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Development of a standard model for quarry rehabilitation enabling their integration into the natural environment: Case study

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ABSTRACT

The objective of this study is to design a standard model for quarry rehabilitation after and during operation, thus contributing to their integration into their natural environments. To this end, an in-depth geomatic analysis and a multi-criteria approach were adopted to propose this model. This methodology was based on the development of various thematic maps (geological, topographic, hydrological, and topographic) to characterize the site. The study focused on mining outcrops with dolomite, limestone, and sandstone facies, located in the Taghramt municipality, in the Fahs Anjra province of Morocco. In this country, quarry rehabilitation practices are not fully consistent with the principles of environmental protection and sustainable development. Following this study, the results obtained reveal that this standard quarry rehabilitation model includes progressive redevelopment stages. Thus, it is necessary to first redevelop the embankments, then reconstruct the soil, and finally reforest the site. The desired goal is to integrate the quarries into their natural environment, thereby protecting the environment from the risks posed by the lack of quarry rehabilitation (passenger falls, disturbance of flora and fauna, soil depletion, and alteration of the hydrographic network, landscape, and air quality). However, the main limitations of this approach concern the need for rehabilitation planning right from the operational phase; and the shortcomings in the Moroccan legal framework, despite its recent progress with the adoption of Law 27-13 of 9/6/2015 on quarries and its implementing decree No. 2-17-369 of 30/11/2017, which requires the presentation of a bank guarantee to guarantee the quarry's redevelopment. The originality of this study lies in the integration of geomatic and ecological tools, to design a practical, reproducible and flexible model for the institutionalization of a quarry rehabilitation procedure adaptable to other open-air quarries and to various geo-environmental contexts.

Keywords: quarry, rehabilitation, geomatics, ecological planning, land management, Morocco.

INTRODUCTION

Quarry exploitation generates numerous negative environmental impacts. It creates vertical extraction faces that pose fall hazards for both human and animal passengers. Quarrying also disrupts natural habitats, affects local flora and fauna, impoverishes soil fertility (Chenot and Lescure, 2019), and alters the hydrographic network, landscape, and air quality. In the long term, it can lead to lasting soil degradation, watershed changes, and persistent deterioration of water resources and air quality (Bell and Donnelly, 2006; Brevik et al., 2017). This results in significant environmental heterogeneity and a lack of integration of the quarry into its original natural environment, favoring the coexistence of new plant species.

Added to this is the phenomenon of quarry abandonment without rehabilitation after exploitation. In Morocco, this phenomenon is facilitated by the absence of legal provisions (such as financial guarantees) before 2017 for the rehabilitation of quarries. It was only recently that Law 27-13 of 9/6/2015 on quarries was adopted, stipulating in Article 14 that quarry operators must present a bank guarantee to guarantee the redevelopment of the quarry. However, this law only came into force after the adoption of its implementing decree No. 2-17-369 of 30/11/2017. Consequently, Environmental Impact Assessments subject to Law 12-03 must outline the appropriate methods for quarry redevelopment and the calculation of the security deposit amount, based on Law No. 27-13 and its implementing decree, as well as on Order No. 124.18 of the Minister of Equipment and Water of 19 Joumada II 1439 (March 8, 2018), relating to the bank guarantee used for quarry redevelopment.

In reality, quarry operators proceed with the opening of quarries and the extraction of materials without considering and planning the rehabilitation process in parallel from the early stages of the project. This failure is often irreversible in terms of softening the mining fronts, gradually redeveloping the slopes, recovering waste rock, and restoring the soil through suitable plantations and plant species.

On the other side of the scale, there is a shortage of quarry materials in Morocco notably in Region Tangier-Tétouan-Alhoceima. This is likely to create a strong demand for raw materials from quarries to supply major construction projects such as stadiums, highways, railways, ports, dams, etc (El-Wamdeni et al., 2024).. Indeed, requests to open quarries have multiplied.

Although Morocco has made efforts to control quarry operations, much remains to be done regarding their rehabilitation. With this in mind, this study will attempt to address this issue of reconciling environmental preservation and the inevitable exploitation of quarries. Therefore, the study intends to use and apply geographic information systems (GIS) software, particularly ArcMap and QGIS, along with detailed spatial multi-criteria analysis methods. The objective is to design an effective standard model for quarry rehabilitation, based on the establishment of quarry rehabilitation plans at the same level as exploitation plans. This model aims to integrate the quarry into its natural environment and correct the negative impacts related to exploitation. Which rehabilitation depends mainly on the initial environment of the site, the type of extracted materials, the future use of the site, the stability of the terrain and the associated socio-economic issues. This model concerns the geological outcrops of the commune of Taghramat, province of Fahs Anjra.

STUDY AREA DESCRIPTION

The study area involves geological outcrops in Taghramt commune, part of Fahs Anjra Province. This province, composed of eight communes, covers around 799 km² and has a population of 100.789 (High Commission for Planning, 2024).

The area is located in the far northwest of Morocco, within the pre-Rif geological and hydrogeological zone (Figure 1). It has a temperate Mediterranean climate and a rapidly growing economy.

Geology

The study site lies within the Rif domain, specifically among the limestone-dolomitic chains and ridges (Figure 3). These formations stretch between Paleozoic ridges in the east and sandstone crests in the west, forming a limestone backbone marked by geological and structural diversity.

Geologically, the site is at the junction between the internal and external Rif domains (Figure 2), specifically in the Haouz limestone ridge. This area exhibits segmented and compressed carbonate masses, causing local inversion of structural vergence and major boundary contacts (Griffon, 1962; Suter et al., 1961).

The quarried rock is thick, massive limestone (~80 m thick) (Figure 4), dipping westward. Tectonic activity has fragmented it into flakes locally injected with flint-bearing limestone. This complex structure affects both material quality and exploitation conditions.

Topography

The study area exhibits a contrasting topography, with elevations ranging from 34 meters in the lowest western zones to 664 meters in the high-relief central sectors (Figure 5). This altitudinal gradient reflects a well-defined topographic organization, illustrating the gradual transition between the low-lying peripheral plains and the higher central mountainous formations. This configuration has a significant influence on the region's hydrographic dynamics, land use patterns, and erosion processes.

The slope map (Figure 6) reveals a distinctly varied topography within the study area, characterized by significant variations in terrain inclinations. Most of the area features slopes ranging from 0° to 30°, corresponding to generally moderate reliefs that are conducive to accessibility

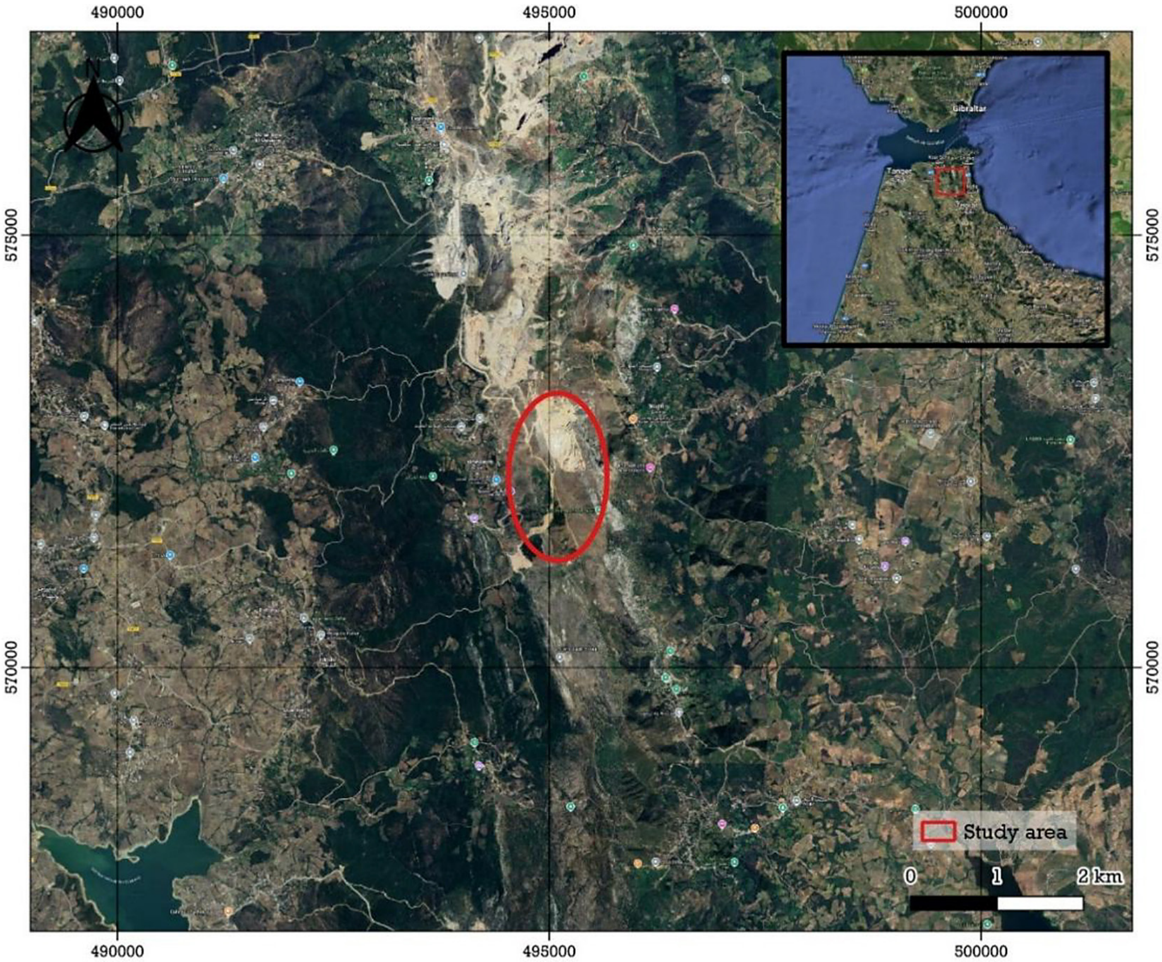

Figure 1. Satellite image of the study area, extracted from Google Earth Pro (2025)

Figure 2. Geological facies map of the study area. Digitized from 1:50,000-scale geological sheets published by the Geological Survey of Morocco (Suter et al., 1961), and georeferenced using ArcMap

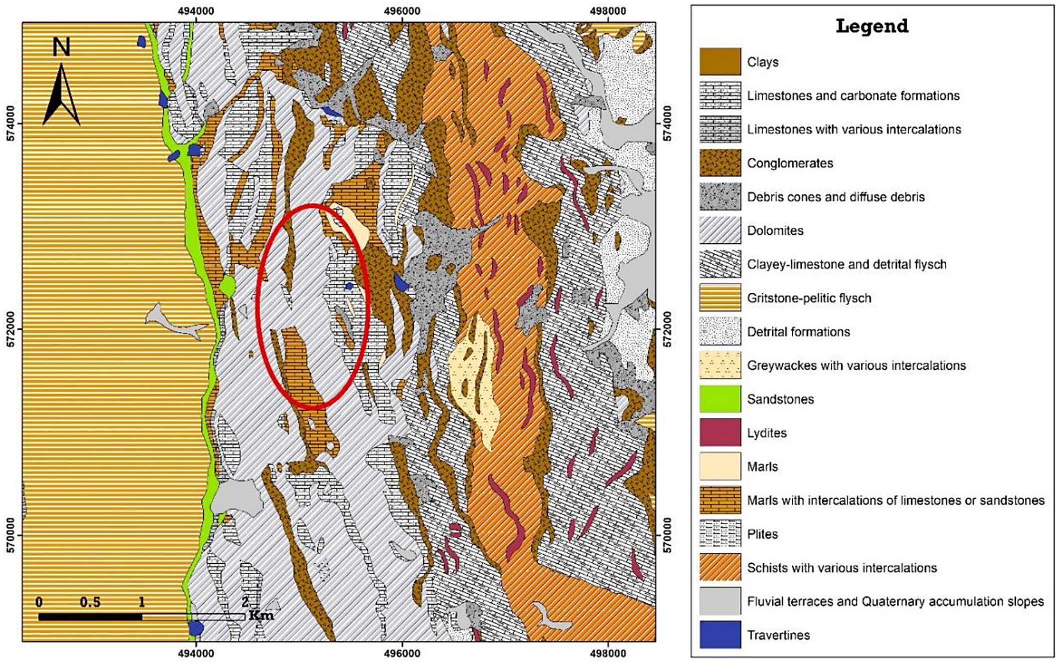

Figure 3. Lithological map of the study area. Digitized from the 1:50,000-scale geological sheets published by the Moroccan Geological Survey (Suter et al., 1961), using Arcmap

Figure 4. Limestone and dolomite rock masses at the site

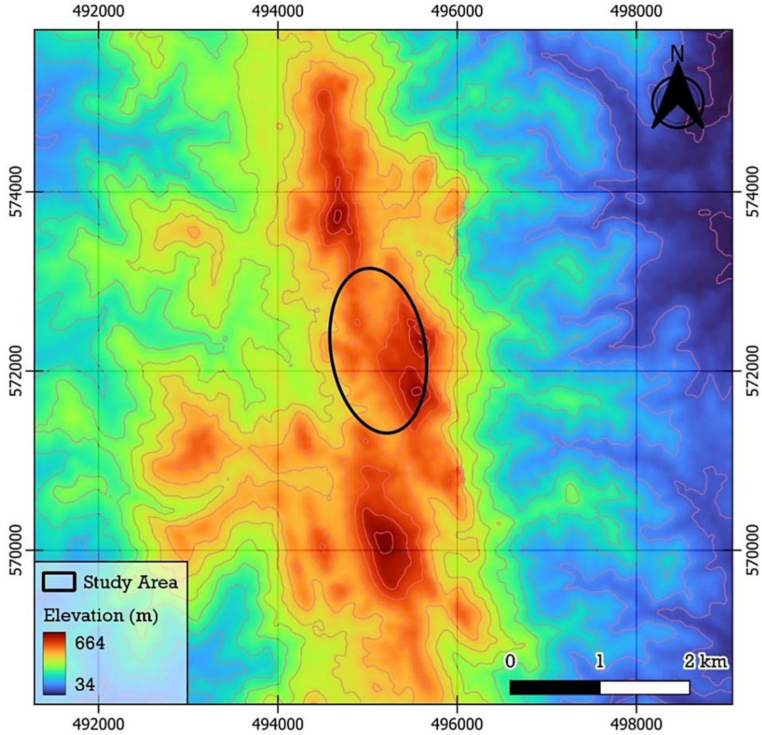

Figure 5. Digital elevation model (DEM) of the study area, extracted from 30 m SRTM data using Arcmap

and land development. However, certain sections stand out with steep slopes exceeding 40°, and in some places even surpassing 60°, indicating the presence of rugged and highly inclined terrain. This morphological heterogeneity plays a crucial role in erosion dynamics, soil stability, and the potential for land use or rehabilitation.

Hydrology and hydrogeology

At the regional level, rivers in the Rif exhibit irregular hydrology, with violent floods and low dry-season flows. Some benefit from sustained flow from karstic limestone units. In the study area, intense rainfall, rugged terrain, and impermeable formations increase surface runoff. However, infiltration remains predominant due to fractured and permeable limestone and dolomite formations.

Hydrogeological flow direction is influenced by geological structure geometry. Flinty limestone, white limestone, and brecciated dolomites enable significant infiltration, though groundwater tends to migrate outside the study area. The limestone ridge's geological layout ensures structural continuity north and south of Tlat Taghramt, explaining the presence of springs around the carbonate formations (Figure 7).

LEGAL AND INSTITUTIONAL FRAMEWORK

In recent years, Morocco has significantly reinforced its quarry-related environmental regulations, with a particular emphasis on environmental sustainability and post-extraction site rehabilitation. This shift reflects growing national concern over the environmental degradation caused by abandoned or poorly managed quarries, and the need to align with international best practices in sustainable resource extraction.

The key legal instrument is Law No. 27-13 on quarries, promulgated on June 9, 2015, which introduced stricter requirements for quarry operations. Notably, Article 14 mandates that all quarry operators provide a bank guarantee to ensure the financial means for post-exploitation site rehabilitation. This law was a response to the historical lack of accountability in quarry site management and a growing body of evidence highlighting the environmental costs of non-rehabilitated quarries.

To operationalize Law 27-13, two critical regulatory texts were introduced :

- Decree No. 2-17-369, dated November 30, 2017, which outlines implementation procedures, including the required contents of

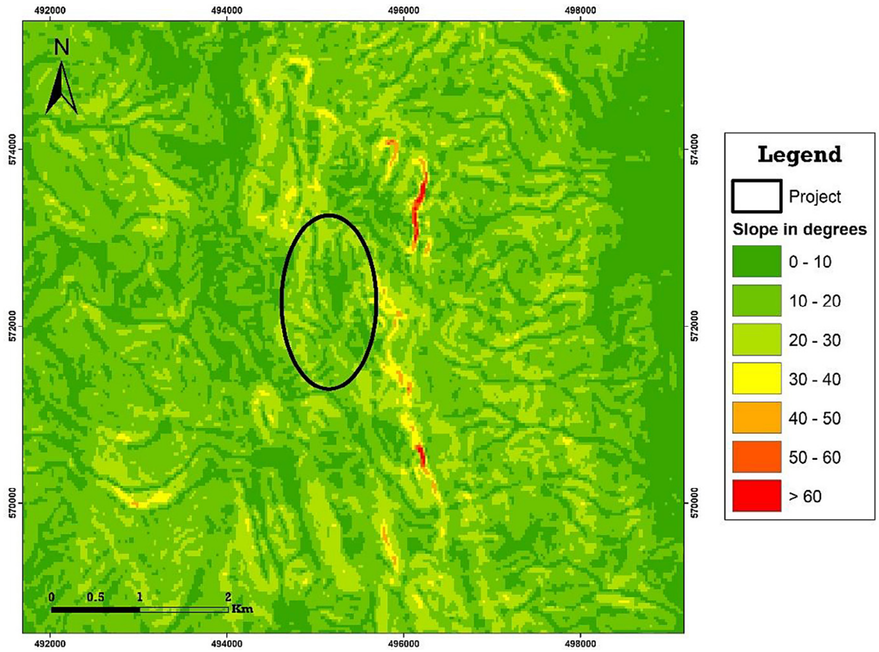

Figure 6. Slope class map of the study area, derived from the DEM using GIS-based slope analysis tools in ArcMap

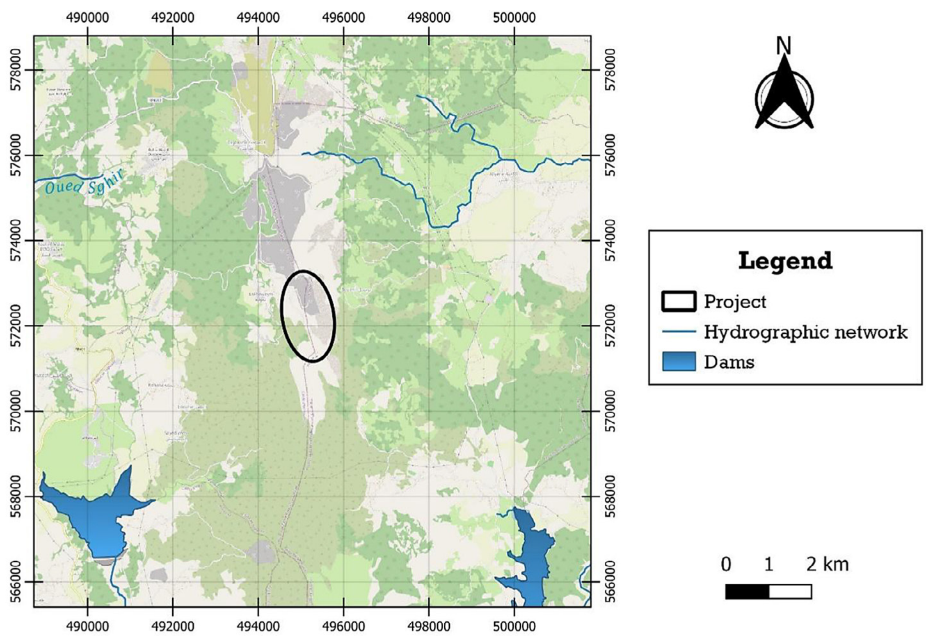

Figure 7. Major watercourses and dams in the study area, vector data from ABHL, mapped with Arcmap

environmental impact studies (EIS) and the conditions for rehabilitation;

- Ministerial Order No. 124.18, issued by the Ministry of Equipment, Transport, Logistics and Water on March 8, 2018, which defines the methodology for calculating the bank guarantee based on the size and nature of the quarry and the scope of proposed rehabilitation works.

These reforms were introduced in a context where Morocco had limited legal precedents governing quarry rehabilitation. Prior to Law 27-13, environmental concerns related to quarrying were only marginally addressed under the more general Law No. 12-03 on Environmental Protection, enacted in 2003, which required EIS for extractive industries but did not enforce specific rehabilitation mechanisms or financial safeguards.

By contrast, several countries with longer traditions of environmental regulation – such as France, Canada, and Australia – had long established mandatory rehabilitation plans backed by financial guarantees or bonds. Morocco's adoption of Law 27-13 can thus be seen as part of a broader international movement toward environmentally responsible resource extraction.

MATERIALS AND METHODS

Data compilation and study area characterization

The study area is situated in the commune of Taghramt, northern Morocco. Its characterization was achieved through the integration of various spatial and environmental datasets, processed within a GIS environment to enable detailed spatial analysis. The data sources included:

- The geological map of the Rif region (scale 1:100,000) from the Geological Service of Morocco (Suter G., 1961);
- Hydrographic vector data (rivers and dams) provided by the Loukkos Hydraulic Basin Agency (ABHL);
- SRTM satellite imagery (30-meter resolution Digital Elevation Model) obtained from the USGS website.
- All datasets were georeferenced and processed using ArcMap 10.8 and QGIS 3.28.3. Key processing steps comprised:
- Digitization of geological and lithological maps;
- Extraction of elevation and slope maps from the DEM;
- Incorporation of hydrographic data from ABHL;
- Creation of thematic maps, including location, geological, lithological, hydrographic, elevation, and slope maps.

Qualitative multi-criteria analysis approach

The study applied a qualitative multi-criteria analysis inspired by spatial decision support methods to guide quarry rehabilitation. This framework integrates three primary information types:

1. Environmental spatial data represented by GIS-derived thematic maps (e.g., slope, hydrography, geology);
2. Legal and institutional constraints, notably those defined by Law No. 27-13 on quarries, which mandates a rehabilitation plan secured by a financial guarantee (Article 14);
3. Expert environmental interpretation through cross-analysis of the site's physical features and regulatory framework, enabling identification of priority intervention zones and tailored rehabilitation measures.

This approach facilitated a coherent, context-sensitive understanding of the area, supporting the formulation of rehabilitation strategies that align environmental conditions with legal obligations.

Rehabilitation model selection criteria

Quarries must establish a rehabilitation plan from the moment they are opened, in parallel with the exploitation plan. Integrating the quarry into its natural environment therefore requires rehabilitation that is closely coordinated with the exploitation process. This rehabilitation takes into account several factors, such as the site's initial environment (geographical location, natural setting, landowners, neighbors, local authorities, and associations), the type of materials extracted, the future use of the site, land stability, and the associated socio-economic issues.

In practical terms, rehabilitation should be carried out progressively, as follows:

- Stripping of topsoil, which will be stored in the form of berms around the quarry, thereby creating a 10-meter buffer zone.
- Backfilling of exploited areas with sterile or unused materials.
- Slope smoothing, made easier by implementing a stepped or benching excavation method.
- Reforestation of slopes with species adapted to the local environment.

RESULTS AND DISCUSSION

Application of the rehabilitation model

The proposed rehabilitation model was applied to studied quarry, following a progressive approach to site restoration. The initial state of the quarry was analyzed through a 3D model based on the topographic survey of the site, which provided a detailed visualization of the terrain, excavation geometry, and site constraints (Figure 8).

The proposed rehabilitation model was applied to this limestone quarry, following a progressive approach to site restoration, integrating rehabilitation measures from the earliest stages of exploitation. The quarry underwent a six-phase extraction sequence structured into benches of approximately 10 meters in height and width. This configuration ensured both operational efficiency and facilitated subsequent restoration efforts by enabling slope regrading and waste management during the exploitation process.

The longitudinal profile shown in Figure 9 was developed using the topographic plan of the quarry site. A representative longitudinal section was selected along an East–West axis, corresponding to the general direction of quarry development. Based on this section, the successive excavation phases were reconstructed according to field observations and operator records, with benches modeled to reflect typical working dimensions.

Creation of the digital terrain model (DTM)

The DTM is obtained based on the contour lines contained in the topographic plan using COVADIS 17.0 software.

Obtaining the longitudinal profile

A longitudinal profile was generated using COVADIS 17.0 software, by clicking on COVADIS VRD (Roads and Miscellaneous Networks), then the linear project was created by standard profiles using the internal data of the drawing: DTM, via Create by PI, tabulating the axis, drawing the longitudinal profile (NT), and finally creating and adjusting the Slope/Ramp (55° in our case) (Figure 9).

Throughout the exploitation, stripped topsoil and inert materials were stockpiled in peripheral berms, forming a 10-meter buffer zone. These stockpiles were later reused in backfilling and slope coverage, ensuring resource efficiency and environmental compatibility. Systematic benching allowed for controlled slope inclinations, eventually regraded to 50–55° to promote geotechnical stability and prepare the terrain for revegetation (Hoek and Bray, 1981; Read and Stacey, 2009) (Figure 10). This step-by-step process aligns with international best practices in concurrent quarry rehabilitation, where restoration begins during–not after–resource extraction (Cooke and Johnson, 2002).

Ecological and landscape integration

A central component of the model is the ecological reintegration of the quarry landscape. Rehabilitation efforts focused on reshaping benches, reusing quarry waste as planting substrate, and encouraging the natural colonization of slopes with pioneer species adapted to local conditions. Seven

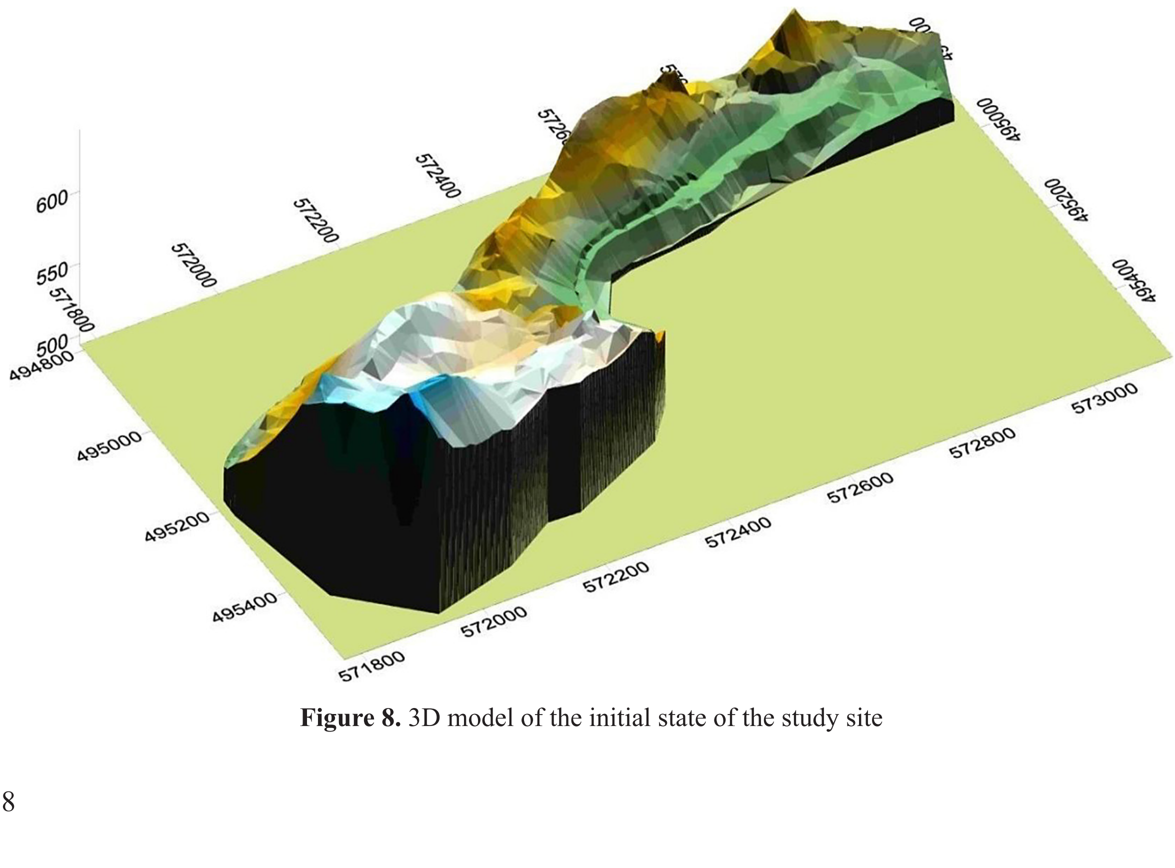

Figure 8. 3D model of the initial state of the study site

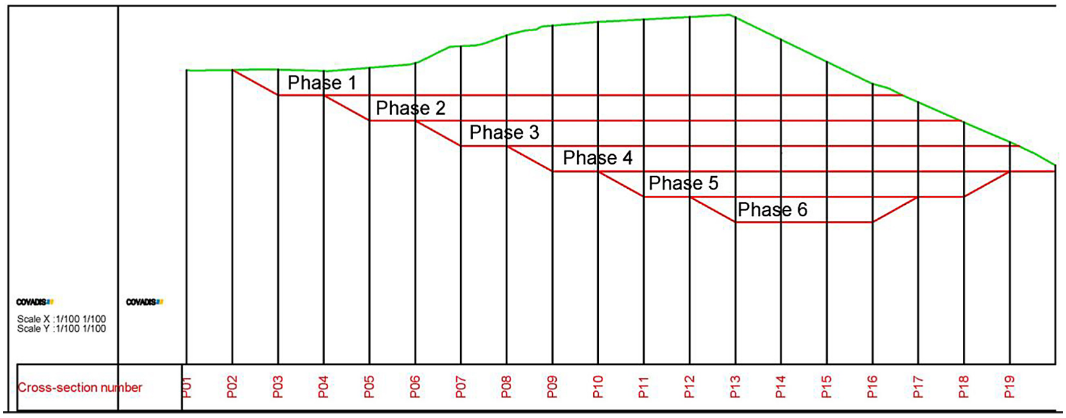

Figure 9. Longitudinal profile of quarry excavation phases

benches were reconfigured with softened inclines and covered with inert materials to facilitate vegetation growth and erosion control (Figure 11).

The method used to obtain the operational and rehabilitation longitudinal profiles by phase (Figure 11) is identical to that used for Figure 9.

Ecological features were deliberately integrated into the design. Talus slopes were constructed to provide habitats for rupicolous fauna, while shallow depressions were excavated to form temporary wetlands, especially beneficial for amphibians and invertebrates. The quarry's final topography featured diverse substrates and microhabitats, including cavities and ledges, which enhanced biodiversity potential (Figure 12). This type of ecological engineering approach is supported by findings from similar post-mining rehabilitation projects (Tordoff et al., 2000), where structural complexity promotes faunal recolonization.

Notably, the site was enriched with native species of ecological and socio-economic value, such as carob, fig, and olive trees. These species support both biodiversity and future agro-ecological land use, reinforcing the multifunctionality of the rehabilitated area.

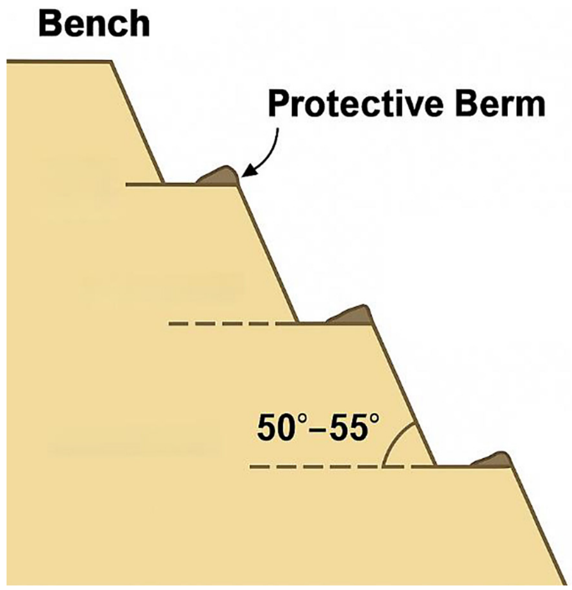

Figure 10. Illustration of the benching and slope-cutting method of the quarry faces

COMPARISON WITH EXISTING PRACTICES

Compared to existing rehabilitation practices in Morocco, the model represents a significant advancement. Many current quarry operations still treat rehabilitation as a post-extraction obligation, leading to poorly planned and often ineffective outcomes. In contrast, the present model incorporates spatial analysis, legal compliance, and ecological design into a unified, operational workflow.

Moreover, while Moroccan Law 27-13 mandates the inclusion of rehabilitation in Environmental Impact Studies, it does not prescribe technical or ecological methodologies. This study fills that gap by offering a replicable model scientifically grounded in both GIS-based decision support and ecological restoration principles. Similar integrative models have been widely adopted in countries such as Canada, France, and Australia, where rehabilitation is mandated through technical standards and backed by financial guarantees (Danielsen and Kuznetsova, 2014).

Thus, this study marks a shift toward institutionalizing scientifically sound rehabilitation

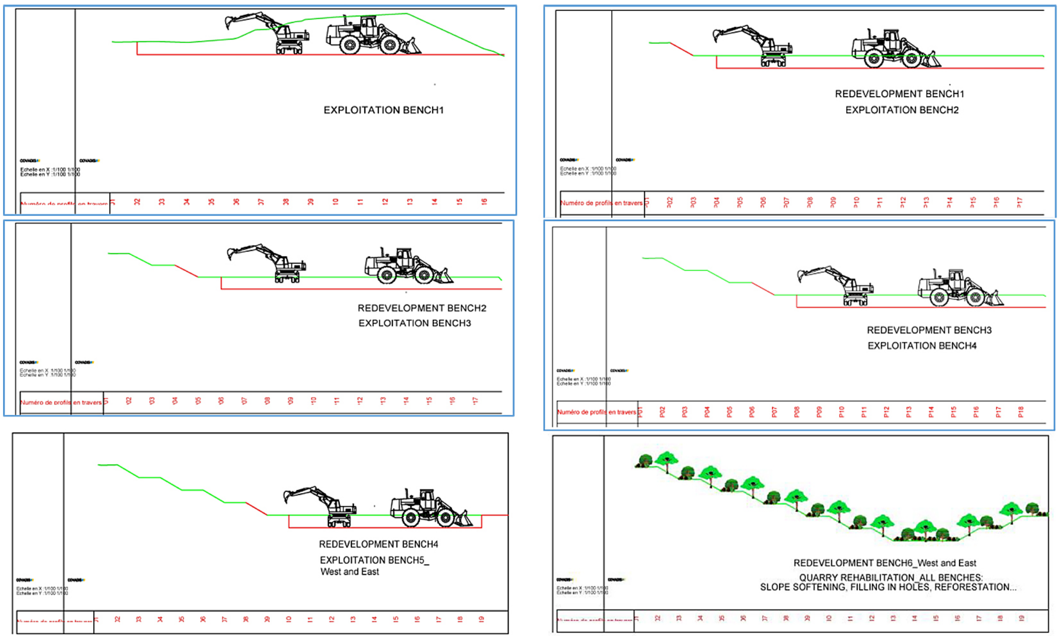

Figure 11. Progressive evolution of quarry rehabilitation

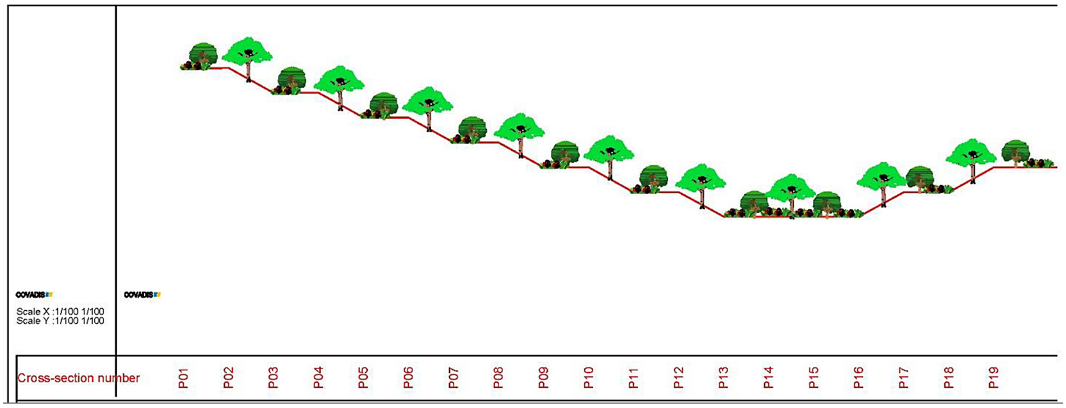

Figure 12. Final state of the site after rehabilitation, showing the landscaping and ecological arrangements implemented

practices in Morocco, contributing a prototype that can be adapted to other quarry types and geological contexts.

Legal and practical implications

The model aligns with the provisions of Law 27-13 and its implementing decrees, particularly regarding the requirement for a bank guarantee (Article 14) and the need for a clearly defined rehabilitation strategy. By grounding the model in legal, environmental, and spatial analysis frameworks, it offers a concrete decision-support tool for quarry operators, consulting firms, and regulatory bodies.

Practically, the model encourages rehabilitation to be planned and executed in parallel with exploitation, which not only reduces long-term costs but also enhances environmental resilience. The use of spatial and environmental analysis tools enables operators to assess physical constraints – such as slope, hydrology, and geology – throughout the project lifecycle, supporting interventions that are both site-specific and aligned with regulatory requirements.

The flexible structure of the model also makes it adaptable to other Moroccan quarries extracting different materials (e.g., clay, sand, dolomite), offering the potential to serve as a national reference framework. Future applications may benefit from incorporating remote sensing for long-term monitoring and using biodiversity indicators to assess ecological performance.

CONCLUSIONS

Quarry rehabilitation represents a major environmental, social, and regulatory challenge, particularly in Morocco, where the construction materials sector is rapidly expanding. This study successfully designed a standardized rehabilitation model for a limestone aggregate quarry located in Taghramt, northwestern Morocco, by integrating geomatics tools, environmental criteria, and the Moroccan legal framework.

The findings demonstrate that rehabilitation cannot be viewed as a separate or post-extraction activity; rather, it must be planned and implemented from the earliest phases of quarry operation. The approach follows a coherent sequence of phases: detailed site characterization through spatial and environmental data, 3D modeling of terrain evolution, stabilization of quarry faces, progressive slope regrading, valorization of waste materials, and ecological restoration through adapted planting and creation of microhabitats.

Beyond restoring the landscape, this model contributes to recovering ecological functions by promoting local biodiversity and enabling socio-economic valorization. The introduction of agroecologically valuable species such as carob, fig, and olive trees, along with management of temporary wetlands and cavities, creates habitats favorable to wildlife, especially amphibians and birds, reinforcing the environmental integration of the rehabilitated site.

Aligned with national legislation (Law 27-13 and its implementing texts), this model guides project owners, consulting firms, and territorial authorities in developing rigorous, measurable, and integrated rehabilitation plans. It represents a step forward in institutionalizing a culture of responsible and sustainable post-quarry management in Morocco.

This study fills a critical gap by proposing a comprehensive rehabilitation framework combining spatial analysis, environmental assessment, and legal compliance – addressing challenges not fully tackled in previous Moroccan quarry rehabilitation research. It opens promising perspectives for adaptation to other quarry types (clay, sandstone, sand, carbonate, dolomite) and diverse geo-environmental contexts, with the aim of establishing a national reference framework of best practices.

Future research should focus on long-term monitoring and evaluation of rehabilitated sites to validate the ecological and social effectiveness of this approach and to refine the model based on empirical field observations.

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