment.

Methods

In the present study systematic procedures were followed to meet out the objective of the study. The steps involved in the preparation of suitability map for quarry site are shown through flow chart (Fig. 3). The selection of suitable area for quarry sites require classification of selected factors and formulating weighted criteria by using GIS approach (Alanbari et al. 2014; Ebistu and Minale 2013; Zelenović et al. 2012; Yoxas et al. 2011).

The Landsat 8 2018 (path 167, row 53 and 54) was used to prepare the land-use and land-cover (LULC) map of the study area. A tentative LULC thematic map was obtained from the false color composite of the image with 30 m resolution which was pan sharpened and redefined to 15 m resolution. Google Earth image was also used for controlling training pixels. Later, final verification and modifications of the prepared LULC map was done through field observation using GPS control points. Distance to existing roads was derived from the Ethiopian road network map prepared by Ethiopian Roads Authority (ERA) in 2006 at a scale of (1:2,000,000), topographical maps (1:50,000) and by Google earth image interpretations. The data for lithology was obtained from the geological map and the field visual observations. Geological maps of Harer and Dire Dawa sheet (1:250,000 scale) were mosaiced and refined to prepare the geological map of the study area. Later, the geological map was verified and modified through field observations. Further, distance to build up areas and distance to water bodies was extracted from the topographical maps (1:50,000) and the Google Earth images. Distance to roads was modified from the Ethiopian roads network map prepared by

Ethiopian Roads Authority (ERA) in 2006 at a scale of (1:2,000,000). Slope angle and relative relief were extracted from ASTER GDEM data set at 15 m resolution and later reclassified for quarry site selection. Thus, desired thematic layers on lithology, distance to buildup areas, land-use and land-cover, distance to water body, distance to roads, relative relief, and slope angle were extracted. Later, all these thematic layers were processed in GIS and vector to raster conversion was made. Further, each of the thematic layers was reprocessed and classification was made.

AHP Model

For valuation of the criteria features, various methods such as logistic regression, AHP model, weight of evidence, ratio estimation and the Delphi process could be chosen (Adewumi et al. 2019). Several researchers have used AHP method of pair-wise comparison matrix, in order to assign the weights to each of the considered factors (Haile and Suryabhagavan 2019; Rajasekhar et al. 2019; Ramík 2017; Mandal and Mondal 2016; Ataei et al. 2008; Vaidya and Kumar 2006). The weights quantify the relative importance of the considered suitability criteria. The essence of pair wise comparison is that two criteria are evaluated at a time to determine their relative importance (Mayunga 2018; Vaidya and Kumar 2006). In this research, AHP model was adopted in order to give value to the criteria and select the best appropriate site. Once the hierarchy has been established, a pair wise comparison matrix of each element within each level is constructed. This pair-wise comparison permits for an independent rating of each factor's contribution, which therefore simplify the decision-making process (Adewumi et al. 2019). The eigenvalue of the comparison matrix gave the relative importance of the criteria being compared. Participants can weigh each element against each other within each level, which is related to the levels above and below it, and mathematically tie the entire scheme together. The consistency check offered by AHP makes it a unique tool in the decision-making since it allows improvement in making decision. The consistency of the weight for various factors was checked through, a single numerical value, the consistency ratio (CR), which measures the level of inconsistency of the pair wise comparison matrix (i.e. the likelihood whether factor weights were randomly assigned). The consistency ratio (CR) can be defined by the mathematical relation equation (Vaidya and Kumar 2006);

$$CR = \frac{CI}{RI} \quad (1)$$

Where CI is the consistency index and RI is random consistency index of a comparison matrix. CI was computed as:

$$CR = \frac{\lambda_{\max} - n}{n - 1} \quad (2)$$

Where ' $\lambda_{\max}$ ' is the largest eigenvalue of the comparison matrix and ' n ' is the number of criteria or factors.

AHP is a powerful and popular technique which can be applied in a GIS environment and provides a means for analyzing complicated problems that allows subjective as well as objective factors to be considered in a decision-making process (Haile and Suryabhagavan 2019; Kou et al. 2016; Jablonsky 2015; Dimopoulou et al. 2013; Vaidya and Kumar 2006).

Formulating quarry site selection criteria based on classification and reclassification of values into certain ranges with regard to suitability was a crucial component for identifying suitable areas for quarry sites. Once the weighting was worked out and criteria for classification was formulated; the next step involved was the creation of individual thematic layers or factor maps to be overlaid. Finally, by weighted overlay analysis and integrating the entire thematic factor layers, quarry sites suitability map was prepared.

Some areas with restrictions such as very low cohesive rocks (alluvium, elluvium and lake sediments), some land uses (residential areas, protected areas), etc are removed from whole considered area according to Boolean logic.

The considered factors for quarry site suitability map preparation, their significance and relative order of importance is presented in Table 1.

Table 1
Factors for quarry site suitability map preparation, their significance and order of importance

S/N	Factors	Significance	Order of importance
1	Lithology	Lithology is the most important factor governing the quality of rock; for example; some flaky, soft and friable rocks cannot be used as aggregate.	Extremely strong influence
2	Land-use and land-cover	Environmental code of practices preserves and protects cultural heritages, archeological sites, parks and built-up areas. Thus, LULC may totally prohibit the development of quarry site even when good quality and quantity material is available.	Very strong importance over the rest
3	Distance to build up area	Community safety is a sensitive issue showing strong influence on quarry site suitability. However, it does not prohibit the development of quarry site. Quarrying can be possible with appropriate environmental protection and by adopting suitable mitigation measures.	Strong influence
4	Distance to water bodies	Lakes and streams are more susceptible to pollution as runoff from quarry sites flow very rapidly into them. Thus, a safe distance to water bodies needs to be maintained from the quarry sites.	Moderately more important
5	Distance to roads	Distance to roads is an important factor. Close proximity of road to the quarry site may result into dangers of fly rock due to blasting and air pollution. Roads at far distance may result into additional project cost due to development of new roads and increased transportation cost.	Least important but more important than Relative relief
6	Relative relief	Important from slope instability point of view, flooding potential, ease of excavation and inaccessibility.	Moderately important than Slope angle
7	Slope Angle	Induce slope instability but is not the sole factor that triggers the instability.	Relatively least effect

The data processing was mainly done for classification and reclassification of various factor maps in GIS environment. Later, appropriate weights were assigned to the processed factor maps. Besides, consistency of the weight assigned to various factors was also checked. In the present study standardization of heterogeneous input data into a uniform scale for all layers were used; particularly 1 by 7 by 1 scaling method was adopted (Table 3). While assigning the ratings to various factors it is important to know the suitability of various factor classes.

Reclassification of thematic layers

Reclassification of thematic layers facilitates the interpretation of raster data by changing a single input value into a new output value. It also helps to group ranges of cell values into a single value. This simplifies weighted analysis as different types of raster data in different factor sub-classes may represent different conditions. Thus, by using reclassification for each thematic layer, ranking scheme based on pre defined weights can be used to work out least and most suitable conditions (Anbalagan 1992). All thematic maps were prepared, geo-processed, reclassified in GIS environment and vector to raster conversion was made. The geological map of the study area was reclassified into seven lithological classes. These classes are; (i) Basalt, (ii) Limestone, Travertine and Dolomite, (iii) Granite, (iv) Gneiss and Amphibolites, (v) Schist, Phyllites, Greenstone, Chert, Serpentinites and Talc, (vi) Detrital Sandstone, Conglomerates and Shales and (vii) Lake sediment, Alluvium and Elluvium products. This re-classification was mainly done based on the relative suitability of each lithological unit for the quarry site selection (Table 2). The distribution of these lithological units in the study area is shown through Fig. 4 (a).

Table 2
Factors and factor class suitability and ratings

Factors/ factor classes	Description	Suitability	R	Factors/ factor classes	Description	Suitability	R
Lithology				Distance to Road (m)			
Lake sediment, Alluvium and Elluvium products	Easily disintegrate, contain heterogeneous layers (clay and silt)	Unsuitable	0	< 500	Too short	Unsuitable	0
Detrital Sandstone, Conglomerates and Shales	Soft and friable	Very low	1	> 10000	Far away	Very low	1
Schist, Phyllites, Greenstone, Chert, Serpentinites and Talc	Highly foliated rock, weak, flaky, contains chlorite and micas	Low	2	10000–7500	Intermediate	Low	2
Gneiss and Amphibolites	Poorly foliated rock; flaky	Moderate	3	7500–5000		Moderate	3
Granite	Coarse grained, non crushable, contains K-feldspar, porphyroblasts and quartz	High	4	5000 – 3200		High	4
Limestone, Travertine and Dolomite	Massive and easily crushed	Very high	5	3200 – 1600		Very high	5
Basalt	Igneous dark fine-grained rock	Extre. high	6	1600 – 500		Extre. high	6
Land-use/ land-cover				Relative Relief (m)			
Protected areas, structures, and settlement	Monument, Cave, Air field, and housing	Unsuitable	0	< 5	Extre. low	Unsuitable	0
Forest	Thickly vegetated land	Very low	1	> 300	Extre. High	Very low	1
water bodies and wetland	Lakes, streams, major rivers and wet lands	Low	2	200–300	Very high	Low	2
Cultivated land	Arable land by plowing	Moderate	3	100–200	High	Moderate	3
Shrubs	Scattered vegetation in the form of wild grass, bushes, and small trees	High	4	50–100	Moderate	High	4
Sand cover	No vegetation and the bed rock covered by sand	Very high	5	25–50	Low	Very high	5
Bare land	No vegetation cover	Extre. high	6	5–25	Very Low	Extre. high	6
Distance to build up area (m)				Slope angle (°)			
< 1000	Very close	Unsuitable	0	< 5	Extre. gentle	Unsuitable	0
> 2500	Far away	Very low	1	> 60	High escarpment	Very low	1
2500 – 2200		Low	2	60 – 45	Escarpment or Cliff	Low	2
2200 – 1900	Intermediate	Moderate	3	45 – 35	Steep	Moderate	3
1900 – 1600	Fairly far away	High	4	35 – 25	Moderately steep	High	4

Factors/ factor classes	Description	Suitability	R	Factors/ factor classes	Description	Suitability	R
1600 – 1300		Very high	5	25 – 15	Gentle	Very high	5
1300 – 1000	Not far not Close	Extre. high	6	15 – 5	Very gentle	Extre. high	6
Distance to water bodies (m)							
< 150	Very Close	Unsuitable	0				
150–300	Close	Very low	1				
300–450		Low	2				
450–600		Moderate	3				
600–750	Far away	High	4				
750–900		Very high	5				
> 900		Extre. high	6				

Table 3

Weights assigned, consistency ratio (CR), pair wise comparison matrix, and scaling to assign rating value

Pair wise Comparison – 9 Point Continuous Rating Scale									
1/9	1/7	1/5		1/3	1	3	5	7	9
Extremely	Very strongly	Strongly		Moderately	Equally	Moderately	Strongly	Very strongly	Extremely
Less Important					More Important				
Order of Importance and Rating Assigned									
Unsuitable	V. Low suitable	Low suitable		Moderately suitable		Highly suitable		V. highly suitable	Extremely suitable
0	1	2		3		4		5	6
Pair wise Comparison - Matrix									
Attributes	LI	LU	DB	DW	DR	RR	SA	Eigenvector weights	Weight (%)
LI	1	-	-	-	-	-	-	0.3543	35
LU	1/2	1	-	-	-	-	-	0.2399	24
DB	1/3	1/2	1	-	-	-	-	0.1587	16
DW	1/4	1/3	1/2	1	-	-	-	0.1036	10
DR	1/5	1/4	1/3	1/2	1	-	-	0.0676	7
RR	1/6	1/5	1/4	1/3	1/2	1	-	0.0447	5
SA	1/7	1/6	1/5	1/4	1/3	1/2	1	0.0312	3
Total								1	100
Consistency ratio (CR)								0.02	consistency is acceptable
Note: LI = Lithology; LU = Land use/land cover; DB = Distance to buildup; DW = Distance to water body; DR = Distance to road; RR = Relative relief; SA = Slope angle									

The Land-use/ land-cover (LULC) and distance to build up areas maps in general represent the environmentally sensitive ecosystem and more valuable land use practices. Before the actual use of the Landsat 8 image; a number of image preprocessing such as; layer stack and pan sharpen enhancements were done. Later the image was subset using the study boundary as an area of interest (AOI) and used in the supervised image classification. In the supervised image classification, a signature of what particular classes look like was provided, and the software algorithms subsequently has used this signature (training) to derive rules for mapping all other pixels into the class values. Thus, the resulting reclassified LULC map of the area is presented as Fig. 4 (b).

For the assessment of proximity to the built-up areas euclidean distance to populated centers was computed for each cell. The euclidean distance calculates, the distance of each cell to the closest settlement. A map of distance to build up areas helps to measure the vulnerability of the adjoining community to dust, noise and vibration hazards (Subhasis et al. 2018). Thus, for the present study distance to build up area was reclassified into seven classes based on the relative suitability of each sub-class for the quarry site selection. The various sub-classes for distance to buildup area and their relative suitability for quarry site are presented in Fig. 4 (c).

It is reasonable to say that water bodies very close to the quarry site will be susceptible to water pollution due to quarry operations while those which are relatively far will be free from pollution due to quarry operations. The water body map, prepared for the present study, was reclassified into seven classes based on the relative suitability of each sub-class for the quarry site selection. For the assessment of proximity to the water bodies euclidean distance tool in Arc GIS was used and the resulting map is presented as Fig. 4 (d).

The road map prepared during the present study was reclassified into seven classes based on the relative suitability of each sub-class for the quarry site selection.

Relative relief and slope angle thematic maps were extracted facet wise from the DEM and later these thematic layers were reclassified as per the suitability for the quarry site selection (Fig. 4 (f) and (g)). Relative relief defines the elevation difference within a given slope (Ermias et al. 2017; Raghuvanshi et al. 2014; Anbalagan 1992). According to Raghuvanshi et al. (2014), relative relief for landslide hazard zonation is classified into classes; < 50 (low), 51–100 m (moderate), 101–200 m (medium), 201–300 m (high) and > 300 m (very high). In the present study for quarry site selection, the same criteria were adopted for reclassification of relative relief. However, the classification was made into seven classes as; <5 m (extremely low), 5-25m (very low), 25–50 m (low), 50–100 (moderate), 100–200 m (high), 200–300 m (very high) and > 300 (extremely high).

For the classification of slope angle the works of (Barakat et al. 2016; Raghuvanshi et al. 2015; Raghuvanshi et al. 2014; Anbalagan 1992) were referred. The slope classification proposed by Raghuvanshi et al. (2014) was formulated for landslide hazard zonation and this classification is further refined for the present study to account for quarry site suitability. Thus, the slope angle was distributed into seven classes and their respective suitability is presented in Table 2.

For the suitable quarry site selection process, the input layers for all factors were processed and prepared in raster format. It was important to evaluate the accuracy of a classified image by using known ground truth locations and values before proceeding into the actual use of the image. Thus, 25 random points were selected and an accuracy assessment was made for the LULC classification using the Google earth image as a ground truth.

The order of importance obtained by AHP was converted to percent according to their relative influence, as the overlay analysis requires weight in percentages (Fig. 4). Thus, lithology, LULC, distance to build up area, distance to water bodies, distance to roads, relative relief and slope angle weights were computed as 35%, 24%, 16%, 10%, 7%, 5%, and 3%, respectively. Decimal values were rounded off to the nearest integer. Later, a weighted suitability overlay analysis was made for each cell in GIS environment by the summation of the products of weight with the respective rating value of each factor.

The weighted overlay of the spatial analyst tool was used to overlay 7 raster layers using a common measurement scale based on their relative influence. To run the weighted overlay, all input raster layers must be an integer. The reclassification tool provides an effective way to do the conversion. During reclassification, each value class in an input raster was assigned with a new value based on an evaluation scale.

5. Results And Discussion

In order to optimize suitable areas for quarry sites seven factors were considered. These factors are lithology, distance to buildup areas, land-use and land-cover, distance to water bodies, distance to roads, relative relief and slope angle.

Lithology

The primary sources of crushed aggregate are various types of rocks such as; basalt, gneiss, dolomite and limestone etc. However, all rocks may not be suitable for crushed aggregate. Thus, keeping this in mind, classification of the various lithologies for their suitability in aggregate was performed for the current study (Table 2). A massive, high cohesion, and homogenous rock like basalt is most suitable for the crushed aggregate and a massive limestone also comes next to basalt (Table 2) (BGS 2019; Leroy et al. 2017; Langer and Knepper 1995). However, detrital rocks such as; sand stone, conglomerate and shale are soft, friable and easily disintegrate and contain heterogeneous layers (Mitchell 2015). Therefore, they are considered as the least suitable for the crushed aggregate (Regessa et al. 2015; Saaty 2008; Gilpin et al. 2007). Low cohesive rocks such as alluvium and elluvium products are on the other hand absolutely unsuitable and they were excluded from the results. The rest were placed in between with moderate rating value.

Land-use and land-cover (LULC)

Most environmental code of practices preserves and protects cultural heritages, archeological sites, caves, religious institutes, monuments and parks and they are absolutely unsuitable for quarry sites. Therefore, these protected LULC, settlement, cave, and artificial structures (power line and Air port field) were excluded and other land uses were assigned rating based on their relative suitability. Particularly, bare land was provided the highest suitability rating but dense forest cover was given the least rating.

Distance to build up areas

The nearer a quarry site to sensitive areas, the more un-suitable the site is for quarry purpose. Residents living in proximity to quarries can be endangered by dust up to 0.5km from the source. Severe concerns about dust were mostly experienced within about 100m of the dust source (Subhasis et al. 2018; EPA Tasmania 2017; Darwish et al. 2011; SOPAC 2005) (Table 2). Therefore, the quarry code of practice (EPA Tasmania 2017), suggested planning authorities need to maintain the separation distances of 1000 m, in areas where regular blasting takes place; however where material is crushed, only 750 m separation can be maintained and where vibrating screens alone are utilized 500 m; and where no blasting, crushing or screening occurs a distance of 300 m. For this study, the extreme blasting condition is anticipated and a minimum separation distance of 1000 m is set. Then every 300 m new classes were established (Table 2). If a quarry site is within 1000 m away from settlements, it is very close to the population centers. Thus, they have higher health hazard. In contrary, quarry sites more than 2500 m from builtup area, are far away from consumers and will have market problem with higher transportation cost. However, an area between 1000–1300 m are not far nor close, with less hazard and is considered as economical distance (EPA Tasmania 2017). Therefore, this class was provided the highest suitability rating.

Distance to water bodies

Run off from quarry sites flow very rapidly towards nearby water bodies, thus lakes and streams are susceptible to pollution from quarries (Pal and Mandal 2019). There needs to be strict control of runoff from the quarry sites. The safest way is to leave adequate buffer zones around water-courses and river corridors (Thennakoon 2016) (Table 2). Some quarry code of practice, suggested disturbance should not occur within 40 m of any watercourses or within 10m of drainage lines (EPA Tasmania 2017). However, this distance is small as it is very short distance for the runoff to enter the watercourse. Thus, in the present study it is modified to 150m of minimum separation distance from water bodies and dry streams were excluded because such stream courses will not be vulnerable for the pollution from the quarry site. The water bodies within 150m distance from the quarry site is very close and may pose difficulty in managing effluents from the quarry activities. However, a quarry site with more than 600 m away from the water bodies is relatively far away and pollution from the quarry activities can be managed. Further every 150 m new classes were established for the present study (Table 2). Thus, suitability ratings were attributed in an increasing order from 150 m to 600 m of distance from water courses.

Distance to road

An area within 500 m distance to existing roads is too short distance hence traffic can easily be endangered by the quarry activities (noise, dust, blast rock fragments, vibrations and other quarry operations), thus quarry sites located very close (<500 m) to the existing roads will not be suitable. Furthermore, an area more than 7500 m from existing roads consume more time and fuel for transportation, cause high pollution and requires more budget for access road construction. Hence, it is highly un-economical and not suitable for a quarry site. In contrast, an area in between 500 to 5000 m is fairly far away with less injury from the quarry activities, less time of transportation and less fuel consumption and requires relatively moderate budget for access road construction. Hence, it is highly economical and highly suitable for the quarry site selection. The rest are areas with an intermediate distance and require moderate budget (Table 2) (Barakat et al. 2016; Gilpin et al. 2007; Robinson et al. 2004). For the assessment of distance to the roads euclidean distance tool in Arc GIS was used and the resulting map is presented as Fig.4 (e).

Relative relief

A slope having relative relief less than 5 m may be stable and accessible for quarry operations however, it may have potential for flooding and difficulty in excavation. Thus, suitability for quarry site for relative relief <5 m is extremely low and the least rating of 1 is assigned and relative relief more than 200 m will have low suitability due to challenges in accessibility and difficulties in operation and management of the quarry activities. In contrast, relative relief 5-25 m (very low) and 25-50 m (low) will have extremely high and very high suitability therefore, rating of 7 and 6 are assigned, respectively. The relative relief in between 5-50 m will provide most suitable conditions for quarry operations by ease of accessibility and excavation (Table 2).

Slope angle

Slope inclination is responsible for the stability of the slope. Steeper slopes are more susceptible for slope instability (Chimidi et al. 2017; Girma et al. 2015; Raghuvanshi et al. 2015). Besides, steep slope sections will also pose problem for accessibility and difficulties in excavation of rock. Thus, it is reasonable to say that steeper slope sections are not suitable for quarry operations whereas, gentle slope sections are suitable for the quarry operations. The code of practice for small quarries, Department of Primary Industries, Earth Resources, the state of Victoria-Australia (DPIER 2010), recommend a maximum gradient of 1:10 (vertical: horizontal) or slope angle of 5.7° for haul roads to reduce noise from the use of brakes and/or increased engine power to climb slopes. However, a bit higher slope angle is suitable for the ease of quarry excavation. Therefore, in the present study, slope class of $5-15^\circ$ is considered as extremely high suitable class for quarry operation. It can be noted from Table 2 that slope angle class $5-15^\circ$ and $15-25^\circ$ are considered as extremely high and very high suitability classes, respectively. These classes will provide most suitable conditions for quarry operations by ease of accessibility and excavation. In contrast, slopes with angles 45° and above will be lower in its suitability owing to difficulties in accessibility and quarry operations. The slope inclinations $<5^\circ$ may pose difficulties in quarry operations due to poor drainage, water logging and pitting for excavation.

On the other hand, slope failure occurs when the downward movements of material due to gravity and shear stresses exceed the shear strength. Processes that can lead to a reduction in the shear strengths of a rock mass are increased pore pressure, discontinuity conditions, and orientation in relation to the slope angle, slope geometry and weathering (Raghuvanshi 2019). The shear stress in rock mass may also increase due to excavation at the bottom of the slope, blasting and seismic effects. A slope geometry that affects its stability includes slope height and angle (Chimidi et al. 2017; Raghuvanshi et al. 2014). Slope stability generally decreases with an increase in the height of the slope (Raghuvanshi 2019). As the slope height increases, the shear stress within the toe of slope increases due to added weight. With increasing slope angle, the tangential stress increases which result in an increase in the shear stress thus reducing its stability (Raghuvanshi et al. 2015). Therefore, though slope angle is not the sole factor that causes instability; considering the slope angle in quarry site selection is helpful for the general evaluation of the area. In the current study, the map of slope angle ($^\circ$) was auto-generated from ASTER GDEM at 15 m resolution (Fig.4 (g)).

6. Preliminary Suitability Map

All the layers intended to be used as an input to run the suitability analysis were prepared and a weighted overlay tool was used to produce a preliminary suitability map for all lithologies in the study area (Fig.5 (a)).

In the present study the consistency of the weight for various factors value was found to be 0.02 (Table 3). If the CR value is less than or equal to 0.1, the weights are consistent and reasonably acceptable (Saaty 2008). Therefore, the current weights assigned to various factors are reasonable and acceptable. Further, during the image classification, an accuracy assessment was also carried out and an overall accuracy of 92% was found which shows that the LULC classification is reasonable.

Slope gradient in terms of the slope angle is equal to $\text{Arctan} (VD/HD)$ and the maximum gradient set for haul roads is equal to 5.7° ($\tan^{-1} (1/10)$) as per the Code of Practice for small quarries, Australia, (DPIER 2010). However, as per works of Anbalagan (1992); Barakat et al. (2016); Raghuvanshi et al. (2015); Raghuvanshi et al. (2014), quarry site with a slope angle between $5-15^\circ$ and relative relief in between 5-25 m is most suitable. The proposed quarry sites shall be placed on bare (open area) land followed by sand covered bed rock and shrubs (Regessa et al. 2015). For the transportation accessibility and to make the quarry site economically viable, the site should be located 500-1600 m away from the existing roads (Dimopoulou et al. 2013; Robinson et al. 2004). For the quarry site to be environmentally friendly, the proposed site should be located not less than 150 m away from the water bodies (Kontos et al. 2005; Yoxas et al. 2011). Further, the quarry sites should be located not less than 1000 m away from the periphery of towns and other build up areas (Dimopoulou et al. 2013; EPP and ASD 1999).

In the present study the results of the weighted overlay analysis have identified four varying degree of suitability classes in the study area. The preliminary suitability map of the study area for all lithologies shows that 136 km^2 (2.75%) of the area is highly suitable for quarry sites, whereas, 1587 km^2 (32.12%) of the study area is moderately suitable for quarry sites. The land which has low suitability, accounts for 2166 km^2 (43.82%) of the study area and remaining 1053 km^2 (21.31%) of the land is classified as unsuitable for the quarry sites (Fig.5 (a) and (b)). The highly suitable areas are dominantly present in the northern (east of Dire Dawa and north of Kombolcha) and south-eastern (east of Girawa and south of Kurfa Chale) portions of the study area. These areas are mostly covered by massive limestone, bare and shrub lands, moderate to low relative relief and gentle to very gentle slopes. Besides, suitable areas for quarry site are sparsely distributed through the study area.

7. Conclusions

GIS and AHP have been combined to select the well suited quarry site in Harer-Dire Dawa area, Eastern Ethiopia. Since optimal site selection for quarry operation is governed by factors such as the availability of suitable lithology, land form, nearness to demand centers, environment and socio-economic considerations; factors such as lithology, land use and land cover, distance to buildup areas, distance to water bodies, distance to roads, relative relief and slope angle were taken into consideration for preliminary quarry site selection. GIS was employed to digitize all the spatial features related to suitability for the quarry site selection and for weighted overlay analysis. Due consideration for all possible factors may facilitate in environmentally friendly and sustainable quarry sites location. In the present study, analysis was carried out to locate the suitable areas for the quarry sites. For each selected factors appropriate classifications were made and criteria were formulated based on suitability for the quarry site selection. In order to assign the weights to each of the considered factors, AHP method of pair-wise comparison matrix was used. Thus, by considering selected factor maps weighted overlay analysis was applied to produce the preliminary quarry site suitability map for the study area for all available lithologies. Also, attempt was made to assess separately the suitable sites for the limestone quarry. This was mainly done with an understanding that the study area is dominated by limestone and limestone is considered to be very suitable rock for aggregate.

The suitability map of the study area for all lithologies shows that 136 km^2 (2.75%) of the area is highly suitable, 1587 km^2 (32.11%) of the area is moderately suitable, 2166 km^2 (43.83%) of the area is low suitable and remaining 1053 km^2 (21.31%) of land is unsuitable for the quarry sites. The most preferable site is with basalt and massive limestone lithology, and with bare land cover. In addition, the closest distance from existing roads, nearest water body, and nearest build-ups to the location is 500 m, 900 m and 1000 m, respectively.

The application of GIS and AHP method has helped in solving time consuming challenges which are often associated with the selection of quarry site. The results of the present study highlight priority and non-priority areas quarry sites, considering the likelihood of causing the least and greatest social, environmental and economic disturbances. Besides, the results of the present study will also help in narrowing down the wider study area to suitable areas that may be further focused for later quarry sites selection and detailed field investigation for the suitable quarry sites.

This result will also greatly serve as a guide for quarry site selection in other regions or other developing countries. Environmental planners can easily apply the criteria to spatially buffer unsuitable locations for quarry sites, identify criteria priorities, and select the most suitable site under each criterion. This minimizes social, economic and environmental impacts which results from quarry operation and management. In addition, the output of this particular study can help in guiding investors for further quarry development and also help the permit authorities for anticipating negative impacts, favoring conservation strategies, and expansion of the quarry industry with the least ecosystem disturbance.

However, the proposed approach does not replace the need for a serious and detailed quarry site studies at large scale. It can and should be used to identify areas where the detail studies could focus to gather more precise, technical, and practical information about the quarry site. This strategy can provide more accurate data to support decisions and reduce the time necessary to obtain the required environmental license, which is considered critical for the development quarry industry. Prioritizing environmental and social factors for quarry site selection issues not only ensures sustainable development, but also maintains high levels of organizational productivity as it ensures uninterrupted operations with minimum failure throughout the project's life.

Abbreviations

AHP: Analytical Hierarchy Process; AOI: Area of interest; CI: Consistency Index; CR: Consistency Ratio; DEM: Digital Elevation Model; DPIER: Department of Primary Industries, Earth Resources, the state of Victoria-Australia; ERA: Ethiopian Roads Authority; EPA: Environmental Protection Authority; GIS: Geographical Information Systems; GSE: Geological Survey of Ethiopia; LULC: Land use and land cover; RI: Random consistency index; SOPAC: South Pacific Applied Geoscience Commission; UTM: Universal Transverse Mercator.

Declarations

Acknowledgements

All kinds of supports extended by Addis Ababa Science and Technology University and Adama Science and Technology University are thankfully acknowledged. The authors are also thankful to Dr. Daniel Alemayehu and Dr. Shanker Karuppannan from Adama Science and Technology University for their technical support and valuable suggestions that has helped in finalizing the present research.

Authors' Contribution

The 1st author done technical, scientific analysis of the research and developed the manuscript. The 1st co-author read and suggested amendments in the analysis and structure of the manuscript and reviewed the final manuscript. The 2nd and 3rd co-authors reviewed the final manuscript and enhanced the overall quality of the manuscript, including language correction. All authors contributed, read and approved the final manuscript.

Funding

No funding was used for this manuscript preparation.

Ethics approval and consent to participate

This manuscript does not contain any individual person's data and ethics approval is not required.

Competing interests

The authors declare that they have no competing interests.

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Figures

Fig.1

Figure 1

Location map of the study area.

Fig. 2

Figure 2

Geological map of the study area

Fig.3

Figure 3

Methodological flow chart.

Fig.4(a-d)

Fig.4(e-g)

Figure 4

Reclassified maps for (a) lithology (b) land-use and land-cover, (c) distance to build up, (d) distance to water bodies (e) distance to roads, (f) relative relief and (g) slope angle.

Fig.5(a-b)

Figure 5

(a) Preliminary quarry site suitability map for all lithologies (b) Percent area suitability for quarry site.