MODELING OF WATERSHED EROSION AND SEDIMENT RETENTION IN MINING ACTIVITY

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ABSTRACT

In Peru, mining has been constantly developed until becoming one of the most important economic activities. Thus, a hydrology topic to develop, when the extractive operations end, is the soil erosion on basins or catchments where the mine has influence. The importance of this article is based on preserving natural ecosystems to maintain water quality of rivers or water courses, and promoting the mining activity as one of the primary activities. In determining the quantity of dregs (sediments), the Modified Universal Soil Loss Equation (MUSLE) will be used, published by United States Department of Agriculture (USDA) in 1997.

The main goal of this paper is to compare the initial and final scenarios; using tools like Geographic Information System (GIS) and sediment models, with the objective of measuring the impact of mining activity on soil erosion and sediment production in a specific gorge. Moreover, the dreg model will allow to design and calculate the retention structures of the basin in analysis.

Keywords: Sediment retention, mining activity, soil erosion, MUSLE.

INTRODUCTION

Soil erosion is a natural phenomenon caused by wind and/or water effects. However; different anthropic activities such as housing construction, felling and, to a large extent, formal and informal mining have accelerated this process by degrading the soil's characteristics to the degree of turning it into an environmental and social issue. High losses of vegetation cover, high levels of sedimentation in stream channels and greater concentration of suspended solids have resulted in the decrease of livestock population, the extinction of river species and the decrease of water quality which in turn affects human consumption as well as its irrigation activities, among others.

In mining, measures for sediment control are currently applied by installing ponds and/or reservoirs during the operation phase that mitigate the sediment discharge to the natural stream channels. In this way; during the closure plan of mining units, it is common to observe the encapsulation of retained sediment in the ponds when these are completely full; this procedure is done by placing a topsoil layer to reduce the erosion rates during the rest of the useful life of the pond.

In this article, the results of erosion modeling through the SEDCAD 4 program (Schwab, Warner & Marshall 2000) are mentioned. This program was specially designed for the calculation of sediment yield, structure design and remediation as contingency measures during the handling of these sediments evaluated for the components of a mining unit that is currently in its initial operation phase. Firstly, two scenarios will be analyzed: operating with final projected components and during closing, through the remediation of such components according to the mine closure plan.

Among the available models, the Universal Soil Loss Equation (USLE), the revised version of this last one (RUSLE) and its modified version (MUSLE) are used in hydrology and environmental engineering to calculate the quantity of potential erosion of soil and sediment yield (Mishra et al. 2006). The formulation used by SEDCAD, and implemented in the multiplication of rasters done with the SIG tool, is based on MUSLE equation. This equation replaces the rainfall factor, which is very uncertain in its determination by USLE equation, with the runoff factor. For this, the sediment yield is estimated on a single storm basis in the outlet of the element (watershed or component) based on the runoff characteristics (peak flow and volumes). It should be emphasized that the MUSLE is a friendly method for applying; however, it needs the experience of the modeler, which is very important for the factor estimation.

EQUATIONS

The modified universal soil loss equation or EUPSM OR MUSLE (Williams and Berndt, 1977) is given by the following formula:

$$Y = 11.8(Q * q_p)^{0.56}.K.L.S.C.P \qquad (1)$$

Where:

Y = Sediments yield of the watershed for a design storm (ton/ha)
Q = Medium runoff volume (m^3)
q_p = Maximum runoff flow (m^3/s)
K = Soil erodibility (t ha hr MJ^{-1} mm^{-1} ha^{-1})
L = Slope length (dimensionless)
S = Slope grade (dimensionless)
C = Vegetation cover (dimensionless)
P = Mechanical practices of erosion control (dimensionless)

GENERAL CONDITIONS

The mining unit located in the northern highlands of the country is currently in its initial operation phase. The components of this unit are at the headwater of 3 watersheds, named watershed 1, 2 and 3, which were ordered by its magnitude in area, shown in Figure 1. According to the physiographic analysis, the shape factor indicates that watersheds 1 and 2 present a moderate runoff response, while watershed 3 has a response that varies from moderate to slow.

The rainfall characterization let us know the pattern of design storms in the mining unit, analyzing extreme hydrological events related to different return periods for the sediment volume estimation. The extreme hydrological events have been analyzed based on the record of extreme rainfalls in local and regional stations in the field of the mining unit. The data series of maximum rainfalls in 24 hours was adjusted to diverse probabilistic models (Normal, Log Normal, Pearson III, Log Pearson III and GEV I) that are based on the diverse statistical indicators and hydrological criteria; for the analysis, the GEV I distribution was selected to give criteria uniformity and to present the best indicators in most of the analyzed cases. Table 1 shows the series of maximum rainfalls in 24 hours, feature for the study area.

Table 1 Maximum daily rainfall – Mining Unit

Return period	Maximum daily rainfall (mm)
2	38,4
5	47,0
10	51,9
25	58,0
50	62,4

Regarding the sedimentology, watershed 1 presents soils with poorly graded gravels and sands, whose vegetation cover is in most of the watershed due to the little establishment of mining components in it. On the other hand, the watershed 2 presents little vegetation cover because most of the projected mining components are located here. Finally, the watershed 3 presents soil surface layers with gravels, sands and clays. Since there are no measures of peak concentrations of sediments for storm events, it was performed the simulation of concentrations that would occur in the analyzed ravines for current and projected conditions. Specifically, the parameter of great influence corresponds to the Eroded Particle Size Distribution (EPSDs), which is usually determined with the laboratory tests using a rainfall simulator. For land characteristics of undisturbed hillslopes with the presence of mining components, it is available the eroded particle size distribution EPSD (source: MYSRL) that is shown in Table 2.

Table 2 Eroded Particle Size Distributions (1)

Particle size (mm)	Top layer (%)	Haul road (%)	Crest of dumps (%)
9,525	100,0	100,0	100,0
4,75	98,6	97,7	99,1
2,36	82,7	77,5	86,7
2	79,6	75,0	84,0
0,85	67,0	68,2	72,8
0,6	63,2	66,5	69,6
0,425	60,0	64,6	67,0
0,15	52,0	55,7	60,9
0,075	46,5	47,3	55,7
0,04	40,3	39,4	48,6
0,02	31,9	31,4	37,4
0,015	27,8	28,6	31,8
0,01	21,8	24,9	23,6
0,005	11,2	18,1	10,6
0,002	0,3	0,8	3,0
0,0015	0,2	0,4	1,5

Table 2 Eroded Particle Size Distributions (2)

Particle size (mm)	Slope of dumps (%)	Inadequate stacking (%)	General disturbance (%)
9,525	100,0	100,0	100,0
4,75	98,3	99,1	98,0
2,36	78,7	87,4	78,1
2	75,0	85,0	75,0

0,85	59,6	74,6	64,1
0,6	54,7	71,3	60,9
0,425	50,4	68,4	58,0
0,15	40,6	60,6	49,0
0,075	36,2	54,5	42,6
0,04	33,3	47,3	36,8
0,02	30,9	37,0	30,7
0,015	29,8	32,0	28,2
0,01	27,7	24,5	24,7
0,005	21,5	11,3	17,6
0,002	2,1	1,0	0,5
0,0015	1,0	0,5	0,25

METHODOLOGY

The modeling of the hydrological response and sediment yield of analyzed watersheds was performed using the SEDCAD 4 model for both conditions: operation and closure.

To estimate the hydrologic response, the model uses the method of unit hydrograph which is representative to determine fast, moderate and slow responses that are associated with dense, medium and poor vegetation covers, respectively. To determine the peak flows and the forms of the response hydrographs, the model determines the time of concentration of each watershed and sub-watershed based on the topographic information that allows estimating slopes and representative average lengths of the flow path from the source up to the outlet of each analyzed watershed.

To simulate the sedimentological response, the model uses the Revised Universal Soil Loss Equation (MUSLE), which will allow us to estimate the peak concentrations and the total amounts of sediment to be obtained at the outlet of each micro-watershed or component according to the parameters of soil erodibility (K), representative slope length (L), representative slope (S), type of soil cover (C) and type of control practice and slope (P), said factor represents the relation between the erosion produced without any conservationist practice P=1, and the erosion produced with conservationist practices.

Figure 1 shows the analyzed mining components divided by contributing hillslopes simulating a gradient; the values for sediment calculations are assigned for each contributing area, the same that have been adopted with information from specialized technical literature.

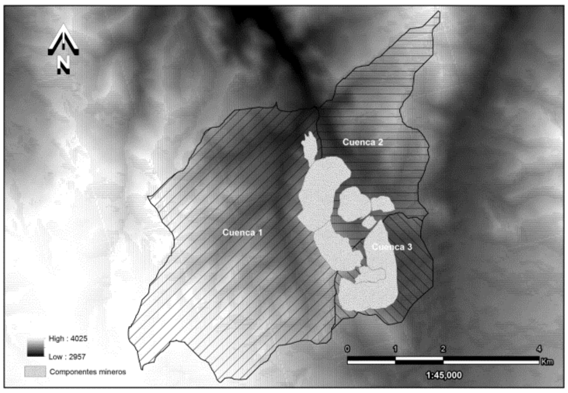

Fig. 1 Watersheds, mining components and contributing zones.

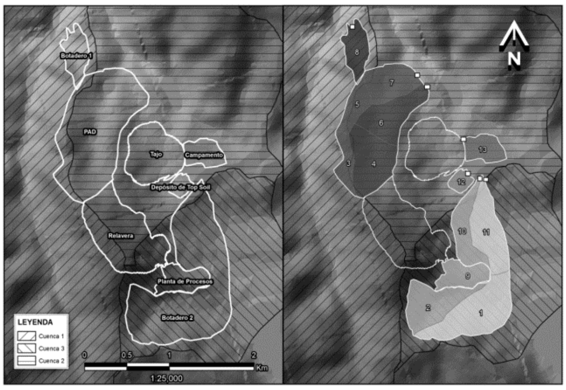

Fig. 2 Mining components and contributing zones for analysis.

In Tables 3 and 4, the values used for each one of the representative zones in the conditions of operation and closure are summarized.

Table 3 Hydrological and Sedimentological Factors – Final operation condition

Production Zone of sediments	Sedimentology				
	K	S (%)	L (pies)	C	P
Undisturbed hillslides	0,45	8	250	0,01	1
Slope of dumps	0,524	60	90	0,26	0,7
Construction of Heap Leach Pad	0,477	8	300	0,8	0,7
Access and Haul Roads	0,412	7	400	0,9	0,7
Topsoil Dump	0,46	60	90	0,1	0,7

Table 4 Hydrological and Sedimentological Factors – Reclamation condition

Production Zone of sediments	Sedimentology				
	K	S (%)	L (pies)	C	P
Topsoil Dump	0,45	(1)	(1)	0,013	1

(1) Depends on the component

Considering the type of vegetation is from aligned crops following the level curves and for a good hydrological condition, a value of 69 for NC was determined; for C factor, considering grass with cover at 80%, a value of 0,013 was determined; and considering that in the future will not exist conservationist practices, 1 was assigned for P value; furthermore, it was determined the respective values of the slope and length (S and L) that depend on each component.

RESULTS

Considering the current and projected mining infrastructure conditions, it was done the modeling for a storm event of 10 years of return period. The analyses consider the peak flows of entry to the control structures and the outlet of the same, as it is shown in Figure 4 and Table 5. Also, for the remediated condition (only with cover modification) lower peak concentrations are obtained (see Table 6).

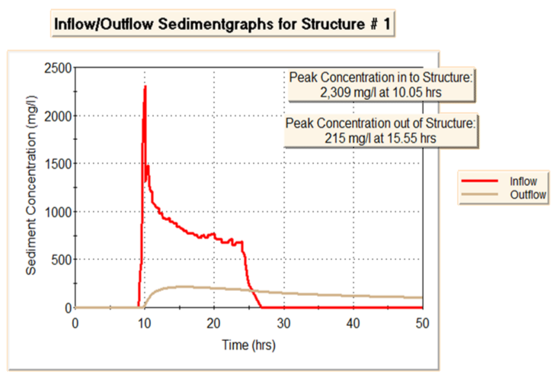

Fig. 3 Representive scheme of SEDCAD results

The results obtained by adding all the components are the following:

- The concentration of total sediment produced in the operation phase is 1 327 932 mg/l.

- Considering contingency measures in the operation phase of mining components, the concentration is 104 794 mg/l, which indicates a reduction of up to 92% with respect to the total concentration without contingencies.

- Considering the implementation of remediation measures, concentration is reduced to 14 949 mg/l, which represents a reduction of up to 99% with respect to the total concentration without remediation.

It should be noted that contingency measures are related to good management practices, which involves the design and construction of a suitable system of surface water management and ponds. Also, remediation measures for closure consider revegetation of all disturbed zones with the planting of native species of the natural grassland itself, such as: Choccho, K'achu pasto, IruIchu and Llama Ichu. In Table 7 and Figure 5 the results of modeling are presented.

Table 5 Hydrological and Sedimentological Factors – Final operation condition

Zone	Accumulated area for component (ha)	Sediments (mg/l)	Sediments (ml/l)
Watershed1			
8	15,2	356206,0	209,0
		11995,0	0,0
Watershed 2			
12	5,6	253226,0	73,2
		1111,0	0,0
13	11,1	186608,0	111,8
		18378,0	0,4
4-6	59,7	102270,0	49,6
		17139,0	0,7
3-5-7	45,6	151759,0	81,9
		24665,0	1,9
Watershed 3			
1-11	74,3	205525,0	120,6
		20724,0	0,0
2-9-10	64,8	72338,0	42,8
		10782,0	0,4

Table 6 Concentration of sediment (mg/l) - Reclamation condition

Zone	Accumulated area for component (ha)	Sediments (mg/l)	Sediments (ml/l)
Watershed 1			
8	15,2	1436,0	0,6
		6,0	0,0
Watershed 2			
12	5,6	823,0	0,5
		1,0	0,0
13	11,1	4624,0	2,9
		72,0	0,0
4-6	59,7	1409,0	0,7
		220,0	0,0
3-5-7	45,6	1688,0	0,9
		146,0	0,0
Watershed 3			
1-11	74,3	2563,0	1,6
		300,0	0,1
2-9-10	64,8	2406,0	1,5
		253,0	0,0

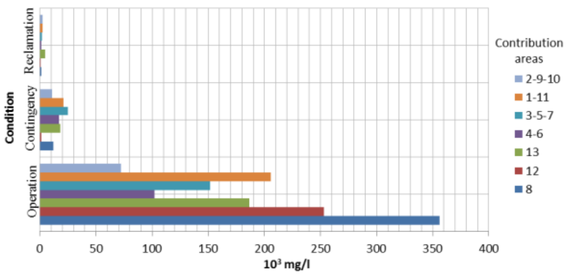

Fig. 4 Concentration (10^3 mg/l) of total sediments produced according to contributing area system for all conditions.

Table 7 Eroded Particle Distribution

Condition	Yield sediments		
	(mg/l)	(kg/m3)	(lb/pie3)
Operation Phase	1 327 932	1 327	83
Contingency measures during operation phase	104 794	104	7
Reclamation condition for closing	14 949	15	1

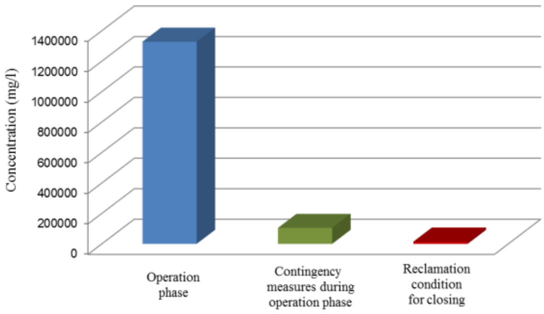

Fig. 5 Concentration (mg/l) of total sediments produced for all conditions.

CONCLUSIONS

- The MUSLE methodology, using SED CAD software, is suitable for sediment yield modeling.
- By implementing good management practices related to design and construction of a proper surface drainage system and ponds, the sediment yield reduces 92% in the operation phase and 99% in the remediation phase.
- The analyzed factors are mainly focus on the design for remediation structures, which significantly reduce the amount of sediment produced in the watersheds compared to those observed in the operation phase.

RECOMENDATIONS

- It is recommended to take soil samples for the evaluation of grading and the determination of K factor for each component.
- It should be implemented automatic stations for flow measuring and turbidity caused by sediments that allow recording continuously the discharges.
- The sediment ponds of great peak attenuation capacity of sediment concentrations in the outlet of the analyzed components will allow reducing the sediment yield; therefore, it is recommended its construction.

ACKNOWLEDGEMENTS

Thanks to Anddes Asociados Company that from its beginnings has promoted research and continuous improvement in its procedures.

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