

Modeling of Land Clearing and Reclamation for Mining Area of Nickel

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Abstract

Land clearing and reclamation in the mining process impact the environmental sustainability. Therefore, understanding the dynamics of land clearing and reclamation is very important. In applying the model to planning land clearing and reclamation of mining areas, there is a threshold for the area to be explored and reclaimed. The simulation process was carried out using data from PT. Manusela Prima Mining regarding the land clearing and reclamation plan for Nickel land in Maluku for 2022-2029. As a result, the logistic equation is suitable for land clearing and exploration planning. We analyze positivity and boundedness of the system. In addition, the study analyzed environmentally realistic equilibrium states by applying the eigenvalues criterion, which is mathematically proven to be locally asymptotically stable. The equilibrium region shows stability for various parameters, including scenarios with no action taken for reclamation and scenarios where two actions coexist in a sustainable manner. Numerical simulations reveal that fighting power significantly converts exploration efforts. This conversion leads to reclamation growth. Our research uses a modified logistic model. It also explores thresholds for environmental sustainability.

Keywords: boundedness, equilibrium states, land clearing, model, positivity, reclamation, simulation, stability

1. INTRODUCTION

Land clearing and reclamation processes are a major topic in environmental, mathematical, and mining research. Mathematical modeling provides preliminary knowledge of complex environmental events. Land clearing and reclamation mechanisms in the response process are easy to find in the mining area [1]-[3]. The imbalance between exploration and reclamation will have an impact on environmental damage. This of course disrupts ecological processes. A maintained environmental balance will have an impact on life in a sustainable manner [1]-[4]. Meanwhile, frequently encountered facts show that the exploration process carried out in several mining areas ignores environmental sustainability factors. It is certain that this will manifest in environmental damage in an indeterminate time interval. Thus, the survival of peoples and various species around the mining area is disrupted due to the environmental damage in

question [5]-[9].

Another factor considered in the preparation of mathematical models of mining dynamics is the reclamation behavior carried out internally by the company. Part of the excavated material from mining can be reused for the reclamation process of former mining areas. This behavior naturally arises and helps the existence of an environment that has been damaged by the mining process. However, the mining and reclamation process must be planned very well so that it does not cause fatal environmental losses. Overlooked this issue has become one of the essential problem that can encourage conflict among miner groups and local communities. This action was driven by a sense of justice regarding the social and environmental impacts that arise as a result of mining activities [3] [4][9]-[12]. The large ratio between land clearing and reclamation processes, which continues to experience the effects of environmental degradation with a declining quality, makes social battles unavoidable [13][14]. It's realistic to assume that exploitation is rare when modeling land clearing and reclamation dynamics. This study will primarily focus on determining the impact of land clearing and reclamation. This paper examines the impact of fluctuating land clearing and reclamation on two mining model variables. The model realistically includes these two variables, which significantly affect mining. Mathematically, various problems can be modeled in a system of differential equations, for example: ecology [15]-[18],

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Table 1. Description of variable and parameter of model Eq. 1.

Variable/Parameters	Description	Units
L	Land clearing of mining area	ha
R	Reclamation of mining area	ha
α_1	Rate of land clearing process	Year ⁻¹
α_2	Rate of reclamation process	Year ⁻¹
A	Carrying capacity	Ha
m	The impact of the number of resources	ha
ω	The minimum reclamation rate	Year ⁻¹
ω^*	The maximum reclamation rate	Year ⁻¹

Table 2. Parameter value of model Eq. 1.

Parameters	Values	Sources
α_1	1.0975	[12]
α_2	1.0975	[12]
A	8.78	[12]
m	0.50	Assumed
ω	0.10	Assumed
ω^*	1.09	Assumed

epidemiology [19][20], eco-epidemiology [21], and others [22]-[27]. Applying a mathematical modeling approach to study the behavior of land clearing and reclamation in mining areas is relatively very interesting. This dynamic can be realized through a system of differential equations [28]-[30]. Each process is divided into two compartments and its behavior is analyzed. Furthermore, the analysis results will be confirmed by the numerical simulation process.

2. MATERIALS AND METHODS

2.1. Model Formulation

In this section, we provide a detailed explanation of the model formulation. We discuss positivity, boundedness, equilibrium states, and stability analysis of the model by presenting the following assumptions (Eq. 1).

$$\begin{cases} \frac{dL}{dt} = \alpha_1 L \left(1 - \frac{L}{A}\right) - \left(\omega + (\omega_* - \omega) \frac{m}{m+L}\right) L, \\ \frac{dR}{dt} = \alpha_2 R \left(1 - \frac{R}{\left(\omega + (\omega_* - \omega) \frac{m}{m+L}\right) L}\right), \end{cases} \quad (1)$$

where $L \equiv L(t)$ and $R \equiv R(t)$ are respectively the processes of land clearing and reclamation at time t . The following assumptions are taken in deriving model (Eq. 1). (A-1) The land clearing process in mining area is assumed to be logistically with constant intrinsic rate $\alpha_1 > 0$ and constant carrying capacity $A > 0$. (A-2) For the sustainable of ecosystem in mining area, the reclamation process is assumed to be logistically with constant intrinsic rate $\alpha_2 > 0$. (A-3) The material of nickel exploration turn into reclamation with the minimum rate $\omega > 0$ and maximum rate $\omega_* > 0$. (A-4) The reclamation process carried out in former mining areas is influenced by the availability of resources at a rate $m > 0$.

Description of variable and parameter shown in Table 1 and the parameter values shown in Table 2. The system can be expressed in the following equations 2 and 3.

$$\frac{dL}{dt} = L \left(\alpha_1 - \frac{\alpha_1 L}{A} - \left(\omega + (\omega_* - \omega) \frac{m}{m+L} \right) \right) = Lf^{(1)}(L), \quad (2)$$

$$\frac{dR}{dt} = R \left(\alpha_2 - \frac{\alpha_2 R}{\left(\omega + (\omega_* - \omega) \frac{m}{m+L} \right) L} \right) = Rf^{(2)}(L,R), \quad (3)$$

with initial condition of Eq. 4.

$$L(0) = L_0 > 0, R(0) = R_0 > 0, \tag{4}$$

where $f^{(1)}(L) = \alpha_1 - \frac{\alpha_1 L}{A} - \left(\omega + (\omega_* - \omega) \frac{m}{m+L}\right)$ and $f^{(2)}(R) = \alpha_2 - \frac{\alpha_2 R}{\left(\omega + (\omega_* - \omega) \frac{m}{m+L}\right)L}$. Next, $\alpha_1, \alpha_2, A, \omega$ are all positive. System (Eq. 1) is defined on the set below.

$$\Omega = \{(L, R) \in \mathbb{R}^2 | L \geq 0, R \geq 0\}$$

In the following we prove the positivity and boundedness of solutions of system Eq. 1. Note that to prove the boundedness of the system Eq. 1, we use the following results [17]:

Lemma 1.

If $\alpha, \beta > 0$ and $\frac{dM}{dt} \leq (\geq) M(t)(\alpha - \beta M(t))$ with $M(0) > 0$, then

$$\lim_{t \rightarrow +\infty} \sup M(t) \leq \frac{\alpha}{\beta} \left(\lim_{t \rightarrow +\infty} \inf M(t) \geq \frac{\alpha}{\beta} \right)$$

Lemma 2.

If $\alpha, \beta > 0$ and with $M(0) > 0$, then for all $t \geq 0$

$$M(t) \leq \frac{\alpha}{\beta - K e^{-\alpha t}}, \text{ where } K = \beta - \frac{\alpha}{M(0)}.$$

In particular $M(t) \leq \max\left(M(0), \frac{\alpha}{\beta}\right)$ for all $t \geq 0$.

2.2. Positivity and Boundedness

Theorem 1.

All solutions $(L(t), R(t))$ of the system (Eq. 1) with the initial conditions (Eq. 4) are positive, i.e., $L(t) > 0, R(t) > 0$, for all $t \geq 0$.

Proof.

From the land clearing equation of system (Eq. 1), it can be concluded that the invariant set is $L = 0$. This further suggests that $L(t) > 0$, for all t if $L(0) > 0$. A similar reasoning using the reclamation equation of the system (Eq. 1) reveals that $R = 0$ is also an invariant set, implying $R(t) > 0$, for all t if $R(0) > 0$. Therefore, any trajectory originating in \mathbb{R}^2_+ is unable to intersect the coordinate axes, leading to the theorem's conclusion.

Theorem 2.

All solutions $(L(t), R(t))$ of the system (Eq. 1) with the initial conditions (Eq. 4) are bounded, for all $t \geq 0$.

Proof.

Using the positivity of variables L, R from (Eq. 1), we can write

$$\frac{dL}{dt} = L \left(\alpha_1 - \frac{\alpha_1 L}{A} - \left(\omega + (\omega_* - \omega) \frac{m}{m+L}\right) \right) \leq L(\alpha_1 - \beta_1 L), \text{ where } \beta_1 = \frac{\alpha_1}{A}.$$

From Lemma 2, we have

$$L(t) = \max\left\{L(0), \frac{\alpha_1}{\beta_1}\right\} \equiv B_1 \text{ for all } t \geq 0.$$

Further, from (Eq. 1) we have

$$\frac{dR}{dt} = R \left(\alpha_2 - \frac{\alpha_2 R}{\left(\omega + (\omega_* - \omega) \frac{m}{m+L}\right)L} \right) \leq R(\alpha_2 - \beta_2 R)$$

where $\alpha_* = \left(\omega + (\omega_* - \omega) \frac{m}{m+B_1}\right) B_1$ and $\beta_2 = \frac{\alpha_2}{\left(\omega + (\omega_* - \omega) \frac{m}{m+B_1}\right) B_1}$.

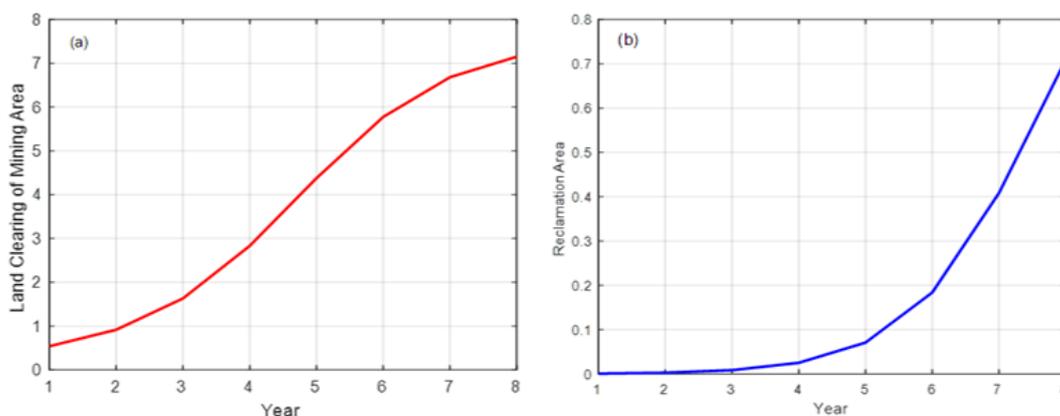


Figure 1. Behaviour of system (Eq. 1) as time series of (a) land clearing area and (b) reclamation area.

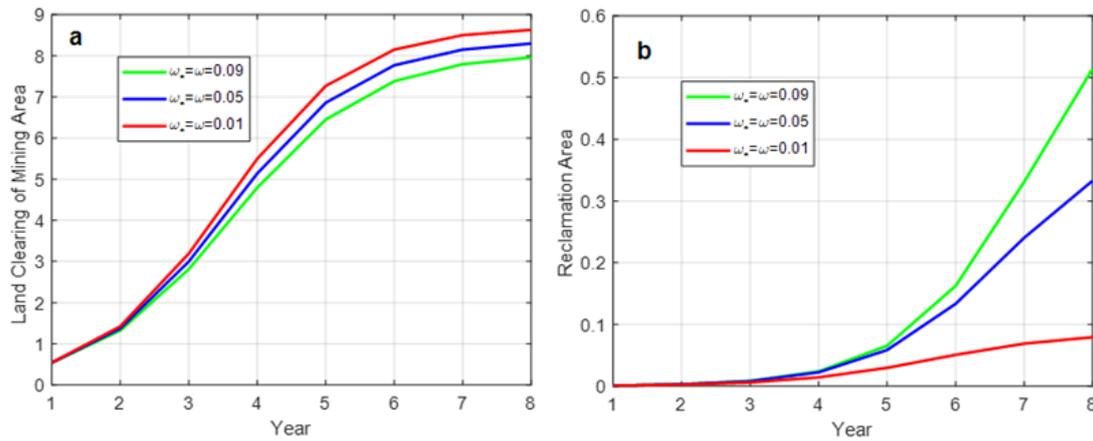


Figure 2. Behaviour of system (Eq. 1) with the various of $\omega^* = \omega$ as time series of (a) land clearing area and (b) reclamation area.

Again from the same Lemma 2 we have

$$R(t) = \max\left\{R(0), \frac{\alpha_*}{\beta_2}\right\} \equiv B_2 \text{ for all } t \geq 0.$$

This completes the proof of the boundedness of solutions and hence the system under consideration is dissipative.

2.3. Stability of Equilibrium Points

By setting the right-hand side of model Eq. 1 equal to zero, we get two equilibrium models. The no reclamation equilibrium state $S_I = (L_I, 0)$, where the value of L_I is the roots of the quadratic equation

$$e_1(L_1)^2 + e_2(L_1) + e_3 = 0,$$

with

$$\begin{aligned} e_0 &= \alpha_1, \\ e_1 &= m\alpha_1 + A\omega - A\alpha_1, \\ e_2 &= Am(\omega_* - \alpha_1) \end{aligned}$$

If $D = e_1^2 - 4e_0e_2 = 0$ and $e_1 > 0$ or $D > 0$ and $e_2 < 0$, there is a coexistence equilibrium while if $D > 0$, $e_1 < 0$, and $e_2 > 0$ there are two coexistence equilibrium states.

The interior equilibrium state $S^* = (L^*, R^*)$, where $L^* = L_I$ and the value of $R^* = \frac{1}{\alpha_1(m + L^*)} [A\beta_1 L^* (\alpha_1 - \omega) + Am\beta_1 (\alpha_1 - \omega_*) + m\alpha_1 L^* (\omega_* - \omega)]$.

Thus, S^* will exist whenever condition $\omega < \omega_* < \alpha_1$ holds. This is because the process of sustainable environmental conservation requires

maximum reclamation in former exploration area. The existence of the point $S^* = (L^*, R^*)$ indicates that the land clearing process runs simultaneously with the reclamation process. This aims to preserve the environment. In addition, the negative impacts of nickel mining land clearing can be reduced.

2.4. Stability of Equilibrium Points

As the description shows, fulfilling the conditions implies the existence of all two equilibrium states. The theorem below describes the local stability of each equilibrium state within the system.

Theorem 3.

For system Eq. 1, we have the following stability properties of its equilibrium states: The equilibrium state S_I is always unstable and the interior state S^* is locally asymptotically stable if $b_1 < 0$ and $b_2 < 0$.

Proof.

The local stability of all equilibrium states can be studied from the linearization of the system (Eq. 1). The Jacobian matrix of the system Eq. 1 at the state (L, R) is given by Equation 5.

$$J = \begin{pmatrix} \alpha_1 - \frac{2\alpha_1 L}{A} - \omega - \frac{(\omega_* - \omega)m}{(m + L)^2} & 0 \\ -\frac{\alpha^2 R^2 \omega (m + L)}{\left(\omega + \frac{(\omega_* - \omega)m}{m + L}\right)^2} & \alpha_2 - \frac{2\alpha_2 R}{\omega + \frac{(\omega_* - \omega)m}{m + L}} \end{pmatrix} \quad (5)$$

By observing the eigenvalues of the Jacobian matrix (Eq. 5) at each equilibrium point, we have the following stability properties. The Jacobian

matrix of the system Eq. 1 at S_1 has eigenvalues $\lambda_1 = \alpha_2$ and $\lambda_2 = \alpha_1$ where $a_1 = \alpha_1 - \frac{2\alpha_1 L_1}{A} - \omega - \frac{(\omega_* - \omega)m}{(m + L_1)^2}$. Consequently $\lambda_1 > 0$ and S_1 is always unstable. The Jacobian matrix of the system Eq. 1 at S_* has eigenvalues $\lambda_1 = b_1$ and $\lambda_2 = b_2$, where $b_1 = \alpha_1 - \left(\omega + \frac{2\alpha_1 L_1}{A} + \frac{(\omega_* - \omega)m}{(m + L_1)^2}\right)$ and $b_2 = \alpha_2 - \frac{2\alpha_2 R_c}{\omega + \frac{(\omega_* - \omega)m}{m + L_1}}$. If $b_1 < 0$ and $b_2 < 0$ then the values of $\lambda_{1,2}$ are negative. Consequently S_* is locally asymptotically stable.

3. RESULTS AND DISCUSSIONS

The analysis results from the previous section are supported by this numerical simulation. Dynamical mining will undergo comparison under different parameter settings. Using parameter values from Table 2 and initial values from (Eq. 4), we solved the model with the Runge-Kutta Fourth-Order method by using the MATLAB. We get point $S_1 = (7.0876189; 0)$ exists but unstable, where $\lambda_1 = -0.786973290 < 0$ and $\lambda_2 = 1.0975000 > 0$. Simultaneously, we get interior point $S_* = (7.0876189; 1.49936902)$ also exists and locally asymptotically stable, where $\lambda_1 = -1.09750000 < 0$ and $\lambda_2 = -0.78697329 < 0$. This case is illustrated in Figures 1(a) and 1(b).

3.1. Behaviour of The System Eq. 1 for $\omega_* = \omega$

Different dynamics arise when we choose the maximum value of reclamation equal to the minimum value. Using the parameters in Table 2 and initial values (Eq. 4), except for $\omega_* = \omega$, we choose $\omega_* = \omega = 0.001; 0.005; 0.09$. Figures 2(a) and 2(b) show the effect of increasing the value of

$\omega_* = \omega$. In these simulation, increasing the value of $\omega_* = \omega$ does not have a significant impact on the wider reclamation area compared to $\omega_* \neq \omega$.

3.2. Behaviour of the System (Eq. 1) for various of ω_*

Additionally, we simulate the effect of parameter ω_* , related to maximum effort to reclamation. Using the parameters in Table 2 and initial values in Eq. 4, except for ω_* , we choose $\omega_* = 0.2; 0.6; 1.01$. Figures 3(a) and 3(b) show the effect of increasing the value of ω_* . In these simulation, increasing the value of ω_* has an impact on the larger area being reclaimed. This shows that the higher the value of ω_* , the wider the mine excavation area that is reclaimed.

3.3. Behaviour of the System (Eq. 1) for various of m

Next, we simulate the effect of parameter m , related to resource availability issue, which describes the probability rate of materials mining materials converted into reclamation materials. Using the parameters in Table 2 and initial values in Eq. 4, except for m , we choose $m = 0.5; 0.7; 0.9$. Figures 4(a) and 4(b) show the effect of increasing the value of m . In these simulation, increasing the value of m has an impact on the larger area being reclaimed. This indicates that the higher the value of m has a significant impact on the reclamation process in the mining area.

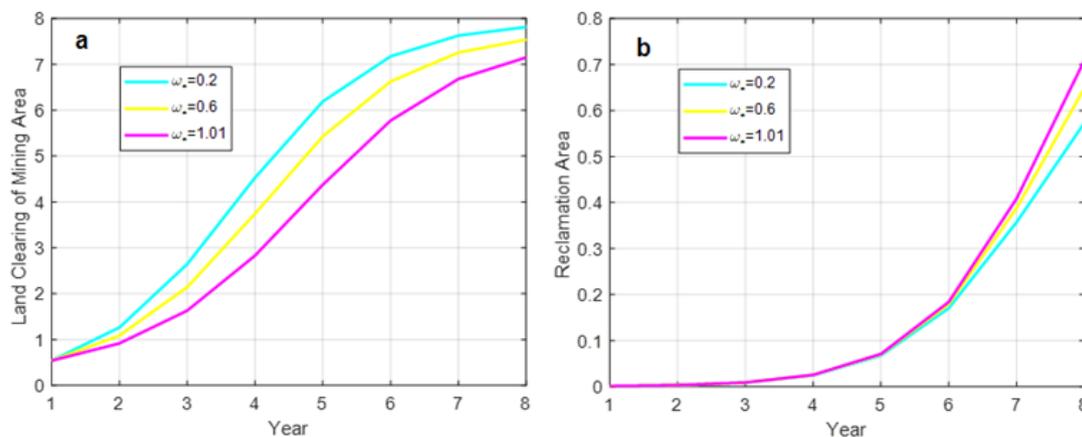


Figure 3. Behaviour of system Eq. 1 with the various of ω_* as time series of (a) land clearing area and (b) reclamation area.

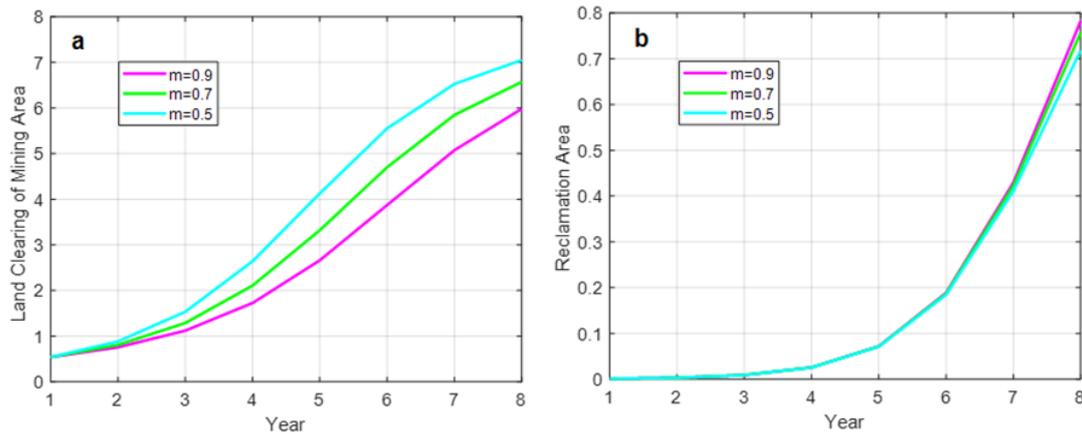


Figure 4. Behaviour of system (Eq. 1) with the various of m as time series of (a) land clearing area and (b) reclamation area.

4. CONCLUSIONS

The modified of system differential equations can be applied to the planning of land clearing and reclamation of the mining area of nickel. Thresholds in land clearing and reclamation are very important in mining planning. In this analysis, parameter A is indicated as the threshold for maintaining natural balance. The increases in value ω^* has an impact on the reclamation process which also increases. The existence of the resources needed for the reclamation process plays an important role in accelerating the process in question. The higher the resources have an impact on the higher reclamation. This has been shown by the role of parameter m in the system. The stability of the interior point S^* in nickel mining dynamics illustrates the processes of land clearing and reclamation that run simultaneously for sustainable environmental preservation. From the analysis results, the reclamation process using half of the mining materials is not optimal because it is not balanced with the size of the mining opening area. This prompted the development of an analysis of the importance of other materials for optimal reclamation processes. It modeled the process using a logistic growth equation, examining the interplay between land exploration and reclamation activities. Due to its focus on a key challenge in responsible mining, the reconciliation of financial operations with environmental recovery, the utilization of logistic models is advised. Analyzing both no-

action and dual-action scenarios yields practical insights for policymakers and mining companies.

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Conflicts of Interest

The authors declare no conflict of interest.

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DECLARATION OF GENERATIVE AI

Not applicable

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