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Geomorphological restoration on tailing deposits: A study case applied to the Rio Blanco mining concession, Ecuador

Restauración geomorfológica sobre depósitos de relaves: Caso de estudio aplicado a la concesión minera Río Blanco, Ecuador

Raúl Moreno

Department of Geodynamics, Universidad Complutense de Madrid. 28040, Madrid, Spain.

*Corresponding author: rmorenofarfan0@gmail.com

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Abstract

This study presents two separate assessments to contribute to the development of a sustainable mining industry with low environmental impact that minimizes possible social conflicts related with this activity. The first is how to apply the concept of geomorphological restoration on degraded spaces to establish geoenvironmental integration proposals, focused on the restoration of mining areas altered by the tailing deposit of the Rio Blanco project, Azuay province-Ecuador, based on the modeling with GeoFluv method and the Natural Regrade software. The second is an analysis of the general aspects of the mining activity in Ecuador, its cautions, and the environmental problems that could show tailing deposits. The main result of the current study has been a stable design that simulates natural conditions, which although it loses a storage capacity of 15% relative to the conventional design, it maximizes the volume of tailings to be accumulated. This significantly increases the stability and environmental integration that would have the tailing deposit.

Keywords: Geomorphological restoration, land modeling, environmental integration, tailings deposits, mining, environment.

Resumen

Con el fin de contribuir al desarrollo de una industria minera sostenible, de bajo impacto ambiental, que minimice posibles conflictos sociales asociados a esta actividad, este estudio da a conocer: 1) cómo aplicar el concepto de restauración geomorfológica sobre espacios degradados, para establecer propuestas de integración geoambiental, enfocadas a la restauración de zonas mineras alteradas por el depósito de relaves del proyecto minero Río Blanco, provincia del Azuay-Ecuador, basadas en el modelamiento con el método GeoFluv y el software Natural Regrade; y 2) un análisis de los aspectos generales de la actividad minera en el Ecuador, sus precauciones, y la problemática ambiental que pueden presentar los depósitos de relaves. Como resultado se obtuvo un diseño estable que imita condiciones naturales, en el que a pesar de perder una capacidad de almacenamiento del 15% en relación con el diseño convencional, logra maximizar el volumen de relaves a acumular, aumentando significativamente la estabilidad e integración ambiental que tendría el depósito.

Palabras clave: Restauración geomorfológica, modelación del terreno, integración ambiental, depósitos de relaves, minería, ambiente.

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Orcid IDs:

Raúl Andrés Moreno Farfán: http://orcid.org/0000-0001-8194-8386

1 Introduction

Ecuador is rapidly growing as a mining investment location in Latin America (Jamasmie, 2017). Ecuador recently ranked 92 out of the 109 most attractive nations to attract investors (Stedman et al., 2019). New campaigns and regulatory frameworks have changed the strategy for a nation that has traditionally based its economy on oil and agricultural exports (Verdugo and Andrade, 2018), specially with an average raw matter extractivity index of 36.93 % between 2000 and 2011 (Hailu and Kipgen, 2017). Between 1999 and 2016, the share of mining GDP to total GDP was between 1.17 % and 1.56 %, with a gradual increase in recent years between 1.48 % and 1.51 % from 2013 to 2016 (Almeida, 2019). According to conservative studies, mining could become 4 % of GDP (Vistazo, 2019).

Since 2016, Ecuador received approximately 420 concession applications, where 160 have already been approved obtaining an investment of more than 100 million dollars to explore areas rich in gold, copper, silver and molybdenum (Jamasmie, 2017). The country has a total area of 105,000 hectares concessioned for mining activities, distributed in seven provinces (BCE, 2021); for example, in 2013 Ecuador awarded the company Ecuagoldmining South America S.A., the Rio Blanco project in the province of Azuay (Figure 1), with reserves totaling 991,000 ounces of gold and 4.7 million ounces of silver, a resource equivalent to an amount not less than US$14 billion (Latinominería, 2012).

Likewise, it must be taken into account that mining has generated problems in the environment (Vásconez and Torres, 2018). Large extractive projects are also part of this controversy for not respecting human and nature rights (D'Angelo and Ruiz, 2018), deriving in social conflicts and legal suspensions (Ruiz, 2018), of projects such as Rio Blanco or Quimsacocha (Massa-Sánchez et al., 2018). In addition, the location of these large mining projects in highly fragile ecosystems, such as in hydric reloading areas, moorlands and wetlands, becomes relevant (Environmental Justice Atlas, 2017). As a result, on February 7, 2021, the people of the province of Azuay voted in a referendum for the prohibition of extractive metal mining activity in watershed areas with an important hydric reload (El Comercio, 2021). In this context, mining must necessarily consider its operational, legal and ethical responsibilities, aspiring to compatibility with respect for the environment and sustainability, for example, through the responsible exploitation of resources, generating benefits (environmental, social and economic) that equal or exceed the values that existed before exploitation (Oyarzún and Oyarzún, 2011).

On the other hand, the management of mining waste or tailings and their subsequent treatment are two factors of important environmental risk involved in mining (Oyarzún and Oyarzún, 2011), since their generation is much higher than the economic products they produce. For example, in the case of copper (Cu) mining, a ton of mineralized rock requires the extraction of 10 kg of the metal in the best case scenario. This means that 990 kg of material would be waste destined for a tailings deposit (Oyarzún et al., 2011), making this activity one of the most persistent sources of heavy metal pollution on the planet, due to: 1) its function is to store solid materials resulting from operations to separate and obtain metals (Espín et al., 2017), and 2) these wastes need to be stored in large areas (Serrato et al., 2010).

Regarding the environmental problems of tailings deposits, their potential to generate acid mine drainage (AMD) stands out, especially in places where deposits with sulfides are exploited (Sarmiento, 2007), and which are subsequently abandoned (Oyarzún et al., 2012). In addition, containment dams may break due to their intrinsic instability (plastic materials with high water content) (Mudd and Boger, 2013) and flood vast areas of land may happen (US EPA, 2015), and can cause huge human losses, such as the case of Brumadinho, Southeast Brazil, which occurred on January 25, 2019, where 257 people died and more than 182 dissapeared (Pereira et al., 2019).

These reservoirs generally have the classic design called "aguas arriba", which presents stability problems (WISE, 2019) such as: 1) the soil on which it sits is not adequate, so that there may be water infiltration and thereafter the base of the dam may give way, as happened in Aznalcóllar (Seville, Spain on April 25, 1998) (Rodríguez et al., 2009), 2) a poor response to seismic activity (relevant issue in Ecuador) (Oldecop and Rodríguez, 2007), and/or 3) the rise of the water level leading to two situations: one where the weight of water can induce rotational sliding type phenomena near the dam, with total or partial loss of the dam; and the other where water overtops the containment dam, and erodes the successive dam(s) leading to the breakage of the dam(s) (Owen et al., 2020).

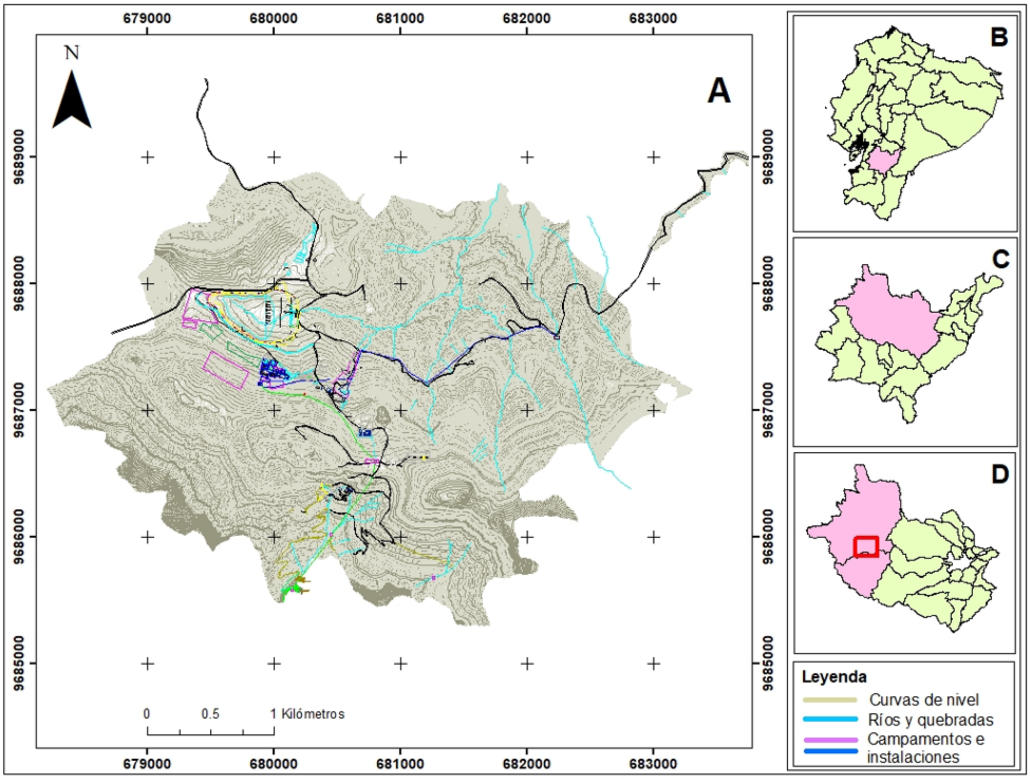

Figure 1. A (General map of Río Blanco mining project), B (location of the province of Azuay in the Republic of Ecuador), C (location of the Cuenca canton in the province of Azuay) and D (location of the mining project in the parishes Molleturo and Chaucha, Cuenca canton).

On the other hand, it is difficult to think of a human activity on the territory that does not involve moving earth or making changes on the first layers of soil, replacing ecosystems that once contributed to generate fertile soils with unfertile (Daily and Ehrlich, 1992). In this context, the application of geomorphological restoration, a recent discipline applied to "land moving" activities such as mining, linear infrastructures, civil works, urban planning, creation of green spaces, etc., is relevant. Currently, this discipline has become a tool for the mining sector (De la Villa and Martín Duque, 2018) because it is an activity that drastically transforms the relief, where restorations allow rebuilding new geoforms, landscapes and ecosystems (Universidad Complutense Madrid, 2021), as well as to create proposals for environmental integration, which tend to sustainability (Zapico et al., 2011), and help to reduce somehow the impacts of this activity (Bastidas-Orrego et al., 2018).

In this sense, GeoFluv method (patented in the USA) (GeoFluv, 2021) and the Natural Regrade software developed by Carlson Software Inc (2020), currently constitute one of the most advanced and complete tools at international level for the design of mature and stable geoforms that mimic natural conditions (Martín Duque et al., 2012) and that are generally applied in spaces affected by earthworks (Martín Duque and Bugosh, 2017). This study shows the application of the GeoFluv method on the tailings deposit of the Rio Blanco mining concession, Ecuador, with the aim of obtaining a conceptual, stable, environmentally integrated geomorphological design that mimics natural conditions.

2 Materials and methods

This section deals with the initial treatment and debugging operations of the starting information, followed by the performance of the restoration model on the tailings deposit using the GeoFluv method and the Natural Regrade software, and finally the definition of the design parameters used in the geomorphological terrain modeling.

2.1 Initial treatment of the information

the starting point of the study began with the treatment of the general information of the project in CAD format provided by the company1 (Terrambiente Consultores, 2012, 2016). Then, object selection and editing methods were used, performing some initial information debugging operations (quality control), such as: cleaning of repeated information, trimming of suitable working spaces, among others. At the end, a simplified map of the area was obtained (Figure 1A). The general topography of the project was detailed using contour lines with elevations, except for the tailings deposit, which did not offer elevations as it was represented as 2D polylines. Therefore, an initial step was to provide elevations to the lines defining this deposit, converting the 2D polylines to 3D. For information purposes, the crest of this tailings deposit is located at 3,763 masl.

2.2 Base design of the tailings deposit

Based on the information obtained in the Natural Regrade software, we focused on the design of the tailings deposit. Using layer management, we introduced: 1) boundary of the surface to be restored, simulating the edge of a river basin, 2) general layout of the fluvial channels and 3) design parameters (settings). Blue lines in Figure 2 represent the 2D polylines of the tailings deposit proposed by the company, and the white lines inside and surrounding it represent the design of the watershed boundary and the layout of the fluvial channels, respectively. Finally, as part of the preparatory process, an initial TIN (triangular irregular network) was performed. From this basic information, it was possible to start with the performance and definition of designs.

2.3 Restoration design parameters

Regarding parameters (Table 1), applying the Natural Regrade software (Carlson Software Inc, 2020), it is highlighted that most of these were obtained from a local or analog reference. Although the complete acquisition of these data was limited due to the intense field work required, the remaining parameters were obtained from similar projects (Martín Duque et al., 2012), obtaining a conceptual restoration design, which if adopted as a restoration solution, should be subsequently validated with local data.

3 Results and discussion

This section presents the results of the restoration design obtained on the tailings deposit, using the GeoFluv method and Natural Regrade software, highlighting the values of cut and fill, in addition to the analysis of slopes and orientations that quantitatively identifies the variation between designs, and finally addresses the discussion resulting from this study.

3.1 Results of the restoration design

The priority of the design was to seek stable morphologies that maximize the volume of tailings materials to be stored. Operations were carried out such as changing adjustments in the program and limiting the amount of affluents to try to generate fewer valleys (space that would not accumulate tailings with respect to the conventional design), distribute and balance the channels, reduce the value of the slope at the head of the channels, or maximize the convex section of the slopes (Figure 3). Finally, a restoration design was obtained, the results of which are detailed in Table 2. With the proposed design, 80,548.35 m^3 of tailings storage capacity is lost compared to the conventional (original) design, equivalent to 15% of the total mine waste (Table 2).

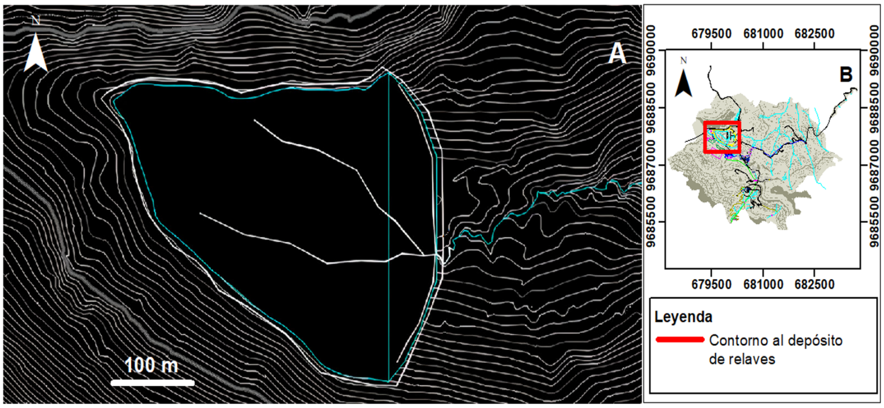

Figure 2. A (CAD map representation of the tailings deposit environment that is the subject of the restoration design and B (location of the tailings deposit within the overall mine project map).

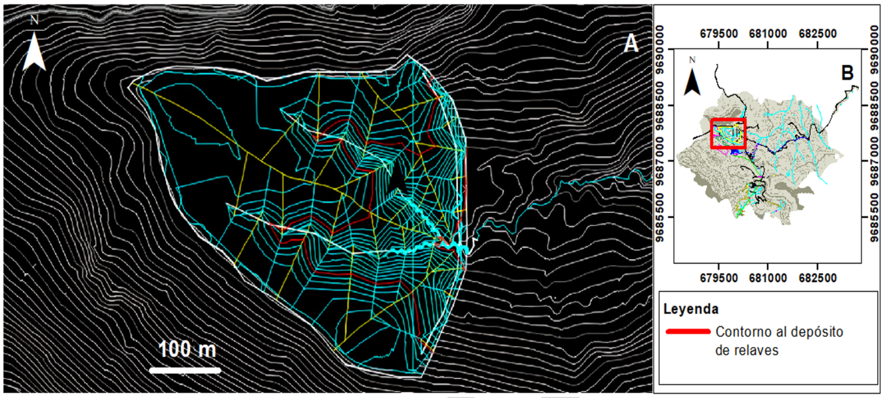

Figure 3. A (final adopted design. Blue shows contour lines and fluvial channels, red shows master contour lines), B (location of the tailings deposit in the general map of the mining project).

Figure 4 presents 3D views comparing images of the conventional design with their equivalents obtained in the proposed restoration design. One of the conditions observed in the results of the restoration design is that it limits the volume of tailings to be stored compared to the original (conventional) design, equivalent to a full reservoir, because the Natural Regrade program designs landscapes with valleys, which means that these spaces imply a reduction in the storage capacity. A design that accumulates 15 % less tailings material has been made in this study, and is much more integrated and stable. However, it will be up to the operating company to assess whether this reduction is feasible or not.

According to information from the general map of Rio Blanco mining project, made by Ecuagoldmining South America S.A., the storage capacity of the tailings deposit in the area would be 804 000 m^3 (Terrambiente Consultores, 2012, 2016). However, in our quantification carried out with accurate topography and using Carlson software, the capacity of the deposit is 535 273.5 m^3, taking the latter as a valid result. Given the environmental risk presented by tailings deposits in terms of: 1) static and dynamic stability; 2) effects associated with seismic response (Vanegas, 2011) and acid rock drainage (ARD), taking as a reference the quantification result obtained with the restoration design of this study implies working with a smaller amount of waste, prioritizing safety, and having a lower risk of breakage.

Table 1. Parameters used in the design using Natural Regrade software.

Parameters	Units	Tailing deposit
Maximum distance between connection channels	m	3
Maximum distance from the crest line to the head of the canal	m	45
Slope of the main valley to the mouth of the primary channel	%	Determined with AutoCAD
Main channel reach	m	36
2yr-1hr (value for a precipitation event that determines the dimensions of the main channel.)	cm	2.15
50yr-6hr (value for a precipitation event that determines the ddimensions of the flood-prone channel.)	cm	8.92
Drainage density variation	%	20
Angle of the subbridge to the channel perpendicular (upstream)	degrees	10
Maximum slopes on the North - East line	%	20
Maximum slopes in a straight line channel	%	33
Max Cut/Fill Variation	%	125
Max Cut/Fill variation	%	80
Overall magnification factor for cut stock		1
Overall reduction factor for fill material		1
Tolerable elevation at the head of the canal	m	1
Tolerable slope at the head of the channel	%	1
Channel settings		
Maximum waterflow velocity	m/s	1.37
Slope (upstream)	%	-12
Slope (downstream)	%	Determined with AUTOCAD
Width - depth ratio	slope>0.04	10
Sinuosity	slope >0.04	1.15
Watershed		
Runoff coefficient (reclaimed areas)		0.3
Runoff coefficient (areas without vegetation)		0.89

In the case of a real application, the results obtained with the restoration design could be contrasted with the information from the operating company, and if necessary the magnitude in relation to the storage capacity could be corrected. In this regards, the pros and cons between the methods used could be compared, a topic that would be investigated in a future research topic.

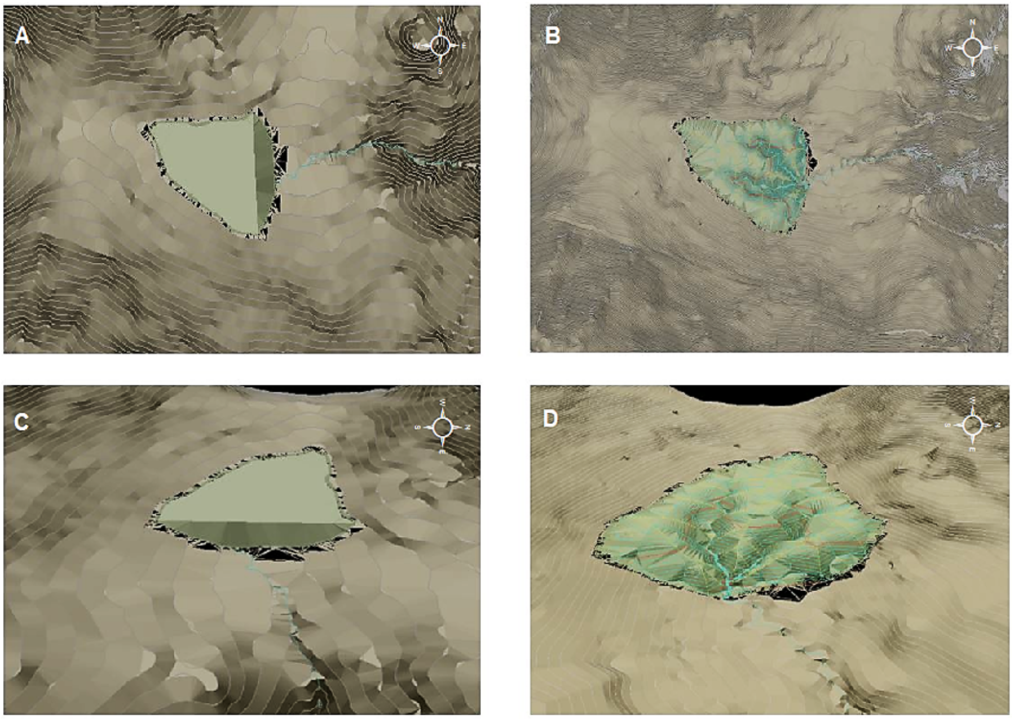

Figure 4. A and B (comparison designs viewed from facility), C and D (compare designs between frontal views).

Table 2. Data on volumes of the selected design version.

Description	Quantity (m^3)
Storage capacity of original deposit	535 237.50
Cut (capacity that does not store the geomorphologic design with respect to the conventional one, especially for the valleys)	142 739.00
Backfill (material that the geomorphological design can accumulate "in excess", with respect to the conventional one, by accumulating material in the hills of the interfluves).)	62 190.00
Difference of "cut-fill", i.e., volume of tailings that the geomorphological design stops accumulating with respect to the conventional design.)	80 548.35

3.2 Results of slope and orientation analysis

As complementary information to the restoration study, an analysis of slopes and orientations was performed for both the conventional and the proposed design, showing quantitatively (percentages of the different classes) the variation between the two designs. Regarding slope analysis: there is little variation in ranges or classes in the conventional (original) design (Table 3). On the contrary, the proposed design presents higher percentages, resulting in a larger area of habitats (Table 4). The most important aspect of this analysis is that there is a large difference in real land areas (sum of the areas of the triangle network) between the designs.

Regarding the orientation analysis: little variability is obtained in the conventional design, since the deposit is mostly flat, with its closing wall oriented towards the east (Table 5, Figure 4). The proposed restoration design has a greater diversity which is considered favorable, since it implies a greater biological diversity because some species will have a greater possibility of establishing in certain orientations, depending on different physical factors (light, humidity, etc.) (Table 6).

Table 3. Slope report, conventional design.

Slope report		
Average slope		4,40 %
Slope ranges or classes	Area (ha)	Percentage of total area in the slope range or class (%)
<10	7.76	83
10 a 20	0.12	1.4
20 a 30	1.46	15.7
30 a 40	0.00	0
>40	0.00	0
Total	9.36	100

Table 4. Slope report, proposed design.

Slope report		
Average slope		9.90 %
Slope ranges or classes	Area (ha)	Percentage of total rea in the slope ange or class (%)
<10	11.94	60.53
10 a 20	5.62	28.5
20 a 30	1.85	9.38
30 a 40	0.29	1.47
>40	0.02	0.12
Total	19.88	100

3.3 Discussion

Ecuador is progressively becoming a country that has embraced mining as a source of economic resources by taxes, royalties and employment, supporting the exploration and exploitation of various mining projects. However, mining activity generates a certain amount of distrust and fear in a context in which environmental and social concerns are becoming increasingly important, which has led to protests against extractivism, especially if these projects are located in environmentally sensitive areas. The high risk associated with mining can be minimized by applying proposals for environmental integration and restoration of areas altered by earthworks. It is possible to contribute to the development of mining that is compatible with sustainable development by applying new methods and software, such as the GeoFluv method and the Natural Regrade software, in such a way that it generates long-term environmental, social and economic benefits.

One of the main problems associated with mining activities at all scales is the disposal and subsequent treatment of tailings deposits. In the case of the Rio Blanco mining project, a natural high mountain valley (tailings deposit crown located at 3763 m.a.s.l.) will be filled with tailings. According to the literature consulted, this is not advisable from an environmental and geomorphological point of view, following conventional techniques and designs, such as the so-called "upstream" design, which presents a series of stability problems (breakage). In addition, according to information collected on the mineralogical studies of the project (Terrambiente Consultores, 2012, 2016) there is the presence of Pyrite in the area (FeS_2), a metallic sulfide that can cause the release of heavy metals and generate acid mine drainage under humidity and oxidation environmental conditions (AMD) (Gray, 1997).

In fact, the contaminating potential of this geochemical phenomenon continues once the activity has ceased. Covers refer to the techniques used for risks of breakage and environmental protection, which prevent tailings from coming into contact with the outside, but these covers would not be entirely effective, since mining disasters that relied on this methodology have occurred (Lottermoser, 2013). Therefore, in addition to the cover system, it is recommended to apply the GeoFluv method and the Natural Regrade software, which allow the design and construction of various geoforms, such as valleys through which a drainage network runs, as well as other sets that mimic natural conditions, designed to respond safely to extraordinary episodes of rain, making them more stable to water infiltration and the effect of water and fluvial erosion.

Conventional mining restoration methods focus on two aspects: 1) the conventional topographic berm-slope-ditch design and 2) the aesthetic aspect carried out through revegetation; these have had unsatisfactory results in different parts of the world, since this type of topography (which does not exist in nature) does not have the necessary capacity to evacuate high runoff values, which form streams and gullies with high erosion and sediment emission rates, also being scarce its landscape integration due to its rectilinear shapes (Nicolau et al., 2021). However, since 2005, the GeoFluv method and the Natural Regrade software have been applied on mining restorations, replacing conventional methods mainly in the United States, as well as others such as the reconstruction of La Revilla or el Alto Tajo (Spain), or large coal mines such as Drayton South (Australia), La Guacamaya and Puerto Libertador (Colombia) and Mina Invierno (Chile), with favorable results in terms of stability and reduction of erosion and sediments (Hancock et al., 2020). In this sense, geomorphological restoration can be used to solve intrinsic problems of tailings deposits.

Table 5. Orientation report, conventional design.

Orientation report		
Zone	Area (ha)	Surface percentage (%)
North	0.26	2.83
Northeast	0.51	5.46
East	2.49	26.65
Southeast	0.56	5.99
South	0.38	4.05
Southwest	2.04	21.87
West	1.79	19.17
Northeast	1.30	13.93
Total	9.36	100.00

Currently there is no real case (not even at the project stage), that may use these methods on high mountain tailings deposits. Hence, the potential importance of the results obtained in this study, specially by putting into practice the methodology and tools described to improve the environmental integration of the project in terms of risk reduction, reduction of environmental impact and ecological and landscape integration, and the improvement of the image of the company from the operational and social point of view.

To standstill the mining activity and the closure of the tailings deposit, a cover system must be applied, whose objective is to keep tailings as stable as possible (in chemical terms), avoiding the formation of acid mine drainage (Matos et al., 2016), an essential cover system when complementing a geomorphological restoration. The proposal of a cover system was not addressed in this study, which can be further investigated.

Table 6. Orientation report, proposed design.

Orientation report		
Zone	Area (ha)	Surface percentage (%)
North	2.91	14.79
Northeast	5.08	25.79
East	3.03	15.39
Southeast	2.93	14.89
South	3.76	19.09
Southwest	1.18	6
West	0.42	2.15
Northeast	0.36	1.87
Total	19.73	100.00

4 Conclusions

The geomorphological restoration proposal offers an optimal result, capable of providing maximum stability and environmental integration with only a 15% reduction of the total storage capacity. Since there are no designs or projects applied with the GeoFluv method and the Natural Regrade software for tailings deposits, there were unknown aspects, such as the contribution (in fact, an essential condition) of placing a series of perimeter channels in front of the deposit (dam). The quantification of the increase in real land area that occurs between designs (flat top and inclined plane at the dam, with respect to a complex topography with valleys, hills, slopes, etc.), is almost double.

Considering that the mining project is located within sensitive high mountain areas and close to other water recharge areas, the best possible extractive management should be sought, since inappropriate management, such as the lack of adequate environmental control, could lead to terrible environmental consequences for the natural and social environment. Therefore, the methodology applied with GeoFluv and Natural Regrade in the Rio Blanco mining project contributes to minimize the associated environmental risk.

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