



## **LAND USE SIMULATION TO FOSTER ENVIRONMENTAL SUSTAINABILITY OF THE RANU PANE VOLCANIC LAKE, INDONESIA**

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### **Abstract**

Sedimentation in the Ranu Pane Volcanic Lake (RPVL) has increased due to land use change (LUC) in the surrounding area and the considerable outflow of materials from the Semeru volcanic eruption. The continued sedimentation will have negative consequences for humans and the sustainability of the RPVL. This research was aimed at building a LUC simulation model for 2024-2036 using a land change modeler (LCM) with the Logistic Regression/Markov Chain algorithm and a built-up land scenario based on historical land use (LU) data to investigate future sedimentation. The secondary data were mosaics from Planet Labs® Norway's International Climate and Forest Initiative (NICFI) imagery, roads, rivers, slopes, elevation, rainfall, and soil types. The primary data collected through fieldwork for validation of the LU were processed using remote sensing and the Geographic Information System (GIS). The simulation model for 2024-2036 was built using the LU data for 2016, 2020, and 2024. The LCM model detected that there would be a decrease in forest area but an increase in built-up land and agriculture in the study area between 2024–2036. The findings indicate that the increased land area and agriculture around Mount Semeru will lead to further sedimentation. The study findings can help planners understand LU patterns and their impacts, which can be useful in designing sustainable lake development strategies and management plans for the area.

**Keywords:** Land Change Modeler, Land Use Change, Ranu Pane Volcanic Lake, Semeru Volcano

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## INTRODUCTION

The Ranu Pane Volcanic Lake (RPVL) is located in the highest village enclave (2100 m above sea level) within the Bromo Tengger Semeru National Park (TNBTS) among hilly areas with remarkably productive soil. As the majority of the people (92%) living in Ranu Pane are farmers (Putri et al., 2022), therefore, this affects their way of life. Agricultural activities on the steep-sloping land have intensified due to population growth and strong demand for agricultural land in the TNBTS (Maulana et al., 2021). Consequently, Ranu Pane is prone to erosion and sedimentation, giving rise to siltation. Rapid land use change (LUC) and unsustainable agricultural practices threaten the sustainability of the RPVL, especially during the rainy season.

Sedimentation in the RPVL is caused by erupted materials and the LUC in agriculture and settlements (Suharto et al., 2023). In addition, agricultural activities are the main cause of the high sedimentation in the RPVL. The management pattern for the agricultural land has changed from terraced to vertical farming. Trees have been replaced with crops to ecologically prevent erosion. Therefore, water carrying soil material flows directly from upstream agricultural areas to the RPVL downstream (Smith et al., 2017). Due to its ecological aspects, the TNBTS can be used as a conservation enclave. However, from a socio-economic perspective considering the livelihoods of the community, this has resulted in the LUC not being in keeping with the principles of conservation.

According to a study carried out by the Japan International Cooperation Agency (JICA) in Ranu Pane, the soil material that is taken away is made up of the topsoil from agricultural land on a 45° sloping hill. Another factor that contributes to sedimentation in the RPVL is the Green Revolution, which has led to the use of chemical fertilisers to boost agricultural output (Putri et al., 2022). Changing land characteristics combined with high rainfall contribute to the erosion and sedimentation processes that have resulted in the narrowing and siltation of the RPVL. This condition indicates that comprehensive and sustainable lake planning and management efforts are needed.

The rehabilitation of the RPVL poses a significant challenge to land management, given Indonesia's growing concern over its commitment on a worldwide scale to preserve the sustainability of the ecological functions of the lake. This is based on the Sustainable Lake Management Draft Resolution that was presented at the United Nations Environment Assembly (UNEA 5.2). This resolution has been integrated with the Sustainable Development Goal (SDG) 6 to protect water ecosystems, especially lakes. Indonesia's commitment was then implemented at the 10<sup>th</sup> World Water Forum in 2024, resulting in a ministerial declaration proposing the establishment of World Lake Day as a concrete manifestation to save critical lakes worldwide (Kemenparekraf, 2024).

Numerous studies on lake planning and management have been carried out, yielding many important conclusions. For example, Cao et al. (2021) highlighted the importance of an ecosystem approach to lake management, which includes understanding the interactions between various ecosystem components, such as water, soil and biota, and the influence of human activities on the balance of these ecosystems. Brown et al. (2018) emphasised that adaptive management involving local stakeholders can help in adapting conservation strategies to changing environmental conditions and ensuring long-term sustainability. Turner and Gardner (2015) mapped the LUC around Lake Tahoe and identified significant sources of sediment and nutrient pollution.

This study was designed to address the gap in the application of spatial mapping techniques that have not been commonly employed in sustainable lake planning and management. An LCM is a model that can be used to predict the past and future effects of LU on sedimentation. The LCM model provides a more thorough method and excellent anticipated accuracy by dynamically adjusting the parameters in response to real-time data. To foresee the growing possibility of siltation due to sedimentation in the RPVL, this research aimed to construct a simulation model of LUC from 2024–2036 using a land change modeler (LCM) with a Logistic Regression algorithm and a built-up land scenario based on historical LU data. The findings of this research can be used as a consideration in the management of land and agricultural areas and in efforts to restrain the sedimentation rate in the RPVL.

## **LITERATURE REVIEW**

### **Land Use (LU) and Its Dynamics**

The dynamics of LUC are considered a significant factor that contributes to environmental degradation. The problem of LU dynamics in various parts of the world has generally had an impact on multiple aspects of life, such as on the demand for crop water for agricultural practices in various countries, hydrological responses (Sujana et al., 2024), biodiversity (Masolele et al., 2024), and disasters (Satir et al., 2023). Studies indicate that the landscape or LUC at local and regional scales is often driven by the consequences of biophysical variables (climate and extreme events) and human factors (demographic, institutional, and cultural), and a complex mosaic of anthropogenically induced natural patches that vary in size, shape, and arrangement (Faheem et al., 2024). Therefore, it is very important to analyse LU and LUC to understand the environmental, social, and ecological impacts.

### **Land Change Modeller (LCM)**

One of the most popular approaches for analysing LU over time and predicting LUC distribution is modelling. An LCM is a model that allows users to obtain

information about potential patterns of LU and its consequences across the study area for various purposes (Wiwoho et al., 2024). While some LCMs have weaknesses, such as the complexity of environmental dynamics, data uncertainty and difficulty in predicting human decisions that impact LUC, an LCM can offer a more integrated approach, improving the accuracy of predictions and dynamically adjusting parameters based on actual data (Bachri et al., 2024).

Land change modeller (LCM)-based research is widely used around the world for various case studies, such as in studies on the control of surface water pollutants (Motovalibashi Naeini et al., 2024), disasters (Bachri et al., 2024), urban growth (Badshah et al., 2024), and water resources (Haider & Rashid, 2024). Based on the research conducted, the LCM is a very effective method for analysing and predicting LU around the lake to support environmental management and sustainable spatial planning. It allows researchers to identify patterns of LUC, analyse the factors that influence them, and predict long-term impacts on lake ecosystems.

## RESEARCH METHODOLOGY

This research was conducted at the RPVL, which is administratively located in the Senduro subdistrict, Lumajang Regency. The RPVL, which is located at latitude 8°0'45.7" south and latitude 112°56'45.6" east with an area of 1.0 ha, is within the TNBTS. The research steps and location are shown in Figures 1 and 2, respectively.

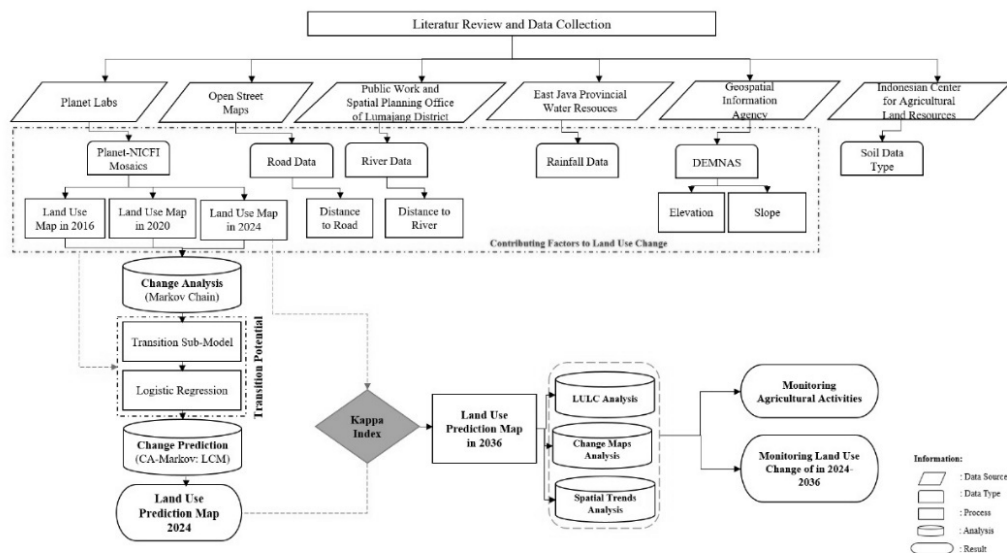


**Figure 1:** A Flow Chart of the Research

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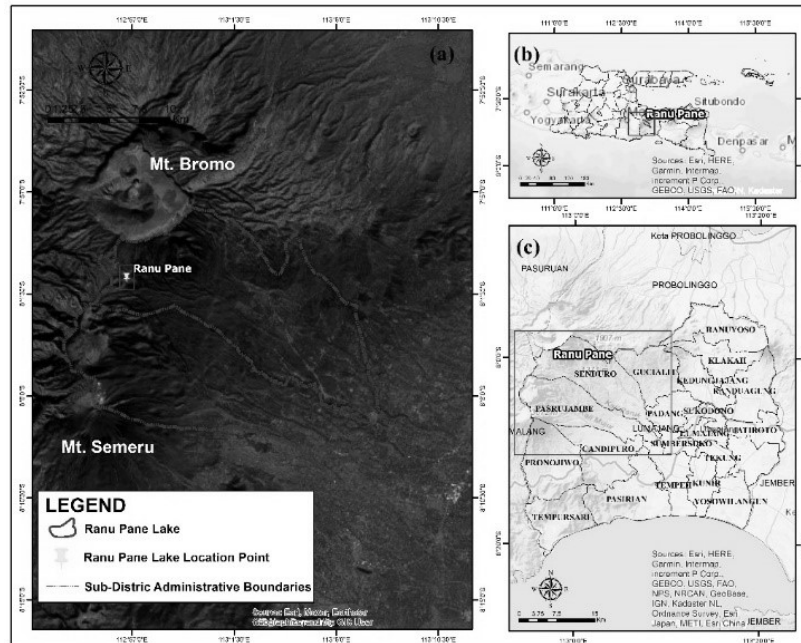


Figure 2: The Research Location

### Data Collection

This research used primary and secondary data. The primary data was used as the validation data for LU, while the secondary data, such as rainfall, elevation, slope, roads, rivers, and soil types, was obtained from several agencies (Table 1).

Table 1: The research materials

| No | Material                  | Source                                                                                     |
|----|---------------------------|--------------------------------------------------------------------------------------------|
| 1. | Planet Lab®-NICFI Mosaics | Planet Labs®                                                                               |
| 2. | Road data                 | Open Street Map (OSM)                                                                      |
| 3. | River data                | Public Work and Spatial Planning Office of Lumajang District                               |
| 4. | Slope                     | DEMNAS                                                                                     |
| 5. | Elevation                 |                                                                                            |
| 6. | Rainfall                  | East Java Provincial Water Resources Public Works Office                                   |
| 7. | Soil type                 | Indonesian Centre for Agricultural Land Resources Instrument Standard Testing (BBPSI SDLP) |

## **Data Analysis**

### **1. Land use (LU) data processing, classification, and validation**

The data in this research used mosaics from Planet Labs® Norway's International Climate and Forest Initiative (NICFI) imagery, with a spatial resolution of 3-5 m, from recordings in 2016, 2020, and 2024, which were processed using Google® Earth Engine. A four-year interval was chosen because the mapping was based on a detailed scale, and the available data included Planet Labs® NICFI mosaics with a lower percentage of cloud distortion. The PlanetScope® Analytic had four bands, including three visual bands (RGB) and near-infrared, and it was orthorectified and calibrated to sensor radiance.

The LU classification in this study was done using the Classification and Regression Tree (CART) algorithm integrated with Google Earth® Engine cloud computing. The CART model is a machine learning algorithm that is widely used in land cover classification (Feizizadeh et al., 2023). Regarding the validation of the LU map, an accuracy assessment was carried out using the confusion matrix by utilising Google Earth® Engine cloud computing. The accuracy obtained in 2016 was 0.8116, in 2020 was 0.8561, and in 2024 was 0.8154. Then, the map results were compared with the results of the ground checking that was carried out with 216 validation points of LU scattered in the Senduro and Pasrujambe subdistricts, which resulted in a Kappa ( $\kappa$ ) accuracy of 0.94. The map accuracy was  $> 0.80$  for the studied years. This value was acceptable and had very strong agreement and interpretation.

### **2. Using a land change modeller (LCM) with a Logistic Regression/Markov Chain algorithm to predict land use (LU) in the Senduro and Pasrujambe subdistricts in 2024 and 2036**

As suggested by Hosmer (1989), binary logistic regression, including data on roads, rivers, slopes, elevation and rainfall, was used in this study to analyse the factors driving LUC in the Senduro and Pasrujambe subdistricts. A general logistic regression equation was formulated as follows:

$$\text{Logit} (P_i) = \alpha + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n \dots\dots\dots [1]$$

where,  $P_i$  is chance of LUC,  $\alpha$  is the intercept,  $\beta_1$  is the coefficient of the 1st to  $n$ th independent variable, and  $X_1$  is 1st to  $n$ th independent variable.

To determine the validity of the results, the regression results were tested using relative operating characteristics (ROC) of between 0.5-1.0, with 0.5 indicating an insignificant influence, and 1 indicating a significant influence on LUC.

Logistic regression was used to determine how much LUC occurred between 2016-2020 so as to predict the LUC, agricultural conditions and

sedimentation in the RPVL area in 2024 and 2036. The results of the LU modelling by the LCM in 2024 were compared with the observed LU in 2024 using the  $\kappa$  index statistics. The map produced in the LCM model became a prediction map, which was then validated using several  $\kappa$  parameters:  $\kappa$  for grid cell level location ( $\kappa_{\text{location}}$ ),  $\kappa$  for no information ( $\kappa_{\text{no}}$ ),  $\kappa$  for strata level location ( $\kappa_{\text{locationStrata}}$ ), and standard  $\kappa$  ( $\kappa_{\text{standard}}$ ) (Pontius Jr. & Millones, 2011).

## RESULT AND DISCUSSION

### 1. Land use (LU) in the Senduro and Pasrujambe subdistricts between 2016-2024

Based on the processing results, it was found that there was a significant LUC between 2016-2024. The forest area was significantly reduced from 279.38 to 235.24 km<sup>2</sup>, which means that the forest area had decreased by 44.14 km<sup>2</sup>. During the same period, the agricultural sector increased from 51.48 to 71.13 km<sup>2</sup> (Table 2).

**Table 2:** The categories of LU in the Senduro and Pasrujambe subdistricts in 2016, 2020, and 2024.

| LUC in the Senduro and Pasrujambe Subdistricts |                         |               |               |                                       |           |           |                        |               |               |
|------------------------------------------------|-------------------------|---------------|---------------|---------------------------------------|-----------|-----------|------------------------|---------------|---------------|
| LU                                             | Area (km <sup>2</sup> ) |               |               | Difference in Area (km <sup>2</sup> ) |           |           | Percentage of Area (%) |               |               |
|                                                | 2016                    | 2020          | 2024          | 2016-2020                             | 2020-2024 | 2016-2024 | 2016                   | 2020          | 2024          |
| Aquatic                                        | 4.17                    | 8.80          | 8.12          | -4.63                                 | -0.68     | 3.95      | 1.18                   | 2.50          | 2.30          |
| Settlements                                    | 1.62                    | 2.58          | 5.76          | 0.96                                  | 3.18      | 4.14      | 0.46                   | 0.73          | 1.63          |
| Agriculture                                    | 51.48                   | 80.14         | 71.13         | 28.66                                 | -9.01     | 19.65     | 14.60                  | 22.72         | 20.17         |
| Forest                                         | 279.38                  | 247.17        | 235.24        | -32.21                                | -11.93    | -44.14    | 79.21                  | 70.08         | 66.70         |
| Cloud Cover                                    | 1.16                    | 0.67          | 24.06         | -0.49                                 | 23.39     | 22.90     | 0.33                   | 0.19          | 6.82          |
| Vacant Land                                    | 14.88                   | 13.33         | 8.38          | -1.55                                 | -4.95     | -6.50     | 4.22                   | 3.78          | 2.38          |
| <b>Total</b>                                   | <b>352.69</b>           | <b>352.69</b> | <b>352.69</b> |                                       |           |           | <b>100.00</b>          | <b>100.00</b> | <b>100.00</b> |

Meanwhile, aquatic, agricultural, forest, and vacant land areas significantly decreased between 2020-2024 due to the large-scale activities of Mount Semeru in 2021 and 2022. Therefore, the community settlement at the foot of Mount Semeru was converted to *Huntara* (Temporary Housing) because it was covered by volcanic material and had to be switched (Thouret et al., 2022). Between 2016-2024, the forest area decreased by 12.52% while settlements and agricultural areas increased by 4.14 km<sup>2</sup> (1.17%) and 19.65 km<sup>2</sup> (5.57%),

respectively. The higher demand for land was inversely proportional to the availability of land, resulting in land conversion (Entahabu et al., 2023). This condition posed a severe challenge in managing land resources to minimise other environmental problems such as flooding and sedimentation in downstream areas, such as the RPVL, due to agricultural land management that was not in accordance with conservation principles.

## 2. Land change modeller (LCM) simulation of an increased settlement scenario in the Senduro and Pasrujambe subdistricts in 2024 and 2036

The five factors supporting LUC include slope, elevation, rainfall, distance to road, and distance to river. From the north to southwest, the Senduro and Pasrujambe subdistricts have predominantly steep to very steep slopes at 15-45% (Figure 3a) and altitudes of > 2000 m (Figure 3b). Rainfall in the area is classified as moderate to high, with rainfall amounts ranging between 2500 to > 3500 mm per year between 2016-2024 (Figure 3c). The high rainfall can increase soil erosion due to LUC from forest to agricultural land so that erosion can deposit sediment into the lake. In addition, rainwater runoff carrying pollutants, such as pesticides from agricultural land, can degrade the water quality in the RPVL.

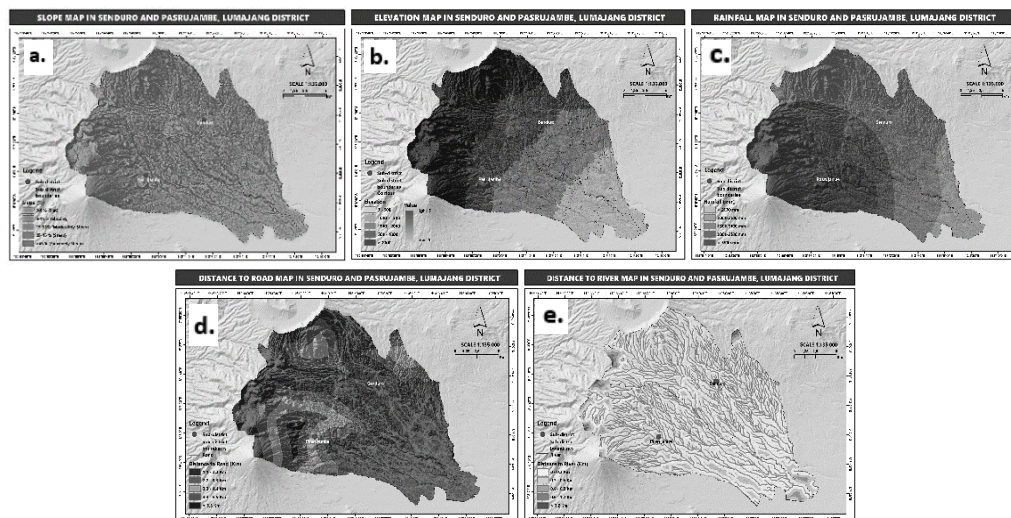


**Figure 3:** The Bound LUC Variables for the Senduro and Pasrujambe Subdistricts: (a) Slope, (b) Elevation, (c) Rainfall, (d) Distance-to-Road, and (e) Distance-to-River.

A relative operating characteristic (ROC) of 1 indicates excellent and appropriate results, while values of < 0.5-0.5 indicate that the results are random

(Pourghasemi et al., 2020). The ROC in this research was  $> 0.80$ . The coefficients of the LUC regression equation are shown in Table 3.

**Table 3:** The regression coefficients of the LUC equation

| Bound LUC Variables        | Constant ( $\beta$ ) | Estimator Variable |          |                     |                   |       | ROC   |
|----------------------------|----------------------|--------------------|----------|---------------------|-------------------|-------|-------|
|                            |                      | Elevation          | Rainfall | Distance -to- River | Distance -to-Road | Slope |       |
| Aquatic to Settlements     | 7.179                | -2.73              | 0.28     | 0.97                | -0.53             | -0.40 | 0.978 |
| Forest to Settlements      | 3.899                | -0.67              | -0.28    | 1.12                | -0.88             | -0.63 | 0.883 |
| Vacant Land to Settlements | 4.541                | -0.91              | -0.57    | 0.19                | -0.08             | 0.039 | 0.891 |

Based on the logistic regression results, the calculated ROC of 0.97-0.88 fell between 0.5-1.0 (Table 3), indicating that the five variables were significant and affected the LUC. The most dominant factors in the LUC at the settlements for the LCM prediction of each model for 2024 were the distance to rivers and the slope. A positive value in each predictor factor would indicate that the increase would consequently increase the distribution/emergence of LU in the Senduro and Pasrujambe subdistricts. Meanwhile, negative values for all the predictor components would suggest that an increase in the predictor factors would decrease the LU distribution in the Senduro and Pasrujambe subdistricts.

### 3. Land change modeller (LCM) simulation of an increased built-up land scenario in the Senduro and Pasrujambe subdistricts in 2024 and 2036

The results of the LU modelling by the LCM, with an additional scenario on the settlements classification for 2024, as shown in Figure 4b, were compared with the observed LU map of the Senduro and Pasrujambe subdistricts in 2024 using the overall accuracy (Figure 4a). A  $\kappa$  statistic for quantity and location was derived based on the evaluation of the predicted LU with the observed LU. The statistics showed that  $\kappa_{no} = 0.8212$ ,  $\kappa_{location} = 0.8118$ ,  $\kappa_{locationStrata} = 0.8118$ , and  $\kappa_{standard} = 0.7475$ . Based on the  $\kappa$  accuracy according to Landis & Koch (1977), all  $\kappa$  indices between 0.61-0.80% show that the results are in substantial agreement, and between 0.81-0.99% show that the results are in almost perfect agreement (Viera & Garrett, 2005).

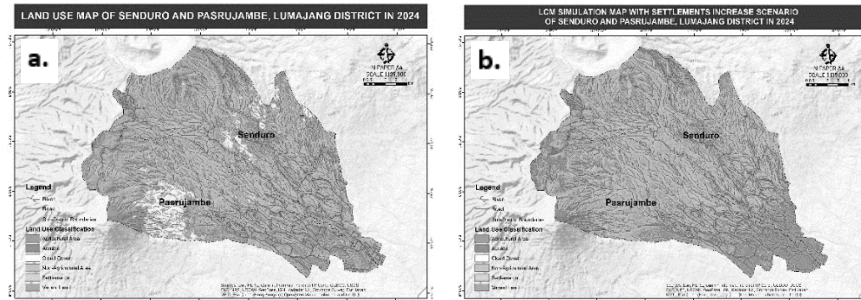


**Figure 4:** (a) The LU Map of the Senduro and Pasrujambe Subdistricts in 2024 and (b) the LCM Simulation Map of an Increased Settlement Scenario in the Senduro and Pasrujambe Subdistricts in 2024.

Furthermore, the LCM results for 2024 were used to model an increased built-up LU scenario for 2036. From the predicted LU map for 2036 (Figure 5), it was found that there would be a decrease for each LU classified as forest and cloud cover areas. In comparison, other uses of aquatic, settlements, agricultural areas, and vacant land would increase. The aquatic area would increase by 0.16%, settlements by 0.29%, agricultural land by 2.60%, and vacant land by 0.63%. Meanwhile, the forest and cloud cover areas would decrease by 0.37 and 6.64%, respectively, between 2024-2036.

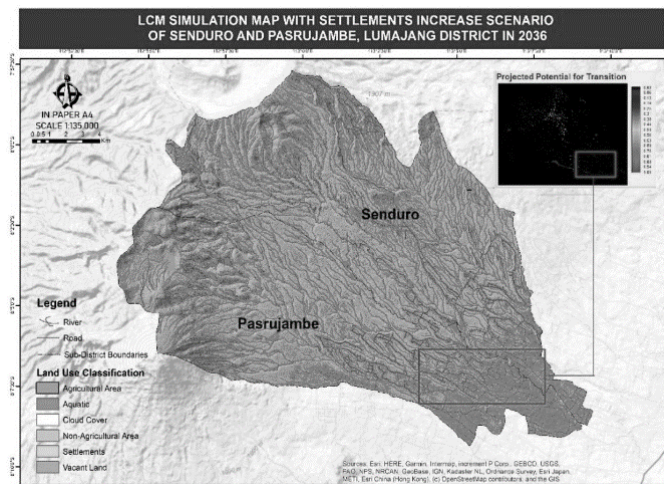


**Figure 5:** The LCM Simulation Map of a Settlement Increase Scenario in the Senduro and Pasrujambe Subdistricts in 2036.

#### 4. Land use (LU) in the Senduro and Pasrujambe subdistricts and its impacts on the Ranu Pane Volcanic Lake (RPVL)

Based on the LCM simulation results, the LU in the RPVL would be changed significantly in 2036. Based on the visualisation in Figure 6, many LUCs would occur in the agricultural areas. The agricultural area here would increase by 0.85% from 2024, which would be an increase of 0.03 km<sup>2</sup> or 3 ha.

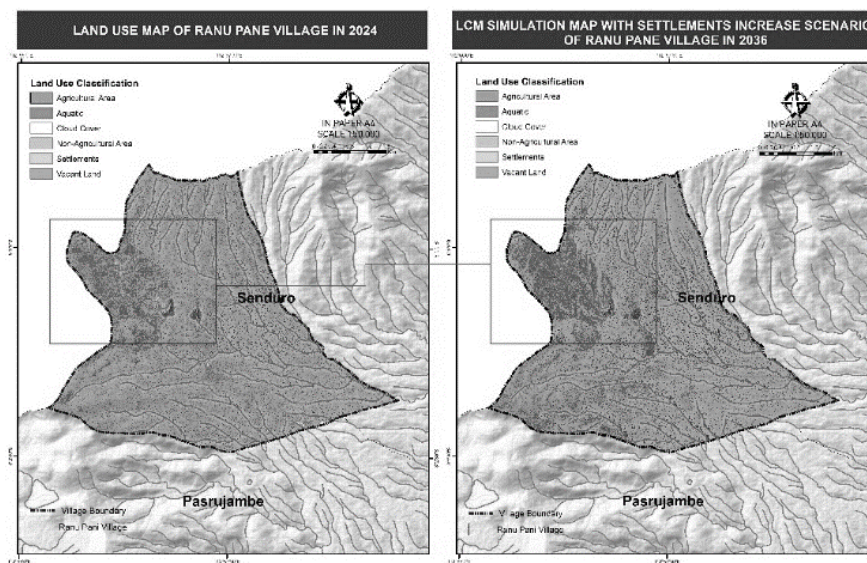


**Figure 6:** A Comparison of the LU of the Ranu Pane Village in 2024 with the LCM Simulation Results for 2036.

The people would prefer to convert LU to support the socio-economic sector, especially the agricultural sector in the north to the southwest of the Senduro and Pasrujambe subdistricts, located on steep slopes leading to the RPVL. Agriculture on the steep slopes is generally focused on increasing production, thus ignoring conservation principles. In addition to being located in a fragile ecosystem, it is also surrounded by extensive forests on very steep slopes, making the Ranu Pane Village area vulnerable to erosion. The high rainfall intensity in the area, accumulating at > 2500 mm per year, results in a high increase in soil erosion due to agricultural patterns in which no terraces are used. When the various driving aspects are integrated and the community engages in unsustainable agricultural practices, it will result in sedimentation and narrowing of the RPVL area.

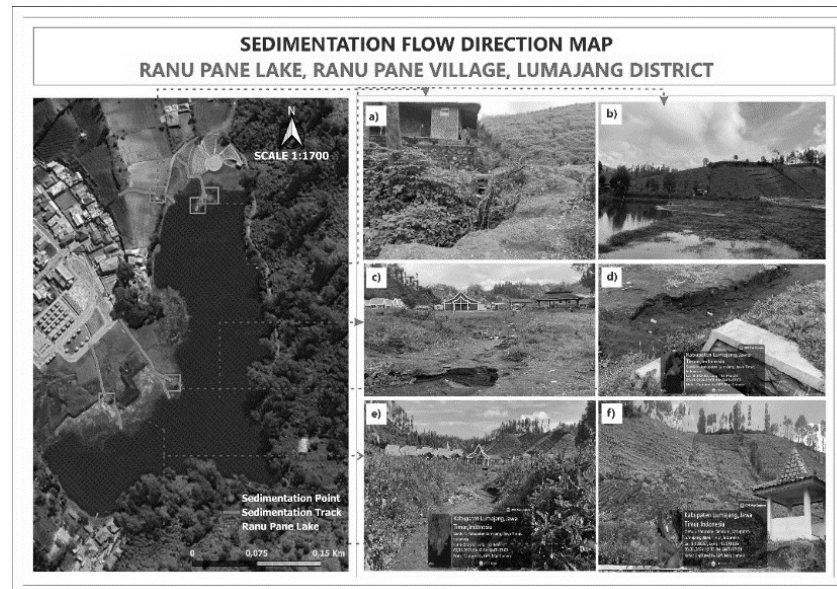


**Figure 7:** A Map of the Sedimentation Flow to the RPVL.

Based on the sedimentation flow direction map (Figure 7), Ranu Pane Village has many steep hills that farmers utilise as agricultural land, according to the direction of the slope without terracing patterns. Based on the flow direction, and considering the location of the RPVL in the downstream area, the water carrying sedimentation material will flow directly into the RPVL. Siltation in the lake is not caused by natural disasters alone. However, unsustainable community activities through farming that do not comply with conservation principles will threaten the sustainability of the RPVL.

In addition to agriculture, the RPVL is also used as a tourism destination and as a support sector for the main hiking route to Mount Semeru. Consequently, many tourism support sectors have emerged, such as community shops around the lake area. However, due to the unavailability of land for waste disposal, visitors, who are unaware of environmental sustainability, throw garbage around the lake. In addition, household waste disposed in the sewers is carried into the RPVL. As a consequence, the quality of the lake is being degraded by pollution and siltation.

Towards SDG 2030, land management must be based on the principles of conservation by regulating certain types of LU to restrain the rate of land quality degradation and erosion. Moreover, the status of the RPVL, which is within the enclave area, requires efforts to restore the condition of the lake and preserve its nature. Therefore, the results of the research can be used as a basis

for the local government and also the TNBTS to formulate policy directions for the integration of certain types of LU with effective regional spatial planning in preserving the RPVL so that the people of Ranu Pane Village can prioritise economic growth in synergy with environmental sustainability as a unity of ecosystem functions.

## CONCLUSION

The accuracy and precision of the LCM stem from its integration of various real data at a detailed scale, such as historical and current data on LU, elevation, slope, rainfall, distance to roads, and distance to rivers. The simulation results of LU in the Senduro and Pasrujambe subdistricts in 2036 showed that there would be a decrease in LU with the classification of forest and cloud cover areas. Waterbodies, settlements, agriculture, and vacant land would increase in future, as predicted by the model. The results of the LCM visualisation map for 2024 and 2036 for the area surrounding the RPVL showed many LUCs, especially in agricultural areas. The LUC to agricultural activities around Ranu Pane caused an increase in surface runoff and erosion, which led to sedimentation and narrowing of the lake. Given that sedimentation is likely to increase in future due to the anticipated LUC, resulting in damage to the lake environment, as shown by the findings of this study, this serves as an important input for the local government as well as the TNBTS and policy planners to formulate some policy directions to discourage certain types of LU to control sedimentation by integrating more effective spatial planning practices for the management and preservation of the RPVL.

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