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A GIS-AHP BASED APPROACH FOR OPTIMIZATION OF QUARRY SITE LOCATION AROUND HARER AND DIRE-DAWA TOWNS, EASTERN ETHIOPIA

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Highlights

- The weighted overlay analysis have identified four varying degrees of suitability classes in the study area.
- 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.
- An attempt was made to assess separately the suitable sites for the limestone quarry.
- The approach followed in this work (i.e. preliminary suitability assessment) can be adopted elsewhere for economic quarry site selection.

Abstract. The problem of environmental degradation and pollution resulting from quarry operations is becoming a critical problem. Therefore, the selection of optimal quarry sites is a prerequisite for safe operation and economic viability. The present study was carried out around Harer and Dire-Dawa towns to identify the optimal location of quarry sites by using an integrated AHP and GIS approaches. The selection was carried out by considering environmental and socio-economic factors. For each of the factors, appropriate classifications and criteria were formulated. Finally, a weighted overlay analysis was applied to produce the preliminary quarry site suitability map. About 136 km^2 of the area is highly suitable, 1,587 km^2 is moderately suitable, and 2,166 km^2 has low suitability for quarry site. The approach followed by the study helped to narrow the area to the suitable sites that may further be studied through detailed field investigation. Hence, it can be adopted elsewhere as a guide for economical quarry site selection.

Keywords: GIS-AHP, quarry site, weighted overlay, suitability, Harer, Dire-Dawa.

Introduction

The problem of environmental degradation and pollution resulting from quarry operation has been a threat to the inhabitants of most developing countries. 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 & Padhy, 2011). Habitats outside the quarry site can also be impacted indirectly by dust deposition, alteration of the water supplies, or as a result of run-off and 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; Regassa et al., 2015; Zaruba & 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.

In most of the African nations, the selection of quarry sites and their operations and management does not take into account environmental sustainability (Darwish et al., 2011). Generally, the methods followed for resource extraction are poor and the site selection for quarrying is not made through systematic methods. Very often, this leads to land collapse, land conversion, environmental

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pollution and may also affect the people residing in the nearby localities (Pal & Mandal, 2017). Thus, the need for proper site selection, quarry 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 & Nwosu, 2018).

For suitable quarry site selection, various factors can be considered such as; lithology, land-use and land-cover (Regassa et al., 2015), distance to the built-up area, distance to streams/water bodies, distance to roads (Robinson et al., 2004), relative relief and slope angle. These factors may influence the quarry site concerning its geotechnical, economic, and environmental suitability during its operational and decommissioning phases of materials extraction. Thus, in the era of sustainable development, quarry site selection has become complex due to the involvement of multiple factors such as technical, social, economic and environmental (Ming'ate & Mohamed, 2016). This puts major constraints for decision makers to optimize a suitable quarry site, particularly for large area. In such cases, decision analysis plays a vital role by considering various criteria.

Value measurement models such as AHP, weighted sum method, and weighted product method are basically utility based models. However, weighted sum method has a weakness of only a basic estimate of one's penchant function or fails to integrate multiple preferences. On the other hand, weighted product method also leads to undesirable results as it priorities or de-prioritise the alternative which is far from average (Kumar & Ramcharan, 2008). Thus, to apply multiple factors, the systematic framework through AHP technique that was originally developed by Saaty (1977) can be applied in a GIS environment. It provides a flexible and easily understandable way of analyzing complicated problems that allow subjective as well as objective factors to be considered in a decision-making process (Haile & Suryabhagavan, 2019; Kou et al., 2016; Jablonsky, 2015; Dimopoulou et al., 2013; Vaidya & Kumar, 2006; Dey & Ramcharan, 2008). These advantages can be utilized to analysis multiple factors and economically identify suitable quarry sites. The method has been adopted in previous works for a selection of groundwater recharge site (Rajasekhar et al., 2019), landfill site (Akanwa et al., 2017; Dimopoulou et al., 2013; Ebistu & Minale, 2013; Zelenović et al., 2012; Yoxas et al., 2011; Ketema, 1982; Chabuk et al., 2016a, 2017, 2019; Alkaradaghi et al., 2019; Khan & Samadder, 2015), and mining methods (Mandal & Mondal, 2016; Ataei et al., 2008).

Quarry site identification process of large area requires huge amount of money, time, and effort. It is, therefore, more economical to follow a stage-wise suitability assessment as it proceeds from cheap to expensive and simple to complex. The preliminary evaluation can be done using readily available office data which then can be refined after detail field work. The main objective of the present study was to identify preliminary suitable quarry sites for

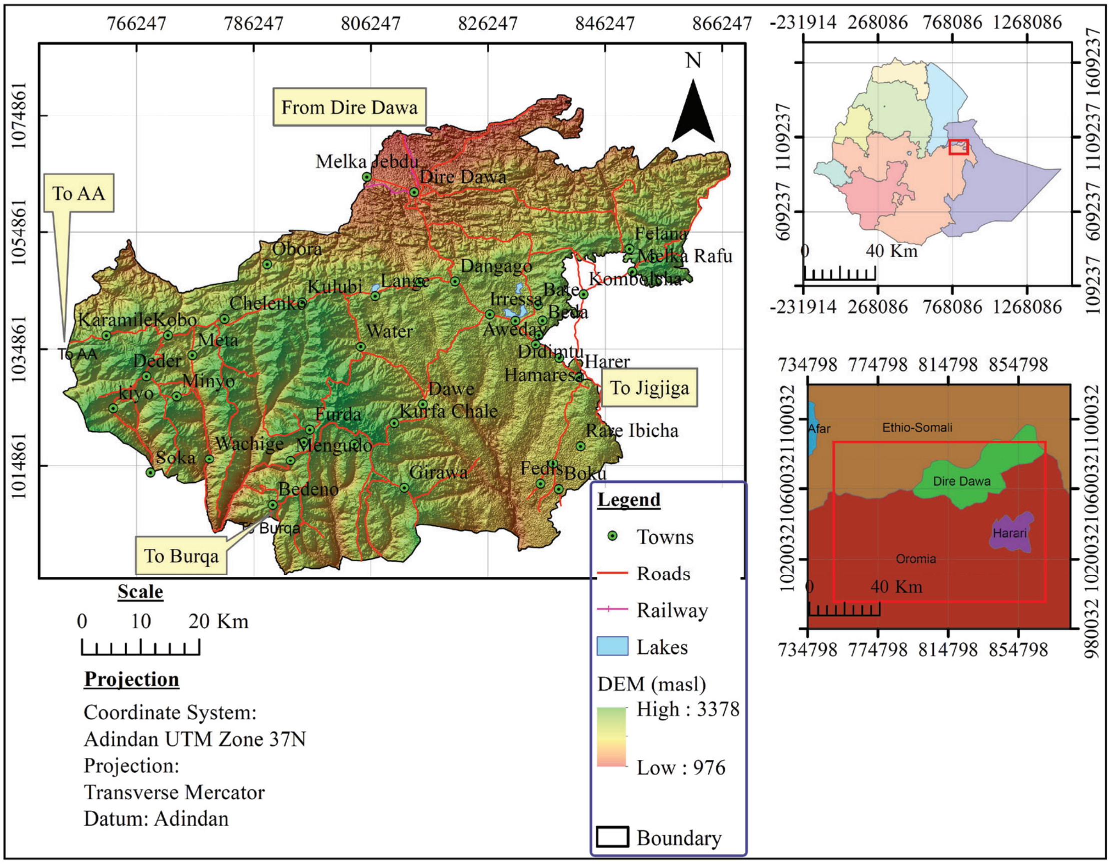


Figure 1. Location map and Accessibility of the study area

crushed stone aggregate around Harer and Dire-Dawa towns by using the integrated AHP and GIS approach. The suitability assessment were done considering readily available office data such as lithology, land use–land cover, proximity to built-up areas, distance to watercourses, distance to existing roads, relative relief, and slope angle.

1. 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 m to 886247 m E longitude and 994861 m to 1084861 m N latitude (Figure 1). Harer town is accessible from Addis Ababa through asphalt road, whereas Dire-Dawa town can be accessed either by road, by air, or by train. The topography of the area is characterized as rugged with elevation ranging from 976 to 3378 m.a.s.l. (Meter above Sea Level). 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 the southern area is characterized by gently undulating surfaces and occasionally cliffs. The total areal coverage of the study area is 4993.25 m^2.

2. Geology of the study area

The geology of the Harer and Dire-Dawa area ranges from Precambrian basement rocks up to recent sediments (Figure 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 the 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 fluviatile sandstone, carbonate, and upper fluviatile sandstone (Bosellini et al., 2001). Cenozoic volcanic rocks (Oligocene) Alaji basalt, and (middle Miocene) Tarmaber basalts are exposed at the 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, interfluves, and wide valley floors both on the plateau and the rift zones (Geological Survey of Ethiopia [GSE], 2010).

The study area is dominantly covered by the Antalo limestone (Figure 2). Gildessa limestone, exposed at the 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

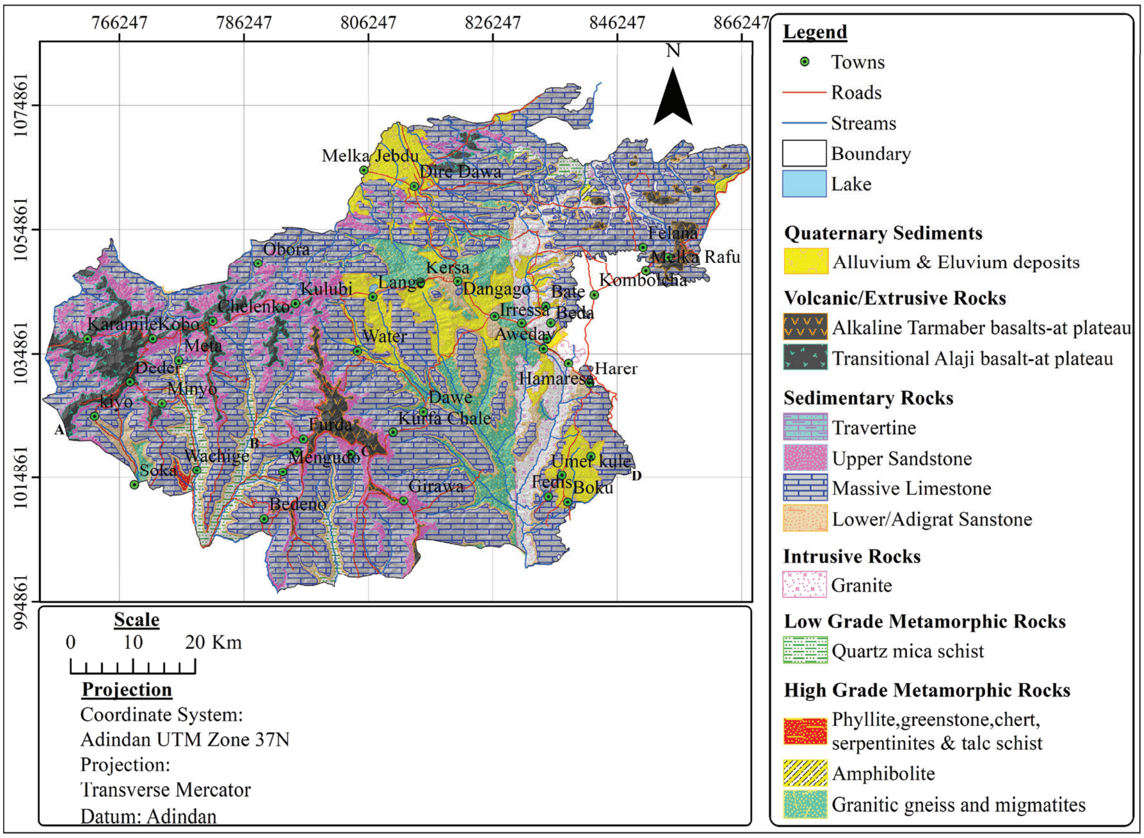


Figure 2. Geological map of the study area (Modified from GSE, 2010)

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 with 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 the N-S direction along with the Ethiopian rift system while minor joint sets are perpendicular to the major joints (Ketema, 1982).

3. Materials and methods

3.1. Materials

The supporting materials and analytical tools used in the present study are: 1:50,000 scale topographic map, 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. Besides, IDRISI was

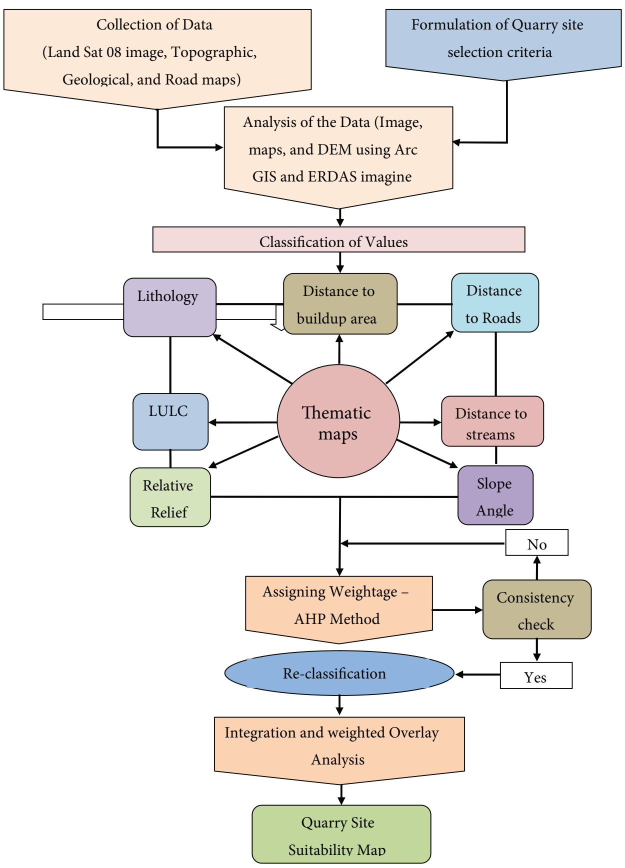


Figure 3. Methodological flow chart

also used for the computation of the 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 sites in the GIS environment.

3.2. Methods

3.2.1. Data pre-processing

Procedures followed in the preparation of a suitability map for the quarry site selection are shown in Figure 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 & Minale, 2013; Zelenović et al., 2012; Yoxas et al., 2011).

The data for lithology was obtained from the geological map and the field visual observations. Geological maps of the Harer and Dire Dawa sheet (1:250,000 scale) were mosaicked and refined to prepare the geological map of the study area. Later, the geological map was verified and modified through field observations.

The Landsat 8 2018 (path 167, row 53 and 54) and band combination of 1, 2, 3 for the Landsat were used to prepare the land-use and land-cover (LULC) map of the study area. Before the actual use of the Landsat 8 image; several 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 have used this signature (training) to derive rules for mapping all other pixels into the class values. 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. Twenty five random points were selected and an accuracy assessment was made for the LULC classification using the Google earth image as a ground truth. Google Earth image was also used for controlling training pixels. Later, final verification and modifications of the prepared LULC map were 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 Google earth image interpretations. 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. For the assessment of proximity to the built-up areas, water bodies and road, euclidean distances to populated centers, water body and road, respectively were computed for each cell. Slope angle and relative relief were extracted facet-wise from the 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 a 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.

3.2.2. Weight assignment

In this research, the AHP model was adopted 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 simplifies the decision-making process (Adewumi et al., 2019; Ramik, 2017). 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 the 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 the inconsistency of the pairwise comparison matrix (i.e. the likelihood of whether factor weights were randomly assigned). The consistency ratio (CR) is defined by the mathematical relation equation (Vaidya & Kumar, 2006).

$$CR = \frac{CI}{RI}, \tag{1}$$

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

$$CI = \frac{(\lambda_{\max} - n)}{(n-1)}, \tag{2}$$

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

Random inconsistency indices (RI) of 1.32 was considered for seven criteria (Chabuk et al., 2016a). Formulating quarry site selection criteria based on classification and reclassification of values into certain ranges concerning suitability was a crucial component for identifying suitable areas for quarry sites (Chabuk et al., 2016b). 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, a quarry site 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 the whole considered area according to Boolean logic.

The considered factors for quarry site suitability map preparation, their significance, and relative order of importance are 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 (Alkaradaghi et al., 2019).	Extremely strong influence
2	Land-use and land-cover	Environmental code of practices preserves and protects cultural heritage, archeological sites (Chabuk et al., 2017), parks, and built-up areas (Alkaradaghi et al., 2019). Thus, LULC may prohibit the development of quarry sites 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 a strong influence on quarry site suitability (Chabuk et al., 2019)an arid area (Babylon Governorate as a case study. However, it does not prohibit the development of quarry sites. 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 flows very rapidly into them (Alkaradaghi et al., 2019). Thus, a safe distance to water bodies needs to be maintained from the quarry sites (Chabuk et al., 2016a).	Moderately more important
5	Distance to roads	Distance to roads is an important factor. The proximity of the road to the quarry site may result in dangers of fly rock due to blasting and air pollution (Chabuk et al., 2017). Roads at a far distance may result in additional project costs due to the development of new roads and increased transportation cost (Alkaradaghi et al., 2019).	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 (Alkaradaghi et al., 2019).	Moderately important than Slope angle
7	Slope Angle	Induce slope instability but is not the sole factor that triggers the instability (Alkaradaghi et al., 2019).	Relatively least effect

The data processing was mainly done for the classification and reclassification of various factor maps in the GIS environment using special analysis tools (e.g. Buffer, Clip, Extract, Overlay, Proximity, Convert, Reclassify and Map Algebra, etc.) (Chabuk et al., 2017). Later, appropriate weights were assigned to the processed factor maps (Chabuk et al., 2016b). Besides, the 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 was used; particularly 1 by 7 by 1 scaling method was adopted (Table 3).

3.2.3. Reclassification of thematic layers and weighted overlay analysis

By using reclassification for each thematic layer, a ranking scheme based on pre-defined weights were used to work out the least and most suitable conditions (Anbalagan, 1992). All thematic maps were prepared, geo-processed, reclassified in the GIS environment and vector to raster conversion was made.

Later, a weighted suitability overlay analysis was made for each cell in the 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.

4. Results and discussion

4.1. Suitability evaluation criteria

For the evaluation and selection of suitable areas for quarry sites, seven factors were considered which include lithology, land-use and land-cover, distance to built-up areas, distance to water bodies, distance to road, relative relief and slope angle. These criteria and their classification and rating based on suitability are discussed below:

4.1.1. Lithology

The geological map of the study area was reclassified into seven lithological classes. These are: (1) Basalt, (2) Limestone, Travertine, and Dolomite, (3) Granite, (4) Gneiss and Amphibolites, (5) Schist, Phyllites, Greenstone, Chert, Serpentinites, and Talc, (6) Detrital Sandstone, Conglomerates and Shales and (7) 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). A massive, high cohesion and homogenous rock like basalt are most suitable for the crushed aggregate and a massive limestone also comes next to basalt (British Geological Survey [BGS], 2019; Leroy et al., 2017; Langer & Knepper, 1995). However, Detrital rocks such as; sandstone, 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 (Regassa et al., 2015; Saaty, 2008; Gilpin et al., 2007). Thus, keeping this in mind, a classification of the various lithologies for their suitability in aggregate was performed for the current study (Table 2). Low cohesive rocks such as alluvium and elluvium products are on the other hand unsuitable and they were excluded from the results. The rest were placed in between with moderate rating value. The distribution of these lithological units in the study area is shown in Figure 4a.

4.1.2. Land-use and land-cover (LULC)

During the image classification, an accuracy assessment was carried out and overall accuracy of 92% was found which shows that the LULC classification is reasonable (Chabuk et al., 2017). Most environmental code of practices preserves and protects cultural heritage, archeological sites, caves, religious institutes, monuments and parks and they are unsuitable for quarry sites. Therefore, these protected LULC, including settlement, and artificial structures (power line and Airport field) were excluded. Whereas bare land was provided the highest suitability rating but dense forest cover was given the least rating. The resulting reclassified LULC map of the area is presented as Figure 4b.

4.1.3. Distance to build-up areas

The nearer a quarry site to sensitive areas, the more unsuitable the site is for quarry purposes. Residents living in proximity to quarries can be endangered by dust up to 0.5 km from the source. Severe concerns about dust were mostly experienced within about 100 m of the dust source (Subhasis et al., 2018; Environment Protection Authority [EPA] Tasmania, 2017; Darwish et al., 2011; South Pacific Applied Geoscience Commission [SOPAC], 2005) (Table 2). Therefore, the quarry code of practice (EPA Tasmania, 2017) suggested the separation distances of 1000 m, in areas where regular blasting takes place; however where the material is crushed, only 750 m separations 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 1000 m away from settlements, it is very close to the population centers. Thus, they have a higher health hazard. On contrary, quarry sites more than 2500 m from built-up area, are far away from consumers and will have market problems with higher transportation costs. However, areas between 1000–1300 m are not far nor close, with less hazard and are considered as economical distance (EPA Tasmania, 2017). Therefore, this class was provided the highest suitability rating. 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 the buildup area and their relative suitability for quarry sites are presented in Figure 4c.

4.1.4. Distance to water bodies

Runoff from quarry sites flows very rapidly towards nearby water bodies, thus lakes and streams are susceptible to pollution from quarries (Pal & Mandal, 2017). The safest way is to leave adequate buffer zones around watercourses and river corridors (Premasiri et al., 2016). Some quarry code of practice suggested disturbance should not occur within 40 m of any watercourses or 10 m of drainage lines (EPA Tasmania, 2017). However, this distance is small as it is a very short distance for the runoff to enter the watercourse. Thus, in the present study, it is modified to 150 m of minimum separation distance from water bodies, and dry streams were excluded because such stream courses will not be vulnerable to pollution from the quarry site. The water bodies within 150 m distance from the quarry site are very close (Kontos et al., 2005; Yoxas et al., 2011) 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.

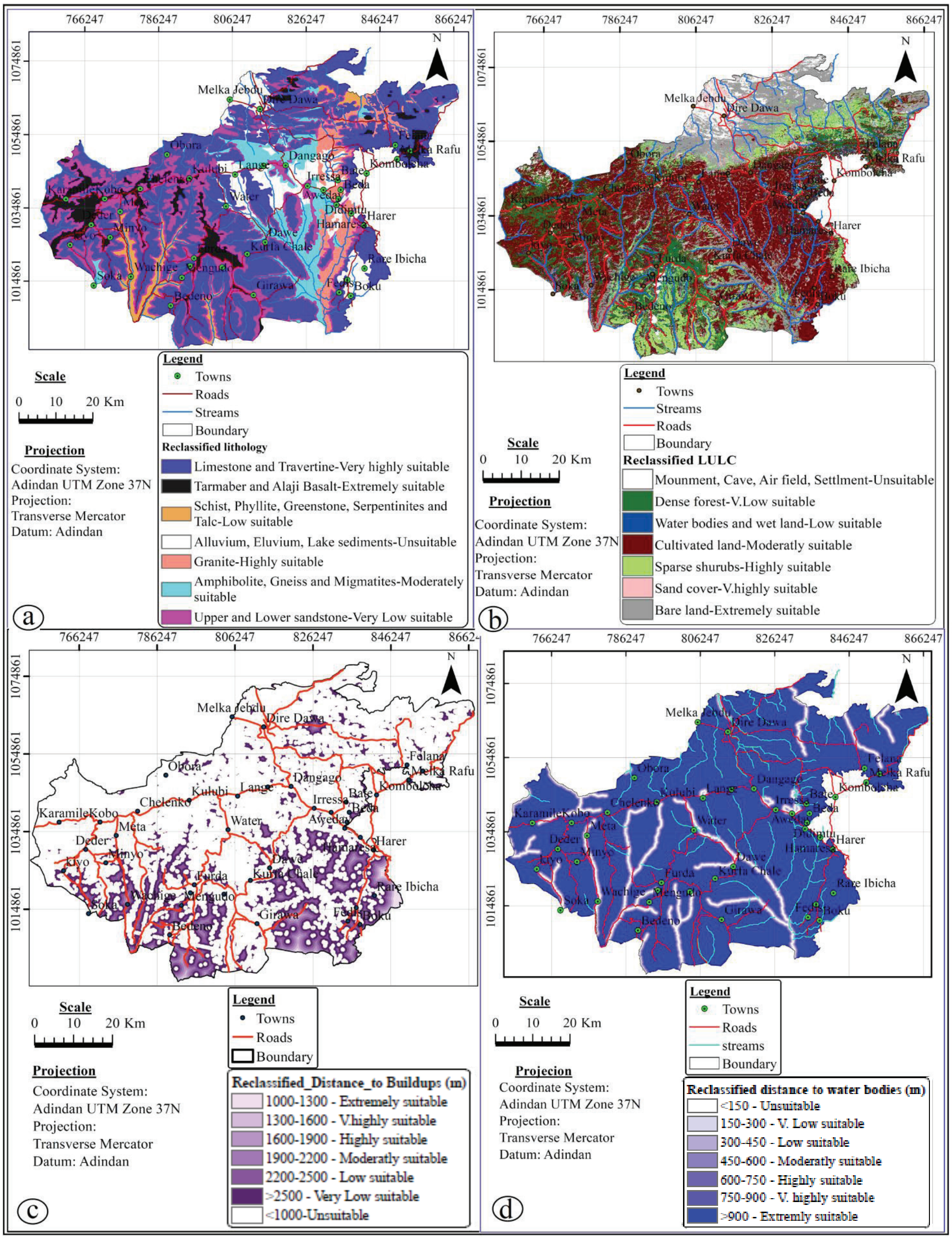


Figure 4. Reclassified maps for (a) lithology (b) land-use and land-cover, (c) distance to build up, (d) distance to water bodies

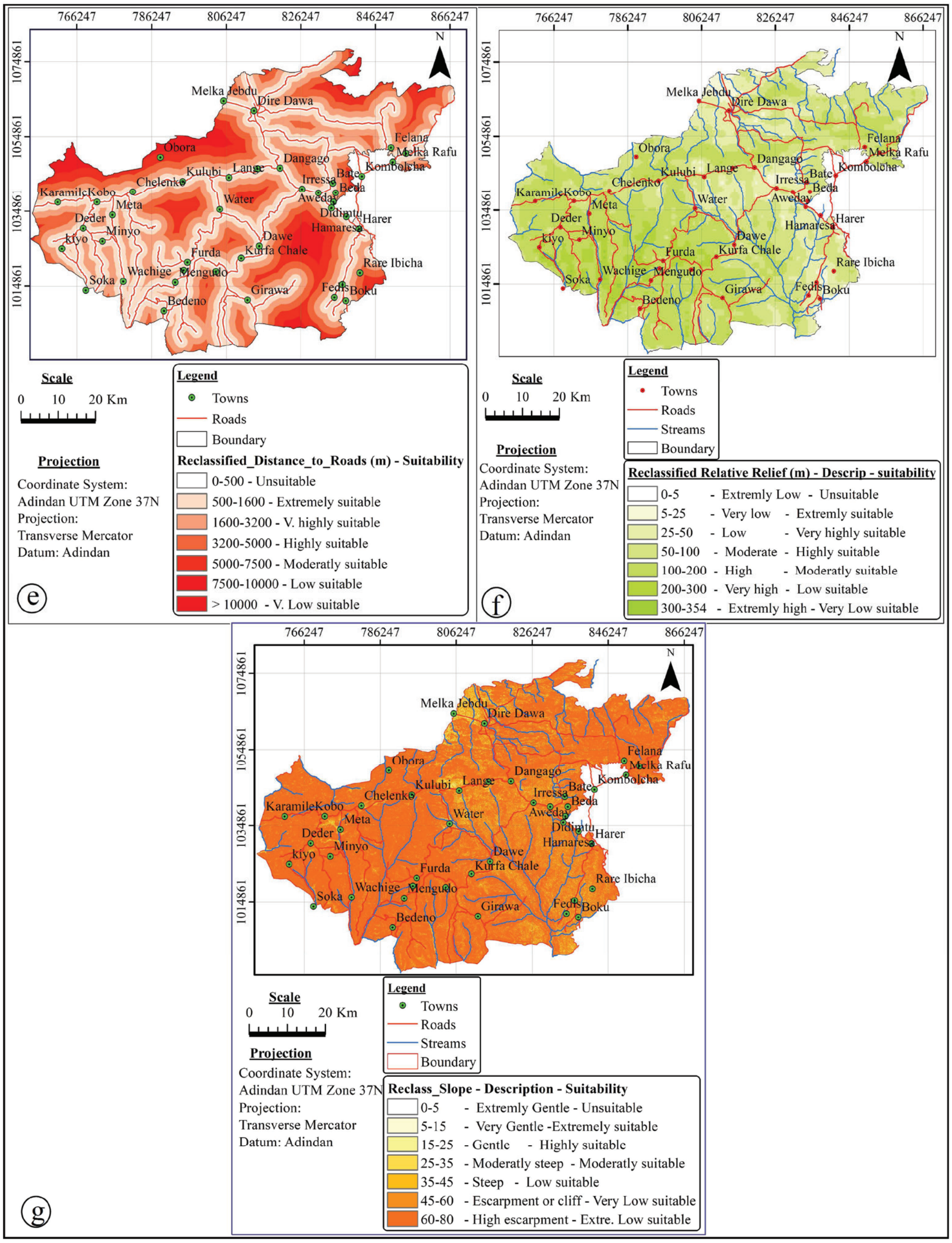


Figure 4. Reclassified maps for (e) distance to roads, (f) relative relief, and (g) slope angle (end of Figure 4)

For the present study, every 150 m new classes were established (Table 2). Thus, suitability ratings were attributed in increasing order from 150 m to 600 m of distance from watercourses. 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. The resulting proximity to water body map is presented as Figure 4d.

4.1.5. 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 consumes more time and fuel for transportation and requires more budgets for access road construction. Hence, it is highly uneconomical and not suitable for a quarry site. In contrast, an area 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 a 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 a moderate budget (Table 2) (Barakat et al., 2016; Gilpin et al., 2007; Robinson et al., 2004). The distance to road map was reclassified

Table 2. Factors and factor class suitability and ratings (Khan & Samadder, 2015)

Factors/factor classes	Description	Suitability	R
Lithology			
Lake sediment, Alluvium and Elluvium products	Easily disintegrate, contain heterogeneous layers (clay and silt)	Unsuitable	0
Detrital Sandstone, Conglomerates, and Shales	Soft and friable	Very low	1
Schist, Phyllites, Greenstone, Chert, Serpentinites, and Talc	Highly foliated rock, weak, flaky, contains chlorite and micas	Low	2
Gneiss and Amphibolites	Poorly foliated rock; flaky	Moderate	3
Granite	Coarse-grained, non-crushable, contains K-feldspar, porphyroblasts, and quartz	High	4
Limestone, Travertine and Dolomite	Massive and easily crushed	Very high	5
Basalt	Igneous dark fine-grained rock	Extre. high	6
Land-use/land-cover			
Protected areas, structures, and settlement	Monument, Cave, Airfield, and housing	Unsuitable	0
Forest	Thickly vegetated land	Very low	1
water bodies and wetland	Lakes, streams, major rivers, and wetlands	Low	2
Cultivated land	Arable land by plowing	Moderate	3
Shrubs	Scattered vegetation in the form of wild grass, bushes, and small trees	High	4
Sand cover	No vegetation and the bedrock covered by sand	Very high	5
Bare land	No vegetation cover	Extre. high	6
Distance to build up area (m)			
<1000	Very close	Unsuitable	0
>2500	Far away	Very low	1
2500–2200		Low	2
2200–1900	Intermediate	Moderate	3
1900–1600	Fairly far away	High	4
1600–1300		Very high	5
1300–1000	Not far not close	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	Intermediate	Moderate	3
600–750	Far away	High	4
750–900		Very high	5
>900		Extre. high	6

Factors/factor classes	Description	Suitability	R
Distance to road (m)			
<500	Too short	Unsuitable	0
>10 000	Far away	Very low	1
10 000–7500		Low	2
7500–5000	Intermediate	Moderate	3
5000–3200	Fairly far away	High	4
3200–1600		Very high	5
1600–500		Extre. high	6
Relative relief (m)			
<5	Extre. low	Unsuitable	0
>300	Extre. high	Very low	1
200–300	Very high	Low	2
100–200	High	Moderate	3
50–100	Moderate	High	4
25–50	Low	Very high	5
5–25	Very low	Extre. high	6
Slope angle (^{0})			
<5	Extre. gentle	Unsuitable	0
>60	High escarpment	Very low	1
60–45	Escarpment or Cliff	Low	2
45–35	Steep	Moderate	3
35–25	Moderately steep	High	4
25–15	Gentle	Very high	5
15–5	Very gentle	Extre. high	6

into seven classes based on the relative suitability of each sub-class for the quarry site selection Figure 4e.

4.1.6. Relative relief

A slope having relative relief less than 5 m may be stable and accessible for quarry operations, however, it may have the 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, ratings of 7 and 6 are assigned, respectively. The relative relief in between 5–50 m will provide the most suitable conditions for quarry operations by the ease of accessibility and excavation (Table 2). Relative relief and slope angle thematic maps were reclassified as per the suitability for the quarry site selection (Figure 4f and 4g). The classification was made into seven classes as; <5 m (extremely low), 5–25 m (very low), 25–50 m (low), 50–100 (moderate), 100–200 m (high), 200–300 m (very high) and > 300 m (extremely high).

4.1.7. Slope angle

Steeper slopes are more susceptible to slope instability (Chimidi et al., 2017; Girma et al., 2015; Raghuvanshi et al., 2015). Besides, steep slope sections will also pose a problem for accessibility and difficulties in the 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 quarry operations. The code of practice for small quarries, Department of Primary Industries, Earth Resources, the state of Victoria-Australia (Department of Primary Industry, Earth Resources [DPIER], 2010), recommends 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, a slope class of 5–15° and 15–25° are considered an extremely high suitable and very high suitability classes, respectively class for quarry operation (Table 2). In contrast, slopes with angles 45° and above will be lower in their suitability owing to difficulties in accessibility and quarry operations. The slope inclinations <5° may pose difficulties in quarry operations due to poor drainage, waterlogging, 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. A slope geometry that affects its stability includes slope height and

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 the road; RR – Relative relief; SA – Slope angle.

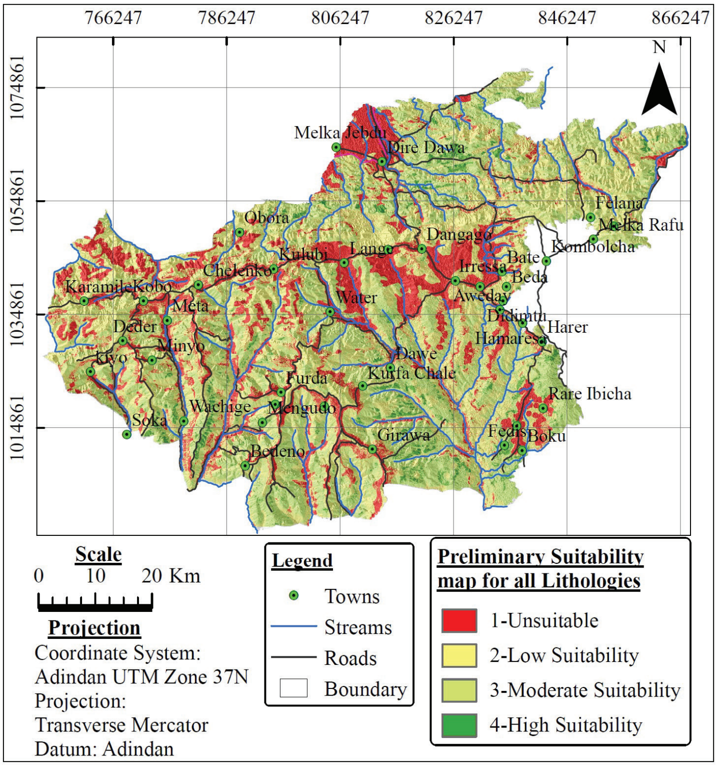
angle (Chimidi et al., 2017; Raghuvanshi et al., 2014). Slope stability generally decreases with an increase in the height of the slope (Raghuvanshi, 2019). With increasing slope angle, the tangential stress increases which also increases the shear stress thus reducing its stability (Raghuvanshi et al., 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 was auto-generated from ASTER GDEM at 15 m resolution (Figure 4g). The slope classification proposed by Anbalagan (1992) and Raghuvanshi et al. (2014) for landslide hazard zonation is 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.

4.2. Preliminary suitability map

The weights of relative importance of the considered factors were estimated using pair-wise comparisons in AHP. The consistency of the weight for various factors value was 0.02 (Table 3), therefore, the weights assigned to various factors are acceptable (Saaty, 2008). Then, the order of importance obtained by AHP was converted to percent according to their relative influence, as the overlay analysis requires weight in percentages (Figure 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. Finally, a weighted suitability overlay analysis was done to produce a preliminary suitability map for all lithologies (Figure 5a).

In the present study, the results of the weighted overlay analysis have identified four varying degrees of suitability

a)



b)

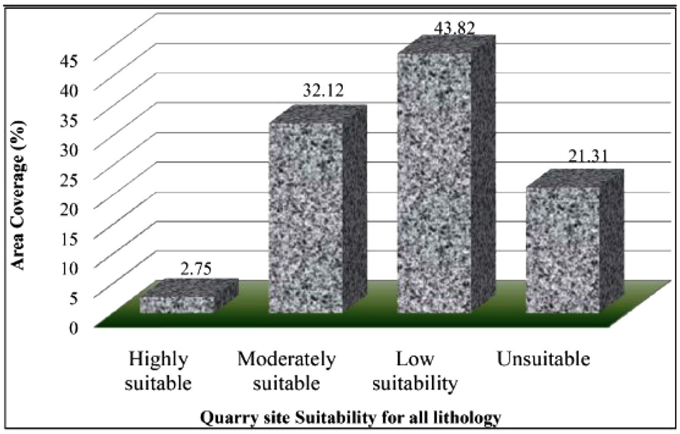


Figure 5. (a) Preliminary quarry site suitability map for all lithologies; (b) Percent area suitability for quarry site

classes. The map shows that 136 km^2 (2.75%) of the area is highly suitable, 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 the remaining 1053 km^2 (21.31%) of the land is classified as unsuitable for the quarry sites (Figure 5a and 5b). The highly suitable areas are dominantly occur 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 shrublands, moderate to low relative relief, and gentle to very gentle slopes. Besides, suitable areas for quarry sites are sparsely distributed through the study area.

Conclusions

In this work, GIS and AHP approach have been combined to select the well-suited quarry site in the study area considering readily available office data. The result showed that about 35% (1723 km^2), 43.8% (2166 km^2) and 21.3% (1053 km^2) of the study area are highly to moderately suitable, low suitable and unsuitable for quarry site, respectively. The suitability is governed by factors like the availability of suitable lithology, landform, nearness to demand centers, environment, and socio-economic considerations. This preliminary evaluation needs to be refined using detailed field investigation to select the final suitable quarry sites. However, it can significantly reduce the area where the detailed field studies could focus which make the selection process economical. The next stage of suitability assessment could be based on field data such as the rock mass quality, slope stability, reserve, depth to groundwater table, and overburden thickness. Finally, sample shall be collected from suitable sites and tested at laboratory to check the quality and suitability of the rock for specific uses such as for aggregate, dimension stone, etc. Environmental planners can apply the approach to identify criteria priorities, spatially buffer preliminary suitable locations for detailed field survey and select the most suitable site. This will minimize the cost of field work and social, economic, and environmental impacts which result from quarry operation and management.

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