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Evaluating the Sediment Yield and Environmental Impact in Mining Expansion Scenarios in Sta. Cruz – Candelaria, Zambales

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Abstract

The study addressed the environmental concerns arising from industrial activities, such as mining, by focusing on the Candelaria-Santa Cruz region. Nickel mining in the region has raised issues related to water quality and sedimentation patterns. Employing the Modified Universal Soil Loss Equation (MUSLE) model, sediment yield computations were conducted, with consideration on factors like bare soil coverage, slope characteristics, and precipitation rates. The results emphasize the need for sustainable land management practices to mitigate adverse effects. The research covers a 10,000-ha area, simulating overburden removal scenarios ranging from 100 ha to 5,847.78 ha, and assesses sediment yield implications under different precipitation rates. The study also determines optimal relative growth rates and plant cover densities for progressive rehabilitation, highlighting the potential for effective erosion control. The findings underscore the significant impact of mining on sediment yield and water quality, prompting the call for comprehensive monitoring, calibration, and validation of the MUSLE model to guide informed decision-making and promote sustainable practices in the region. This research highlights the crucial role of integrated approaches in understanding and mitigating the consequences of resource exploitation on the environment and local communities.

Keywords: Nickel Mining, Modified Universal Soil Loss Equation, sediment yield, sustainable land management practices, water quality and soil erosion.

INTRODUCTION

The exploitation of natural resources, driven by industrial activities like mining, often raises concerns about environmental degradation and its consequential effects on ecosystems and communities (Maus et al., 2020; Ramli et al., 2020; Nearing et al., 2017; Yellishettya et al., 2013; Dissanayake & Rupasinghe, 1996). Moreover, there have been a call for a more holistic approach to representing the extractive sectors' land use impacts in scales that are measurable and easy to understand (Maus et al., 2020). In this context, the nickel mining operations in the Candelaria-Santa Cruz region have come under scrutiny due to reported changes in water quality and sedimentation patterns in major rivers and pristine water bodies. This analysis aims to unravel the intricate relationship between nickel mining, sediment yield, and water quality in this area, shedding light on the potential impacts of mining activities on the local environment. By employing the Modified Universal Soil Loss Equation (MUSLE) model, sediment yield computations are carried out, taking into account factors such as bare soil coverage, slope characteristics, and precipitation rates. The results offer a quantitative basis to assess the implications of these mining activities on water bodies and highlight the pressing need for sustainable land management practices to mitigate their adverse effects.

Candelaria is nestled at the foot of the Zambales Mountains in the east and lies along coastline of the South China Sea in the west, with a total land area of 33,359 hectares (82,430 acres), making it the third-largest town in terms of land area in Zambales. It constitutes about 9.19% of Zambales's total area. This municipality is known for Uacon Lake, the cleanest lake in Central Luzon, and for its numerous beach resorts. The monthly precipitations vary; ranging from above 400mm, and at times 150mm in most wet months and below 30mm in most dry months. The Municipality of Sta. Cruz has a total land area of 41,404.00 ha. Considering the natural topography of Sta. Cruz which is hilly and mountainous, the Sta. Cruz –

Candelaria Mining Project will greatly affect the slopes and natural topography of the area. The process of mining activities will remove vegetative cover to extract mineral ore.

This research aims to assess the sediment yield and environmental implications of potential mining expansion by the Zambales Diversified Metals Corporation (ZDMC) in the context of Mineral Production Sharing Agreement (MPSA) No. 191-2004-III. The research objectives are presented numerically and the sediment yield values are calculated. The Modified Universal Soil Loss Equation or MUSLE model's constant values for poorly managed soils and steep slopes were considered based on ocular and data from diverse research sources; the typical of the locality and as documented from the Soils/Land Resources Evaluation Project, 1988 from the Department of Agriculture, Bureau of Soil & Water Management Manila. The precipitation values are from Meteoblue (2023) and the Weather and Climate PH, (2023). The Modified Universal Soil Loss Equation MUSLE (Williams, 1975; Shi et al., 2022; Berteni et al., 2021; Sadeghi et al., 2014); is employed to estimate total sediment yield in the study area which has features of a watershed. The equation's components are detailed, and the dimensions of constants are explained. This includes rainfall-runoff erosivity, soil erodibility, slope length and steepness, cover and management, support practice, and erosion control practice factors. Through computation and modeling tool, the total sediment yield is generated for a seven-scenario model, accounting for various factors such as precipitation, slope, soil types, and land use. The scenarios represent areas that have been excavated over the considered hydrologic response unit area of 10,000ha constrained as considerable unit leading to a diverse catchment area with watersheds characteristics and features through the defined climatic, hydrologic responses, reliefs, ecological similarities and geologic origin. Hence, the 10,000-ha utilized in this research cuts across the municipality of Candelaria and Santa Cruz, Zambales, Philippines. The modeled overburden removal ranges from 100 ha, 500 ha, 1,000 ha, 3,765.39 ha, 3,847.78 ha, 4,847.78 ha, and 5,847.78 ha as evident from the satellite images and simulated using MUSLE model. The visualizations are generated through line plots, violin plots, heat map and box plots to illustrate the relationship between sediment yield values and the areas mined and the ones to be mined in the future. Python code snippets are used during the computation using the model variables and then create the plots, aiding in understanding the trends and variations among the scenarios.

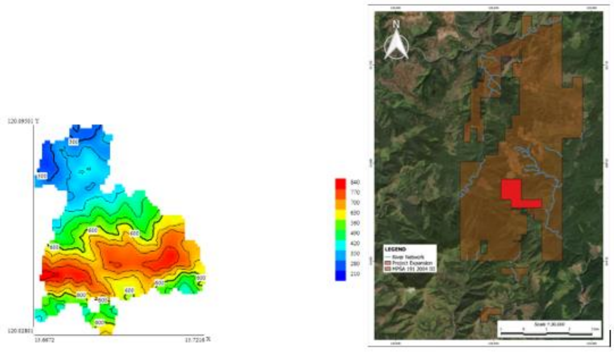

Figure 1
The Topographic Map and the Geospatial Information System (GIS) Satellite Map with the delineated study area located within Candelaria-Santa Cruz Zambales, Philippines

Figure 2
The Cross-section Profile of the entire study area from The Google Earth Pro 2023

In this study, the proponents determined the appropriate relative growth rate and plant cover density for the progressive rehabilitation program to mitigate soil erosion and reduce sediment yield from cleared areas using Hunt, (1996) plant's relative growth rate model, we needed to find the optimal combination that promotes effective vegetation establishment. The goal is to strike a balance between fast growth and sufficient plant cover. Hence, we assumed that the higher the relative growth rate and the denser the plant cover, the more effective the erosion control and as such (Zhan et al., 2015) position on the role of re-vegetation in controlling soil erosion proposed. We then proceeded to calculate the sediment yield reduction for different combinations of relative growth rates and plant cover densities and then plot the results.

METHODOLOGY

The analysis adopts a comprehensive approach to assess the intricate interplay between mining activities, sediment yield, and water quality. The Modified Universal Soil Loss Equation (MUSLE) model serves as the foundation for calculating sediment yield, integrating variables such as soil erodibility, slope characteristics, and land cover management. Precipitation rates and their intensity are factored in to estimate runoff volume and peak flow rates, critical components in sediment mobilization. For each probable single rain event, sediment yield is computed and expressed in tons per event. The MUSLE model provides a systematic framework to quantify soil erosion and sediment yield in response to various factors, including land use changes, slope characteristics, precipitation, and management practices. QGIS was utilized for the spatial modeling of the coordinates and the MPSA area as well as to generate the total watershed coverage area. This approach is simplified in (Mitasova et al., 2013) for the research that are geared towards soil erosion and land use management. Coupling this approach with the employment of the MUSLE model, stakeholders and decision-makers can gain insights into the potential impacts of mining on soil erosion and water quality, enabling them to make informed choices about mitigation strategies and sustainable land management practices.

Average Slope in the coverage area is 50%, the soil types are silt, clay and loam, with moderate organic content and moderate gravel particles; Department of Agriculture; Bureau of Soil and water Management, Manila. (1988).

The Slope Length Steepness Factor is derived from;

$$LS = (1+0.06 \cdot L0.065+0.045 \cdot L) \cdot (1+0.06 \cdot S0.065+0.045 \cdot S)$$

Where:
L is the slope length in meters (m).
S is the slope steepness, expressed as a decimal.

The equations runoff_volume = (precipitation_rate / 1000) * coverage and peak_flow_rate = runoff_volume / 3600 are used to estimate the runoff volume and peak flow rate, respectively, based on the given precipitation rate and coverage area.

runoff_volume = (precipitation_rate / 1000) * coverage:

Precipitation rate is given in millimeters (mm) and represents the amount of rainfall falling on a specific area.

To convert the precipitation rate to cubic meters (m^3) per area (in hectares), the rate is divided by 1000 (to convert mm to meters) and then multiplied by the coverage area (in hectares).

This calculation estimates the total volume of water that runs off the surface due to the given rainfall.

peak_flow_rate = runoff_volume / 3600:

Runoff volume, obtained from the previous equation, is the total volume of water that runs off the surface.

To calculate the peak flow rate, which represents the maximum rate at which water flows during a rainfall event, the runoff volume is divided by the time (in seconds).

Dividing by 3600 converts the time from seconds to hours, providing the flow rate in cubic meters per second (m^3/s).

The Modified Universal Soil Loss Equation (MUSLE) with all the variables:

$$S = 11.8 \cdot (Q \cdot qp)0.56//A \cdot (K \cdot LS \cdot C \cdot P)$$

Where:
S is the sediment yield (ton/probable single rain event).

Q is the runoff volume (m^3) during a single rain event.

qp is the peak flow rate (m^3/s) during a single rain event.

A is the catchment area (ha).

K is the soil erodibility (t h t $(^1)$ m $(^1)$ cm $(^1)$).

LS is the slope length steepness factor (dimensionless).

C is the crop management factor (dimensionless).

P is the soil erosion control practice factor (dimensionless).

These equations are essential in the MUSLE model for estimating sediment yield, as they determine the amount of water and the rate at which it flows over the land surface, contributing to soil erosion and sediment transport. The calculations account for the role of precipitation and the coverage area in influencing runoff and flow rates, which in turn influence the erosion potential and sediment yield within the watershed.

A range of scenarios involving varying bare soil coverage, precipitation rates, and slope characteristics are simulated as recommended in the work of (Laflen & Flanagan, 2013; Maus et al., 2020; Anache et al., 2015). The findings are depicted through line plots, heat maps, and box plots, providing a visual representation of sediment yield trends across different scenarios. The implications of these trends on surface water quality and ecosystem health are discussed, considering the potential consequences of mining expansion and the exacerbation of sedimentation under changing climate conditions. In response to potential expansion, the study contemplates a rehabilitation program for the mined-out areas proposed by the proponent firm; employing tree seedlings with varying growth rates. The research computes the necessary plant growth rate to achieve full coverage and mitigate sediment erosion and yield, considering each scenario's parameters.

RESULTS

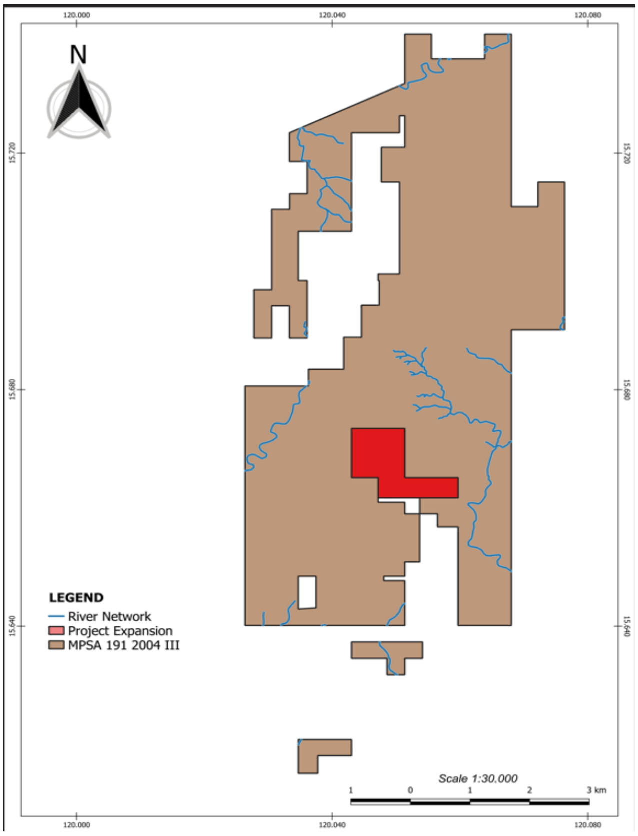

Figure 3
The Study Area
**Red Area indicates the proposed expansion area*

Data Presentation and Discussion on the Sediment Yield Assessment of Nickel Mining Activities and the Implications for Water Quality and Ecosystem Health. Following the methodology, the comprehensive analysis of the obtained data from the computations of the sediment yield using the MUSLE model and its subsequent visual representation through various plots (Figure 4) provided a clear picture of the potential impacts of nickel mining activities in the Candelaria-Santa Cruz area. The research has illuminated how varying factors such as bare soil coverage, precipitation rates obtained from Weather and Climate PH (2023) and slope characteristics contribute to sediment yield, quantified in tons per probable single rain event over the approx. 189.54 days in a year for the locality.

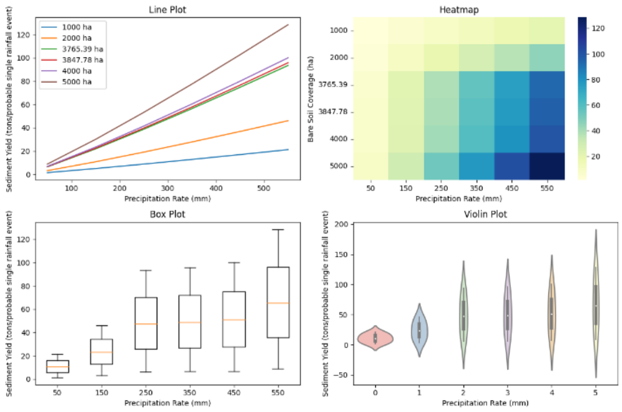

Figure 4

The multiple plots; highlighting the values of the sediment yield in tons against the 189.45 days wet months or single raining season (annual precipitation rate) and the mine-out areas and the projected areas within the study. The precipitation rate on the violin plot indicates the possibilities of high of sediment yield spread over the numerical values of 1 to 5 representing the increasing annual rainfall values from 50 to 550mm model projections and simulation.

The findings vividly demonstrate the alarming sediment yield values under certain scenarios, especially in the cases where larger areas are cleared for mining and where higher precipitation rates are considered. For instance, the plots clearly highlight that the sediment yield becomes notably elevated as the mining area is expected to expand from 3765.39 ha to 3847.78 ha – a shift that can be considered substantial. The numerical values, such as sediment yield reaching values exceeding 100 tons for the less than 200 days of raining, provide convincing evidence that such activities have the potential to lead into a significant sediment deposition and erosion, adversely affecting the quality of surface water. With the wet month precipitation rate exceeding 150mm to as high as 550mm during high intensity rainfall event, high discharge and peak flow rate within the 189.54 raining days estimated for the locality, the sediment yield becomes notably elevated as the mining area is expected to expand from 3765.39 ha to 3847.78 ha, the runoff volume would yield 2070.965 m3, and the peak flow rate amounting to 0.575 m3/s while from the conservative precipitation rate of 50mm to 150mm, the runoff volume would be 564.8085 m-3 and the peak flow rate 0.157 m3/s leading to a higher sediment yields from 55 tons/single rainfall event for the year to 75tons for the year causing massive increment in siltation along the catchment areas' network channels over the coverage area of 10,000 ha as seen in Figure 4 above.

These findings have profound implications for the environment and the local communities. The observed red and orange coloration of major rivers during high-intensity rainfall periods is directly correlated with the excessive sediment yield from the mining activities. The detrimental effects are not confined solely to water bodies but might have led to the extension of degradation to natural landmarks such as the Uacon Lake, which has undergone a visible decline in its aesthetic appeal due to increased sedimentation. More also, incremental contaminated soil and siltation from high slope area might pose a host of threats to farmlands as demonstrated in (Remli et al., 2020; Nearing et al., 2017). The expansion plans, especially when coupled with the unpredictable weather patterns arising from climate change and predicted annual rainfall increases, are likely to exacerbate the problem. The intensified weather variability, characterized by more intense and frequent rainfall events, can amplify sediment mobilization and transport, further worsening the condition of water bodies and exacerbating the loss of water quality.

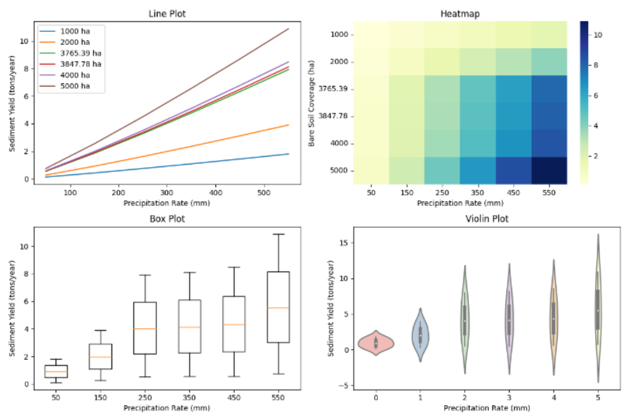

Figure 5

The multiple plots; highlighting the values of the sediment yield in tons with low peak flow or runoff rate and low discharge volume against the 189.45 days wet months or single raining season (annual precipitation rate) over the mine-out areas and the projected areas within the study area. The precipitation rate on the violin plot indicates the possibilities of a lower sediment yield spread over the numerical values of 1 to 5 representing the increasing *annual rainfall values from 50 to 550mm model projections and simulation.*

On the event that the peak runoff and the volume of discharge is maintained over the 10,000 ha at the precipitation rate of 150 mm or less, the expected runoff volume would be 564.809 m3 and the peak flow rate maintained as 0.157 m3/s as seen in the figure 5 over the year.

Implications on Turbidity

1. *Increased Sediment Input.* The expansion of mining areas leads to higher sediment yield, increasing sediment input into the rivers downstream, which raises turbidity levels.

2. *Reduced Water Clarity.* Higher sediment load results in reduced water clarity, as suspended sediment particles scatter and absorb light, making the water appear cloudy.

3. *Impact on Aquatic Life.* Elevated turbidity can affect aquatic ecosystems by hindering photosynthesis, reducing oxygen availability, and disrupting habitats.

4. *Water Quality Degradation.* High turbidity levels often correlate with poor water quality, as turbid water can carry pollutants and pathogens, further compromising the ecosystem.

5. *Impaired Ecosystem Function.* Increased turbidity affects the functioning of aquatic ecosystems by disrupting food chains, altering sediment deposition patterns, and modifying habitat availability.

The contour plot generated from the sediment yield reduction calculations provides valuable insights into the relationship between relative growth rate and plant cover density in mitigating soil erosion and reducing sediment yield from cleared areas.

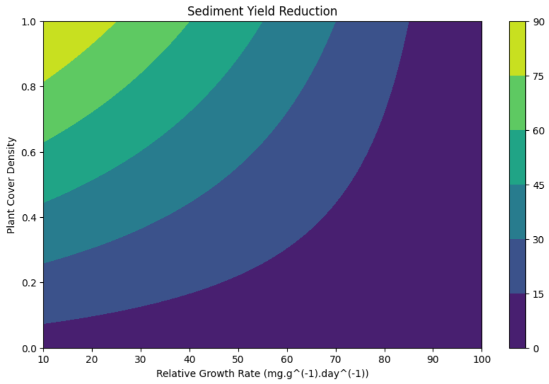

Figure 6
Contour plot generated from the sediment yield reduction calculations showing the relationship between relative growth rate and plant cover density in mitigating soil erosion and reducing sediment yield from cleared areas.

The plot above (Figure 6) shows that higher sediment yield reductions are achieved when the relative growth rate is closer to the upper end of the range 100 mg.g-1.day-1and when the plant cover density is higher (close to 1, representing dense vegetation cover). The darkest regions in the plot indicate the combinations that offer the highest reduction in sediment yield. The optimum planting growth rate can be determined by identifying the point where the sediment yield reduction is maximized. Numerically, the optimum growth rate would be around 100 mg.g-1.day-1, and the plant cover density would be around 1. These values lead to the greatest reduction in sediment yield from cleared areas. In real-life scenarios, achieving a planting growth rate of 100 mg.g-1.day-1 might be challenging, as it represents extremely fast growth. The feasibility of such a high growth rate depends on various factors, including plant species, soil quality, climate conditions, and available resources for nurturing plant growth. ZDMC would need to assess whether such growth rates are achievable through careful selection of appropriate plant species, adequate soil preparation, irrigation, and nutrient management.

DISCUSSION

To support the revegetation of excavated areas and proper soil management in the region, utilizing locally sourced biochar can be beneficial. Biochar, a stable form of carbon produced through pyrolysis of organic materials, can enhance soil structure, water-holding capacity, and nutrient retention, ultimately aiding in soil restoration. Incorporating biochar into soil management practices can improve the physical and chemical properties of soil, promoting plant growth and biodiversity. To effectively implement this strategy, collaboration between mining companies, local communities, and relevant authorities is crucial. Funding and resources can be allocated towards research and development of biochar production methods tailored to the region's waste materials. Additionally, capacity-building programs can educate local communities on the benefits of biochar and encourage its utilization in revegetation efforts.

Conclusion. The research provides compelling evidence that nickel mining activities, particularly when expanding into forested areas with high slopes and considering prevailing climate change trends, are strongly linked to elevated sediment yields and water quality degradation. The implications of these findings underscore the importance of well-informed and data-driven land use planning, environmental management practices, stringent erosion control measures, and sustainable land use planning to mitigate the adverse impacts on the catchment area, water bodies, and the broader ecosystem. It's crucial to consider both the immediate and long-term repercussions of such activities to ensure the preservation of valuable natural resources and the well-being of local communities.

Recommendation. To ensure the reliability of the MUSLE model in monitoring soil and water management practices in Santa Cruz and Candelaria and even to expand this model to cater for the land/soil and water management in the neighboring municipalities, a comprehensive approach to calibration and validation is necessary. The model should be calibrated using field data collected from representative sites within the region for general adoption for the locality and beyond. Local factors such as soil types, land cover, and slope characteristics should be resampled and documented to for future research prospects. Calibration can be achieved by comparing model predictions with observed sediment yield measurements over a defined period. Validation involves applying the calibrated model to independent datasets to assess its predictive accuracy. Continuous monitoring of soil erosion and sediment yield at various mining sites will provide data for ongoing model refinement and validation. Collaboration among researchers, environmental agencies, and mining companies is vital to ensure access to data and to facilitate knowledge exchange. Ultimately, a well-supported, calibrated, and validated MUSLE model can serve as a powerful tool for evaluating the effectiveness of soil and water management practices, guiding informed decision-making, and promoting sustainable mining practices in the region.

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