Application of Remote Sensing for Monitoring the Impact of Lapindo Mud Sedimentation for Mangrove Ecosystem: Case Study in Sidoarjo, East Java

Akbar Cahyadhi Pratama Putra, Tantri Utami Widhaningtyas, M. Randy Aswin

***Abstract*—**Indonesia, as an archipelagic nation, has a very long coastline with significant potential for marine resources, including mangrove ecosystems. The Lapindo mudflow disaster in Sidoarjo, East Java, resulted in mudflow being discharged into the sea through the Brantas and Porong rivers. The mud material transported by the river flow is feared to be dangerous because it contains harmful substances such as heavy metals. This study aims to map the mangrove ecosystem in terms of its density and assess the impact of the Lapindo mud disaster on the mangrove ecosystem, along with efforts to sustain its continuity. The mapping of the coastal mangrove conditions in Sidoarjo was carried out using remote sensing products, specifically Landsat 7 ETM+ images, taken during dry months in 2002, 2006, 2009, and 2014. The density of mangroves was determined using NDVI, which utilizes band 3 (the red channel) and band 4 (the near IR channel). Image processing to generate NDVI was performed using ENVI 5.1 software. The NDVI results were used to assess mangrove density on a scale from 0 to 1. The growth of mangrove ecosystems, both in terms of area and density, showed a significant increase from year to year. The development of mangrove ecosystems was influenced by the deposition of Lapindo mud in the estuaries of the Porong and Brantas rivers, where the silt provided a suitable medium for the growth of the mangrove ecosystem, leading to an increase in its density. The rise in density was supported by public awareness to mitigate heavy metal contamination, allowing for mangrove breeding near the affected areas.

***Keywords*—**Archipelagic nation, Mangrove, Lapindo mudflow disaster, NDVI.

I. Introduction

MANGROVE ecosystems are widespread and dominate coastal wetlands in tropical and subtropical regions around the world. They provide various ecological and ecosystems that contribute to abrasion protection, water filtration, fish and shrimp breeding grounds, tourist attractions, and more [5]. Mangroves are coastal ecosystems that grow in tidal areas and have many functions, one of which is an ecological function, including protection from coastal erosion, spawning grounds, and nurseries for various biota, absorbing CO_2, and protecting from wind and waves [7]. Indonesia has wide coastal areas with a long coastline reaching 95,181 km [6]. Physically, mangrove forests protect the coast from great waves, strong winds, and storms from the sea, minimizing potential damage that could occur [2]. An excess of mangrove ecosystems can live in sediment and can neutralize waste contained in the sediment. The total area of existing mangroves in Asia is 42%, Africa 20%, North America and Central America 15%, with a total global mangrove area of 16,530,000 Ha [5]. The area of mangroves in Indonesia constitutes 23% of mangrove ecosystems worldwide. with an area of 1,671,140.75 Ha of mangrove forests in Indonesia in good condition, while in damaged condition covering 1,817,999.93 Ha. The application of remote sensing offers some advantages for monitoring territory. Remote Sensing offers up-to-date data, obtainable data, and is easy to process [1]. Remote sensing can monitor the mangrove ecosystem and the condition of trees every year.

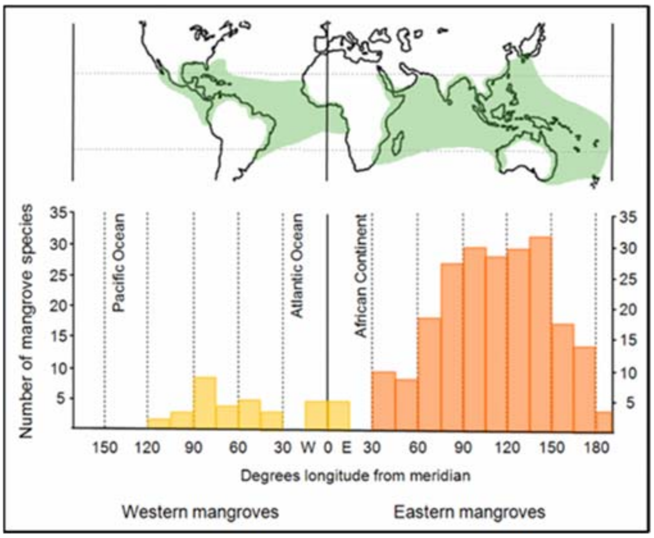

Fig. 1 Generalized global distribution of mangroves and diversity of mangrove species per 15° of longitude [5], [8]

Remote sensing is an excellent method for monitoring and mapping mangrove ecosystems, which are currently under threat [5]. Many research studies on this subject have been conducted globally [2], [5]. Mangrove forests in tropical and subtropical environments are among the most vulnerable ecosystems in the world [5]. In 2006, a massive disaster occurred in Indonesia when there was an overflow of Lapindo mud in Sidoarjo. The Lapindo mud caused significant sedimentation in the Brantas estuary, leading to mudflow into the sea. Consequently, this sedimentation resulted in shallower river depths and posed a threat to the mangrove ecosystem.

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Excessive sedimentation led to damage to the mangrove ecosystem, causing a reduction in the water level that affects the mangroves [1]. The purpose of this research is to map the mangrove ecosystem over multiple periods, observe the condition of the mangroves due to the Lapindo mudflow, and take measures to ensure the sustainability of the mangrove trees. The sustainability of mangroves must be maintained because they serve as a natural barrier against erosion caused by sea currents and help mitigate the harmful substances resulting from the sedimentation of Lapindo mud.

II. Research Area

The research area is situated in the Brantas and Porong estuaries, both of which are within the Brantas watershed. The Brantas watershed is extensive, but this study specifically focuses on the lower reaches of the Brantas watershed in Sidoarjo, East Java. This location was chosen for the study due to the increasing presence of mangroves and the growing issue of sedimentation in the Brantas and Porong estuaries, primarily caused by the high deposition of mud material. The precise coordinates of this research area are approximately 706012 meters east and 9164105 meters north, situated in the vicinity of the Brantas and Porong estuaries.

Fig. 2 Mapping research area

III. Data and Method

A. Data

The data used in this study consist of Landsat 7 ETM+ images recorded on the following dates: September 8, 2002; August 2, 2006; August 2, 2009; and September 9, 2014. These images were employed to monitor the condition of the mangrove ecosystem, specifically by assessing the level of mangrove density. Mangrove density can be identified by analyzing the red and near-infrared wavelengths through the use of NDVI transformations. Image processing was performed using ENVI 5.1, encompassing both radiometric and geometric corrections. This software was also employed to classify the levels of vegetation density. Additionally, Macromedia Flash was utilized to visualize the changes in the condition of the mangroves over the years. The output of this research includes an analysis of the levels of mangrove ecosystem density and its changes in size.

B. Methods

The methods employed in this survey involve the use of multi-temporal data. These multi-temporal data are processed using software to perform radiometric and geometric corrections. Geometric correction ensures that the image's geometry aligns accurately with the features in the field. Radiometric correction is applied to obtain the original spectral reflectance values and serves as one of the prerequisites before image transformation can commence. The classification of mangrove density is achieved through the utilization of NDVI, with the transformation utilizing near-infrared and red wavelengths. On Landsat 7 ETM, the vegetation index is generated based on the difference between band 4 and band 3 compared to the total between the two bands. Band 4 is chosen for the vegetation index because it exhibits high reflectance values for vegetation, whereas band 3 has lower reflectance. Image transformation is executed using two or more bands with significant differences.

$$\text{NDVI} = \frac{(\text{Near InIIrared} - \text{Red})}{(Near\ InIIrared + Red)}$$

The classification of canopy density is determined based on the Vegetation Index (NDVI) and follows the classification provided by LAPAN.

TABLE I
The Classification of the Density of Mangrove Canopies from LAPAN

NDVI Value	Density Class
0,0001 – 0,25	Density Heading Rarely
0,25 – 0,50	Medium Density Heading
0,50 -1,00	Heading Heavy Density

IV. Result

The utilization of remote sensing imagery can be employed for monitoring sediment growth caused by the "Lapindo" mud, which is transported to the sea through the Porong River and Brantas River. When examining Landsat 7 ETM+ imagery using the composite 453, following the guidelines provided by the National Space and Aviation Agency (LAPAN), sediment appears with a blue and bright hue, while mangroves are represented in orange around the river delta, as depicted in Fig. 3 (b).

The selection of composite 453 is based on the characteristics of the bands: in band 4 (NIR), vegetation exhibits high reflectance; in band 5 (SWIR1), moist soil reflects poorly; and in band 4 (Red), dry soil can be identified. Landsat 7 ETM+ composite 453 is particularly suitable for observing soil and water. Therefore, this composite allows for the detection of water and moist soil content.

In line with the imagery from 2002, the sediment carried by the river flow appeared limited and dispersed. However, following the occurrence of the Lapindo mudflow on May 29, 2006, a substantial amount of mud was transported by the

Porong River and Brantas River flows, leading to a noticeable increase in sediment around the river delta, characterized by a shift in color to a youthful blue. From this observation, it becomes evident that the Lapindo mudflow significantly increased the volume of material transported by the river flow, ultimately depositing it in the estuary of the Brantas River.

Fig. 3 (a) Condition in 2002 before the Lapindo mud disaster

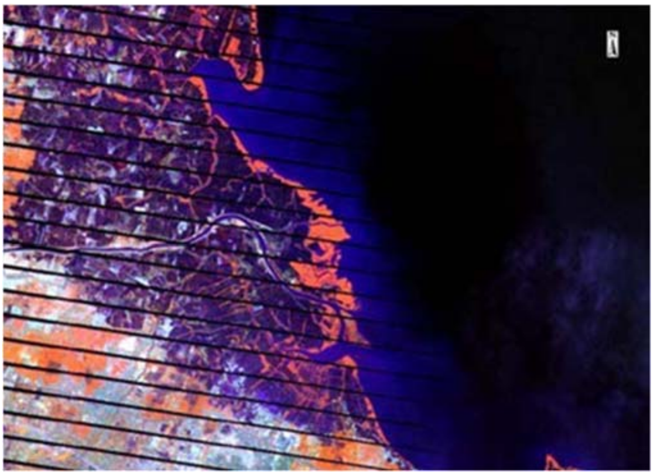

Fig. 3 (b) Conditions in 2014 after the Lapindo mud disaster occurred

By September 2006, sediment was already visible, albeit in small quantities, in the eastern estuary. Subsequently, sediment became more concentrated in the estuaries of the Brantas River and Porong River. However, by 2009, the sediment formation had diminished. It is conceivable that the energy of ocean currents surpassed that of river flows, causing the sediment to be displaced towards the southern part of the Brantas River estuary. Furthermore, the growth of sediment in the southern Brantas River estuary led to a shift in the direction of the river flow towards the south.

Many individuals hold the belief that Lapindo mud poses a threat to coastal ecosystems. As a countermeasure, the Department of Marine and Fisheries has harnessed Lapindo mud for mangrove cultivation. The deliberate planting of mangrove trees serves as tangible evidence that Lapindo mud is not detrimental to the environment and can even mitigate coastal erosion while acting as a barrier against harmful substances, thereby safeguarding the integrity of coastal and marine ecosystems. This approach is justified by the composition of Lapindo mud, dominated by materials conducive to mangrove habitat growth, particularly clay loam [4]. Moreover, the tidal nature of the area, where seawater mingles with freshwater, makes it a suitable environment for mangrove planting.

The chemical composition of Lapindo mud is a cause for concern due to its potential environmental harm if left unaddressed. Notably, Lapindo mud contains high concentrations of heavy metals, particularly lead (Pb) and copper (Cu) [4]. While mangrove plants can tolerate a certain level of heavy metal presence in their habitat, it is essential to ensure that these levels do not exceed the permissible threshold. Mangrove roots are equipped to absorb heavy metals, retaining them within the plant structure, from the roots to the leaves, albeit at varying concentrations. Non-essential heavy metals, such as lead (Pb), exhibit higher concentrations in the leaves than in the roots, whereas essential heavy metals like copper (Cu) tend to accumulate more in the roots than in the leaves [3]. Therefore, the healthy growth of mangroves can be considered an indicator that Lapindo mud does not contain heavy metals exceeding the established threshold, thereby preventing harm to coastal and marine ecosystems.

Remote sensing serves as a viable method for identifying mangrove density, with the NDVI transformation being a key tool. The mangrove density levels from 2002 to 2014 are depicted in Fig. 4.

Based on multi-temporal observations, it can be observed that the mangrove ecosystems exhibited robust growth from 2002 to 2014. The presence of thriving mangrove ecosystems along the waterfront is reflected in the remote sensing imagery, showcasing the highest density indices. Many individuals utilize mangrove ecosystems for fish ponds and as a buffer zone to mitigate damage caused by marine erosion. A model-based approach for the development of mangrove ecosystem ponds is illustrated in Fig. 5.

In 2002 sedimentation had not yet formed in the Porong River. The Lapindo mud disaster occurred after 2002, more precisely in 2006. Therefore, the suspended materials in the water column, which appear blue in Fig. 3 (b), were primarily a result of river erosion. As the transported materials were limited, sediment had not yet accumulated in the Brantas and Porong river estuaries. The subsequent remote sensing imagery was from Landsat 7 ETM+ recorded in August 2006, revealing significant differences from the earlier images. In this imagery, sedimentation areas were evident in both the north and south of the Brantas River estuary, indicating the proportional growth of sedimentation due to the onset of the Lapindo mudflow in May 2006.

In 2006, the sedimentation was not particularly pronounced due to the levees that had been constructed around the Lapindo mudflow area after the disaster, preventing excessive sedimentation during the period from May to August. In the NDVI results, a low-level vegetation density classification was observed. However, from the imagery in 2006, it was evident that the sediment was still in motion, indicating its susceptibility to the flow velocity of the Madura strait.

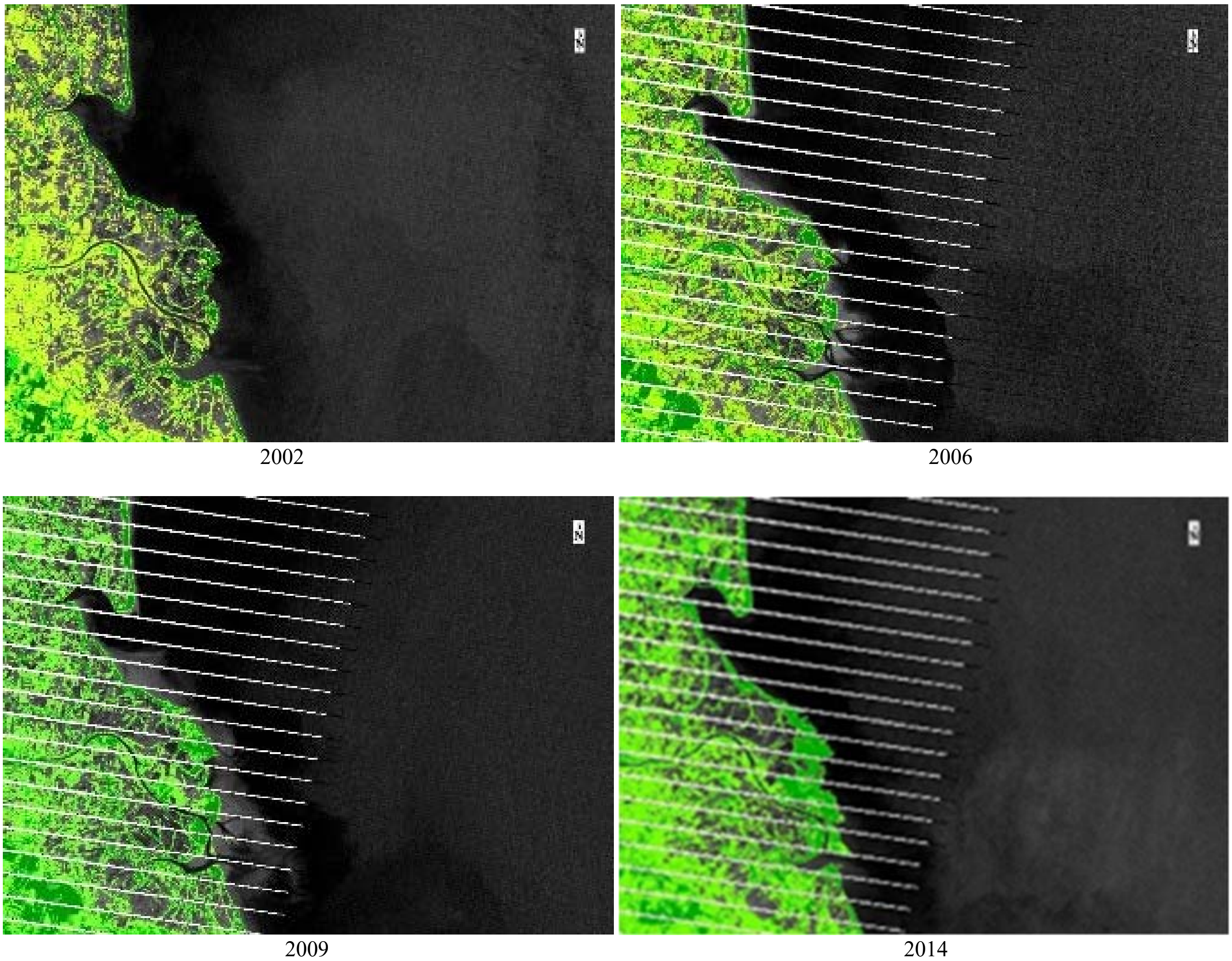

Fig. 4 The density of mangroves from 2002 to 2014

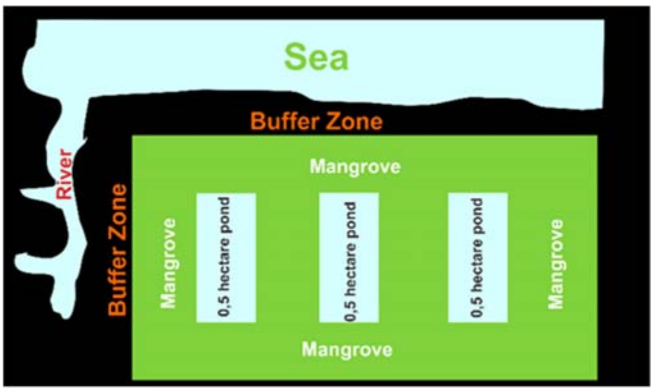

Fig. 5 Model of the development model of mangrove ecosystem ponds

By 2009, sediment growth was concentrated in the northern estuary and had expanded southward. This rapid growth of sedimentation over three years was attributed to the levees becoming full, necessitating the discharge of mud through the Brantas and Porong rivers. The persistence of sedimentation was reinforced by the presence of mangrove plantations in the area, further enhancing sedimentation resistance against the flow velocity of the Madura strait. The NDVI results also indicated moderate vegetation density on the sedimentation.

The Brantas River, being larger than the Porong River, had a greater capacity to transport materials, which contributed to the higher prevalence of sedimentation in the Brantas estuary. Over five years, the growth of sedimentation in the estuary was pronounced, with extensive sediment accumulation almost covering the Brantas estuary. As the sedimentation grew, it further justified the importance of mangrove planting in 2009. Without the presence of mangroves, the sedimentation would remain unstable and susceptible to transportation by the strait's currents, potentially preventing the formation of sedimentation, as observed in 2014.

V. Conclusion

The mapping of mangroves can be accomplished through multi-temporal remote sensing, utilizing Landsat 7 ETM+ imagery from 2000, 2006, 2009, and 2014. The condition of the mangroves in the Sidoarjo coastal region is seen to adapt to the texture of Lapindo mudflow, serving as a key factor in the medium for mangrove growth. Conservation efforts for mangrove ecosystems include the utilization of Lapindo mud for mangrove development. Additionally, a model-based approach has been implemented for the establishment of mangrove ponds, which incorporates the creation of buffer zones and the planting of mangroves around the ponds to mitigate coastal erosion threats that could otherwise impact local economies.

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