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Spatial Suitability Analysis for Quarry Site Selection in Northern Morocco Using GIS and MCDA: Towards Sustainable Resource Exploitation

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ABSTRACT

The exploitation of quarries represents a strategic component of Morocco's construction-materials sector, especially amid rapid urbanization and infrastructure expansion. To ensure that extractive activities remain environmentally sustainable and compliant with national regulations, this study applies a spatial suitability analysis based on Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA) within the ArcGIS Pro environment. The methodology integrates six key criteria: lithology, slope gradient, hydrographic buffers, land-use/land-cover patterns, accessibility to transport networks, and exclusion of urbanized or ecologically sensitive zones. Each parameter was weighted using the Analytical Hierarchy Process (AHP) to generate a composite suitability map for quarry site selection in north-western Morocco. The resulting classification shows that 18% of the total area is highly suitable, 34% moderately suitable, and 48% unsuitable for sustainable quarrying. Priority zones occur mainly within carbonate formations in the Tangier–Assilah Province and, to a lesser extent, within Numidian flysch units in the Fahs-Anjra Province. These findings demonstrate that GIS–MCDA methods offer a robust and transparent framework for optimizing quarry site selection, reducing ecological risk, and improving decision-making for land-use planning and resource management in Morocco's extractive sector.

Keywords: Remote Sensing; Environmental Impact Assessment; Geotechnical Parameters; Land-Use Conflicts; Multi-Criteria Evaluation; Decision Support Tools

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1. Introduction

The extractive sector, particularly quarrying, plays a fundamental role in Morocco's economic and infrastructural development. It provides aggregates, cement, clays, and other raw materials essential for housing, transport, ports, and energy infrastructures. With rapid urbanization and large-scale public works, national demand for construction materials has sharply increased, making quarrying a strategic activity for achieving Morocco's development goals [1]. However, intensive exploitation of geological resources generates severe environmental impacts, including soil degradation, groundwater contamination, erosion, and biodiversity loss. In the Mediterranean region, studies have shown that quarrying without rigorous site selection leads to irreversible ecological damage and long-term landscape instability [2,3]. These findings highlight the urgent need for approaches that reconcile economic growth with environmental protection.

In Morocco, quarry site selection often lacks systematic and scientifically rigorous methods. Decisions are still largely driven by accessibility and economic convenience, with limited consideration of geotechnical constraints, ecological sensitivities, and long-term land-use planning. Although Geographic Information Systems (GIS) and remote sensing have been increasingly applied in environmental and coastal management, their systematic use in quarry planning remains scarce. The absence of comprehensive frameworks that integrate geological, topographic, hydrological, environmental, and socio-economic parameters into a unified model constitutes a significant gap that this study seeks to address.

The aim of this research is to establish a spatially explicit multicriteria framework for identifying quarry sites that are both technically viable and environmentally sustainable. By integrating satellite imagery, cartographic datasets, and field surveys into a GIS environment, the study generates suitability maps and classifies potential sites according to their geological quality, accessibility, and environmental sensitivity. The novelty of this approach lies in the operationalization of GIS–MCDA methodologies within the Moroccan extractive sector, where such tools have rarely been applied. Through the combination of geoscientific data with decision-analysis methods such as the Analytical Hierarchy Process (AHP) and Boolean logic [4–6], the research demonstrates how quarry site selection can be optimized to support rational natural resource management. Recent advances in Multicriteria Decision Analysis (MCDA) and spatial modeling have already proven efficient in Europe, Asia, and Africa [7–10] but remain underdeveloped in Morocco.

Furthermore, Moroccan research has emphasized the role of GIS and remote sensing in coastal and land-use management. For instance, geomatics-based digital simulation has been used to analyze coastal kinematics along the Atlantic margin [11], while remote sensing combined with statistical methods has proven effective for shoreline-change monitoring in the Tahaddart region [12]. These studies highlight the transferability of spatial decision-support methods to extractive resource management, strengthening the case for their use in quarry planning in northwestern Morocco. This study therefore contributes to filling the existing gap by applying a GIS–MCDA methodology to the Tangier–Assilah and Fahs-Anjra provinces. The results provide decision-makers, local authorities, and industry stakeholders with an evidence-based tool for sustainable resource exploitation, aligning quarry development with Morocco's National Development Agenda.

2. Study Area Description

2.1. Location

The study area, covering the municipalities of Tangier, Assilah, and Fahs-Anjra within the Tanger–Tétouan–Al Hoceïma region (**Figure 1**), lies in the External Rif, a geodynamically active zone of the Moroccan Alpine belt shaped by the convergence of the African and Eurasian plates [13].

The Tangier–Assilah sector is dominated by Upper Cretaceous to Miocene marly-limestone formations deposited in deep-marine settings, deformed by Alpine tectonics into thrusts and folds [14]. In contrast, the Fahs-Anjra sector is mainly composed of Numidian flysch (Eocene–Miocene sandstones, marls, and shales), whose variable mechanical properties raise challenges for slope stability and quarry exploitation [15]. Quaternary deposits, such as consolidated dunes and fluviomarine terraces, also mark the Atlantic margin and provide additional exploitable resources [16].

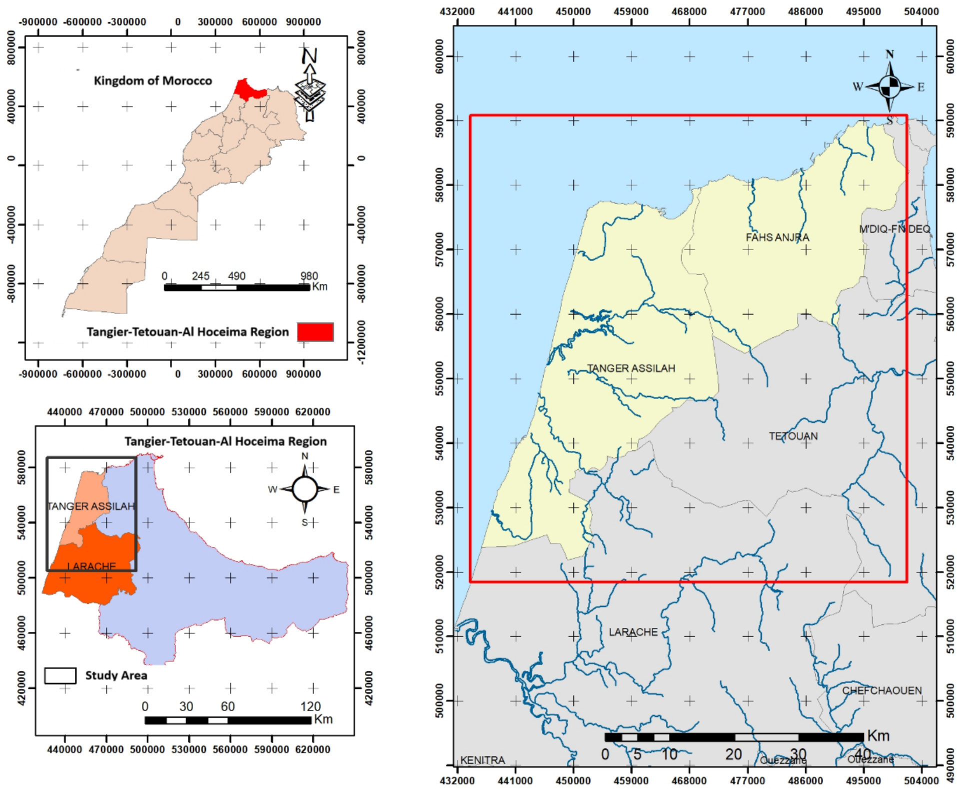

Figure 1. Location of the study area: (**a**) General position of the Tanger–Assilah–Fahs-Anjra prefectures within Morocco; (**b**) Administrative boundaries of the study area; (**c**) Major physiographic units.

From a geodynamic perspective, GPS data confirm ongoing crustal shortening (2–4 mm/year), reflecting active convergence across the Rif–Alboran region [17]. This tectonic activity, combined with lithological heterogeneity, directly influences quarry feasibility and environmental sensitivity. Moreover, the area's strategic position near the Strait of Gibraltar and the Tangier Med port enhances logistical accessibility, while simultaneously requiring careful land-use planning to balance resource exploitation with urban and ecological constraints [18].

In summary, the Tangier–Assilah–Fahs-Anjra region integrates favorable lithologies for quarrying, but its structural complexity and environmental sensitivity demand the use of GIS-based multicriteria evaluation for sustainable site selection.

2.2. Geological and Structural Framework of the Tangier–Assilah–Fahs Anjra Region

The lithological framework is highly diverse, encompassing marl-limestone sequences, flysch units, turbiditic facies, and Quaternary deposits (**Figure 2**). In the northwestern sector, the Tangier unit predominates with Upper Cretaceous to Lower Miocene marly-limestone formations deposited in deep-marine environments, reflecting alternating detrital and carbonate sedimentation during the Paleocene, Eocene, and Lower Miocene (**Figure 2**) [19,20].

Southwards, the Loukkos unit comprises Albo-Aptian to Eocene marls and marly-limestones [21], while the substratum further south is dominated by the Prerif and Habt nappes, consisting of gray marls, sandy turbidites, and black argillites deposited from the Lower Miocene to Oligocene, frequently folded and thrusted, indicative of intense Alpine deformation (**Figure 2**) [22,23]. Along the coast, Quaternary deposits including fluviomarine terraces, consolidated dunes, and bioclastic sands record successive marine transgressions and recent alluvial-aeolian activity, shaping present coastal geomorphology and providing valuable aggregate resources (**Figure 2**) [23,24].

Structurally, the Rif is classically subdivided into Internal, Flysch, and External domains [25,26]. The Internal Domain comprises Paleozoic metamorphic and crystalline terrains: Sebtides, with peridotites, kinzigites, gneisses, and Paleozoic–Triassic metasediments [27]; Ghomarides, composed of slightly metamorphosed Paleozoic nappes such as Aâkaili, Koudiat Tizian, and Beni Hozmar [28,29]; and the Calcareous Dorsal, formed by Triassic–Liassic thrust sheets overlain by condensed Jurassic–Cretaceous and Tertiary series [30]. The Flysch Domain consists of allochthonous Cretaceous–Tertiary nappes intercalated between the Internal and External domains [31]. Finally, the External Domain, originating from the Mesozoic–Paleogene North African margin, is subdivided into the Intrarif (Albo–Cenomanian to Lower Miocene formations, e.g., Ketama and Loukkos [32]), the Mesorif (Callovian–Oxfordian clays and Miocene calcarenites [33]), and the Prerif (Jurassic calcarenites and Tortonian olistostromes [34]), reflecting characteristic nappe tectonics and the imprint of Alpine orogeny **(Figure 2)**.

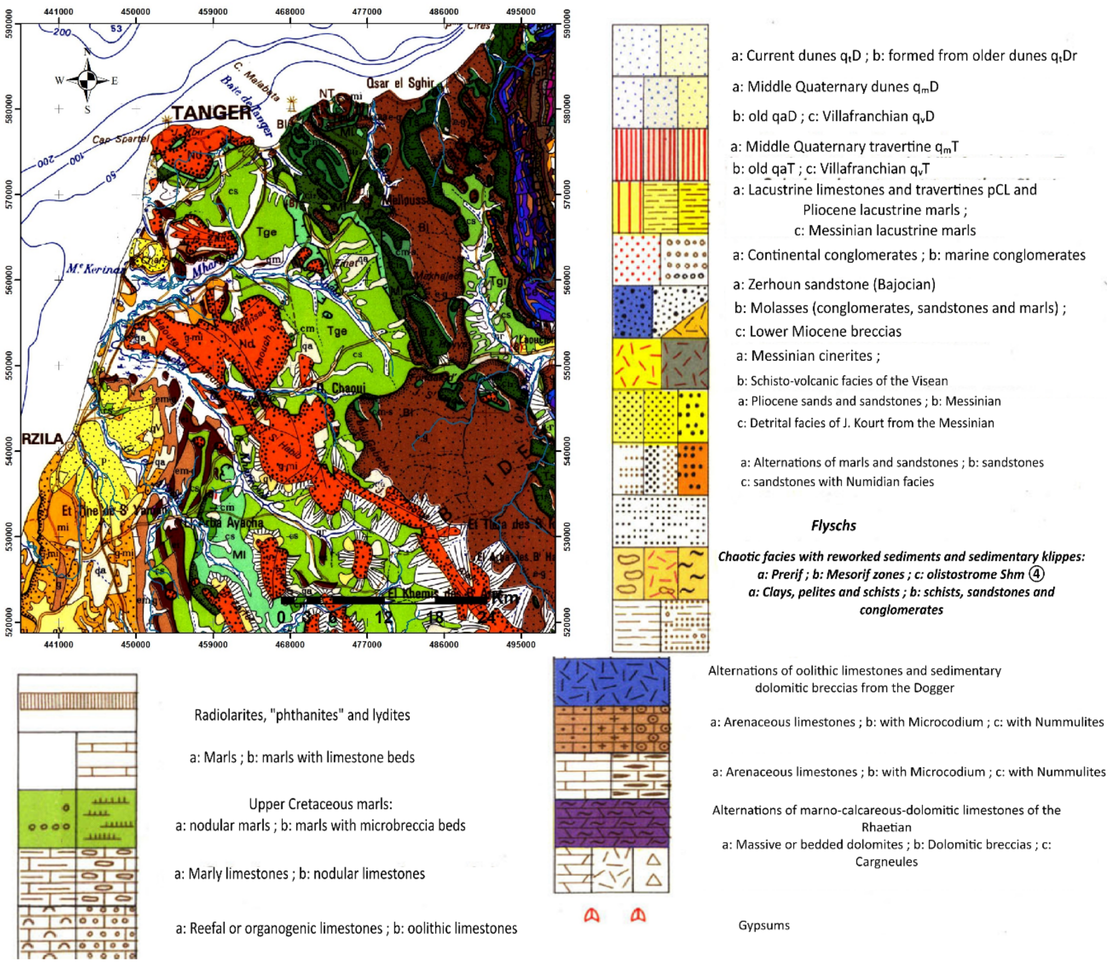

Figure 2. Geological and Structural Zonation of the Study Area.

2.3. Geomorphological and Hydrogeological Context for Quarrying

The Tangier–Assilah–Fahs Anjra region, part of the Rif Mountains, features steep alpine relief with peaks such as Jbel Tidighine at 2456 m [35] and a dense tectonically controlled drainage network. The Atlantic coast includes sandy beaches and rocky outcrops, while the East–West continental shelf contrasts with the internal Rif's northeast–southwest alignment [36,37]. Pleistocene marine formations, including *Ostrea cucullata*-bearing sandstones, occur near Larache at up to 20 m elevation (**Figure 3**) [38,39].

Slope gradients derived from a high-resolution DEM indicate areas favorable for quarrying at 0–15%, moderate constraints at 15–30%, and high-risk zones above 30% (**Figure 4**).

The hydrographic network includes Oued M'harhar, Oued El Hachef, and Oued Ayacha, with dams regulating flow and clay-shale formations controlling aquifer permeability, except at Charf El Akab where groundwater potential is high (**Figure 5**).

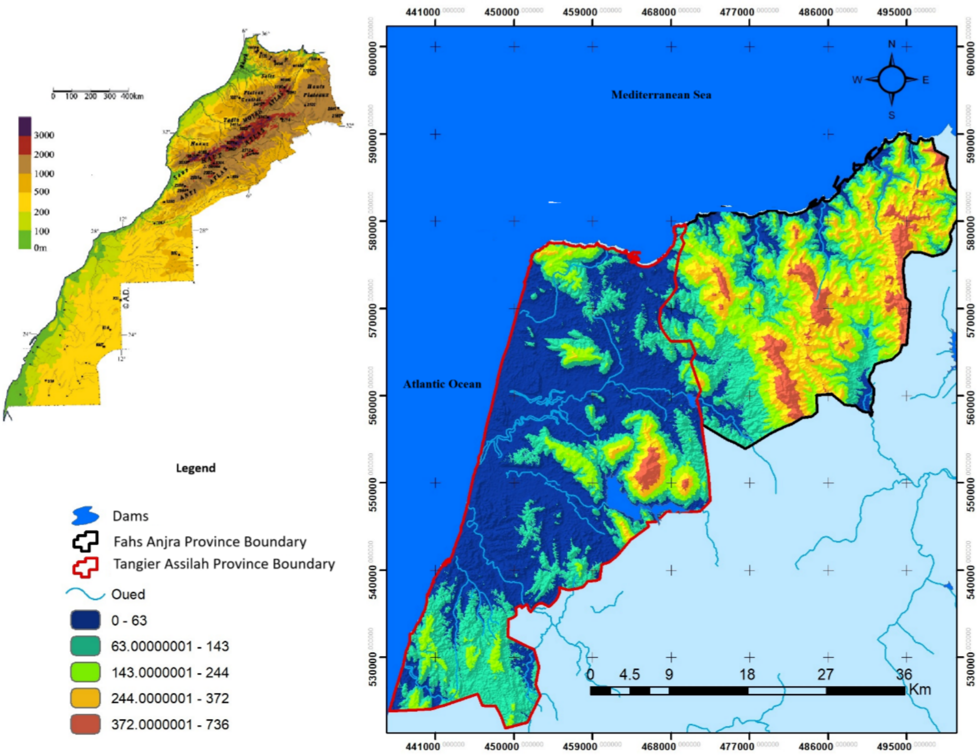

Figure 3. General Topography and Hydrographic Network Derived from High-Resolution DEM.

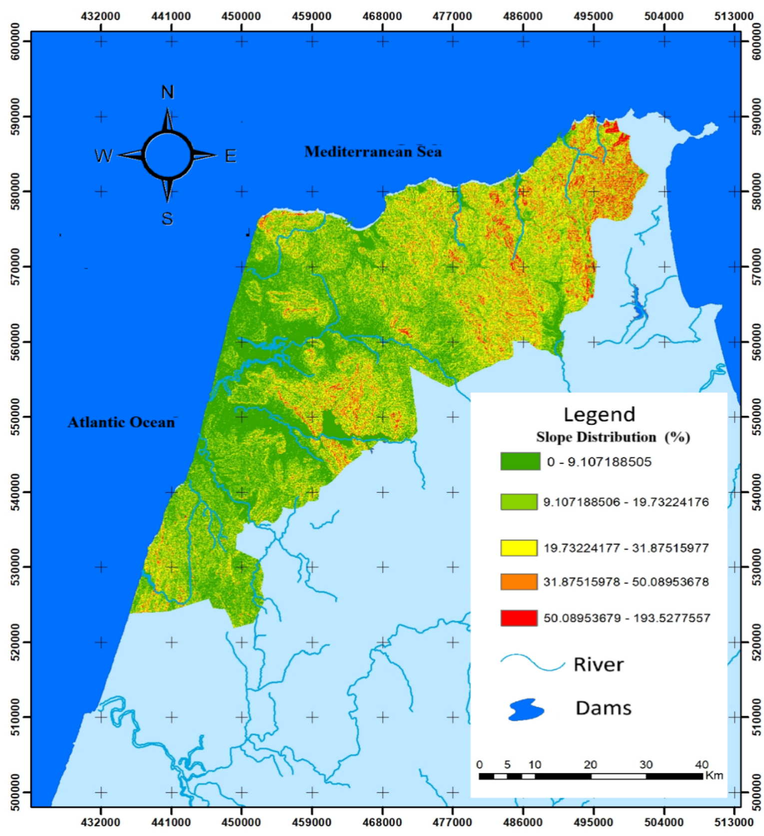

Figure 4. Slope Distribution of the Study Area (%).

Source: Derived from High-Resolution DEM (2025).

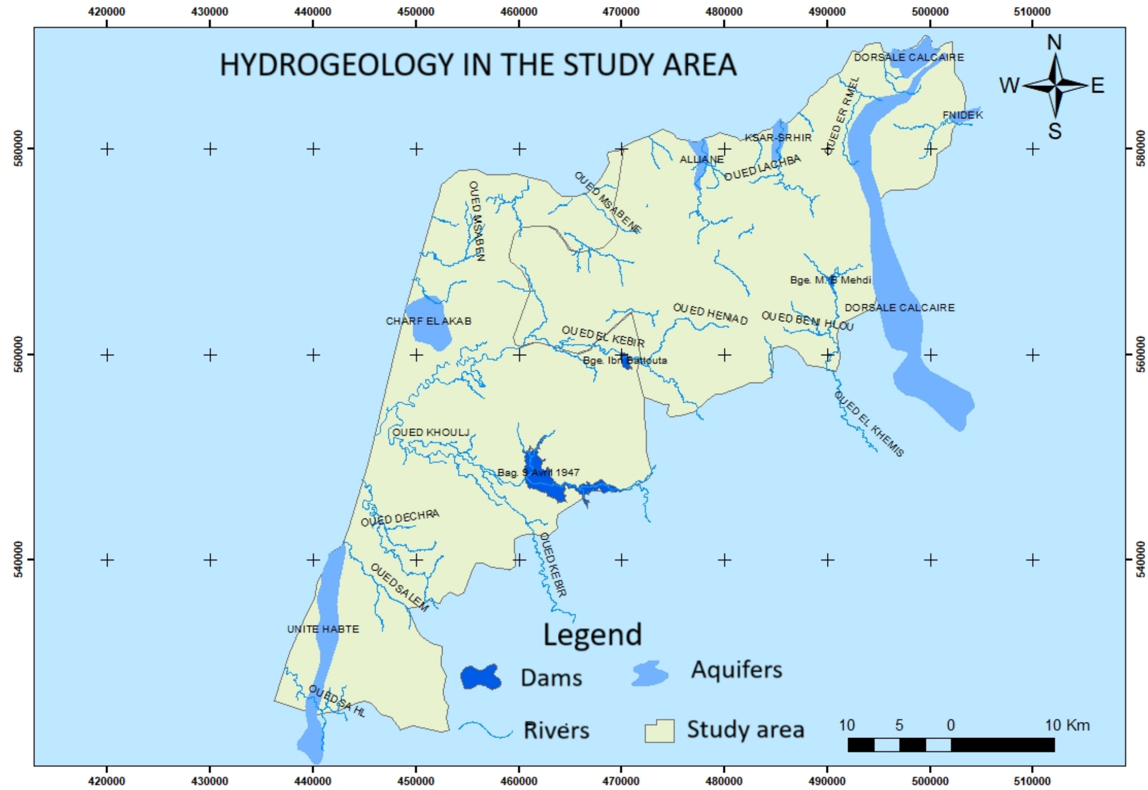

Figure 5. Hydrogeological framework of the study area.

3. Regulatory Framework and Methodological Justification

Quarrying is a strategic component of Morocco's construction materials economy, but its development is tightly regulated to ensure sustainability and territorial cohesion. National legal instruments include Law No. 13-03 on environmental protection, which requires Environmental Impact Assessments (EIAs) for industrial and extractive projects, and Law No. 13-09 on renewable energy, which promotes energy efficiency in industrial operations [40,41]. In addition, the National Land Use Plan (PNAT) provides a strategic framework to balance extractive industry development with urban expansion, agriculture, and ecosystem conservation [42].

At the international level, Morocco aligns its policies with the UN Sustainable Development Goals (SDGs), particularly Goal 12 (*responsible consumption and production*) and Goal 15 (*life on land*), which emphasize sustainable resource management and biodiversity protection [43].

In this context, the integration of Geographic Information Systems (GIS) offers a methodological framework that addresses both regulatory requirements and scientific rigor. GIS enables the multicriteria integration of geological, topographic, hydrological, socio-economic, and environmental datasets, while respecting exclusion zones such as urban settlements, aquifers, and protected areas. Recent research highlights the effectiveness of coupling GIS with Multicriteria Decision Analysis (MCDA) techniques—including the Analytical Hierarchy Process (AHP), fuzzy logic, and weighted overlay—for objectively ranking quarry site suitability in line with environmental and planning regulations [44–50].

This combined regulatory and methodological framework provides decision-makers with a robust tool to align quarry development with Morocco's national land-use strategies and its commitments to sustainable development at the international level.

4. Data Sources and Technical Specifications

4.1. Data Sources and Attributes

The methodology relies on the analysis of multiple geographic data layers sourced from reputable institutional and scientific entities. **Table 1** summarizes the main datasets utilized in the spatial analysis.

Table 1. Datasets used for multicriteria analysis.

Data Type	Source	Expected Format	Resolution/Scale
Topographic Maps	ANCFCC	TIFF	1:25,000 to 1:50,000
Satellite Imagery	Sentinel-2, Landsat 8	TIFF/GeoTIFF	10 m to 30 m
Aerial Photographs	ANCFCC, Ministry of Planning	TIFF/GeoTIFF	0.5 m to 2 m
Digital Elevation Models	CNESTEN, SRTM, ALOS	GeoTIFF	30 m (SRTM), 12.5 m (ALOS)
Hydrographic Data	ABH Loukkos, ONEP	SHP	Vector Data
Geological Data	High Commission of Mines	SHP/TIFF	National geological map

4.2. GIS Data Processing and Analysis Workflow

Raster data processing began with the georeferencing of scanned topographic maps using the North Morocco coordinate system, followed by the application of a second-degree polynomial transformation to correct geometric distortions. Satellite imagery and aerial photographs were then superimposed, geometrically corrected, and mosaicked to produce a consistent and updated spatial representation of the study area.

Digital Elevation Models (DEMs) were processed to derive slope maps, elevation classes, and topographic profiles through spatial analyst tools in ArcGIS. Specifically, slope gradients were classified into three categories: (i) 0–15% (favorable zones), (ii) 15–30% (moderately constrained zones), and (iii) >30% (high-risk zones), thereby excluding areas with steep terrain that pose geomechanical instability and erosion hazards [51]. In parallel, hydrological modeling from DEMs was used to delineate drainage networks, and buffer zones were created around rivers and streams to reduce risks of water contamination and flooding [52,53].

Exclusion criteria were applied systematically to restrict quarry site identification in sensitive or incompatible areas. These included urban settlements, biologically protected areas, groundwater resources, and major infrastructure, each defined by minimum buffer distances (**Table 2**; **Figure 6**).

Table 2. Exclusion criteria and recommended minimum distances.

Exclusion Criteria	Justification	Minimum Recommended Distance
Urban Areas	Nuisance protection	≥2 km
Biologically Sensitive Sites	Biodiversity conservation	≥2 km
Groundwater Resources	Water resource protection	≥800 m
Major Infrastructure	Infrastructure safety buffer	≥500 m

Finally, geological and tectonic layers were integrated into the GIS database to determine lithological characteristics (limestone, marl, sandstone) and their extraction potential, thus complementing the topographic and hydrological constraints. This integrated workflow ensures that the delineated sites combine geological suitability with environmental safeguards.

4.3. GIS-Based Quarry Site Identification

Application of Exclusion Criteria. Regulatory and environmental constraints were applied to remove unsuitable areas for quarry exploitation. This included:

- a 2 km buffer around urban settlements, sensitive facilities (schools, hospitals), and major infrastructure [54];
- exclusion of biodiversity hotspots such as Important Bird Areas (IBAs), Biological and Ecological Interest Sites (SIBEs), and protected natural reserves [54];
- groundwater protection through buffer zones of at least 800 m around aquifers and hydrographic networks [55]. Morphological and Topographical Analysis. DEM-derived slope analysis was used to classify terrain into three categories: (i) 0–15% slopes considered favorable, (ii) 15–30% moderately constrained, and (iii) >30% unsuitable due to instability and high development costs [56]. Elevation and slope orientation were also considered to refine site accessibility and extraction feasibility.
- Multicriteria Spatial Integration. All filtered spatial layers (geological, structural, hydrological, environmental, and socio-economic) were combined in a GIS environment using Analytical Hierarchy Process (AHP) weight-

ing and Boolean logic operators. This produced a composite suitability map, highlighting areas with optimal conditions for quarry development where constraints were minimized and favorable lithologies predominated (**Figure 7**).

- Field Validation and Verification. Potential quarry sites identified by the GIS model were verified through on-site inspections and checked against local geological and environmental conditions. Environmental Impact Assessments (EIAs) were also integrated to ensure protection of soils, biodiversity, and water resources, thereby aligning the GIS outputs with real-world feasibility.

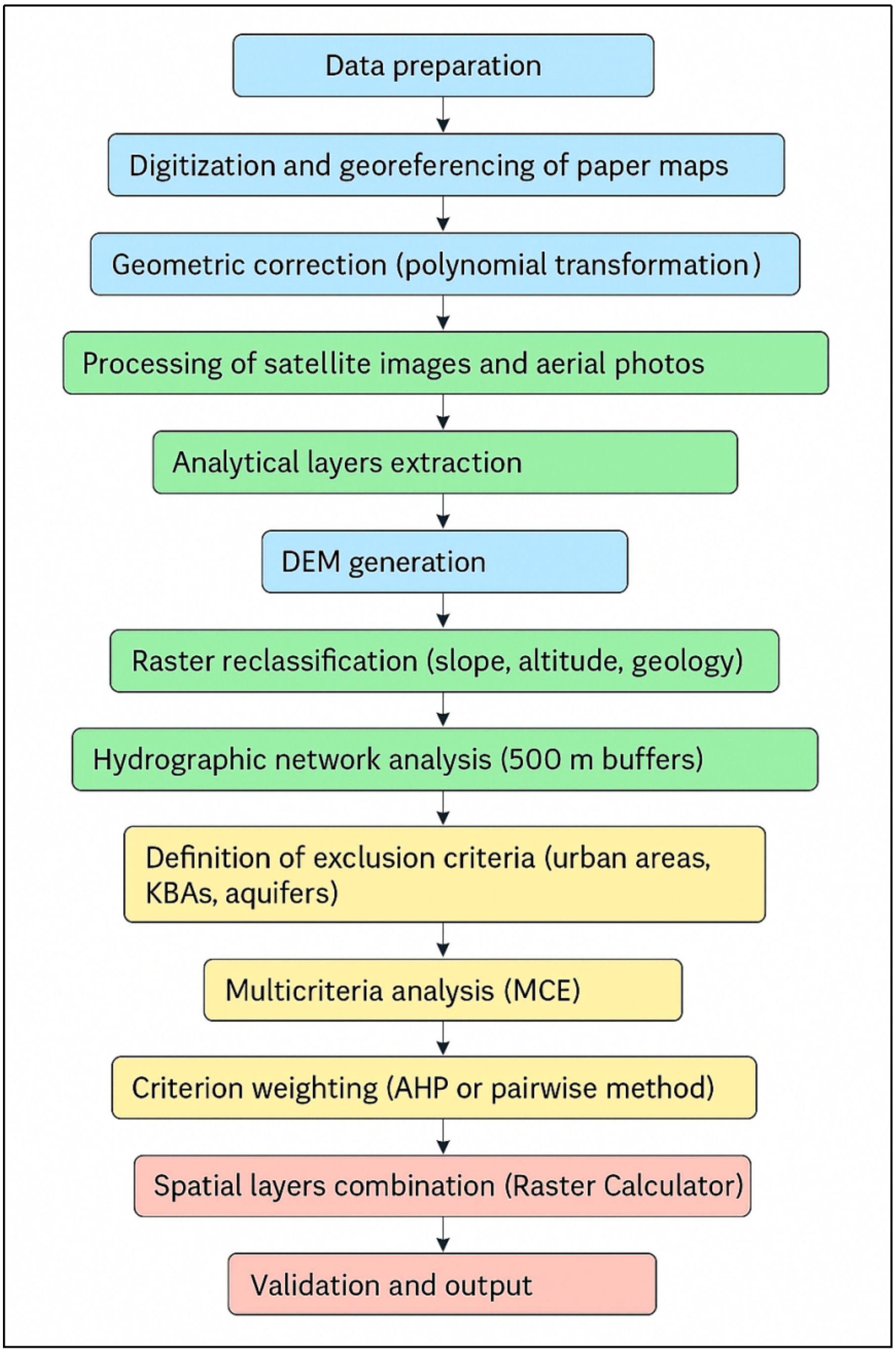

Figure 6. Geospatial Data Processing and Analysis Methodology.

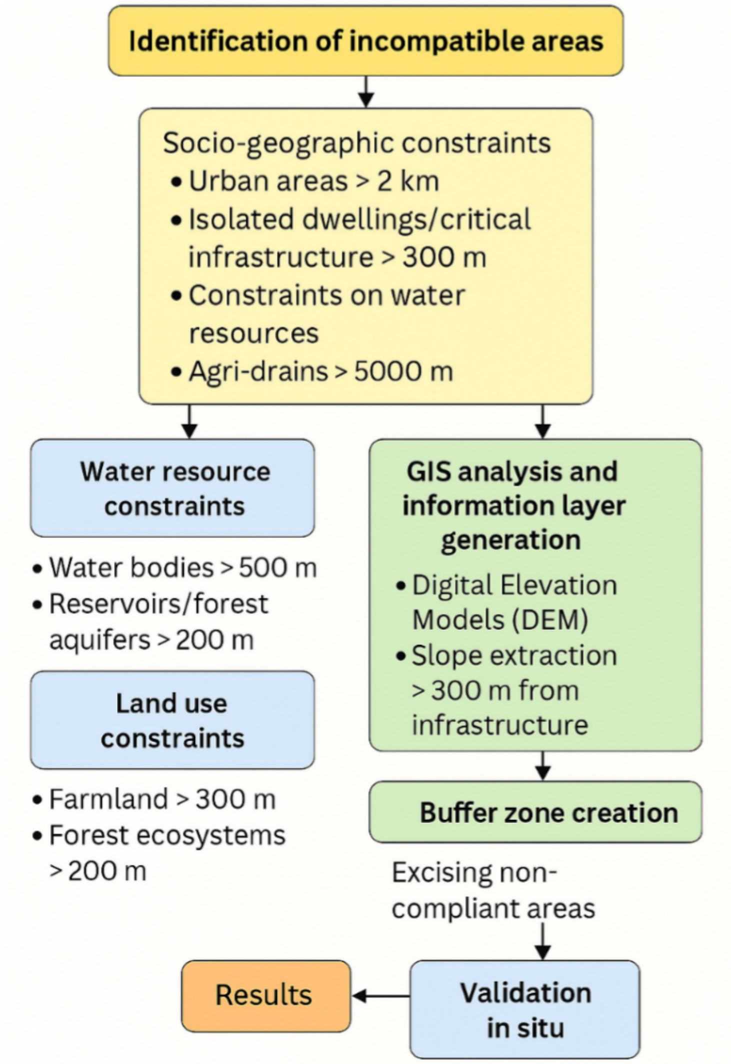

Figure 7. Conceptual Framework for Multicriteria GIS-Based Quarry Site Selection.

5. Results

5.1. Tanger-Asilah Sector: Geological Potential and Quarry Feasibility

The multicriteria GIS analysis identified two high-potential quarrying zones: the northwestern sector (Tanger–Assilah Province) and the central-eastern sector (Fahs-Anjra Province). In the Tanger–Assilah area, priority sites (Site 1, Site 2, Site 6, and Site 7) were delineated based on their lithological and logistical advantages. These sites consist of Upper Cretaceous massive dolomitic limestones with high uniaxial compressive strength (UCS > 80 MPa), homogeneous petrography, exploitable thicknesses greater than 25 m, and limited fracturing. Such properties make them particularly suitable for aggregate production and other construction applications (Gómez & Pérez, 2019).

In addition, their proximity to major road networks (within 3 km of the N1 and N2 highways) ensures efficient material transport and cost-effective operations, while complying with environmental and regulatory constraints (**Figure 8**).

Integration of geological and spatial data within a Geographic Information System (GIS) enabled the identification of seven potential quarry sites, categorized according to lithostratigraphic context and exploitation potential. The resources include plastic clays, limestones, sandstones, and siliceous sands suitable for diverse industrial applications, including construction, ceramics, and glassmaking (**Table 3** and **Figure 9**).

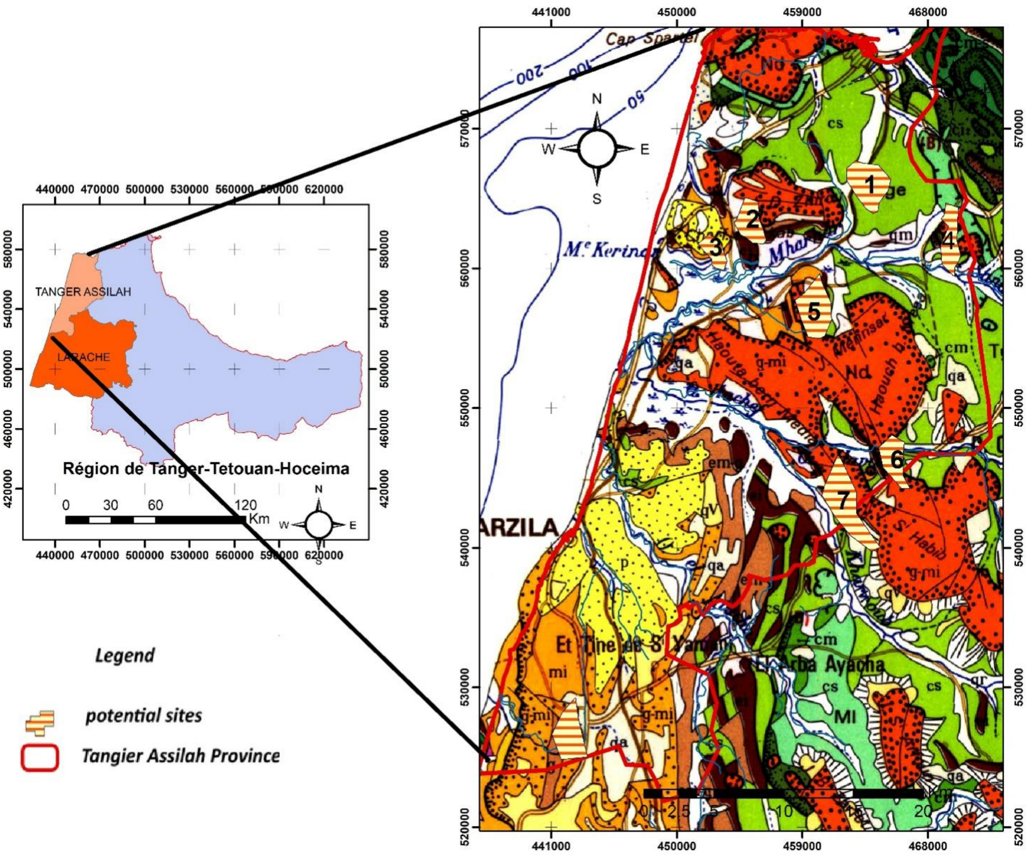

Figure 8. Potential Quarry Sites – Tanger-Assilah Prefecture.

Table 3. Technical and Environmental Characterization of Potential Quarry Sites in Tanger-Assilah Province.

No.	Site Name	Geological Context	Main Resource	Possible Uses	Technical/Environmental Evaluation
1	Daimousse Aouama Clay	Miocene marls (Aouama Basin)	Plastic clays	Bricks, tiles, cement	>8 m depth, favorable $CaCO_3$ content, stable site
2	Aïn Dalia	Massive dolomitic limestones	Dolomitic limestone	Aggregates, concrete, lime	High mechanical quality, mitigation required
3	Diidate Aïn Zaytoun	Quaternary fluviomarine terraces	Siliceous sand	Mortars, glass	Erosion-sensitive site, restoration plan required
4	Qalia Kherob Zenat	Miocene bioclastic limestones	Hard limestone	Aggregates, dimension stone	Low slope, geotechnical stability to be confirmed
5	Hajer EnHal	Siliceous flysch	Siliceous sandstone	Crushed aggregates, ballast	Moderate cohesion, rapid weathering, potential instabilities
6	Dar Zhiro Clay	Tertiary marls	Illitic red clay	Tiles, bricks	Good potential, erosion-vulnerable
7	Dar Chaâ Sand	Fossil dunes and beach deposits	Very fine sand	Glass, abrasives	RAMSAR zone, very high ecological constraint

High-Potential Sites:

- **Daimousse Aouama Clay:** Miocene marls rich in plastic clay (>8 m thickness) with ideal $CaCO_3$ content for firing; site is geotechnically stable with minimal environmental constraints.
- **Aïn Dalia:** Massive Cretaceous dolomitic limestones, UCS > 80 MPa, exhibiting excellent mechanical performance; mitigation measures required due to proximity to residential areas.
- **Qalia Kherob Zenat:** Thick-bedded bioclastic Miocene limestones on slopes <10%, suitable for aggregates and dimension stone; prior geotechnical assessment recommended.

Moderate-Potential Sites:

- **Dar Zhiro Clay:** Tertiary red marls rich in illite; potential for ceramic production; erosion-prone, necessitating sedimentation basins.
- **Hajer EnHal:** Siliceous sandstones (Numidian flysch) with moderate cohesion and pronounced anisotropy; prone to shallow landslides, requiring stability monitoring.
- **Diidate Aïn Zaytoun:** Quaternary siliceous sands with suitable granulometry for concrete and glass; high coastal erosion risk requires ecological restoration planning.

High-Risk Site:

- **Dar Chaâ Sand:** Fossil aeolian dunes with very fine sand located in an ecologically sensitive RAMSAR zone; exploitation contingent on a rigorous Environmental Impact Assessment (EIA).

The results of the GIS–MCDA analysis highlight that the Tangier–Assilah sector presents significant quarrying potential, with sites varying in terms of geological suitability, technical feasibility, and environmental sensitivity.

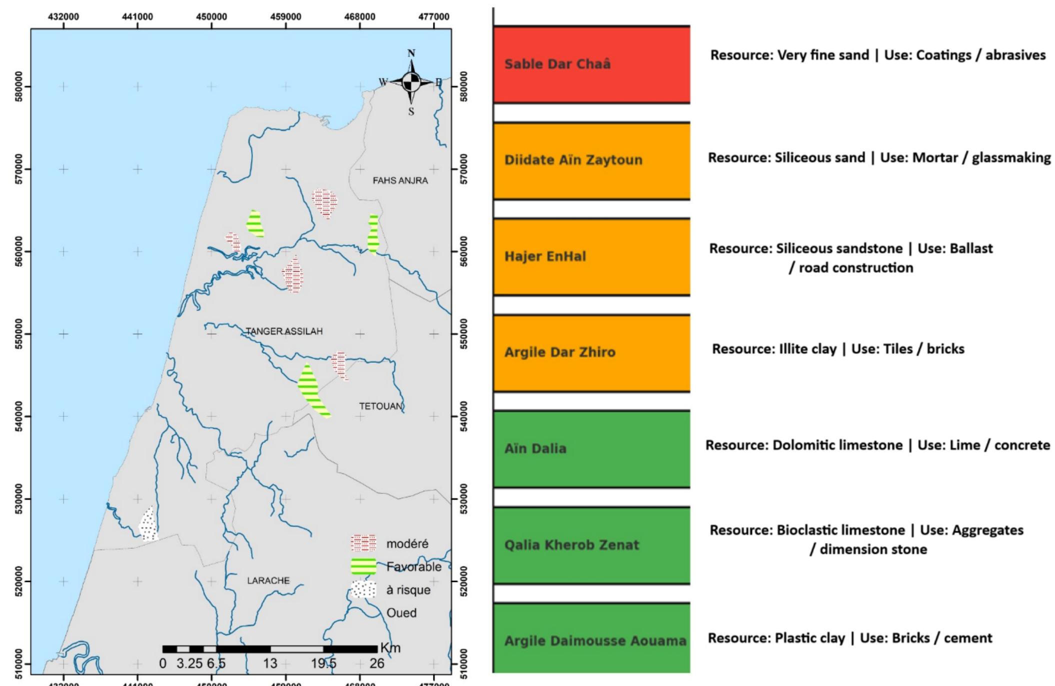

Figure 9. Geological Characterization of Exploitable Sites.

Carbonate-rich formations, particularly Sites 2 (Aïn Dalia) and 4 (Qalia Kherob Zenat), show high mechanical strength, consistent petrographic characteristics, and good accessibility to major transportation networks. These factors make them particularly suitable for aggregate production, lime manufacturing, and cement industries. Their location along the margins of stable carbonate units further strengthens their technical viability.

In contrast, clay-rich sites such as Daimousse Aouama (Site 1) and Dar Zhiro (Site 6) are technically exploitable, with favorable thickness and mineral composition for brick and tile production. However, their sensitivity to erosion and water runoff requires the implementation of specific mitigation measures, such as sediment retention basins and slope stabilization.

Siliciclastic deposits, represented by Sites 3 (Diidate Aïn Zaytoun) and 7 (Dar Chaâ), offer promising raw materials for glassmaking and construction sand. Nevertheless, their exploitation is conditioned by strict environmental safeguards due to their proximity to coastal aquifers and, in the case of Dar Chaâ, their location within a RAMSAR-designated wetland.

From a spatial perspective, **Figure 10** illustrates that high-potential sites (Daimousse Aouama Clay, Qalia Kherob

Zenat, and Aïn Dalia) are located along the periphery of major carbonate units, while sites classified as moderate or high risk are concentrated near environmentally sensitive areas or within geologically complex terrains. This distribution underscores the necessity of balancing geological potential with ecological vulnerability when selecting quarry sites.

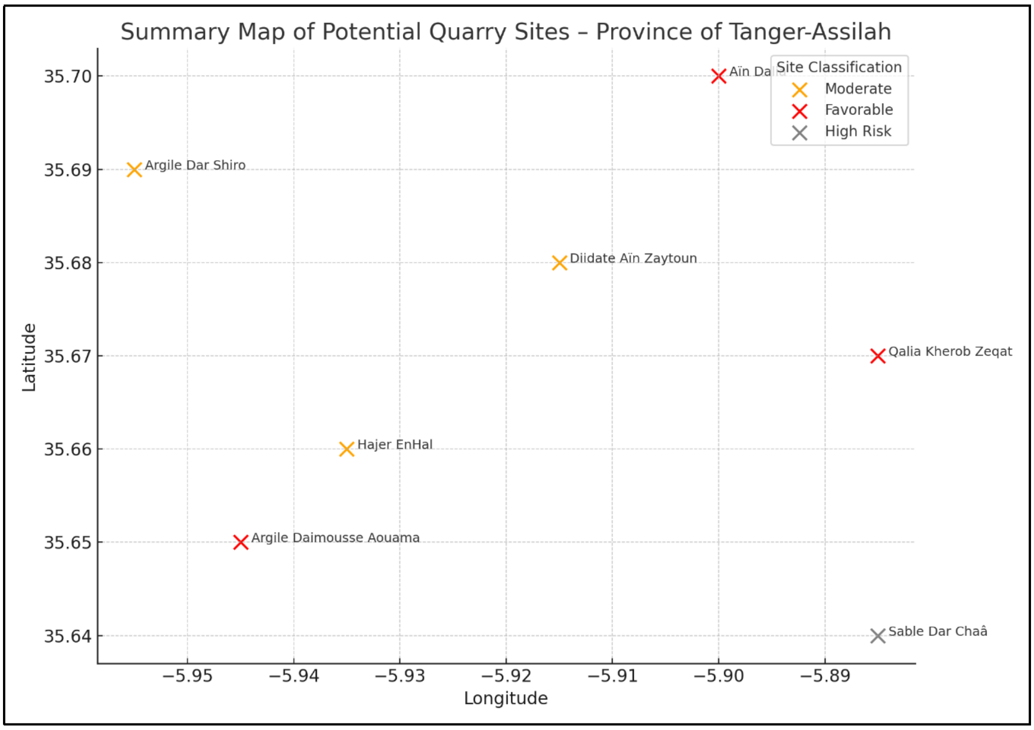

Figure 10. Synthesis Map of Potential Quarry Sites – Tanger-Assilah Province.

5.2. Fahs-Anjra Sector: Geological Potential and Quarry Feasibility

Fahs-Anjra Province, within the external Rif zone, offers strategic potential for sustainable quarrying due to its lithological diversity, including Numidian flysch, Tertiary marls, and alluvial deposits. Using satellite imagery, geological maps, GPS surveys, petrography, and GIS-based multicriteria analysis considering mechanical strength, lithological homogeneity, structural stability, and weathering six priority sites were identified: Tagheramt North, Tagheramt South, Melloussa East, Errouz, Kherb Mechlaoua, and Oued Mrel, each presenting distinct geotechnical and logistical suitability for construction material production (**Table 4**).

Table 4. Technical and Environmental Characterization of Potential Quarry Sites in Fahs-Anjra Province.

Site Name	Dominant Geological Formation	Material Type	Accessibility	Estimated Slope	Environmental Constraints	Preliminary Assessment
Tagheramt North	Siliceous Numidian flysch	Siliceous sandstone	Good (trail)	<10%	Near seasonal stream	Moderate
Tagheramt South	Cretaceous marls and schists	Compact clay	Medium	10–15%	Moderate erosion, deep soil	Moderate
Melloussa East	Flysch with marly intercalations	Clayey sandstone	Good (trail)	<8%	Low landslide risk	Favorable
Errouz	Marly-schistose limestones	Limestone	Very good	<5%	Low-density rural environment	Favorable
Kherb Mechlaoua	Tertiary red marls	Sandy clay	Medium	10–15%	High water sensitivity	Moderate
Oued Mrel	Recent alluvium and coastal sand	Very fine sand	Good (road)	<5%	RAMSAR zone, shallow aquifer	High Risk

A technical score was assigned to each site based on four criteria: strength, homogeneity, stability, and weatherability (inversely scored). The results are presented in **Table 5** below:

Table 5. Comparative Geotechnical Scores.

Site	Strength	Homogeneity	Stability	Weathering	Average Score
Tagheramt north	5	4	5	4	4.5
Tagheramt south	5	4	5	4	4.5
Melloussa east	3	3	3	3	3.0
Errouz	3	3	3	3	3.0
Kherb Mechlaoua	3	2	3	2	2.5
Oued Mrel	2	2	2	1	1.75

A radar diagram was generated to visually illustrate the geotechnical performance of the studied sites (**Figure 11**). It shows that Melloussa East and Errouz have balanced profiles with satisfactory performance across all criteria, justifying their classification as favorable sites. In contrast, Oued Mrel exhibits low resistance and high weatherability, highlighting its geomechanical and environmental vulnerability.

Six quarry sites in Fahs-Anjra, aligned with the NE–SW structural trends of the external Rif (**Figure 12**), were evaluated for sustainable exploitation. The most favorable sites Melloussa East and Errouz are located on stable, accessible lithological units with low slopes and proximity to transport routes, making them suitable for construction material production. Moderate-potential sites Tagheramt North, Tagheramt South, and Kherb Mechlaoua equire specific mitigation measures due to geological or environmental constraints. The high-risk site, Oued Mrel, presents geological instability, high hydrological sensitivity, and regulatory restrictions, necessitating a full Environmental Impact Assessment before any mining activity (**Figure 13**).

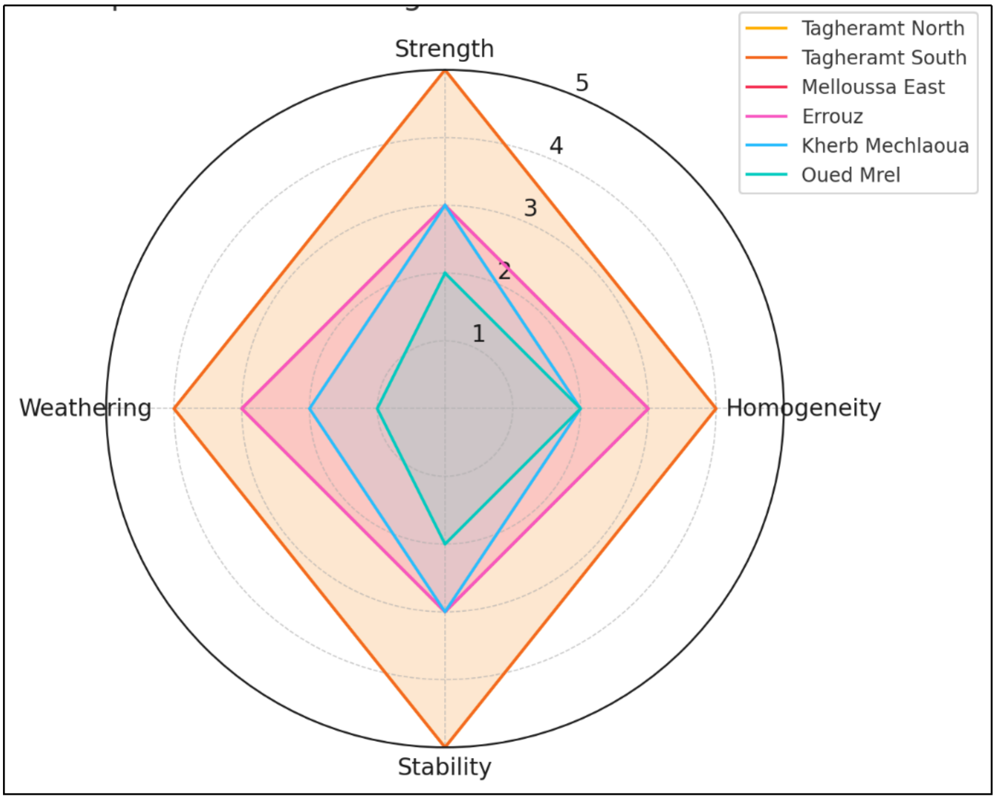

Figure 11. Comparative Radar Diagram of Geotechnical Scores.

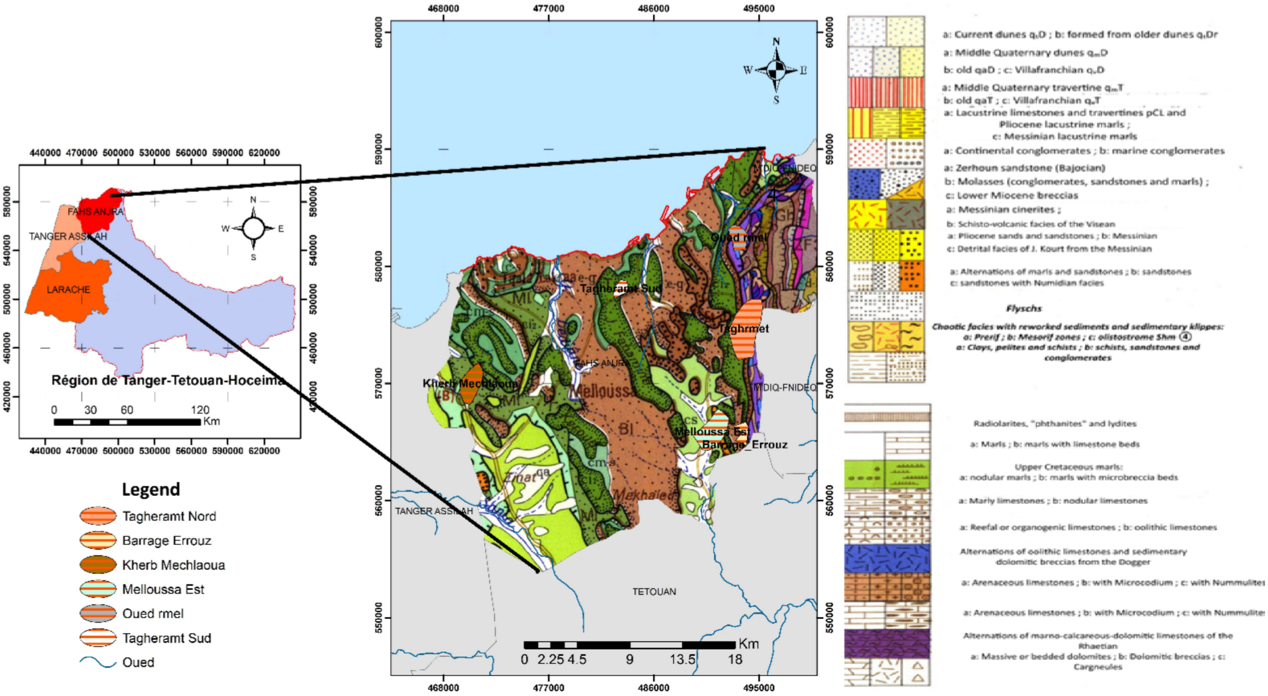

Figure 12. Geological Map and Site Locations in the Fahs-Anjra Province.

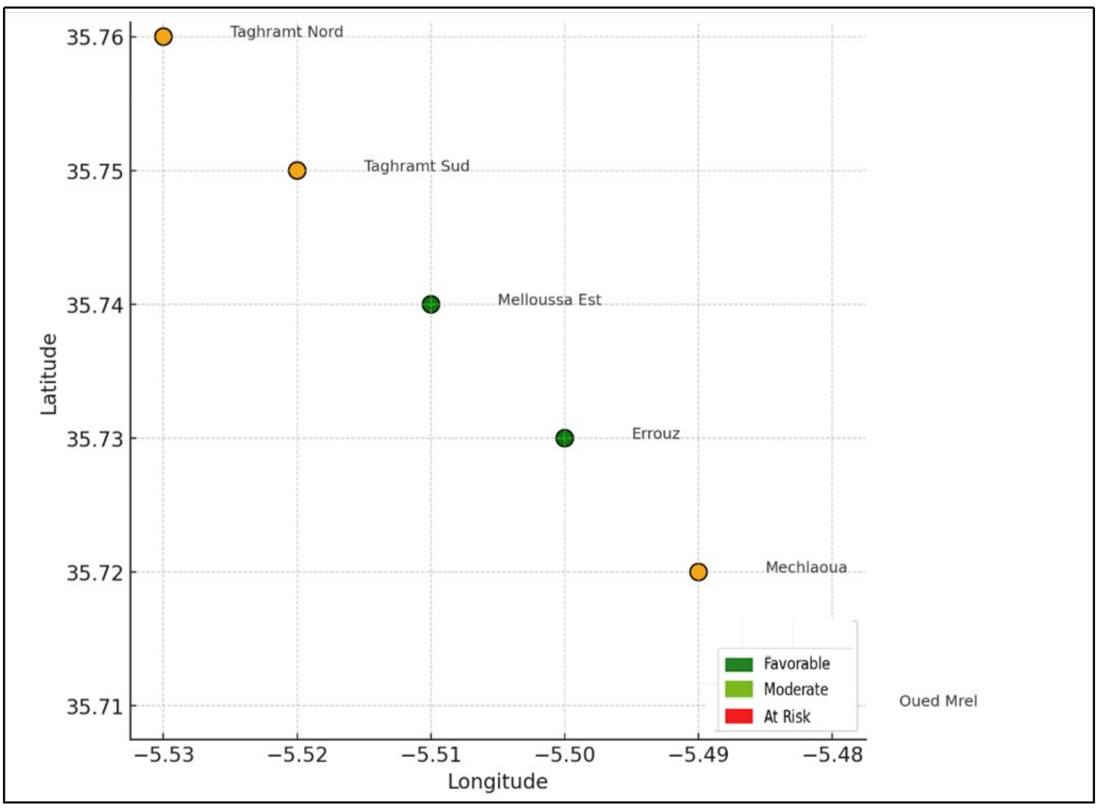

Figure 13. Site Locations by Exploitation Potential.

6. Geomechanical and Lithological Validation of Quarry Sites

Field verification in the Tanger–Assilah Prefecture confirmed the results of the multicriteria GIS analysis (**Figure 14**). Observed outcrops exhibited well-developed quarry faces with thick, gently dipping strata (<15°), characteristic of marine-origin dolomitic limestones, marls, and marl-sandstone units associated with the Numidian flysch. Lithological heterogeneity ranges from yellow to dark gray, combining homogeneous marly deposits with more resistant siliceous sandstones. Moderate vertical and horizontal fracturing were noted but does not compromise slope stability, and no evidence of collapse or landslides was observed. Established access tracks and the absence of nearby settlements further support the technical feasibility and sustainable potential for quarry exploitation in this sector.

Field investigations in Fahs-Anjra confirmed the extractive potential of the identified sites (**Figure 15**). Stratified outcrops exhibited consistent bedding, gently inclined layers, and regular thickness, reflecting continuous sedimentation. Lithologies primarily include marls, sandstones, and limestones of the Numidian flysch, consistent with mapped geological data. Photographic analysis indicated moderate fracturing and localized differential weathering, suggesting overall petrographic coherence. No visible instabilities were observed, corroborating geotechnical results from the multicriteria assessment. Accessible tracks and the absence of nearby anthropogenic or environmental constraints further support the technical and environmental feasibility of these sites, validating the adopted methodology for sustainable quarry site identification and prioritization.

(**a**) Formations of grayish clay outcropping on the surface in the Aouama.

(**b**) Formations of grayish clay outcropping on the surface in the Aouama.

(**c**) Silica sand in Dar Chaoui.

(**d**) Yellow sandstone blocks in the Sahel chamali.

Figure 14. Photographic Documentation of Surface Outcrops and Quarry-Relevant Lithologies in the Tanger–Assilah Region.

Figure 15. Sand and aggregate formations in the municipality of Taghramet.

7. General Conclusion

This study demonstrates the effectiveness of a GIS–MCDA approach for the identification, evaluation, and prioritization of potential quarry sites in the provinces of Tangier–Assilah and Fahs-Anjra. The methodology integrated geological (lithology, stratigraphy), geotechnical (UCS values, lithological homogeneity, fracturing), topographic (slope gradients, elevation), environmental (protected areas, hydrographic buffers, aquifers), and socio-economic (proximity to roads, urban centers, and industrial demand) variables, providing a robust, evidence-based framework for sustainable land-use planning.

The quantitative results show that, across the two provinces, approximately 22% of the study area was classified as highly suitable, 37% as moderately suitable, and 41% as unsuitable for quarry development. In Tangier–Assilah, carbonate formations (Sites 2 and 4) and selected clay deposits (Site 1) constitute the most promising reserves, while in Fahs-Anjra, Melloussa East and Errouz emerged as the most favorable locations due to their geotechnical stability and accessibility. Conversely, ecologically sensitive zones such as Oued Mrel and Dar Chaâ were identified as high-risk and unsuitable for exploitation.

These findings confirm that GIS–MCDA provides decision-makers with a powerful decision-support tool for balancing resource exploitation with environmental and social safeguards. At the policy level, the results directly contribute to Morocco's National Development Agenda, align with the African Union's Agenda 2063 (particularly goals on sustainable industrialization and environmental resilience), and support the UN Sustainable Development Goals (SDGs 9, 12, and 15) by promoting responsible consumption, infrastructure development, and biodiversity conservation.

Recommendations

1. Policy: Integrate GIS–MCDA suitability maps into regional land-use planning and quarry licensing procedures to ensure transparent and science-based decision-making.
2. Technical: Prioritize carbonate-rich and stable clay sites while enforcing engineering controls in erosion-sensitive zones (e.g., runoff management, slope stabilization).
3. Environmental: Prohibit exploitation in high-risk ecological areas (RAMSAR wetlands, aquifers) and strengthen environmental monitoring around moder-

ately suitable sites.

4. Socio-economic: Encourage quarrying near existing transport corridors to reduce costs and limit landscape fragmentation, while involving local communities in impact assessments.

Overall, this study confirms that quarry development in northwestern Morocco can be both technically viable and environmentally sustainable, provided that scientific tools such as GIS–MCDA are systematically employed in planning and policy implementation.

Author Contributions

Conceptualization, M.N., E.H.M.Y. and E.A.A.; Methodology, E.H.M.Y. (design of GIS MCDA workflow, AHP weighting scheme, exclusion buffers, and suitability classification thresholds); Software, E.H.M.Y. (ArcGIS Pro/ArcPy tools, QGIS processing, raster algebra, AHP calculations and consistency ratio checks); Validation, M.N., E.H.M.Y., E.A.A., and Z.A. (field verification, GPS control points, petrographic cross-checks, and comparison with regulatory constraints); Formal analysis, E.H.M.Y. (statistical summaries of suitability classes, geotechnical scoring, and sensitivity analysis of weights); Investigation, E.H.M.Y. (field mapping, site reconnaissance, photo-documentation, and lithologic logging); Resources, E.A.A., M.N. (institutional data access, liaison with agencies, and laboratory facilities); Data curation, E.H.M.Y. (metadata, versioning, projection harmonization, and QA/QC of layers); Writing original draft preparation, E.H.M.Y.; Writing review & editing, E.A.A., Z.A.A., and M.N. (technical revisions, clarity, and conformity to journal style); Visualization, E.H.M.Y. (cartography, figure standardization ≥300 dpi, legend and symbology harmonization); Supervision, E.A.A.; Project administration, E.A.A.; Funding acquisition, E.A.A. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable. This study did not involve humans or animals. It was conducted exclusively through analysis of geospatial, geological, and environmental datasets obtained from institutional and public sources.

Informed Consent Statement

Not applicable, since the research did not involve human participants or identifiable data.

Data Availability Statement

All datasets used and analyzed during this research are fully referenced in Table 1 of the manuscript. These include topographic maps from the ANCFCC, hydrographic and environmental datasets from ABH Loukkos, geological maps from the High Commission of Mines, and satellite imagery from Sentinel-2 and Landsat-8 missions. Derived GIS layers, slope rasters, and quarry suitability maps generated during the study are available from the corresponding author upon reasonable request. No new datasets were created or publicly archived in connection with this study.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript;

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