

Identifying Aggregate Locations Using Weighted Overlay Analysis and Analytic Hierarchy Process

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Abstract

Aggregates are a crucial component in the construction of buildings and roads, providing essential strength, durability, and support. This paper examines the limitations and potential of aggregate resources in the Nowshera district, Pakistan, and aims to identify suitable aggregate locations using GIS techniques: Weighted Overlay Analysis, and the Analytic Hierarchy Process (AHP). The study incorporates various socioeconomic and environmental factors, including land use, proximity to highways, rock type, elevation, and slope, to minimize conflicts between different land uses. These variables were mapped and analysed using the weighted overlay and AHP techniques, with each factor ranked according to its significance. The spatial relationships among the thematic layers were integrated to produce a final suitability map based on both analyses. The findings revealed that several areas in the study area hold significant potential for aggregate extraction. These areas have been categorized into low, moderate, and highly suitable zones, considering environmental constraints, transportation accessibility, current land use, and the availability of mineral deposits. Moreover, a comparison between AHP and weighted overlay analysis demonstrated that AHP offers higher accuracy. Therefore, the AHP-GIS approach is recommended as a reliable method for assessing land resources and classifying aggregate suitability, which can assist policymakers and local authorities in making informed decisions regarding quarry approvals and land-use planning.

Keywords

Aggregate resources, GIS, Weighted Overlay, AHP, Suitability map.



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Introduction

The construction and engineering sectors play a vital role in societal development, relying heavily on the extraction of raw materials, particularly aggregates (Hussain et al., 2023). Natural aggregates are the primary nonfuel mineral resource worldwide, ranking third in terms of overall usage, after air and water (Aswathanarayana, 2003; Shah et al., 2022). Due to the increasing demand for rock minerals, comprehensive evaluations are essential to pinpoint new potential sources in resource-rich areas. However, like other industrial activities, aggregate mining has significant detrimental environmental effects, mainly related to biodiversity, ecosystems, and landscape. Therefore, it is imperative to approach exploration activities with a strong commitment to environmental management, considering that aggregate quarry operations inherently entail potential dangers to both the landscape and the ecosystem (Aigbedion & Iyayi, 2007; Langer, 2002).

Exploring new resources requires extensive data that includes information on demand, production, land use, transportation networks, and geological properties of rocks (K. Hussain et al., 2022; Kuff, 1984; Stanley et al., 2000). Many researchers have attempted to address concerns with the sustainable management of quarry resources (Andrea Blengini & Shields, 2010; Escavy et al., 2022). Several researchers have employed GIS approaches to create predictive models using regional spatial characteristics. These models aid in identifying suitable sites for stone production, considering factors such as land management, environmental considerations, and market limitations (Barakat et al., 2015; Karakaş, 2014; Tajbakhshian et al., 2017).

The ongoing demand for construction materials in the study area is driven by increased urbanization and infrastructure development, including the construction of new roads, highways, and drivable pathways (J. Hussain et al., 2022). Historically, the region has relied on alluvial aggregates to meet its construction needs. However, the availability of these deposits has diminished over time, leading to an insufficient supply to meet growing market demand (Hussain et al., 2023). As a result, there has been a change in the overall supply pattern in recent years, with crushed carbonate rock aggregates (limestone and dolomite) playing a larger role in meeting demand. Aggregates are sourced from multiple quarries, often located near urban and rural areas, which presents challenges for spatial planning and land use management (Langer, 2002; Ren et al., 2022).

Nowshera district is rich in a wide variety of geological mineral deposits (Malkani et al., 2017). However, the ongoing growth of the real estate sector, coupled with the development of major infrastructure like roads, highways, and metropolitan areas, has led to a substantial rise in the demand for construction materials. The region has consistently depended on alluvial aggregates to meet its aggregate demands. However, due to the increased demand, it has become evident that the alluvial resources are being depleted and are no longer enough to meet the market demand. Addressing the developmental challenges in the region is essential while ensuring a sustainable supply of quarry materials over the long term.

Although GIS-based AHP and WOA approaches have been widely applied in aggregate resource studies, this work is novel in its regional focus on Nowshera District, a geologically diverse and underexplored area under increasing urbanization pressure. Our work advances aggregate resource assessment through three key contributions: (1) it integrates high-resolution (1:20,000) geological maps from the Geological Survey of Pakistan with 2022 Landsat 9 imagery, enhancing spatial accuracy in the geologically complex Nowshera District; (2) it introduces a novel AHP-based weighting scheme that balances lithology (44.7%) with land use (23.4%) and transportation access (14.8%), offering a more realistic representation of quarry development constraints than prior studies; and (3) it empirically demonstrates AHP's superior predictive performance ($AUC = 0.86$) over weighted overlay ($AUC = 0.76$), highlighting its value in data-scarce settings. These innovations collectively strengthen the methodological and practical foundations for sustainable aggregate resource planning. Comparative performance evaluation adds practical value for future resource planning in similar data-scarce, rapidly developing regions.

Description of the study area

The research was conducted in the district of Nowshera, situated within the Khyber Pakhtunkhwa province of Pakistan, focusing on the critical issues of soil erosion and land degradation. District Nowshera is in the province's east, next to district Peshawar (Figure 1). The geographic coordinates are $30^{\circ} 25' 12''$ to $34^{\circ} 5' 24''$ N latitude and $71^{\circ} 24' 36''$ to $72^{\circ} 9' 0''$ E longitude with elevation ranging from 239 to 1,531 feet (SRTM DEM) and 950 feet (290 m) at Nowshera cantonment (Khan et al., 2022). Nowshera stands as the largest district in the Peshawar Valley, covering an area of 1,748 km². It is traversed by two major rivers, the Kabul and Indus, which converge at Kund near Khairabad, intersecting with three districts: Nowshera, Swabi, and Attock. Ecologically diverse, the district experiences a semi-arid climate, characterized by an average annual temperature of 22°C, 61 mm of precipitation, and fluctuating daily relative humidity.

Considering these geographical, geological, and climatological features, the assessment of aggregate suitability in District Nowshera requires a thorough understanding of the landscape's intricacies and vulnerabilities. Employing a geospatial approach facilitates systematic analysis of these factors, guiding sustainable resource management strategies and disaster risk reduction efforts.

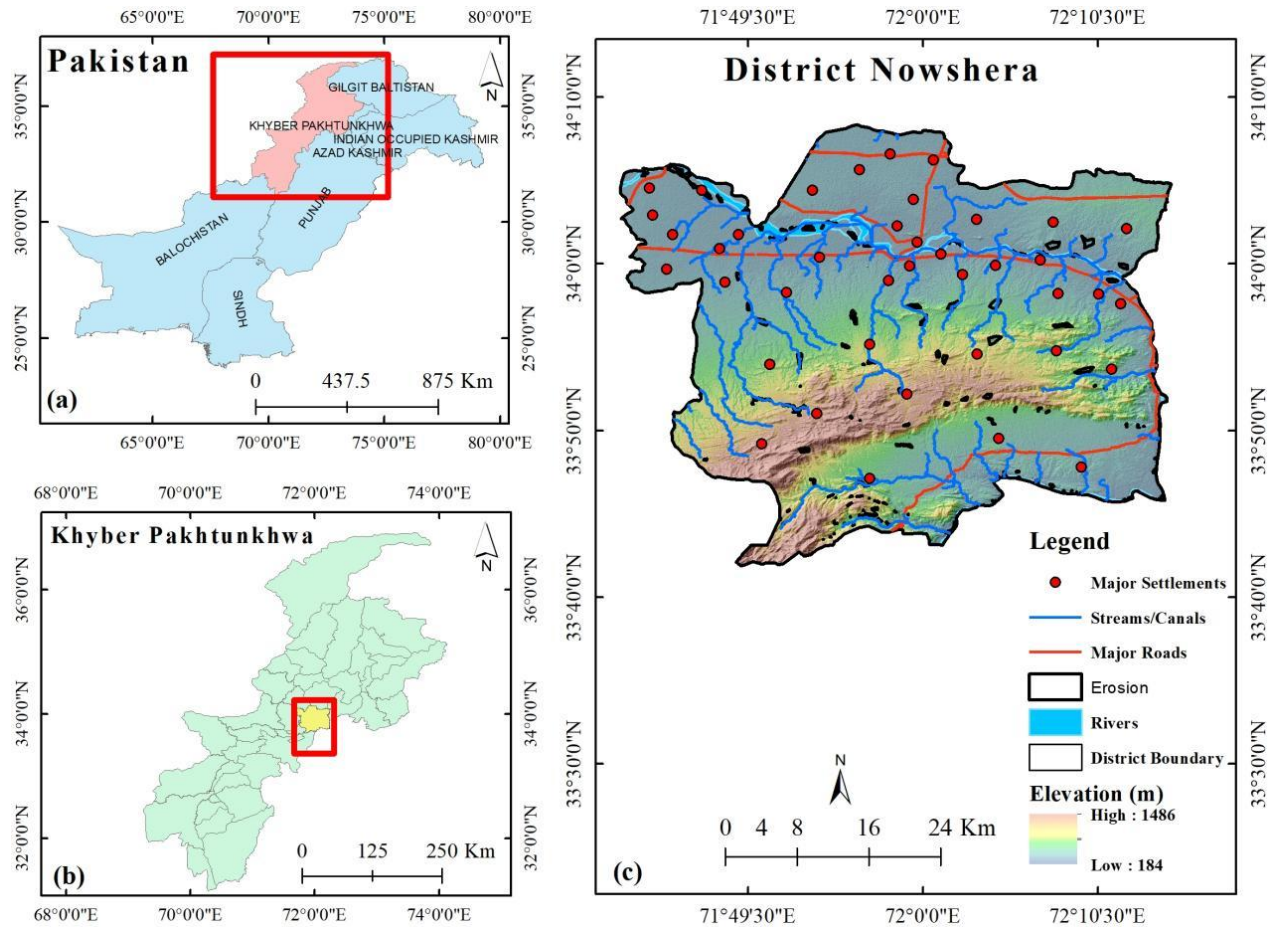


Fig 1. Location map of the study area

Regional geological setting and stratigraphy

District Nowshera is characterized by its location within the Peshawar Valley, which lies within the broader tectonic framework of the Indian Plate colliding with the Eurasian Plate. This collision has resulted in complex geological formations and structures in the region. The study area primarily sits on the Indo-Pak continental collision zone, where the Indian Plate converges with the Eurasian Plate at a rate of about 40-50 millimeters per year (DiPietro et al., 2008). As a result, the area experiences significant seismic activity, with numerous fault lines and tectonic movements contributing to the landscape's geological diversity.

The Himalayas and the Tibetan Plateau formed as a result of the Cenozoic Indian and Eurasian plate collisions, a major geological event that transformed the topography of the study area (Viola et al., 2003). Due to continuous tectonic activity in the foreland of the 2489 km-long Himalayan highland in Pakistan, the region is surrounded by active thrusting and folding, creating a complicated structural arrangement (Yaseen, Shahab, et al., 2021). Many significant thrust faults, such as the Main Karakorum Thrust (MKT), Main Mantle Thrust (MMT), Main Boundary Thrust (MBT), and Salt Range Thrust, were created as a result of this compression associated with convergence (DiPietro & Pogue, 2004; Yin, 2006).

The research area is situated between the Main Boundary Thrust (MBT) and the Hissartang fault, between their respective hanging and footwalls, which indicates a large amount of compression in the area. The region is bordered to the north by the Attock-Cherat ranges, which are made of metasedimentary rocks from the lower

Himalayas. The region is bounded to the south by the foreland basin strata of the Kala Chitta Range (Figure 2). The geological composition of the area ranges from Jurassic to recent lacustrine sediments, including Eocene Margalla Hill Limestone; the Palaeocene Hangu, Lockhart, and Patala formations; the Cretaceous Chichali, Lumshiwal, and Kawagarh formations; and the Jurassic Datta, Shinawari, and Samana Suk formations (Hashmi et al., 2018; Yaseen, Shah, et al., 2021). The succession in the study area is presented in a generalized stratigraphic column as shown in Figure 3.

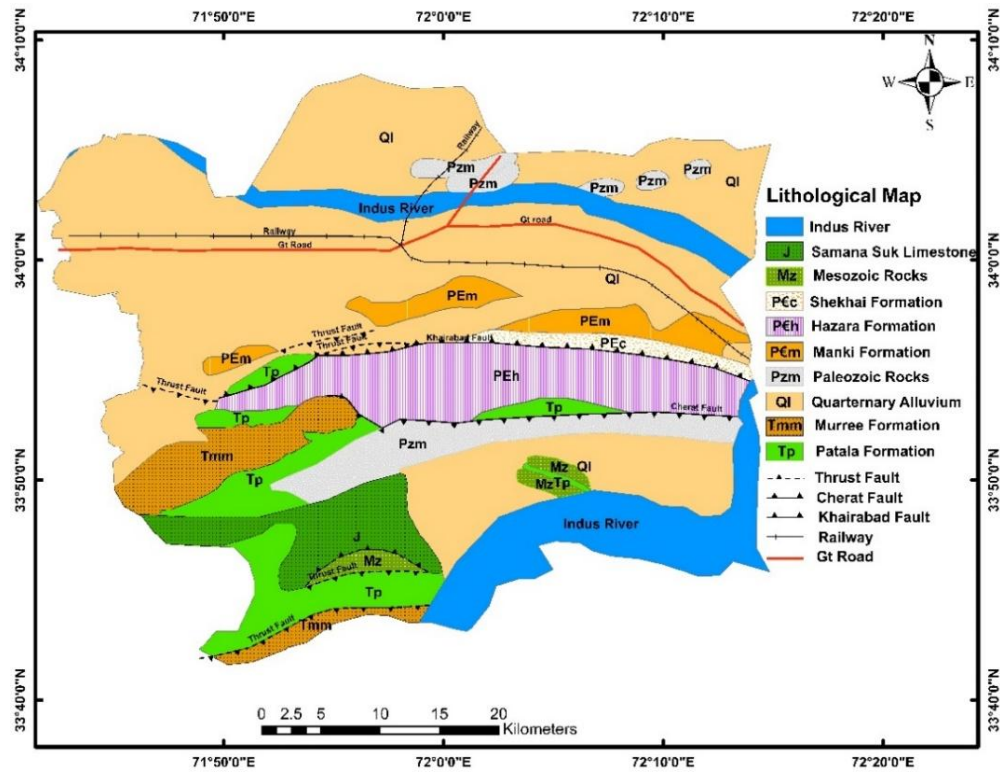


Fig. 2. Geological map of the study area

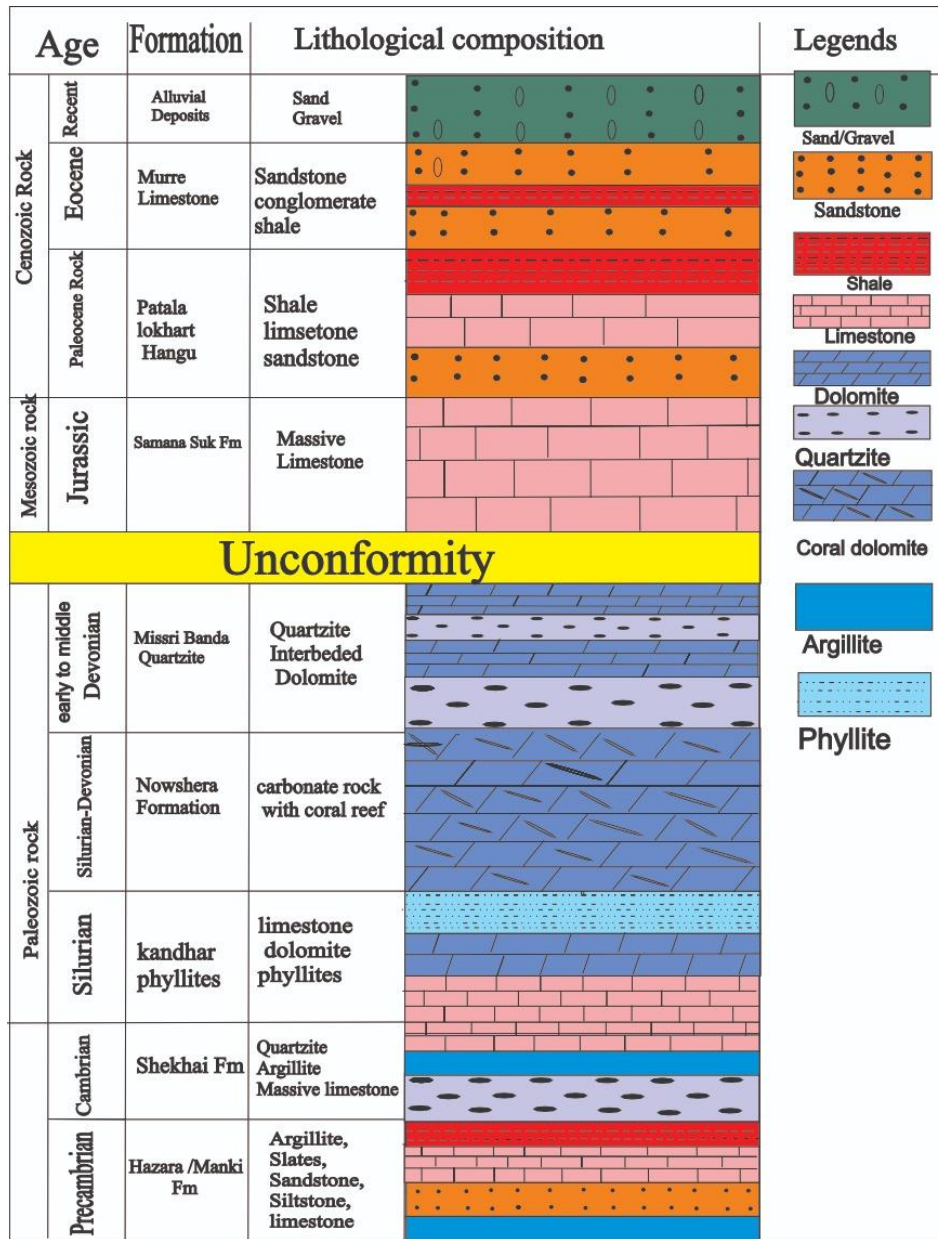


Fig. 3. Stratigraphic setting of the study area.

Materials and Methods

GIS techniques offer a comprehensive perspective on large geographical regions, enabling detailed assessments of geological and lithological features as well as land-use patterns. GIS is widely used in criteria-based evaluations for identifying potential mineral reserve areas due to its adaptability in sustainable mineral resource management. Through the integration of environmental and economic aspects, our research employed a GIS approach to identify crushed stone resources classified as significant and non-significant. All relevant factors were systematically evaluated using GIS methodology, as outlined in Table 1.

The analysis of areas with potential for crushed rock aggregate was conducted following the methodology proposed by (Karakaş, 2014), which involved selecting key factors such as geology (bedrock potential), distances to county centers, land use, and proximity to main roads and highways. A weighted overlay and AHP approach were employed to integrate various thematic maps in GIS and derive actionable insights regarding the locations of new aggregate potential areas. The detailed modeling steps undertaken to generate the final map for new potential crushed

stone areas are shown in Fig. 4. In our study, considerations such as rock lithology, elevation, slope, distances to roads, land use, and user activities have been considered to prevent conflicts between the land users and the environment. This study included the following thematic layers:

All datasets used in this study were selected based on their availability, relevance, and spatial resolution appropriate for regional-scale analysis. Land use was derived from Landsat 9 imagery (October 2022, Path/Row 150/37) with 30-meter resolution, processed using supervised classification. Geological and lithological maps were obtained from the Geological Survey of Pakistan's 2020 mineral inventory at a scale of 1:20,000. Elevation and slope were extracted from ASTER DEM (30-meter resolution), Version 3 (2011), accessed via USGS Earth Explorer, while road network data was digitized from the 2021 National Transport Authority maps (scale 1:250,000). These data sources are widely accepted for geospatial analysis and reflect recent conditions in the study area.

Weighted Overlay Analysis

The preparation of GIS thematic layers for these variables entails digitizing existing maps and integrating field data. Afterward, all thematic layers were superimposed using a weighted overlay analysis method to evaluate places with potential aggregate resources. The conversion of thematic maps from vector format to raster format was carried out to streamline subsequent analysis, as raster data format offers a more efficient computational process compared to vector data format (Chang, 2014). The Raster Conversion Tool in ArcGIS version 10.8 was used to transform all vector datasets into raster files. The raster maps obtained were first classified into common suitability scores based on the research objectives. The "Reclassify" function in the spatial analyst tool within ArcGIS software was used for this purpose. Higher scores indicated more suitable features, while lower scores indicated unsuitable.

The raster layers were reclassified and then combined using the raster calculator tool in ArcGIS to create the final suitability map. Multiple weighing scenarios were evaluated, considering the significance of each aspect, and the most realistic option was chosen. In this scenario, weight values of 45%, 24%, 15%, 8%, and 8% were assigned to characteristics such as lithology, suitable land use area, distance to main roads, lower elevation, and gentle slope, respectively. The weight percentage allocated to each factor layer, up to a total of 100%, is displayed in Table 1.

Table 1. Classification scores of each sub-factor and the weight of factors used for the selection of potential aggregate rock sites

Factors and subfactors	Rank	Area (%)	Classification score	Weight (%)
Lithology				
Rocks type				
Samana suk Limestone	Very High	10.6	5	45
Murree Formation				
Shekhai Formation				
Hazara Formation	High	19.6	4	
Manki Formation				
Paleozoic Rocks				
Mesozoic Rocks				
Patala Formation	Medium	7.1	3	
Quaternary alluvium	Low	51.4	2	
Channel deposits	Very low	11.30	1	
Land use				
Barren land	—	29.6	5	24
Urban	—	23.3	4	
Agriculture	—	40.9	3	
Forest	—	4.5	2	
Water	—	1.7	1	
Distance from roads (km)				
1– > 2	—	30.5	5	15
>2–4	—	39.2	4	
4– >12	—	21.0	3	
12–22	—	9.3	2	
Elevation (m)				
239–381	—	52.4	5	8
381–526	—	21.5	4	
526–713	—	14.1	3	
713–971	—	8.8	2	
>971	—	3.2	1	

Slope (degrees)

1° –4°	—	44.8	5	8
4° –8°	—	24.7	4	
8° –16°	—	15.0	3	
16° –24°	—	8.0	2	
24° –66°	—	7.5	1	

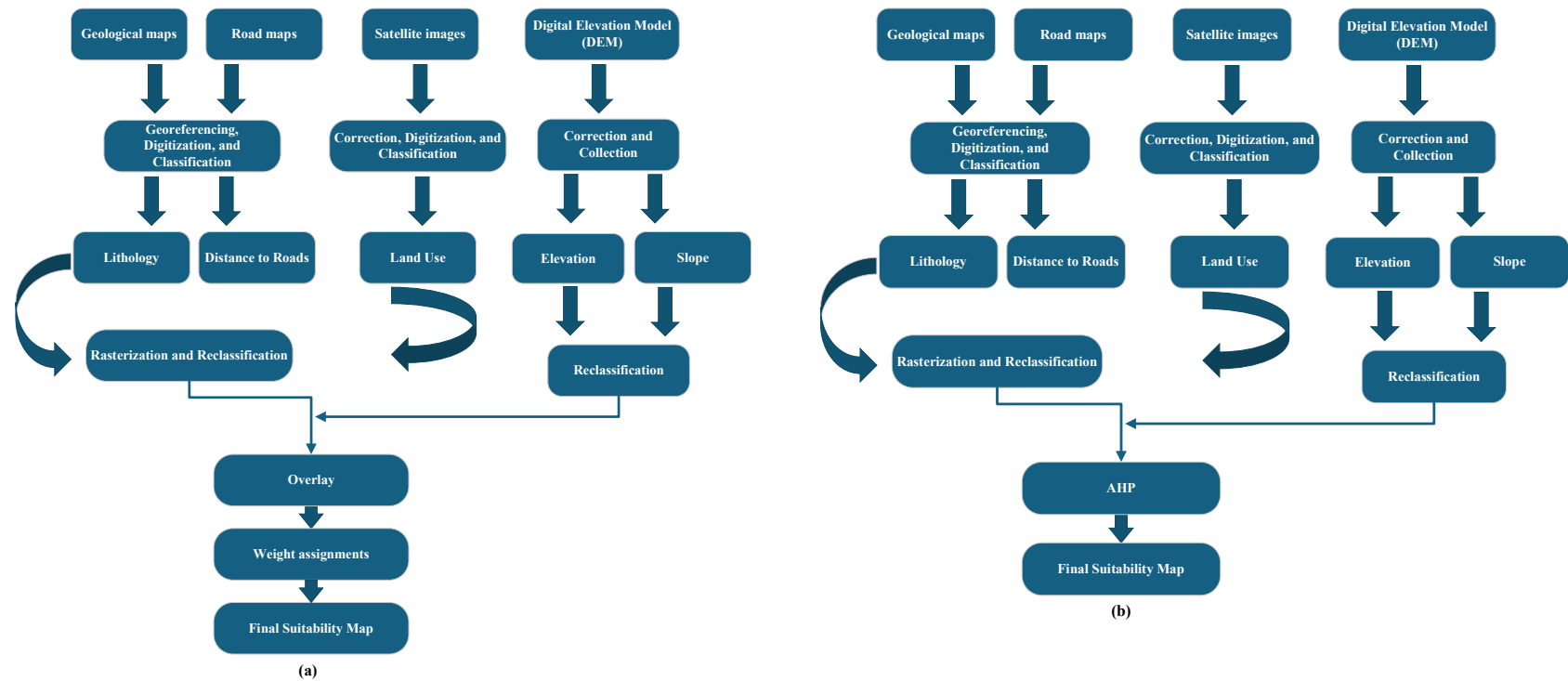


Fig 4. The flowchart illustrates the steps to create the final suitability map: (a) Weighted Overlay Analysis; (b) AHP Analysis.

AHP Analysis

The AHP is a widely used multicriteria decision-making (MCDM) approach that has been applied across various fields, including economics, politics, and engineering (Dhingra et al., 2022; Vaidya & Kumar, 2006). It aids decision-makers by enhancing their understanding in the selection of alternatives and resolving conflicts involving multiple, often contradictory and subjective, criteria. Originally developed by Saaty & Katz (1990), the AHP technique is recognized as a powerful tool for evaluating multiple factors and is frequently integrated with GIS-based methods to assess suitability (Ayodele et al., 2018). This process assigns appropriate weighting factors by comparing the identified relevant criteria using a preference matrix (Table 2).

The AHP has been utilized in a range of soil management strategies, including innovative approaches for assessing soil health (Xue et al., 2019), analyzing landslide risks (Myronidis et al., 2016), evaluating land-use changes (Memarbashi et al., 2017), managing regional soil resources (Wang & Qu, 2009), and developing soil remediation plans (Bascetin, 2007; Kallas et al., 2022).

The initial phase of the AHP involves breaking down a complex decision-making problem into smaller, more manageable components to create a decision hierarchy (Goepel, 2013). Following this decomposition, which is facilitated by pairwise comparisons using AHP software (as illustrated in Table 2), the cardinal rankings for the criteria are established. Simultaneously, two alternatives and their significance are evaluated, simplifying the ranking process. Table 3 presents the comparison matrix for the five criteria that were developed. The composite weights are calculated by multiplying the comparison matrix by a predetermined factor.

Normalization of the choice matrix is essential after squaring it and determining the row sums. This normalization process is successively applied until the weights from successive phases exhibit minimal variation. Once the weights for each criterion are established, the geometric formula operation is employed (Ohri et al., 2011) to calculate the total scores of the alternatives within a GIS environment, resulting in a suitability map for potential aggregates. Table 3 presents the percentage weights allocated to each feature: lithology (44.70%), land use (23.40%), distance to roads (14.84%), elevation (8.53%), and slope (8.53%). These results indicate that lithology is the most significant factor, while distance to road is the least critical consideration for determining area suitability.

Table 2. Resulting weights based on the eigenvector of the decision matrix, eigenvalue = 5.093

Features	Lithology	Land Use	Distance to road	Elevation	Slope
Lithology	1	3	3	4	4
Land use	0.33	1	2	3	3
Distance to road	0.33	0.5	1	2	2
Elevation	0.25	0.33	0.5	1	1
Slope	0.25	0.33	0.5	1	1

Table 3. Resulting weights based on pairwise comparisons, CR 2.1%

Features Priority	(%)	(+, %)	(-, %)
Lithology	44.70	14.5	14.5
Land use	23.40	5.4	5.4
Distance to road	14.84	2.2	2.2
Elevation	8.53	1.4	1.4
Slope	8.53	1.4	1.4

The pairwise comparisons used in the AHP were constructed based on expert judgment, incorporating local knowledge of geological resource potential, accessibility, and environmental conditions. Input was collected from specialists in geology, mining, and land use planning. The process followed Saaty's AHP framework, using a standardized comparison scale to assign relative importance values. A consistency ratio (CR) of 2.1% was obtained, confirming the logical coherence of the judgments. While the final weights reflect expert opinion, the factor selection and their relative importance align closely with previous studies such as (Karakas, 2014).

Results and Discussion

Analysis of thematic layers

Lithology

To accurately predict areas containing aggregate rocks, detailed surface lithological data alongside historical records of regional aggregate sources across the entire targeted region are essential. Assessment usually includes the evaluation of sedimentary, metamorphic, and igneous rocks. ArcGIS 10.8 was utilized to demarcate probable aggregate sites by analyzing various types of exposed rock formations in the research area. The dolomitic limestone and dolomite, whether visible on the surface or covered by a thin layer of overburden, have the greatest capacity for crushed stone. Although the research region contains widespread surface Quaternary deposits, their distribution is limited. Limestone and other carbonates make up a substantial part of the rocks used for crushing or as crushed stone, while the remaining portion is composed of detrital rocks.

The presence of abundant limestone deposits suggests a high likelihood of major aggregate supplies, covering approximately 30.2% of the total region. Igneous and metamorphic rocks that are visible or located close to the surface have a moderate potential, mainly in specific remote places. Although sandstones and conglomerates are generally considered to have little potential for usage as bedrock, conglomerates are frequently utilized as crushed stone in certain areas of the study area. The natural aggregates obtained from open-cast quarries in plains and hilly areas are derived from sand and gravel deposits that were created by the process of water erosion. These deposits are widespread in rivers, streams, terraces, and alluvial fans, making up around 11.30% of the region. Furthermore, regions with clay and silt deposits have a lower potential for crushed stone, especially in places where the soil profiles are well-developed and consist of heterogeneous strata.

Based on the characteristics of exposed bedrock and data regarding aggregate quarries in the region, the mapped units were categorized into five potential classifications: very high, high, medium, low, and very low. The attribute table of the bedrock potential map outlines these classifications along with their corresponding values. It indicates that 16.22% of the mapped area demonstrates low suitability, 69.05% is categorized as medium suitability, and 14.72% falls within the high-suitability category (Figure 5).

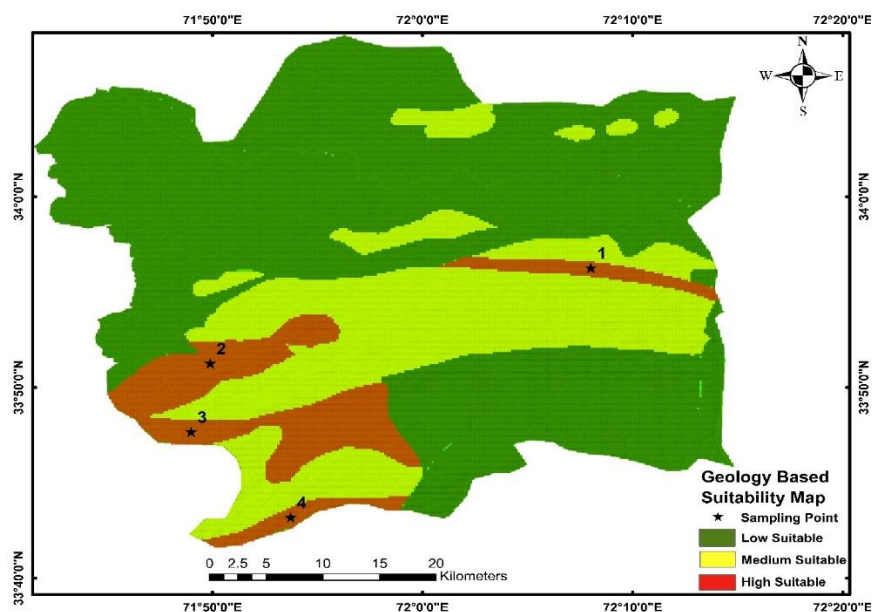


Fig 5. Map showing the sampling points and suitability of the study area based on lithological analysis.

Land Use

Aggregate extraction near urban areas presents considerable environmental challenges. These challenges include alterations to the landscape, elevated noise levels, dust emissions, and ground vibrations (Bolen & Tepordei, 2001; Smith & Collis, 2001). This activity often entails the conversion of land use, transforming undeveloped or agricultural areas into excavated sites, leading to habitat loss, increased noise, dust emissions, vibrations, erosion,

sedimentation, alterations to the visual landscape, and potential site abandonment (Lake et al., 2000). Consequently, a land-use assessment was conducted to identify suitable aggregate resources for long-term management in the study area.

The vector version of the land-use map was used to create a land-use layer, which was then categorized on a scale from 1 to 5. Class 1 represents areas that are least suitable for aggregate supply, while Class 5 represents the most suitable areas. The highest score of 5 was assigned to barren land, which represents around 29.6% of the entire research area. The rank of 4 was assigned to urban areas, which cover 23.3% of the total area. Class 3 was assigned to agriculture, which made up 40.9% of the research area. The area covered by forest was 4.5% of the total, while water, which made up 1.7% of the region, was considered the least suitable place (Fig. 6).

The global mining industry is facing growing challenges due to conflicting land uses, zoning rules, community resistance, licensing limitations, and environmental issues (Langer, 2002). Aggregate extraction in the Nowshera district is similarly constrained by land use restrictions imposed by landowners, along with the difficulties posed by its arid, hilly terrain.

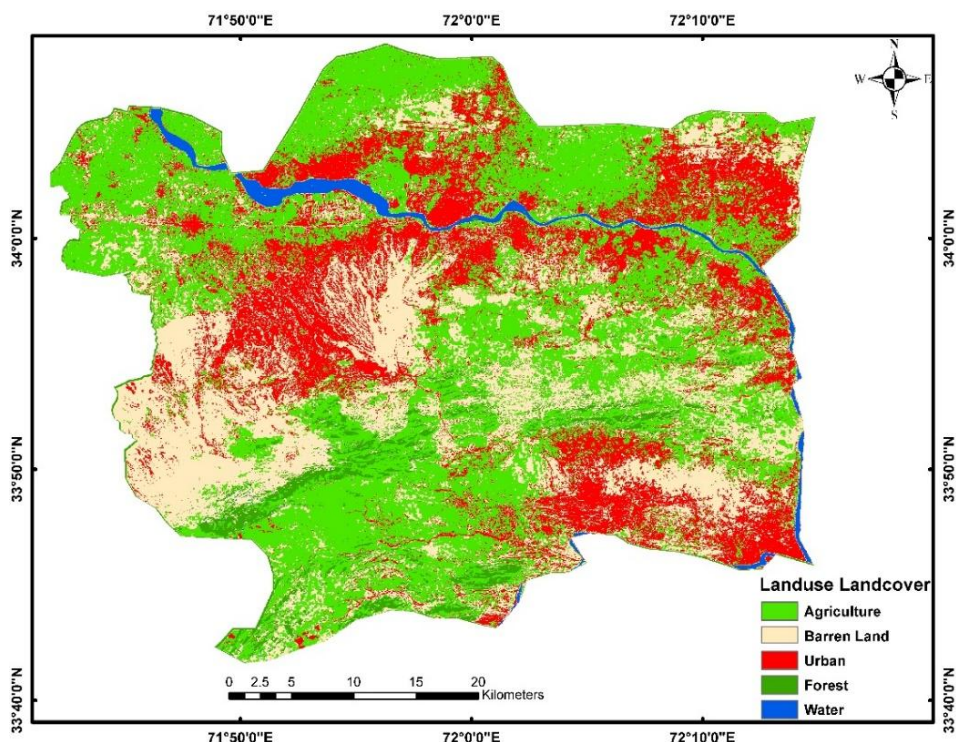


Fig. 6. Land use land cover map of the study area.

Topographic Elevation

The study area exhibits a diverse elevation range spanning from 239 to 1544 meters above sea level (Fig. 7), which holds significant implications for aggregate extraction. While the region possesses abundant sources of crushed rock, particularly in its mountainous and rocky areas, quarrying at higher altitudes presents considerable challenges. Extracting construction materials in mountainous, high-altitude environments involves logistical challenges such as deploying extraction equipment, restricted operating seasons, and increased economic demands. Therefore, the process of extracting aggregates in these places presents significant difficulties.

Elevation data, including the Digital Elevation Model (DEM), was obtained from the ASTER DEM provided by the US Geological Survey (USGS) and processed using GIS techniques. The elevation map was subsequently divided into five interval groups. Areas ranging from 239 to 381 meters were designated a rating of 5, encompassing around 52.4% of the study area. Altitudes ranging from 381 to 526 meters were classified as rank 4, accounting for 21.5% of the total area. Similarly, altitudes ranging from 526 to 713 meters were assigned rank 3, covering 14.1% of the total area. Areas with elevations between 713 and 971 meters were categorized as rank 2, covering 8.8% of the

total region. Regions that exceeded 971 meters were designated as ranked 1, representing 3.2% of the research area. Areas at higher elevations are considered less desirable because of the higher transportation expenses and difficult road conditions. As a result, they are ranked worse in terms of overall value and accessibility.

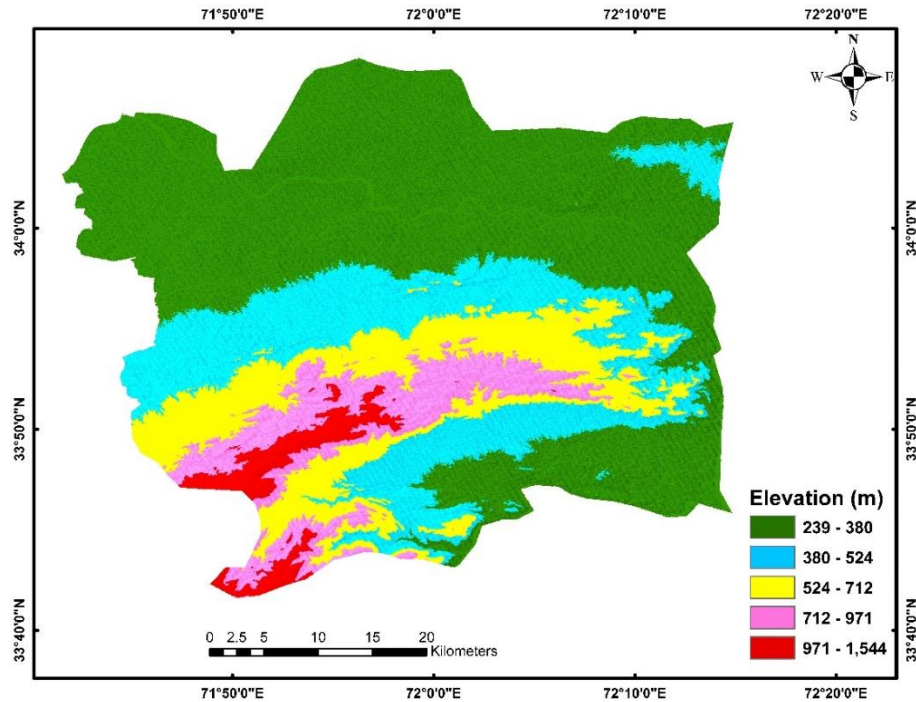


Fig 7. Elevation map of the study area

Topographic Slope

The assessment of mountainous terrain slope is important in determining the most suitable sites for new quarries since it directly affects the accessibility of transportation (Akinci & Demirarslan, 2022; Barakat et al., 2016). The DEM was employed to create the slope layer, which was classified into five categories according to gradient angles. Slopes ranging from less than 1° to 4° were categorized as gentle, indicating the most favorable conditions for quarrying activities. 4° to 8° are moderate; 8° to 16° are steep; 16° to 24° are very steep; 24° to 66° are extremely steep. The last two categories, due to their steepness, are considered unsuitable for aggregate supply. Figure 8 presents the categorized slope map along with the percentage distribution for each category. The map shows that gentle slopes cover 44.8% of the area, moderate slopes account for 24.7%, steep slopes make up 15%, very steep slopes represent 8%, and extremely steep slopes cover 7.5% of the region.

The analysis of elevation and slope maps reveals key topographic characteristics of the study area. The southwestern region is characterized by mountainous terrain with steep slopes, posing significant challenges for transportation infrastructure development. This part of the district is sparsely populated, featuring extensive areas of forests and agricultural land with low population density. In contrast, the northern section consists of flat plains with gentler terrain, predominantly utilized for agriculture, although urbanization is gradually increasing in this area.

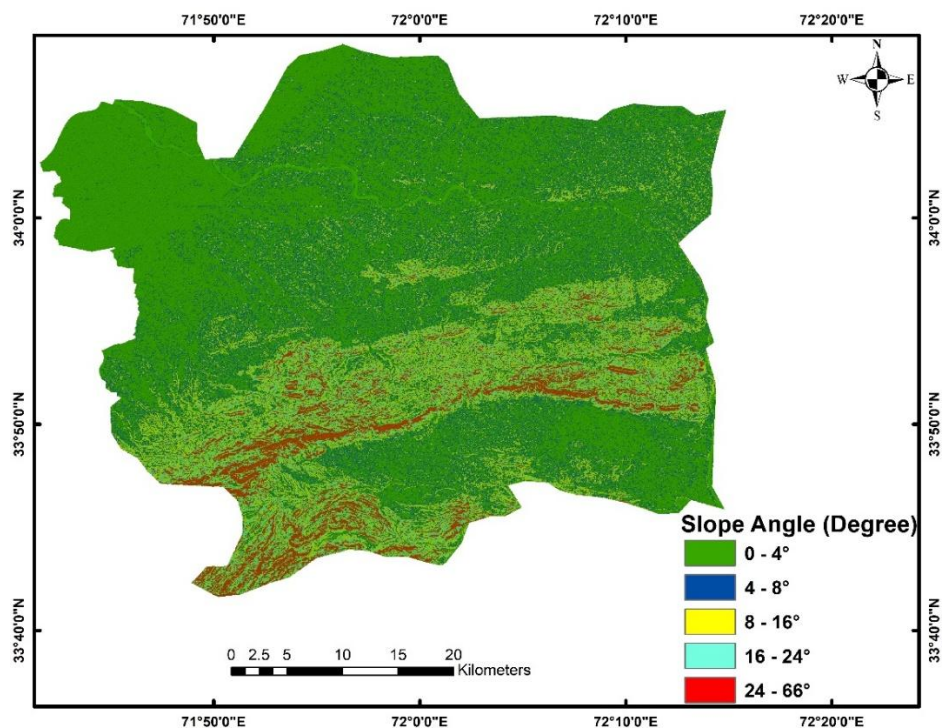


Fig 8. Slope map of the study area.

Distance from Roads

Establishing aggregate resources near major roads offers several advantages. The close proximity to transportation networks facilitates economic benefits, enabling the swift transport of finished products while minimizing costs associated with accessing and maintaining necessary quarry materials. This strategic location enhances operational efficiency and can significantly reduce logistical expenses (Rademeyer, 2000). Therefore, attempts were made to choose locations with accessibility to existing roads. The road network was manually constructed using polylines by processing digital scans of source maps with ArcGIS software and spatial analytic tools. The resulting network was then georeferenced with longitude and latitude. There is a well-developed road network in the study area that facilitates movement between the municipalities, according to the road layer (Fig. 9). The continuous expansion and enhancement of the road network, which encompasses highways as well as national, regional, and provincial roads, represents a significant advancement in infrastructure development. This growth facilitates improved connectivity and accessibility, thereby supporting economic activities and regional development.

To highlight the importance of proximity to roads, a map was generated by applying a buffer around the existing road network. The buffer was divided into four different ranges: 1- >2 km, >2- 4 km, 4- > 12 km, and 12-22 km (Fig. 9). Subsequently, the buffer-zone datasets were reclassified, with new values of 5, 4, 3, and 2 being assigned to them, respectively. The research area within the 1-2 km buffer was recognized as 30.5% and assigned a rank of 5. The 2-4 km buffer was assigned a score of 4, covering 39.2% of the total study area. Similarly, the buffer with a radius of 4-12 km was assigned a rank of 3, covering 21.0% of the study area. On the other hand, the buffer with a radius of 12-22 km, which covered 9.3% of the total research area, was assigned a rank of 1. This ranking system prioritizes the proximity of each buffer to the chosen location, assigning higher values to closer buffers. This indicates that certain buffers are more suitable for developing aggregate queries.

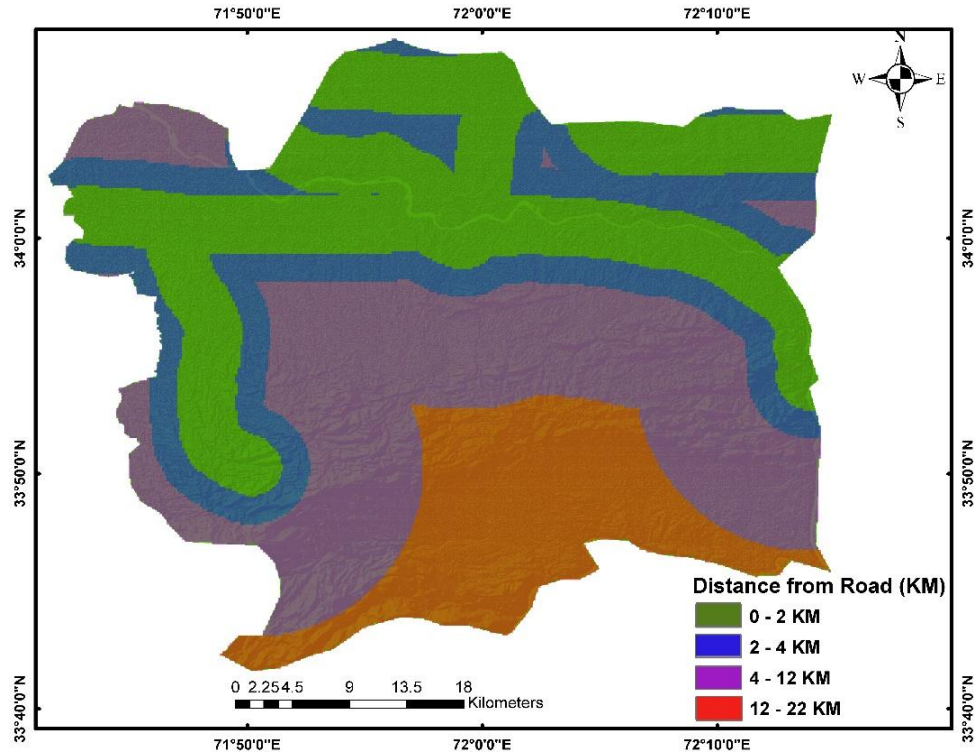


Fig. 9. Distance from the road map of the study area.

Aggregate resource potential map

To generate the suitability map for aggregate resources, two distinct methods have been employed.

Weighted Overlay Analysis

To generate suitability maps for aggregate resource areas, the classified maps derived from each individual variable were combined. The integration of suitable regions was accomplished by superimposing the suitable bedrock classes, land use, proximity to main roads and highways, elevation, and slope layers. Weighted overlay analysis was used in GIS to overlay the classes depending on their respective rates and the relevance of their thematic layers. Although this methodology has disadvantages, such as its dependence on assessors' judgments and the inconsistency in decision weights for different criteria, numerous weighing scenarios were created by modifying weight coefficients for various factors. Subsequently, these scenarios were evaluated to choose the most credible one. Geology, land use, distance from major highways, elevation, and slope were prioritized in descending order to pinpoint suitable regions for aggregate extraction. Subsequently, the ArcGIS raster calculator tool was used to build the final site suitability map (Fig. 10). This tool executes simple attribute arithmetic that considers the weight of each layer. Approximately 16.22% of the research region was categorized as "low suitable," 69.05% as "moderately suitable," and 14.72% as "suitable" according to the weighted overlay analysis.

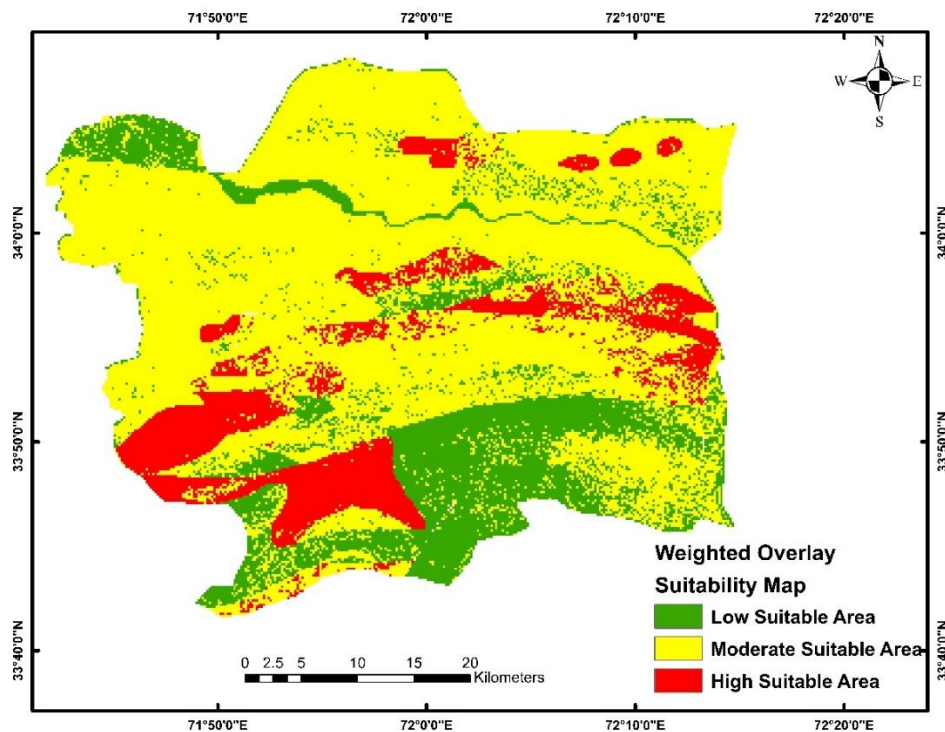


Fig 10. Final suitability map of potential aggregate based on weighted overlay analysis.

AHP Analysis

The suitability map for aggregate resources in the study area was generated using a GIS-based Analytic Hierarchy Process (AHP), which is a multicriteria assessment technique (Figure 11). This analysis incorporated five conditioning factors: slope degree, elevation, lithology, land use, and distance to roads. Traditionally, the AHP method relies on ratings provided by experts to evaluate these factors effectively (Appolloni et al., 2022; Rabello Quadros & Nassi, 2015). Expert advice plays a crucial role in addressing complex issues such as identifying suitable aggregate resources. However, it is important to recognize that opinions among experts may differ, leading to potential cognitive limitations influenced by ambiguity and subjectivity. In this study, each parameter was spatially analyzed to facilitate expert assessment. The pairwise comparison matrix for the factors and sub-factors was developed using Saaty's approach (1990; AHP software-based). The consistency ratio (CR) was calculated for all components and found to be 2.1%, indicating that the assigned weights were both appropriate and reliable. A GIS-based suitability map for aggregate resources has been developed, illustrating the results of this analysis. The results show that 16.22% of the region's terrain or area is classified as low suitable, 69.05% as moderately suitable, and 14.73% as high suitable areas using AHP analysis.

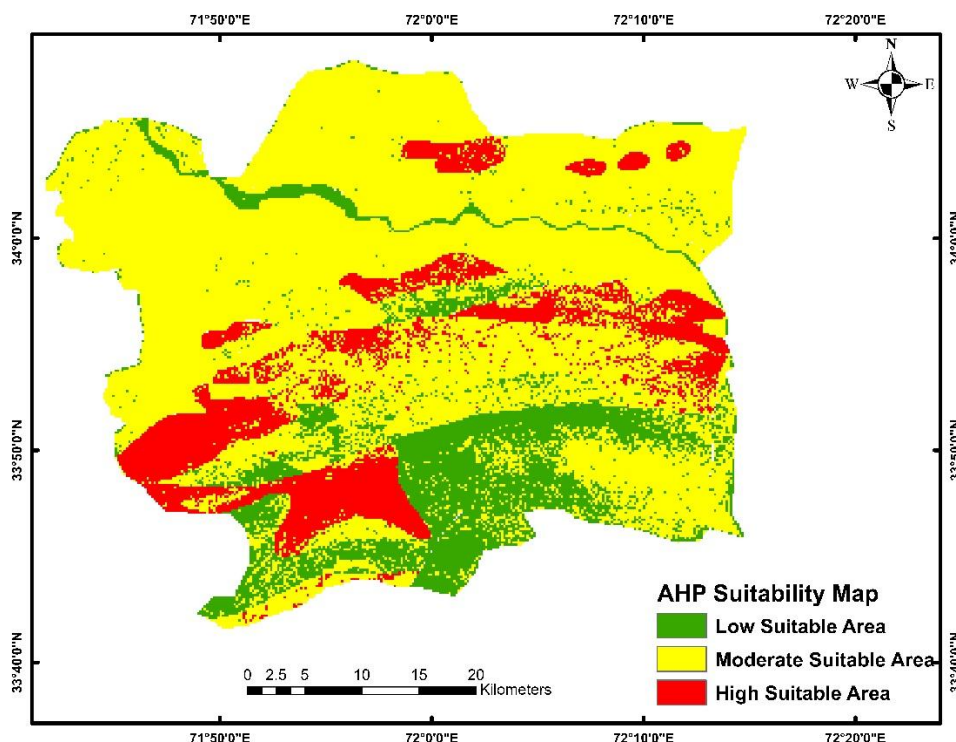


Fig. 11 Final suitability map for potential aggregate resources derived from AHP analysis.

Comparison of the Weighted Overlay Analysis and AHP Method

The suitability map for aggregate resources in the Nowshera district was categorized into three zones: low, moderate, and high suitability. This classification was achieved through weighted overlay analysis and the Analytic Hierarchy Process (AHP). The ROC curve was used to evaluate the classification performance of both suitability models. Binary ground truth data—based on known quarry site locations and high-suitability zones—were compared to model outputs. The AUC values of 0.86 (AHP) and 0.76 (WOA) indicate strong overall accuracy, with AHP demonstrating better discrimination capability. This suggests that AHP more effectively distinguishes suitable zones, providing enhanced reliability for spatial decision-making. The AHP model achieved an area under the curve (AUC) of 86%, while the Weighted Overlay Analysis scored 76%. While direct field observations were not newly conducted for this study, the results were cross-referenced with existing quarry locations, known lithological units, and infrastructure proximity to ensure spatial consistency. This indirect validation supports the practical reliability of the findings.

The Weighted Overlay Analysis (WOA) employed the same five criteria as the AHP method to ensure comparability: lithology, land use, distance to roads, elevation, and slope. The weights for each factor in WOA were assigned based on expert judgment and literature guidance, then normalized to a total of 100%. In contrast to AHP, which uses a structured pairwise comparison matrix, WOA applies static weights directly to reclassified raster layers. The ROC curve (Figure 12) was used to compare the predictive performance of both methods, revealing that AHP achieved a higher accuracy (AUC = 86%) than WOA (AUC = 76%), likely due to its ability to model inter-factor relationships more rigorously.

While both WOA and AHP identified similar high-potential areas, the AHP model demonstrated greater precision in delineating zones with the most favorable combination of geological, infrastructural, and environmental characteristics. This advantage stems from AHP's structured weighting process and logical consistency checks. Areas ranked as 'highly suitable' by AHP closely align with carbonate-rich lithologies and low-slope zones near major roads, making them more feasible for development. These outputs provide a reliable decision-support tool for policymakers to prioritize resource extraction while minimizing environmental and logistical challenges.

Our study advances the AHP-GIS literature in three important ways. First, it demonstrates that AHP offers superior predictive accuracy (AUC = 0.86) compared to weighted overlay (AUC = 0.76) in data-scarce, geologically

complex regions—an empirical contribution that reinforces AHP's value in under-resourced settings. Second, our weighting structure challenges prevailing assumptions in the literature, where proximity to infrastructure often dominates. In contrast, our findings reveal that lithology (44.7%) and land use compatibility (23.4%) are more critical in the Nowshera context, suggesting the importance of localized, context-specific weight calibration. Third, by applying the model in a rapidly urbanizing region of a developing country, we extend theoretical discussions on sustainable resource planning beyond the typically studied, well-resourced environments. These contributions collectively refine existing knowledge and offer a framework adaptable to similar regions worldwide.

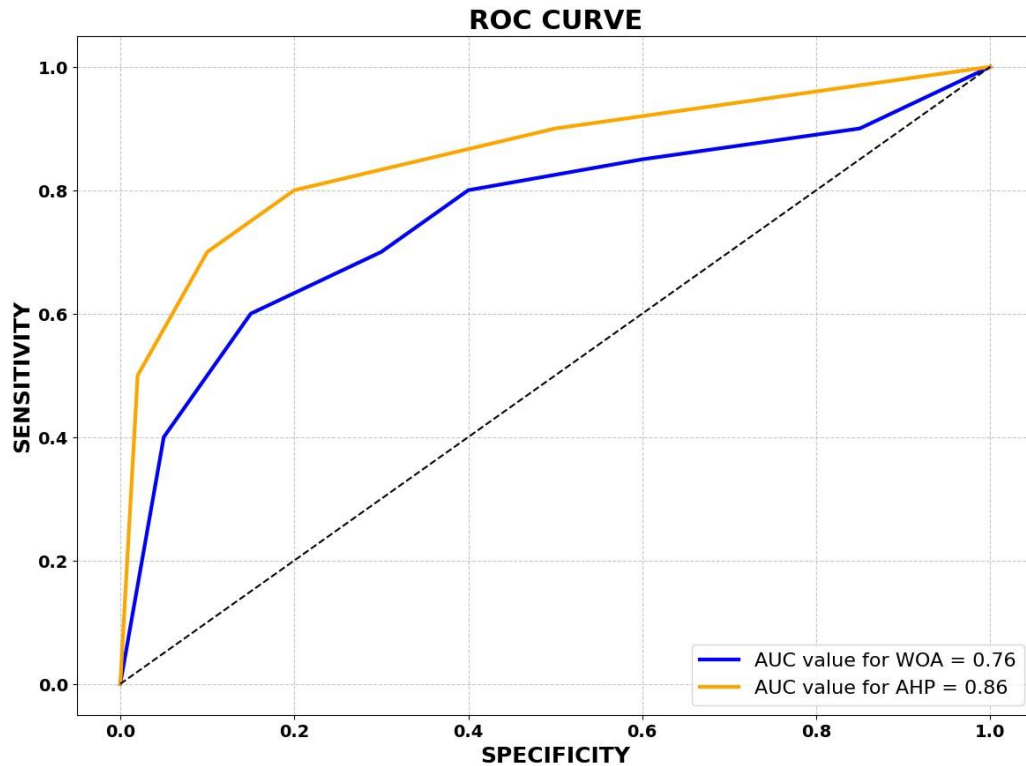


Fig. 12. Comparison of AHP and weighted overlay analysis using the ROC curve.

Field-based validation

The following images illustrate the field validation process carried out to verify the geological suitability of the sites identified through the weighted overlay analysis. These images provide visual evidence from the sample collection sites and confirm the presence of limestone, along with other geological features, in the high-potential zones. The field observations strongly support the predictive accuracy of the model.

The primary material considered in this study is limestone, which is extensively used in the construction industry as a key aggregate material. Other lithological units, including granite, sandstone, and shale, were also considered. However, limestone remains the dominant resource of interest. Consequently, the proposed sites identified through the weighted overlay analysis predominantly feature limestone-rich zones, with some occurrences of sandstone and shale.

The first sample was obtained from a location situated at latitude 33°56'11.22"N and longitude 72°8'4.72"E. This site falls within the high-potential red zone and contains high-purity limestone with additional coal deposits observed in the surrounding vicinity (Figure 13).



Fig. 13. Showing a coal deposit along with the limestone bed.

The second sample was collected near the second location, specifically at latitude $33^{\circ}47'32.58''\text{N}$ and longitude $71^{\circ}49'7.82''\text{E}$. Based on field observations, the presence of limestone was confirmed, further reinforcing the predictive accuracy of the weighted overlay model (Figure 14).



Fig. 14. Showing the limestone bed lying diagonally.

The third sample was taken from a site located at latitude $33^{\circ}43'6.68''\text{N}$ and longitude $71^{\circ}53'42.39''\text{E}$, and field observation revealed the presence of laterite, accompanied by subordinate quantities of sandstone and shale (Figure 15).

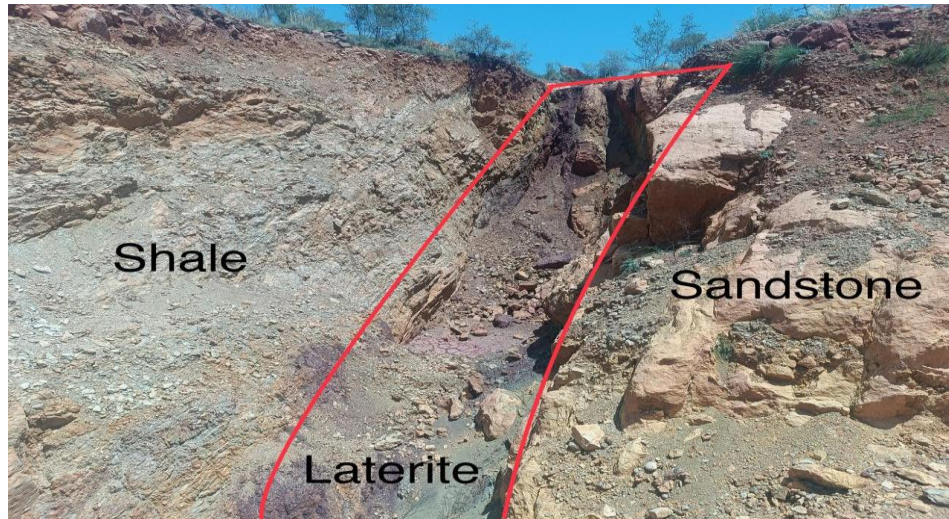


Fig. 15. Showing the Laterite intruded shale and sandstone.

Conclusions

Assessing potential sites for establishing aggregate quarries is crucial for maintaining the effective and sustainable utilization of existing mineral aggregate resources, especially in developing countries. As a result, there has been increased interest in conducting site suitability evaluations to determine suitable locations for different development projects, particularly in the aggregates sector. GIS techniques are becoming increasingly important for performing evaluation studies because they can easily manage spatial data from many sources, providing simplicity and cost-effectiveness, especially when compared to other methods.

The current research utilized the AHP and weighted overlay analyses to evaluate the impact of various factors on identifying new sources of crushed rock aggregate. The results indicate that the final maps produced from both analyses highlight potential locations suitable for crushed rock aggregate extraction. Consequently, several areas within the study region have been identified and classified into three categories: low suitability, moderate suitability, and high suitability.

The suitability of areas identified through both weighted overlay and AHP analysis is primarily based on overlaying regions with high bedrock potential, particularly those containing carbonate rocks. Factors influencing aggregate production suitability included land use (meadow, forest, pasture, urban), proximity to major roads and highways, and lower elevation zones. Additionally, a comparison between the AHP and weighted overlay analysis was conducted to assess accuracy, with AHP demonstrating a higher level of accuracy.

Environmental constraints were indirectly accounted for through land use (e.g., exclusion of forests, water bodies, and urban areas) and slope criteria, which helped avoid ecologically fragile and erosion-prone zones. For example, the Kabul River riparian corridor, an ecologically sensitive zone, was classified as low suitability due to its steep slopes and protected land cover, aligning with conservation objectives. Nonetheless, we acknowledge that this approach only partially captures ecological complexity. Future research should incorporate explicit environmental datasets such as biodiversity hotspots, protected areas, and hydrological buffers to enhance ecological risk assessments. This would strengthen the model's capacity to support truly sustainable aggregate resource planning.

The suitability maps generated, particularly those using the AHP method, offer actionable tools for regional planners and decision-makers. For instance: (1) areas identified as highly suitable, such as barren limestone zones adjacent to major highways, can be prioritized for quarry licensing to reduce land use conflicts and infrastructure costs; (2) moderately suitable areas may warrant further scrutiny, including environmental impact assessments, before development is approved; and (3) the demonstrated higher accuracy of the AHP approach ($AUC = 0.86$) supports its integration into regional mineral planning frameworks. Institutions like the Peshawar Development Authority could adopt these spatial outputs to inform land use zoning, streamline permitting processes, and safeguard ecologically or socially sensitive areas. By aligning technical modeling with real-world decision needs, our study offers a practical pathway toward more efficient and sustainable aggregate resource management.

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