ENVIRONMENTAL ASSESSMENT OF QUARRYING IN VOLCANIC ISLANDS: THE CASE OF 'CERRO QUEMADO', GALAPAGOS, ECUADOR

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ABSTRACT
The 'Cerro Quemado' Quarry on San Cristobal Island, Galapagos, Ecuador (UNESCO World Natural Heritage site) is a volcanic cinder cone that supplies aggregate and stone materials for the local construction industry. Increasing anthropogenic activities such as tourism increase the demand for raw materials in the construction sector. Thus, this work aims to evaluate the influence of extraction on the physical environment of an area with a fragile natural heritage by assessing impacts for the design of mitigation strategies for the affected area. Therefore, this work suggested three phases: (i) identification of activities; (ii) evaluation of impacts according to exploitation phases; and (iii) generation of preventive and corrective proposals. Of the 22 activities identified, 17 are environmental, with a moderate impact influence and a more significant influence in the production phase of the quarry (78%); however, severe impacts are more critical in the closure phase (25%). The latter classification impacts soil contamination (high alkalinity values) and landscape degradation (reduction of the cinder cone area). Finally, this work proposes actions that include a sustainable development programme in the surrounding community, waste management strategies, occupational health and safety plan, integration of geotourism as an alternative use, conserving natural and geological values of importance for the establishment of 'nature–human' links that explain its ecosystemic role for the development of anthropogenic activities in an area of recognised abiotic and biotic nature.
Keywords: contamination, sustainable development, waste management, raw materials.

1 INTRODUCTION

Like other types of surface mining, quarrying disturbs environmental conditions in areas with fragile ecosystems that are important for sustaining life. These changes are evident in the degradation of abiotic elements such as geology and geomorphology [1], with the consequent affectation of natural water and soil conditions (acidity, erosion, lowering of the water table) and the loss of biotic heritage (flora and fauna) [2].

However, despite the adverse effects of mining activity, there is a demand for stone materials essential for economic development, requiring sustainable approaches to the multiple extraction stages [3], [4]. In addition, to avoid conflicts between quarry operations and the preservation of the environment [5], environmental assessment approaches must be

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simple to apply and accessible to local stakeholders unfamiliar with the technical aspects of quarrying [6].

In the literature, various assessment methods for quantifying environmental impacts include quantitative, qualitative, and semi-quantitative methods. These methods are tailored to the specific needs of environmental monitoring projects. One of the most commonly used methods in environmental assessments is the Leopold method, which uses cause–effect matrices to establish the magnitude of environmental impacts with their relative relevance, facilitating decision-making and prioritising corrective measures [7], [8]. The 'Checklist' method identifies possible implications for proposed actions based on a systematic enumeration of environmental factors [9]. Batelle's method uses a checklist of weighing scales with four hierarchy levels to cover environmental components at general and specific levels [10]. Other methodologies, such as map overlay, combine spatial data and predictive models to achieve a complete and unified understanding of environmental effects to help mitigate adverse environmental impacts [11].

In the Galapagos Islands, seven quarries supply construction material, the product of the extraction of volcanic slag, which is necessary for the adaptation of infrastructure required by the inhabitants and tourism on the three populated islands of the archipelago. Due to the island's fragile ecosystem and location far from mainland Ecuador, this material is promoted to avoid the entry of invasive species, such as pathogenic organisms, in high volumes of material and the increase in construction costs due to the high transport costs. One is the 'Cerro Quemado' Quarry, composed of a large mantle of pyroclastic material, whose exploitation is mainly artisanal.

Due to the importance of the operation phase to witness the changes caused by the activity to the ecosystem, an environmental analysis of the natural and anthropic elements of the area is necessary, especially those critical elements that threaten to degrade the islands' natural heritage. Therefore, this work proposes the following research question: What mitigation strategies can be proposed through an environmental impact study on a protected island, which can serve as a basis for stakeholder implementation? In addition, the objective is to evaluate the environmental impacts on the physical environment caused by a quarry located within an island area with a recognised natural heritage (San Cristóbal Island, Galapagos) to design mitigation and resilience strategies for the adverse effects of the extraction of stone material.

2 MATERIALS AND METHODS

2.1 Study area

'Cerro Quemado' Quarry is located on San Cristobal Island, part of the Galapagos Archipelago (World Heritage site and Biosphere Reserve by UNESCO). It is one of seven quarries on the islands for the extraction of construction materials, operated under the direction of the Council of Government of the Special Regime of Galapagos (CGREG, in Spanish). The local geology of the sector is characterised by the presence of small cones overlying ancient flows of dark basaltic lavas. In the location, the quarry face sits on reddish volcanic lavas and scoria, characteristic of the richness in weathered ferromagnesian materials (Fig. 1). The exploited material presents a rough, greyish texture with abundant external and internal porosity.

Figure 1: Cerro Quemado Quarry mining face.

2.2 Workflow

The methodological workflow for environmental assessment of quarrying in volcanic islands is shown in Fig. 2.

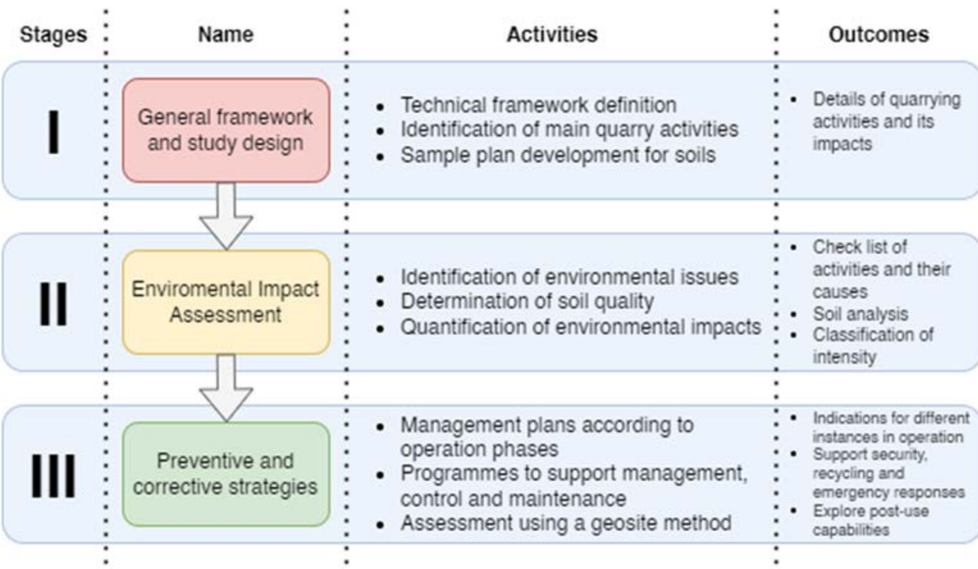

Figure 2: Methodological workflow for environmental assessment of quarrying in volcanic islands.

2.2.1 Stage I: General framework and study design

The first phase consisted of acquiring the necessary information to lay the foundations for the analysis of the influence of the operation on the physical environment of the ‘Cerro

Quemado' Quarry. Therefore, this phase focused on consultation through interviews with stakeholders regarding data relevant to five characteristic aspects of quarrying: (i) extracted material, (ii) daily extraction volume, (iii) extraction method, (iv) operating plans, and (v) environmental regulations.

In addition, this stage determined a soil sampling plan for soil quality through a protocol that included representativeness assurance, depth determination (10 cm from the contact layer), estimation of a total number of samples (17 single samples of 200 g, one sample of 0.49 kg, and three composite samples of 1 kg), sampling quality measures (e.g. removal of the first layer, collection on sunny days), and preservation (e.g. storage in a dry container and the shade).

2.2.2 Stage II: Environmental impact assessment

It comprised three points related to (i) the identification of environmental aspects related to the operation, (ii) the on-site collection of soil samples and (iii) the measurement of noise levels. Specifically, environmental aspects were classified according to the stages of operation, components, and activity. These activities allowed an assessment to establish the magnitude of each impact on the ecosystem and its capacity to affect the natural conditions of the environment, specified in the criteria in Table 1.

Table 1: List of impact evaluation criteria [7].

Name	**Description**
Sign	It refers to the benefit (+) or harm (−) of the actions on the factors considered.
Intensity (IN)	Incidence of the action on the factor.
Extension (EX)	Area of influence of the impact in relation to the environment of the activity.
Moment (MO)	Time between the appearance of the action and the beginning of the effects on the factor.
Persistency (PE)	Persistence time of the effect since its appearance.
Reversibility (RV)	Possibility of return to initial conditions.
Recoverability (RE)	Possibility of reconstruction of the affected factor.
Synergy (SI)	Possibility of more powerful effects by combination of effects.
Accumulation (AC)	Quantification of the progressive increase due to the persistence of the effect.
Effect (EF)	Form of manifestation of the effect on a factor.
Periodicity (PR)	Regularity of manifestation of the effect.

Simultaneously, 18 soil data points were collected, applying the 'quartering' method, which consisted of four steps: (1) homogenisation of single soil samples; (2) drying; (3) division of the sample into four sections; and (4) taking one of the four soil portions as a representative sample. Additionally, decibel (dB) values of maximum, average and minimum noise levels were recorded at different locations in the quarry at three different times of the day (9:00 AM, 13:00 PM and 16:00 PM), using the Splend Sound Meter mobile application (available in Google Play/Android software, downloaded February 2024).

2.2.3 Stage III: Preventive and corrective strategies

This stage considered the suggestion of preventive and corrective measures based on the analysis of environmental impacts with high significance value within the quarry extraction

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and closure works to propose indications for their adaptation in the different stages of the project. As such, this stage proposed three management plans based on: (i) prevention and mitigation; (ii) monitoring and tracking; and (iii) closing and abandonment. Simultaneously, these management plans were complemented by the generation of five management programmes containing: (i) environmental training; (ii) occupational health and safety; (iii) waste management; and (iv) emergency and contingency to facilitate the management, control, and maintenance of the elements of the quarry's physical environment.

In addition, this work explored the site's capabilities for obtaining added values for post-mining use by assessing the site's potential as a geosite [12], using a widely accepted international methodology (IELIG method) [13].

3 RESULTS

3.1 Identification of main activities

The identification revealed that the quarry activities need more technification, reflected in the lack of an extraction plan, resource management, calculation of reserves, and recording of the daily amount of material extracted and processed. As such, the environmental aspects of the closure and operation stages are summarised in Table 2.

Table 2: Environmental aspects identified in 'Cerro Quemado' Quarry.

Stage	**Components**	**Activity**	**Environmental aspect**
Operation	Transport	Loading and transportation of material	Generation of particulate matter
			Generation of vibrations and noise
			Soil disturbance
	Extraction	Excavation	Generation of particulate matter
			Combustion gas emission
			Generation of vibrations and noise
			Soil disturbance
		Material crushing	Generation of vibrations and noise
			Energy consumption
			Generation of particulate matter
	Maintenance	Installation and assembly of equipment	Combustion gas emission
		Equipment maintenance	Consumption of natural resources
			Generation of hazardous waste
Closing	Accesses	Road closures	Traffic and transportation
		Revegetation	Landscaping and aesthetic value
	Slope stabilisation	Stock movement	Generation of particulate matter
		Construction of retaining walls	Soil disturbance
		Slag injection	Landscaping and visual alteration
	Filling and levelling the area	Slag injection	Generation of particulate matter
		Area levelling	Landscaping and visual alteration
	Camp dismantling	Disassembly of the assembly booth	Generation of waste
		Cleaning the area	Consumption of resources

3.2 Environmental impact assessment

This section evaluated the environmental aspects of the mining operation's stages, operation and closure, identified in the previous phase.

3.2.1 Operation

Table 3 presents the impact matrix for the operation stage, where it was identified that, of the nine impacts studied, only one of them (hazardous residues generation) has a severe level (S), showing persistence during this stage and the need for attention even during the closure class. On the other hand, seven aspects were listed within the moderate (M) classification, showing development opportunities related to the interactions of anthropogenic activities (water consumption, emission of combustion gases, waste generation) with the abiotic environment (soil, water, air).

Table 3: Environmental impact scores and classification for the operation stage of 'Cerro Quemado' Quarry.

Aspect	**Im**	**NA**	**IN**	**EX**	**MO**	**PE**	**RV**	**SI**	**AC**	**EF**	**PR**	**MC**	**Sc**	**Cls**
Soil alteration	S	−	4	4	2	4	4	2	1	4	4	4	45	M
Emission of combustion gases	A	−	1	1	1	2	2	1	4	1	1	4	21	L
Water consumption	W	−	2	2	1	2	2	2	4	1	2	4	28	M
Industrial safety	HH	−	4	2	1	2	2	4	4	4	2	4	39	L
Monitoring	A	+	1	2	2	4	1	4	4	1	4	2	29	M
Production time	A	−	2	4	1	2	2	2	4	1	2	2	30	M
Maintenance (machinery/equipment)	S	−	4	2	2	4	4	2	4	4	4	4	44	M
Residues generation	S	−	4	2	2	4	4	2	4	4	4	4	44	M
Hazardous residues generation	S	−	4	2	2	4	4	4	4	4	4	8	50	S

Abbreviations: I, Impacts = S, soil; A, air; HH, human health; W, water consumption; Sc, score; Cls, classifications = L, low; M, moderate; S, severe.

3.2.2 Closing

In contrast, two of the eight impacts assessed (Table 4) were severe in the closure phase (S). These impacts correspond to visual degradation, which manifested itself as a permanent and widespread impact on local landscaping, together with the impact on soil health. Meanwhile, the other six impacts assessed have moderate (M) ratings, evidencing mitigation capabilities with adequate measures during the previous phase.

3.3 Soil chemical properties

Table 5 presents the chemical analysis results, where it is evident that the TPH values significantly exceed the maximum permissible value. Additionally, the pH values exceed the recommended values for soil in a 'healthy' state, indicative of slightly alkaline soils, evidenced in the results of the amounts of sodium in the soil.

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Table 4: Environmental impact scores and classification for the closing stage of 'Cerro Quemado' Quarry.

Aspect	I	NA	IN	EX	MO	PE	RV	SI	AC	EF	PR	MC	Sc	Cls
Removal of machinery and equipment	S	−	1	4	1	4	4	2	1	1	4	4	32	M
Monitoring	S	+	2	4	1	4	4	1	4	1	2	4	35	M
Soil quality	S	−	4	4	8	4	2	2	4	4	4	4	52	S
Slope stabilisation	S	−	4	4	1	2	2	4	4	4	4	4	45	M
Landscaping and visual alteration	V	−	8	8	1	4	4	4	4	4	4	8	73	S
Residues generation	S	−	2	4	1	4	4	1	4	1	2	4	35	M
Water consumption	W	−	1	2	1	2	2	1	1	1	2	4	21	L
Camp dismantling	S	−	2	4	1	4	4	1	4	1	2	4	35	M

Abbreviations: I, Impacts = S, soil; A, air; HH, human health; W, water consumption; V, visual; Sc, score; Cls, classifications = L, low; M, moderate; S, severe.

Table 5: Results of the analysis of soil physico–chemical parameters [14]–[17].

Parameter	Result	Threshold	Units	Interpretation
pH	9.36	6 to 8	pH units	Disturbed
EC	7.89×10^{-6}	2	S/m	Non-hazardous
Organic matter	0.26%	–	%	Non-hazardous
Micronutrients				
Iron (Fe)	BLM	>250	mg/kg	Non-hazardous
Manganese (Mn)	0.44	>330		Non-hazardous
Zinc (Zn)	0.19	60		Non-hazardous
Microelements				
Sulphur (S)	20.76	250	mg/kg	Non-hazardous
Cadmium (Cd)	0.3	0.5		Non-hazardous
Copper (Cu)	0.05	30		Non-hazardous
Chromium (Cr)	0.05	20		Non-hazardous
Cobalt (Co)	0.04	10		Non-hazardous
Nickel (Ni)	0.09	20		Non-hazardous
Lead (Pb)	BLM	25		Non-hazardous
Sodium (Na)	148.27	>500		Moderate
TPH	26640	0.5		Severely disturbed

Abbreviations: BLM, below level minimum; EC, electrical conductivity; TPH, total petroleum hydrocarbons.

3.4 Preventive and corrective strategies

3.4.1 Management plans

Three management plans are presented below for: (i) prevention and mitigation (Table 6); (ii) monitoring and tracking (Table 7); and (iii) closure and abandonment (Table 8). The prevention and mitigation plan considered that aspects related to non-extractive human activity may represent a significant environmental aspect, requiring attention in short periods. Additionally, the prevention approach offers attention without neglecting the participation of the biotic component through dedicated strategies to improve the conditions of different elements of the abiotic natural heritage of the surroundings, such as actions to avoid air degradation due to particulate matter emissions by planting vegetation around emission areas and sustainable water management to ensure the sustainability of the mining operation.

Table 6: Summary of strategies for a prevention and mitigation plan.

Aspect	Proposed activity	MM	Frequency
Hazardous residues generation	Adequation of maintenance areas	R, P	Permanent
	Use of adsorbent materials	R	Monthly
	Residues handling framework	R	Quarterly
	Audits and monitoring	R, P	Semi-annual
	Engage good practices with workers	R, P	Daily
Non-hazardous residues generation	Classification of residues	R	Daily
	Allocation of waste areas	P	Permanent
	Warning for improper waste disposal	P	Quarterly
	Cleaning of existent areas having residues	R, P	Quarterly
Equipment and logistics	Use of less polluting fuel alternatives	R	Annual
	Maintenance focused on combustion efficiency	R	Quarterly
	Time and route management to reduce equipment needs	R	Permanent
Emission of particulate matter	Plant vegetation around emission areas	R	Annual
	Dust control through track wetting	R	Weekly
	Coverage of material transport vehicles	R	Weekly
Water use	Promote responsible use of water	R	Quarterly
	Collect and store rainwater	R	Monthly

Abbreviations: MM, Monitoring methods; R, report; P, photography record.

Table 7: Summary of strategies for a monitoring and tracking plan.

Aspect	Proposed activity	MM	Frequency
Physical environment monitoring	Analysis of soil samples	R, L	Annual
	Noise and vibration monitoring	R	Daily
	Maintenance of monitoring equipment	R	Semi-annual
Management and compliance monitoring	Identification of trends for additional interventions	R	Semi-annual
	Generation of periodic progress reports	R	Semi-annual
	Record of activities in the quarry	R	Semi-annual
	Review of compliance with regulations and standards established by law	R	Monthly
	Identification of areas of improvement and adjustments	R	Annual
	Worker training programs	T	Semi-annual

Abbreviations: MM, monitoring methods; R, report; P, photography record; L, laboratory analysis; T, training sessions.

Similarly, Table 7 presents the proposals for a monitoring and tracking plan. This plan summarised the proposals into two kinds of monitoring, the first paying attention to the physical environment of the quarry and the second tracking compliance with the first set of activities. For the first set, the economic and logistical factors limited the suggested frequency of activities to more than six months, unlike noise monitoring, which was set to a daily frequency. For the second set, because it consisted of activities to ensure compliance with the requirements of the previous group, it considered longer times (annual and semi-annual) under approaches of continuous monitoring, order in the activities, local and national regulatory frameworks, improvement proposals, and training.

Finally, Table 8 summarises the proposals for a closing and abandonment plan. This plan included three aspects related to removing infrastructure and equipment, monitoring compliance with activities during the execution of the plan, and finally, rehabilitation of geotechnical conditions through slope stabilisation. Additionally, for this set of activities, longer frequency times were suggested for the internal monitoring activities of the quarry closure, so the closure activities are as environmentally friendly as possible.

Table 8: Summary for a closing and abandonment plan.

Aspect	**Proposed activity**	**MM**	**Frequency**
Removal of infrastructure and equipment	Camp dismantling	P	Uniquely
	Machinery removal	R, P	Monthly
	Final closing	R	Annual
Evaluation and monitoring of activities	Preliminary assessment	R	Annual
	Insurance and guarantees	R	Annual
	Residues handling	R	Quarterly
Geotechnical conditions	Slope stabilisation	R, P	Quarterly

Abbreviations: MM, monitoring methods; R, report; P, photography record.

3.4.2 Comprehensive management programs

Simultaneously, this work proposed four management programmes based on: (i) environmental training; (ii) residues handling; (iii) occupational health and safety; and (iv) emergency and contingency (Fig. 3). These programmes are complementary to the plans listed in the previous phase. They are necessary for integrated management and to ensure compliance with the proposals for the improvement of the physical environment of the quarry.

3.4.3 Restoration proposals through geotourism approaches

The assessment using the IELIG method exhibited scores that fall into the second highest scoring class ('high') for the three central values: Scientific (3.775/10), Educational (5.375/10), and Touristic (5.5/10). Although the values on average slightly exceed half of the total possible score, it evidences an opportunity for development to make visible the volcanic features of the island and how a post-quarrying use is possible, highlighting nature–human links, and raising awareness of sustainable mining practices, as evidenced by several authors in mine restoration, including the adequacy of trails, interpretation spaces, recreation of initial conditions, and safety measures in the rehabilitation of spaces [18]–[20]. However, more detail is needed in the evaluation as a geosite to comprehensively identify its capacities for use according to the three values assessed by the methodology.

4 CONCLUSIONS

This work carried out an environmental assessment focused on the physical environment of a quarry in an island protection environment. In the initial assessment process, the phases of

Figure 3: Summary of comprehensive management programs.

operation identified in the quarry list a diversity of impacts, distinguishing those relevant to the integrity of abiotic elements in the surroundings. Moderate impacts can be mitigated with non-complex measures and in the same phase in which they occur, for which management programs must be developed simultaneously with prevention and mitigation, monitoring and tracking, and closing and abandonment plans.

In contrast, severe impacts focus on the risk of soil contamination and continued visual degradation. This was evidenced in the physical–chemical parameter scores, with cadmium values exceeding environmental standards and high TPH scores, showing that uncontrolled activities can threaten the area's physical environment. Similarly, mitigation of the effects of the activity on the landscape can be aided by listed activities dedicated to the physical environment (e.g. slope stabilisation).

In addition, evaluating the quarry's capacity as a site of geological interest in post-activity use offers a basis for the sustainable use of the quarry in a phase after the exploitation of stone material. However, future actions are required to improve the site's scientific and touristic capacities. Finally, this work recommends a further environmental assessment that includes the socio-economic and biotic factors of the site to complement the strategies and plans designed for the abiotic environment in the different stages of operation of the quarry proposed by this work.

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