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Implementation of a methodology to evaluate and optimise closure measures at a coal mining operation in northern Colombia

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Abstract

The study was conducted at a thermal coal project located in northern Colombia in one of the largest open pit coal mines in the world. The objective of the study was to evaluate the erosion rates in the waste dumps by implementing erosion plots combined with a rainfall simulation system. This system modelled different precipitation intensities based on the hydrological conditions of the site. Through this simulation, sediment volumes generated under different vegetation cover conditions were obtained to define closure measures for landscape rehabilitation.

The activities carried out included the hydrological analysis of the study area, the design and installation of the rainfall simulation equipment, the creation of the erosion plots (including their instrumentation and the required hydraulic structures), the definition of the vegetation cover to be analysed and the execution of the corresponding tests.

This study provided valuable information for decision-making in the design of erosion control measures and optimisation of waste dump management strategies in the mine closure plan. Furthermore, the results revealed differences in erosion rates depending on the vegetation cover studied, as well as the positive influence of vegetation cover in reducing erosion. Analysis of the data generated allowed relationships to be established between rainfall intensity and the effectiveness of the cover implemented. The erosion rate data will be used to calibrate and develop a land evolution model that will allow future evaluation of landforms with and without erosion control measures. In addition, the work performed is the first step in a series of analyses that the mine owner intends to develop to assess other variables such as vegetation type, plowing methods, and water and sediment management structures that could result in more efficient and economically viable closure measures.

This project contributes to the knowledge of land management and rehabilitation in tropical open pit mines and is a step towards sustainable mine closure in the country of Colombia.

Keywords: *erosion rate, simulation, erosion plots, waste dump, closure measure*

1 Introduction

Open pit mining entails significant transformations of the landscape, including the removal of vegetation cover, modification of the relief and alterations in surface hydrology. It is clear that these actions increase the risk of soil erosion, affecting the environmental quality of the site and its surroundings. This is a situation that is especially important in areas with sensitive ecosystems and cultural diversity, as is the case in several regions of Latin America, which is why planning for mine closure (progressive and final) becomes a key element in achieving the recovery of the intervened territory.

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Under this scenario, the design of closure and rehabilitation strategies must be supported by tools that allow the quantification of soil behaviour and validation of the performance of the measures implemented, a concept that is becoming increasingly widespread and accepted among the main international players. Thus, in countries with a long mining tradition such as Australia, Canada, Chile and South Africa, a multidimensional approach has been adopted that includes technical, social and economic aspects. Documents such as the International Council on Mining and Metals (2019) and Australian practices given by the Australian Government, (Department of Industry, Innovation and Science 2016) are good examples of this approach. It is also worth mentioning the efforts recently made in this regard by countries with less mining tradition than those mentioned above, such as Colombia, which in recent years has issued guidelines that have the character of 'recommendations' for mine closures which, although not binding, do establish frameworks for future regulations and standards.

In response to these challenges, WSP Colombia implemented a methodological strategy at a coal mine located in northern Colombia based on the instrumentation of erosion plots and the use of rainfall simulators, with the purpose of generating technical information to evaluate erosion rates and the performance of closure rehabilitation measures. This strategy is oriented to two fundamental objectives:

- carry out a technical follow-up of areas already rehabilitated
- analyse different rehabilitation alternatives to determine which are most effective in reducing erosion.

This paper focuses on the second purpose: the optimisation and analysis of rehabilitation processes through controlled experimental tests. This methodology is considered to provide data that reduces technical uncertainty, aids in field decision-making, and improves the efficiency of implemented measures.

2 Conceptual framework

Soil erosion is a natural process that can be accelerated by open pit mining activities due to the loss of vegetation cover, poorly compacted soils and steep slopes. According to studies, soil loss rates can exceed 100 t/ha/year (Evans & Brazier 2005), affecting soil stability, water quality and the effectiveness of rehabilitation measures in mine closure processes. The complexity of a thorough understanding of the soil erosion process is due to the large number of variables involved in this process, for which different methods of analysis, including mathematical models and experimental measurements in the field, have been used.

Regarding mathematical models, these are a widely used tool for estimating soil loss rates as a function of climatic, edaphic, topographic and land use variables. One of the best-known models is the universal soil loss equation (USLE) developed by Wischmeier & Smith (1978) which has been adapted and improved in versions such as revised universal soil loss equation (RUSLE) and modified universal soil loss equation (MUSLE) to incorporate the influence of individual events and run-off. These models use factors to represent the variables that affect the erosion process, such as rainfall, soil erodibility, length and slope of the terrain, and type of vegetation cover. The relative ease of implementation makes them suitable for regional assessments and predictions in hypothetical scenarios, although their accuracy in specific field conditions may be limited if not properly calibrated (United States Department of Agriculture 1997).

In these types of methodologies, there are also models of greater complexity, such as water erosion prediction project (WEPP) and European soil erosion model (EUROSEM) that integrate detailed simulations of hydrological processes and sediment transport. In particular, the WEPP model, developed by the United States Department of Agriculture – Agricultural Research Service, allows the simulation of individual events or long periods, and is especially useful in altered or modified terrains such as those present in mining environments, although its application requires detailed data on soils, vegetation, topography and site management (Flanagan et al. 2001). EUROSEM, on the other hand, models surface flow at the plot and basin scale, considering temporal variations in rainfall intensity and soil properties (Morgan 2005). Both models offer greater accuracy but require calibration and validation with local data to ensure their applicability in specific scenarios.

On the other hand, there are the field experimental methods (applied by WSP for the present study) which allow obtaining direct observational data on erosion behaviour under real conditions. Among the most used techniques are:

- measurement of sediments collected in canals or traps
- evaluation of morphological changes in microplots
- use of rainfall simulators to study the immediate response of the soil to controlled erosive events.

According to Nearing et al. (2001), these methods are essential to validate theoretical models and adapt rehabilitation practices to local conditions. In the case of the mine where the study was carried out, WSP tried to combine the aforementioned techniques through the in situ construction of instrumented erosion plots. In this regard, an instrumented erosion plot can be defined as an experimental space designed to quantify soil loss and surface run-off under different conditions or variables of interest such as slope, type of cover or erosion management and control measures. These plots provide empirical data allowing for comparative evaluation of the effectiveness of different rehabilitation practices (Loch 2000).

International examples of the use of erosion plots can be found in bauxite mining projects in Australia (Tibbett 2010), in coal mines in South Africa (Evans et al. 2004), iron ore mines in Brazil (Silva et al. 2012) or in China as an aid in model calibration (Qiankun et al. 2015). As far as Colombia is concerned, there is no record of implementation of this type of technique at the scale presented here, so the work carried out is considered a pioneer of its kind for the country.

3 Methodology description

The methodology implemented by WSP at the coal mine focuses on the use of instrumented erosion plots as a tool to evaluate and optimise rehabilitation measures in both rehabilitated and to-be-rehabilitated areas with comprehensive mine closure in mind. The approach combines the installation of field plots, erosion cells for rainfall simulation and hydro sedimentological monitoring, adapted to site-specific conditions. A conceptual explanation of this methodology is given in the following paragraphs.

3.1 Hydrologic analysis: rainfall characterisation

As part of the studies required to perform measurements in the erosion cells, it is necessary to characterise the rainfall in the study area by means of a hydrological study of the site. As part of the methodological procedure followed by WSP, it was considered appropriate to define three levels of rainfall intensity (high, medium, and low) which are associated with rainfall of different return periods, where the selection of the return period will depend on internal standards of the companies owning the mining operation, previous experiences and industry recommendations.

3.2 Definition of design criteria

The aspects to be defined within the design criteria must involve elements that allow the sizing of the plots, hydraulic works (i.e. weirs, collection canals) and erosion cells according to the site conditions previously identified in the field visit. Similarly, part of the design criteria involves defining aspects such as simulated rainfall intensity, definition of the characteristics of the structure that will be used to assemble the erosion cell in terms of type of material, special calculations or civil works required for its construction.

3.3 Design of plots, erosion cells and measuring equipment

The design of both erosion plots and erosion cells involves the activities that allow the definition of their location, dimensions, total number of plots and cells, punctual location of erosion cells, calculations of hydraulic/civil structures and definition of the instrumentation to be used. That said, regarding the erosion plots, these are made up of the following elements:

- Perimeter berm: configured to limit the entry of run-off from adjacent plots and/or areas.
- Collection canal: formed between the slope toe and the lower berm. A temporary erosion control liner is recommended. The ditch will be provided with a set of check dams designed to retain bottom scour material and generate subcritical flow conditions upstream of the hydraulic control section.
- Control section for flow measurement: consisting of a triangular metal weir with a discharge capacity according to design.
- Instrumentation: the typical erosion plot comprises the following parameter measurement equipment: rain gauges, triangular metal weir, piezometric sensor.

Figure 1 shows a general schematic of an erosion plot as described in this document.

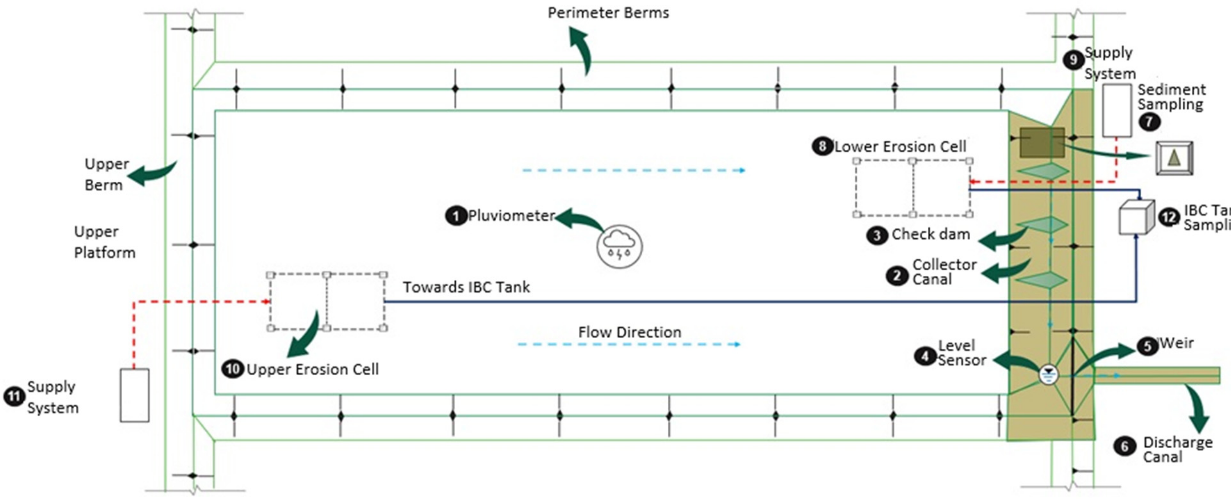
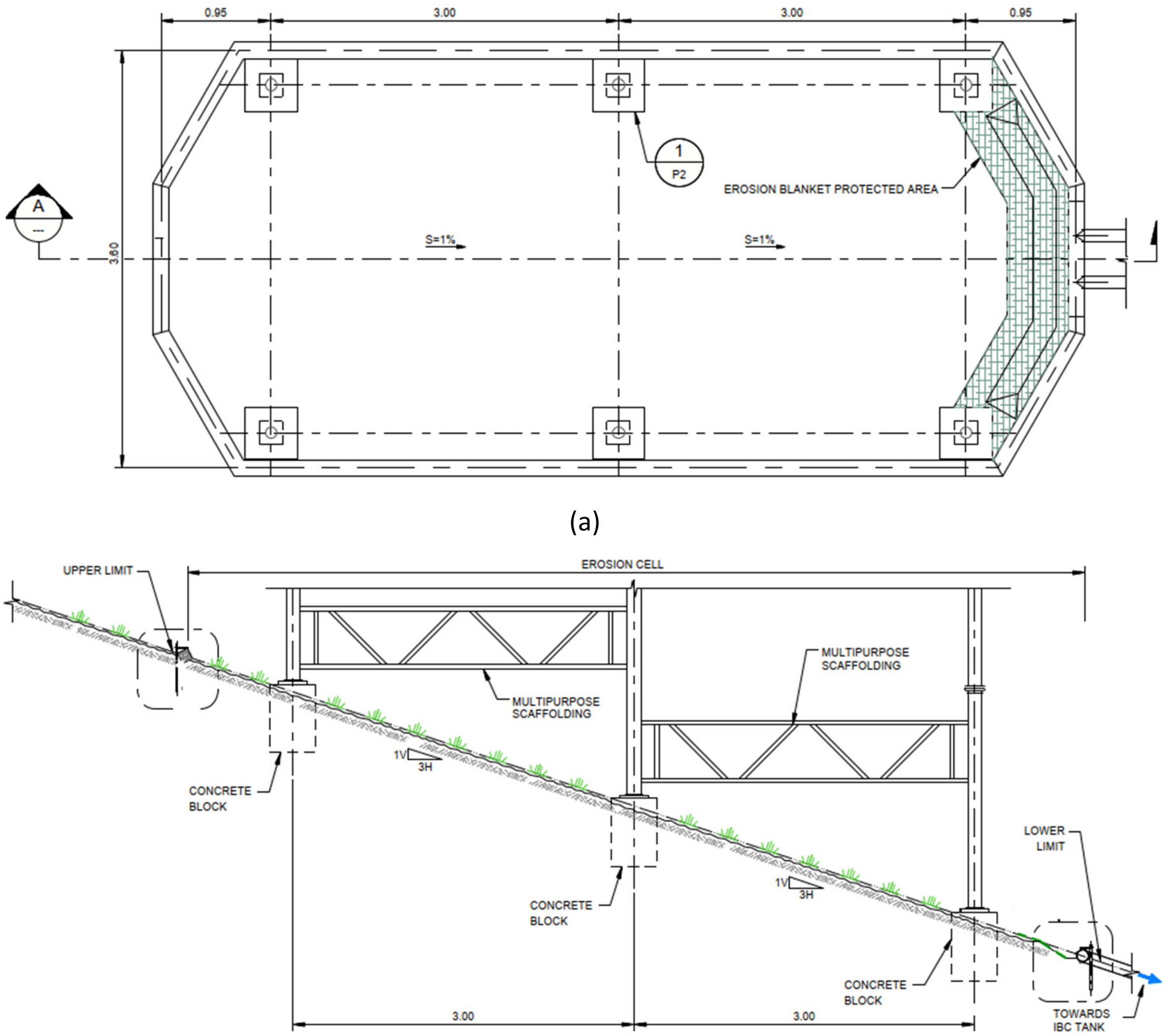


Figure 1 General layout of the erosion plot

Erosion cells, on the other hand, involve the following elements:

- Pumping system: in charge of supplying the necessary pressure to satisfy the working pressures of the spray, as well as the flow rates required in each one of them.
- Dismountable structure on which the piping and spray system is placed.
- Water distribution system: made up of a network of pipes where the water will enter, and the flow rates will be distributed until it reaches each sprayer that makes up the erosion cell. It will consist of PVC pipes, ball valves and high-density polyethylene hoses. The spray nozzles emit atomised water and simulate rain at a certain intensity, distributing the water over the surface within a specific radius of reach through their nozzles.
- Collection system: located in the lower part of the cell, it consists of a channel section with an erosion control blanket and a pipe that connects to an intermediate bulk container (IBC) tank.
- Erosion cell instrumentation: the following measuring instruments are used for this component – rain gauge, pressure gauge (to verify discharge and working pressures in the spray nozzles), IBC tank required for sampling and temporary storage of run-off generated by the rain simulator.

Figure 2 shows a general plan and profile schematic of an erosion cell as has been described.



(b)

Figure 2 General outline of an erosion cell. (a) Plan view; (b) Cross-section

3.4 Field implementation of erosion plots and cells

In order to achieve a successful field implementation process of the erosion plots methodology and the respective rainfall simulation cells it is considered relevant to consider:

- Ease of access to the measurement site for light (pickup truck) and heavy (tanker) vehicles.
- Close to a water source that provides sufficient water for irrigation.
- Depending on the mine's security conditions, it may be necessary to set up guard stations.
- They should be located at a prudent distance from sectors with significant erosion and geotechnical instabilities. Likewise, areas with the presence of canals or other water storage works that imply a risk of flooding should be avoided.
- The structure of the rainfall simulation system to be installed in the erosion cell should be easily dismountable to facilitate its mobilisation to other plots.

Spare equipment and tools should be available to ensure continuity during the monitoring stage.

As regards the measurement process, this involves calibration and monitoring activities in the erosion plots that have been set up. In terms of calibration, the variables to be considered involve verifying that the rainfall intensity is correct, and that the weir designed to measure flow rates is working properly. The monitoring tasks both in the cell and in the erosion plot are described in Table 1.

Table 1 Activities to be carried out to monitor erosion rates

Erosion plot	Erosion cell
Flow rate measurements are taken by reading the water level above the weir with the help of level and barometer sensors.	Shallow pits and granulometric analysis to be carried out at representative points of the plot.
Run-off sampling at the outlet of the landfill and total suspended solids (TSS) testing.	Collect the volumes of run-off produced over the cells by means of the sampling tank, located at the bottom of the plot.
Natural rainfall recording by rain gauge within the plot.	Synthetic rainfall is recorded using rain gauges
Photographic record of the erosion plot before and after each cycle of tests.	Photographic record of the erosion cell before and after each cycle of tests.
Once the natural rainfall event/s has ended, the extraction of sediments deposited on the lower channel must be coordinated with the mine owner, for subsequent weighing and physical characterisation (granulometry).	Water samples are extracted (one at each intensity change interval) and will be sent to the laboratory for TSS testing
Visual inspection, equipment cleaning and data processing.	Visual inspection, maintenance of equipment

4 Implementation of the methodology at a mine in northern Colombia: case study

The methodology was applied in areas with geometry at the closure stage in one of the waste dumps of a mine located in Colombia. As this was the first study, the idea was to evaluate only one of the several variables that can affect the behaviour of closure measures. In this case, the aim was to identify whether the methodology shed light on the revegetation processes currently used in the mine, seeking to learn more about the behaviour of erosion processes in this tropical environment as the vegetation cover develops in such a way that procedures can be refined and opportunities for improvement can be identified. Details of the activities carried out in the field are presented below.

4.1 Site condition

The mining complex is located in the Caribbean region of Colombia. The orebody corresponds to a carboniferous type deposit. Figure 3 shows the general location of the area in Colombia where this kind of deposit is present.

Figure 3 General Location of the mine project

4.2 Rain characterisation

Based on data from hydro-meteorological stations in the study area, the most important storm events were identified, which made it possible to obtain the characteristic rainfall pattern according to which rainfall in this area of interest lasts approximately two hours, as shown in Figure 4.

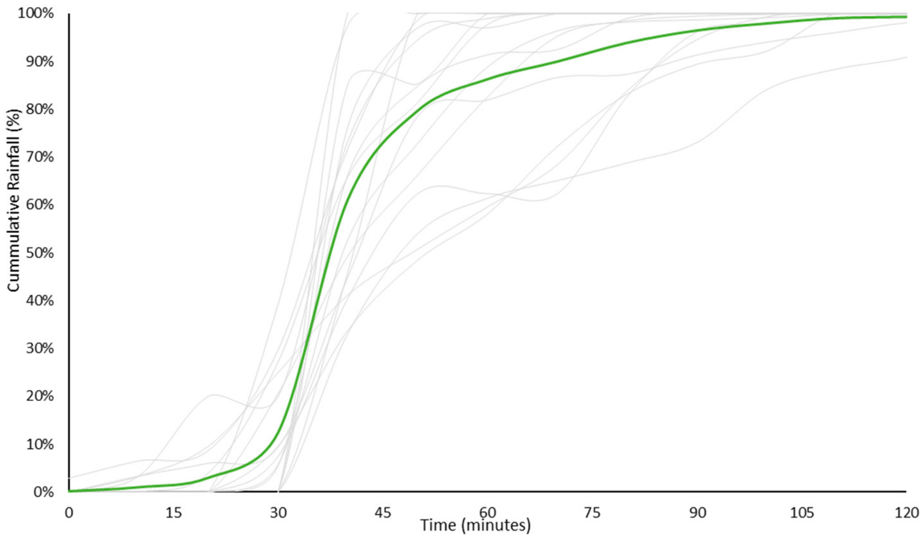


Figure 4 Cumulative rainfall curve. Rainfall pattern in the area of study

Based on this characteristic rainfall, we elaborated hyetographs associated to return periods of 2, 5, 10, 20 and 50 years using the alternating block method (Figure 5). Three levels of rainfall intensity were defined from these hyetographs as follows:

- Low precipitation: precipitation associated with a return period of two years.

- Medium precipitation: associated with a five year return period.
- High precipitation: associated with a return period of 10 years.

These precipitation intensity levels are the ones that were used for the simulation in the erosion cells.

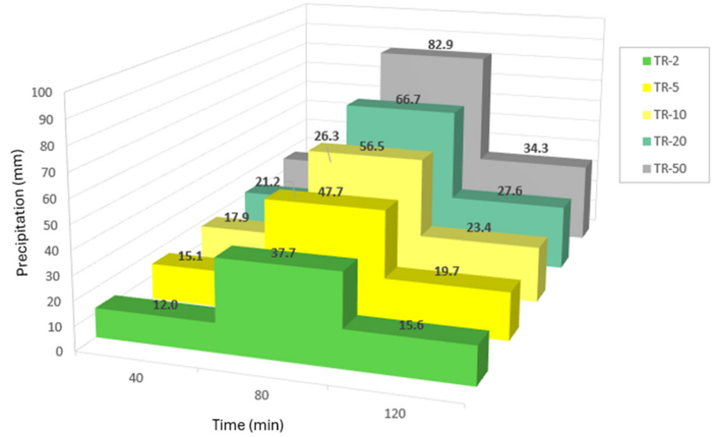
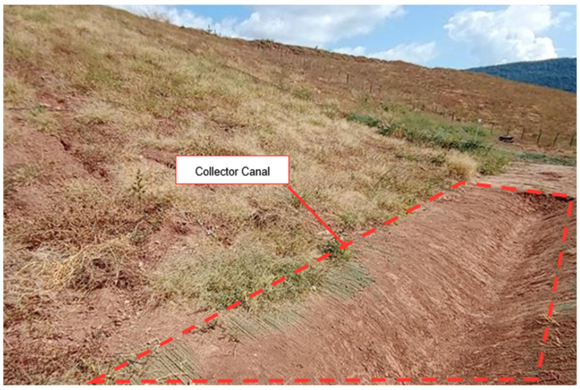


Figure 5 Rainfall simulation hyetographs

4.3 Erosion plot configuration at site

The instrumented erosion plots were the fundamental element of the project developed at the coal mine. Sediment measurements, simulation of rainfall of different intensities and collection of samples for laboratory tests (e.g. granulometry, total suspended solids [TSS]) were carried out in these plots. For the case study, which has been used as a frame of reference for future modelling, it was decided that the variable to be analysed would be the degree of vegetation cover of the same type of tree species, in view of which erosion plots of similar dimensions were constructed with different 'degrees' or levels of revegetation on slopes with the same characteristics in terms of inclination, surface soil, plowing method and planting technique. For the case study presented, the quantification of sediment production and run-off production rates was carried out in three experimental plots of approximately 1,200 m^2 of area (60 × 20 m) with similar edaphic and geomorphological characteristics, subjected to different cover densities of the same type of plant species. The conformation of these plots was carried out by the mine owner under the guidance of WSP professionals. Figure 6 shows the general layout of this cell. It should be noted that the tests were carried out on plots 2, 3 and 4.



(a) (b)

Figure 6 Implemented erosion plots. (a) Plots defined for conducting tests; (b) Collector canal

The characteristics of these plots are presented in Table 2.

Table 2 Erosion plot characteristics

Characteristic	Plot no. 2	Plot no. 3	Plot no. 4
Slope inclination	15%	15%	15%
Particle size distribution of top soil	Sand: 17–27% Silt and clay: 73–83%	Sand: 16–23% Silt and clay: 75–84%	Sand: 14–28% Silt and clay: 72–84%
D50	0.014–0.024 mm	0.013–0.027 mm	0.013–0.025 mm
Type of vegetation	Grass (Graminea)	Grass (Graminea)	Grass (Graminea)
% cover	40%	0%	80%
Gullies presence	No	Yes (10 cm depth)	No

4.4 Erosion cells configuration at site

The erosion cells were configured in a 6.0 × 9.0 m arrangement in which six spray nozzles were placed in the centre of a 3.0 × 3.0 m quadrant. Finally, due to time constraints and conditions in the mine, it was decided to install only one erosion cell in each plot, for which concrete bases were constructed to support a scaffold-type metal structure.

Over the area occupied by the erosion cell to be installed, barriers made of wooden planks and ditches were implemented. The planks prevent the migration of sediment material in or out of the erosion cell, while the ditch located at the upper level of the cell prevents run-off generated by natural rainfall from entering the erosion cell area. Finally, a lower ditch was formed to capture the volumes of run-off and sediments. These details are shown in Figure 7.

It was decided that the structure for the rainfall simulation system should be made up of scaffold-type metal supports to facilitate its installation and uninstallation. These scaffolds form quadrants of 3.0 × 3.0 m over each erosion cell for a total of six quadrants. The assembly of the metal supports is shown in Figure 8, while Figure 9 presents a typical erosion cell.

(a) (b)

Figure 7 Details of the erosion cell. (a) Bottom ditch of the erosion cell; (b) Wooden barriers

Figure 8 Installation of the scaffolding that forms the structure of the simulation system

Figure 9 Typical view of an erosion cell

Finally, for the temporary storage and sampling of the run-off generated in the erosion cells, sampling tanks were used that allowed for the quantification of the run-off volume and served to take water samples for conducting TSS tests.

4.5 Monitoring and sampling at site

Prior to the launch of the rainfall simulator and the monitoring, the following activities were carried out:

- Visual verification of the uniformity of precipitation over the cell area with the help of manometers to check the working pressures in the spray nozzles.
- The working pressures in the sprinklers in the three parallel spray lines were verified to be equal and the lower lines were corrected by partially closing the valves.
- It was verified that the PVC discharge pipes have a positive slope from start to finish. Additionally, the sampling tanks are properly levelled.
- The rain gauges were placed at an average height of 0.8 m above the ground surface which was not too low to prevent sediment from entering the equipment and not too high to monitor the precipitation pattern over the ground.

The development of the activities was carried out over 23 days during which a total of 27 rainfall simulation tests were conducted (nine in each cell). Each test lasted two hours (120 minutes), with shifts of 40 minutes. The simulated rainfall patterns had to correspond to the synthetic hyetograph defined in the rain characterisation stage. In Figure 10, an example of the low-intensity precipitation record for the localised erosion cell in plot no. 2 is presented.

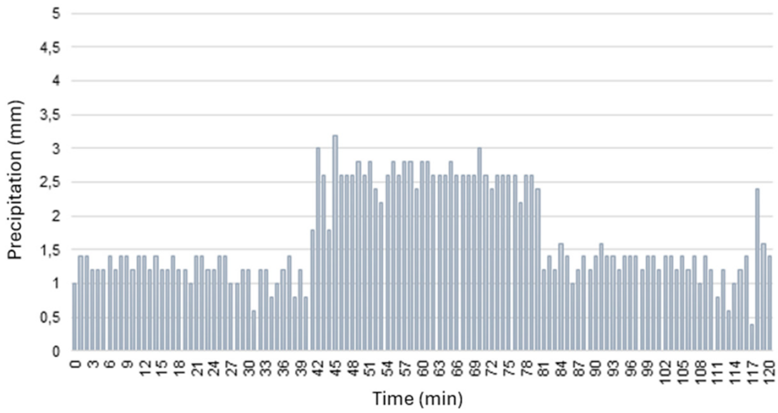


Figure 10 Example of precipitation record. Low-intensity precipitation in the erosion cell of plot no. 2

Based on the operating flow rates, the rainfall simulator system, and the reach angle of each spray nozzle, the precipitation intensities generated in the tests were calculated (Figure 11). These intensities correspond to return periods of 10, 20, and 50 years.

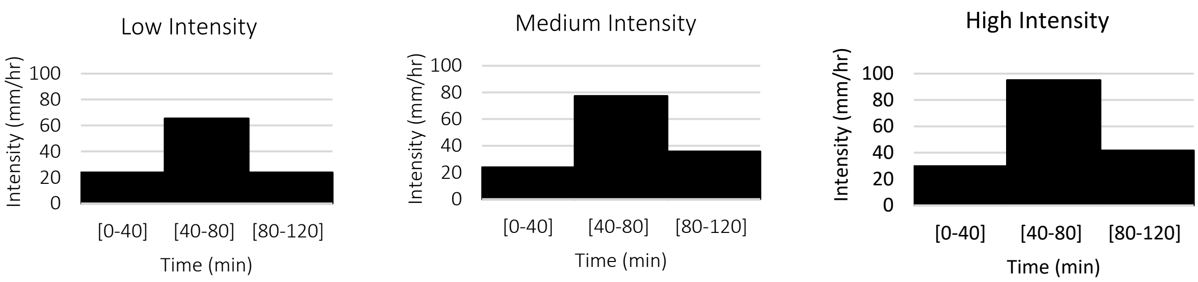


Figure 11 Precipitation intensities effectively used in the tests

After each test, water samples were taken from the IBC tanks to conduct TSS tests, the results of which were the basis for estimating the erosion rates in each cell. Similarly, samples of sediments transported by erosion were taken to conduct granulometric tests.

Regarding the record of natural rains and their erosion capacity, during the work, there were three events, none of which were strong enough to generate a run-off flow in the excess weir that would allow determining a run-off flow. In two of these events, it was possible to collect sediments deposited in the channel, however, these data were discarded since it was not possible to determine the hydrological characteristics of these rains.

5 Results

Results and calculations that allowed the definition of erosion rates exclusively from the rain simulation tests are presented since, although the initial objective of the study aimed to measure rates both in cells and in erosion plots, the intensity of natural rains during this pilot was not sufficient to allow the determination of run-off rates. In this context, Figure 12 presents the results of the TSS tests conducted in each of the tests carried out in the erosion cells of each plot. It should be noted that the three TSS values in each test correspond to each modelled rainfall intensity level (low, medium, and high), as indicated in Figure 11.

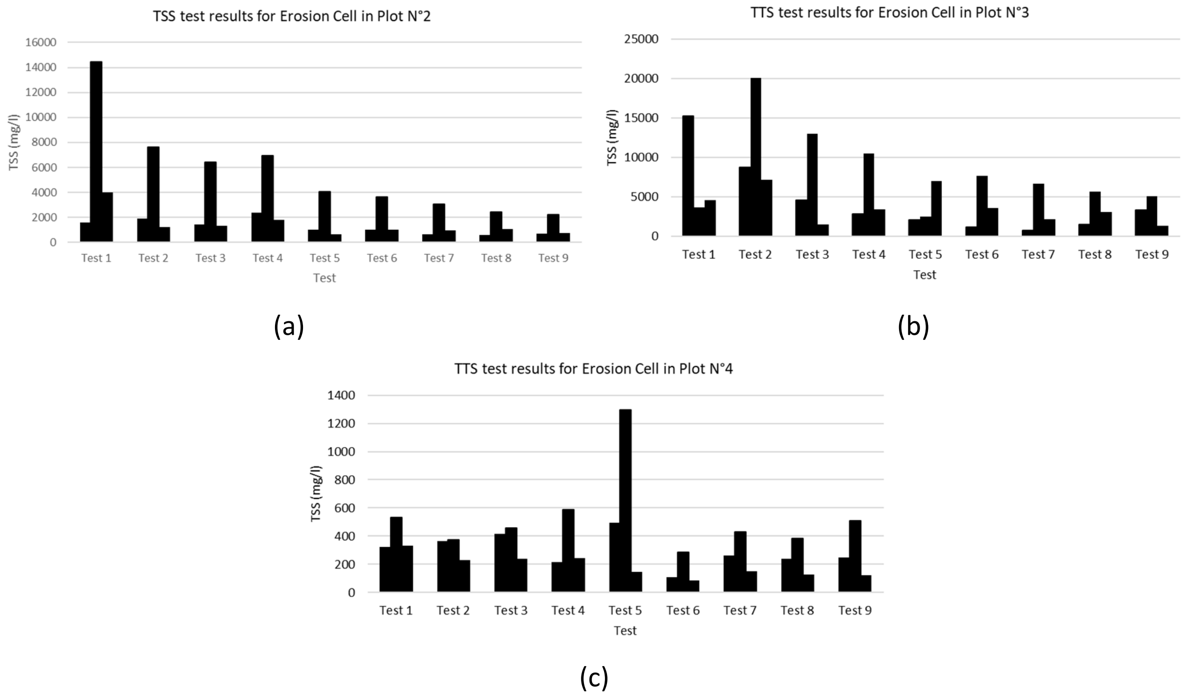


Figure 12 Results of laboratory tests on solid concentration. (a) Erosion cell in plot no. 2; (b) Erosion cell in plot no. 3; (c) Erosion cell in plot no. 4

In these results of TSS, some values do not match the pattern of all the samples, which were not considered in the erosion analysis. Such is the case of test 1 of the erosion cell in plot no. 2, which yielded TSS values far above those of tests 2 and 3, which were conducted at the same precipitation intensity. Presumably, this is due to the greater availability of material to be transported by run-off and the lack of natural rainfall in the study area in the weeks prior to the execution of the tests. Another example is provided by tests 1 and 5 of the erosion cell in plot no. 3, which show values that do not meet the expected pattern, such that a much higher TSS is obtained in the last rain pattern, when the storm is subsiding.

5.1 Calculation of erosion rates

Based on these TSS measurements and other known parameters such as cell area, precipitation intensities or sheets, and estimated run-off coefficients, a sediment production volume was obtained and subsequently the erosion rate per unit area (tonne/ha), using the following equations:

$$S = \frac{Q_{op} \times V_{sed}\ SST \times C_e \times t_e \times 60}{1.000.000} \tag{1}$$

$$T = \frac{S}{10A} \tag{2}$$

where:

S = sediments production (kg)

Q_{op} = operative flow for the interval (L/s)

V_{sed} TSS = total suspended solids (mg/l)

C_e = run-off coefficient for the time interval

t_e = time interval (40 min)

T = erosion rate (tonne/ha)

A = erosion cell area (m^2).

Of the aforementioned parameters, it is worth highlighting the run-off coefficient (C_e), which represents the volume of surface run-off in relation to the total volume of precipitation (Aparicio 1992). The value of this index depends on rainfall factors such as duration, intensity, and precipitation pattern, as well as the characteristics of the land surface, such as slope, soil, infiltration capacity, and evapotranspiration. This parameter was calculated based on the ratio of run-off volume to rainfall volume (generated by the rainfall simulator).

$$Ce = \frac{V_{ed}}{V_{ll}} \tag{3}$$

where:

V_{ed} = run-off volume for the time interval

V_{ll} = rainfall volume for the time interval.

The results obtained from erosion rates in each cell and the run-off coefficients C_e are presented in Figures 13 and 14.

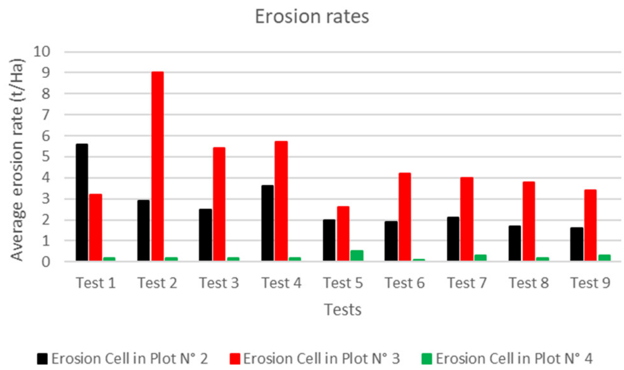


Figure 13 Erosion rates for each conducted test

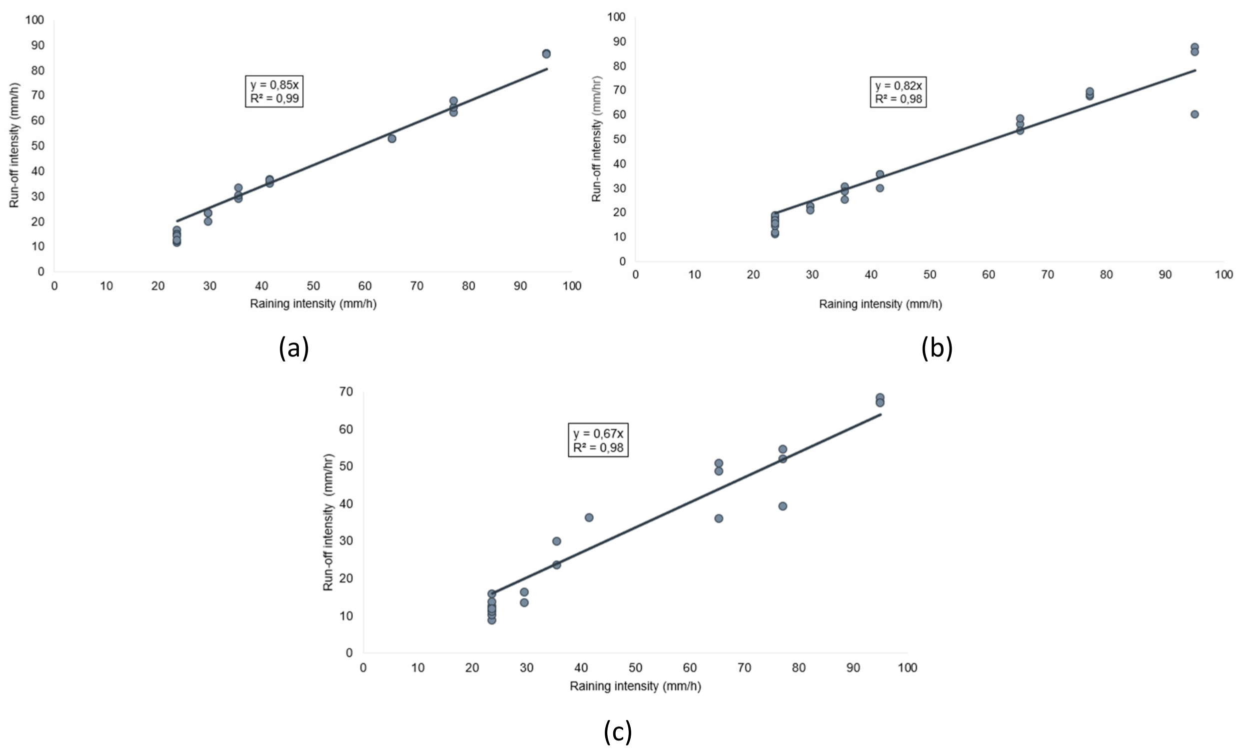


Figure 14 Run-off coefficients: (a) Erosion cell in plot no. 2; (b) Erosion cell in plot no. 3; (c) Erosion cell in plot no. 4

The results indicate that the raindrops falling on the soil surface are dissipated thanks to the presence of vegetation, as long as it is well-developed and has leaves, which promotes water retention through infiltration and increases energy dissipation

Based on the results of erosion rates, an average was estimated for each precipitation intensity (low, medium, and high) for each plot, with the results indicated in Table 3.

Table 3 Average erosion rates for each rain intensity

Erosion cell	Rain intensity	Average erosion rate (tonne/Ha)
Plot no. 2	Low	2.7
	Medium	2.5
	High	1.8
Plot no. 3	Low	4.3
	Medium	4.9
	High	3.8
Plot no. 4	Low	0.2
	Medium	0.3
	High	0.3

In general terms, the results for erosion cell in plots 1 and 3 were as expected, therefore the greater the rainfall intensity, the greater the amount of sediment. However, this did not occur with the erosion cell in plot no. 2 which seems to go against logic. Nevertheless, this result could be explained by:

- Intense initial erosion and depletion of loose material: in successive erosion events, it is possible that most of the susceptible soil is lost in the first events. As simulations or natural rainfall are repeated, the availability of loose particles on the surface decreases, which in theory would reduce the magnitude of erosion.
- Initial soil moisture conditions: if high-intensity rainfall occurred when the soil was already saturated by previous events, the increase in run-off may be immediate but without further infiltration or action on the soil structure, which reduces the potential for erosion. In the specific case of plot no. 2, the time between each test may have been insufficient.

As mentioned above, the tests carried out are only an initial phase of what is intended to be carried out with this erosion plot methodology. In this regard, in the short-term, the results obtained will be used to calibrate a land evolution model that will allow evaluation of landforms with and without erosion control measures related to vegetation. In the medium term, the mine owner plans to conduct further tests to evaluate other variables such as vegetation type, plowing methods, and water and sediment management structures, which could lead to more efficient and economically viable closure measures.

6 Conclusion

WSP's recent experience in the implementation of the erosion cell methodology at the most important coal mine in Colombia and South America has been detailed. These types of tests are the first to be developed in Colombia and aim to obtain data through in situ measurements that will allow for the optimisation of rehabilitation measures already implemented in the mine or new alternatives that are to be evaluated.

The most important contribution of this work lies in the development of a step-by-step methodological process for conducting this type of test, which can be easily reproduced by the mine owner. This will allow them in the future to conduct the tests at different moments of the year and, above all, to consider different variables to optimise their closing measures.

The installation of instrumented plots makes it possible to measure soil loss under site conditions, allowing comparison of different management practices and identification of which ones are most effective in terms of surface stability. This information could be especially useful in the early stages of closure, where critical aspects are defined, such as:

- geomorphological configurations (slopes, berms)
- the type and sequence of soil treatments
- optimal vegetation cover per land unit.

Having this data would reduce the use of general assumptions or extrapolations, adjusting closure designs to the actual conditions of each functional unit (i.e. waste dumps, open pits) of the landscape to be rehabilitated.

Likewise, the results obtained can be used in small-scale hydrological models, which would improve the estimation of expected maximum flows, reduce the risk of localised erosion, and could facilitate informed decision-making in the design of hydraulic management and sediment control structures.

In terms of the final landform design, it is expected that further testing will enable technical recommendations to be made on aspects like maximum permissible slopes or the orientation of furrows, so that the rehabilitated landscape promotes infiltration, minimises concentrated run-off, and contributes to the long-term stability of the system. Regarding the specific finding, based on the methodology described here, it was possible to take measurements in three erosion plots and simulate rainfall in the same number of erosion cells, where, based on the characterisation of the area's rainfall, the conditions for different return periods were successfully represented.

Due to the time of year when the tests were conducted, it was not possible to obtain representative results of the effects that natural rain exerts on the different conditions of vegetation cover density analysed. However, as mentioned earlier, the activities carried out already have a methodological process to follow, which will allow new tests to be conducted when the client deems it appropriate.

Average run-off coefficients were estimated for the three plots. It is concluded that the run-off coefficient is higher with an increase in precipitation intensity and that plot no. 4 has a lower coefficient compared to the other two plots. It is important to mention that when comparing the values obtained for the uncovered plot versus the plot with 40% coverage, similar run-off coefficients were obtained, which may be due to the weighting method or the characteristics of the eroded soil.

The analyses indicated that to reduce the erosion rate, it is not necessary to have fully developed coverage; however, it is relevant to consider that as vegetation grows faster, better results will be obtained, decreasing the probability of gully formation during the wet season. In this sense, it is considered that tests on areas that have been vegetated for a long time will provide an indicator of the long-term efficiency of these measures and the need to propose additional measures to ensure performance until the final closure of the mine.

Acknowledgement

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