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Analysis of Mangrove Vulnerability Level using Remote Sensing Data in Comal Estuary, Pemalang

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ABSTRACT
Human activity around mangrove areas can harm their health, despite their economic benefits to local communities. A study of the Comal estuary found that increased human activity was not matched by efforts to protect the mangroves. This lack of awareness is likely due to a lack of information about the importance of mangroves and their vulnerability. The study used Sentinel-2A and field measurements to assess vulnerability based on factors like mangrove density, salinity, and distance from the shore. That factor were used to generate vulnerability value based on weighted overlay analysis (vulnerability index). The results showed that the eastern part of the estuary was highly vulnerable to wave damage (abrasion) due to its location. In contrast, the central part of the estuary had low vulnerability due to its denser and healthier mangroves. These findings were confirmed by field observations: areas with low vulnerability had dense, healthy mangroves, while areas with high vulnerability had damaged and broken trees. The existence of the vurnerability class can be used as a recommendation for further mangrove management. Restoration can be applied in areas of high mangrove vulnerability. The area has a very low mangrove density due to the large number of mangroves damaged by abrasion, so replanting mangroves in the area is highly recommended. Mangrove planting also needs to require great attention, especially in the area has a problem in the form of large ocean waves, so the construction of a breakwater with a "Shark Tooth" formation is recommended.

INTRODUCTION

Mangroves are unique coastal forests between 25° north and 30° south (Kuenzer et al., 2011). It thrives in salty water, including seawater, where evaporation concentrates salt levels. A special adaptation allows them to survive in oxygen-poor soils: root systems that protrude above the ground to breathe (Setyawan et al., 2005). Mangrove ecosystems are vital coastal habitats that provide numerous ecological and socio-economic benefits. They act as natural barriers against storm surges, support biodiversity, and contribute to carbon sequestration. Globally, mangroves are distributed across 112 countries in tropical and subtropical regions, with significant concentrations in Asia, Latin America, and Africa (Monroy et al., 2017). However, these ecosystems face deforestation, climate change, and coastal development threats. Effective management and conservation strategies are essential to preserve their ecological functions and services.

Indonesia boasts the world's largest mangrove area, with these ecosystems covering 18-23% of its coastline (Rusila Noor, Y., M. Khazali, 2006). Almost all Indonesian coastal areas have mangrove ecosystems (Djamaluddin, 2018). The Comal River estuary in Java is one such example. Designated an Essential Ecosystem Area in 2017 (Pemerintah Kabupaten Pemalang, 2018). It faces threats like conversion to ponds, farms, and settlements (Ilman et al., 2016). Climate change adds another layer of complexity. If these pressures continue, Indonesian mangroves could disappear (Joesidawati, 2017).

Monitoring mangrove health is crucial (Julkipli et al., 2018). Traditional methods like field measurements are limited by cost and time. Here, remote sensing offers a powerful tool (Li et al., 2013). It can capture vast areas repeatedly, allowing for detailed detection of changes in the ecosystem (Mumby, 2006). Research on the level of vulnerability with many factors will be easy if remote sensing is used because it can be observed in a large area in a short time. For example, measuring the distance from the shoreline will be easier when using remote sensing compared to traditional measurements and can shorten the measurement time on these parameters. Using Sentinel-2A images with a resolution of 10 meters can extract parameters and present information on each parameter well.

The Comal River estuary highlights a critical issue: human activity often increases alongside a decline in awareness about mangrove conservation. This lack of understanding threatens the very resource that benefits coastal communities. The area's designation for ecotourism is promising, but damage from human actions is already reducing its potential. Healthy mangroves are essential for a thriving ecotourism industry and sustainable fisheries (Ikbal et al., 2019).

To assess vulnerability, scientists consider physical (mangrove condition), biological (surrounding factors), and hazard (ongoing and potential threats) parameters (Yunus et al., 2018). Physical parameters like root condition, tree height, and trunk diameter require field measurements. Remote sensing can gather biological data, while hazard information comes from secondary sources. Biological parameters are prioritized in this research because those parameters are easier to collect using remote sensing data. Physical mangrove vulnerability includes mangrove conditions that are not easily observed using remote sensing and require specialized experts in the field of biology for identification. So, this study only focuses on biological parameters. This study focused on biological parameters using weighted overlay based on GIS Analysis.

RESEARCH METHODS

Research Location

This study analyses the vulnerability of mangroves in Comal Estuary, Pemalang Regency, Indonesia. The upstream of Comal River is on the northeast slope of Mount Slamet. Comal River has a length of approximately 109.18 km, flows from south to north and ends in the Java Sea. Comal River is the largest river that crosses the Pemalang Regency, Central Java. The Comal River cuts through the Pemalang district, passing through various land uses, so the Comal River estuary is very dynamic. The upstream of the Comal River has forest land use and mountainous areas, while the downstream has fish pond land use and mangroves.

Methods

Remote sensing data will be the primary tool for this analysis. The primary data used in this study is Sentinel-2A imagery. Remote sensing has some limitations, such as cloud cover in that area. The other limitation is spatial resolution related to the mangrove condition in the Comal Estuary. The mangrove in that estuary consists of more than four species that are sporadically distributed with different coverage areas, and this becomes a problem with varying pixel coverage.

Researchers conducted fieldwork downstream of the Comal River in Indonesia to collect physical parameter samples. These samples, remote sensing data, and other existing information will be used to analyze mangrove vulnerability in the area comprehensively (Figure 1). The research team employed various tools, including computers and spatial analysis software, GPS for location tracking, cameras for capturing visual data, measuring tapes for field measurements, a refractometer for salinity measurements, and drill mud and sample bottles for collecting soil samples.

Figure 1. Research Area Comal Estuary (Source: Data Processing, 2025)

The study involved several stages:

1. Pre-processing stage: Images were corrected geometrically and radiometrically to improve quality and allow for accurate information extraction.
2. Information extraction stage: Remote sensing data was used to classify the area into mangrove and non-mangrove regions. The Normalized Difference Vegetation Index (NDVI) was applied to analyze mangrove density within the classified mangrove areas. The corrected images also measured the

distance between the coastline and the mangroves.

3. Field survey stage: Fieldwork was conducted to gather information that can not be obtained from remote sensing, such as salinity, tidal range, and mud substrate. Salinity was measured directly in the field using a refractometer during the surveys. The tidal range was determined by observing tides and inundation patterns combined with existing data. Mud substrate information was obtained by collecting samples in the field and performing laboratory tests to identify the type and content of the substrate (underlying layer).
4. Mangrove vulnerability analysis stage: This stage involves scoring various parameters to assess the vulnerability of mangroves in the study area. Scores were assigned to mangrove density, distance from the coastline, salinity, and tidal range (the explanation of each parameter is below). These scores were then overlaid to create a final map of mangrove vulnerability using weighted overlay analysis. The laboratory test results for the substrate type were used as additional data for the vulnerability analysis.

The following is an explanation of the score value for each parameter:

1. Mangrove density.

Researchers can assess mangrove density using remote sensing images and applying vegetation indexes. The Normalised Difference Vegetation Index (NDVI) generated the vegetation density. This analysis measures the density of the mangrove canopy cover based on the imagery. NDVI will produce a value from -1 to 1. Vegetation has an NDVI value from 0 to 1. The closer the NDVI value to 1, the higher the vegetation density. The table below will explain the NDVI value and its vulnerability score.

Table 1. Score of Mangrove Density

Score	1	2	3	4	5
NDVI Value	>0.8	0.5-0.8	0.25-0.5	0.01-0.25	0
Type of Density	very high density	high density	medium density	low density	Non
Percentage	>80%	50-80%	25-50%	1-25%	0

2. Distance from coastline

Mangroves act as a natural barrier, weakening wave energy before it reaches the coast. This reduces erosion and protects the shoreline from abrasion caused by waves (Spalding et al., 2014). Additionally, remote sensing data can determine the distance between the mangroves and the coastline.

Table 2. Score of Distance

Score	1	2	3	4	5
Distance	very far >80m	far 60-80m	moderate 40-60m	near 20-40m	very near 0-20m

3. Salinity

Salinity, measured as the amount of dissolved salts in water, significantly impacts aquatic organisms (Subekti et al., 2020). This influence relates to the pressure salts exert on the organism's internal fluids. While the specific response of mangrove root growth to salinity varies between species, research suggests that root salt content remains stable or changes minimally even with increasing salinity levels (Krauss et al., 2014).

Table 3. Salinity Based on Mangrove Type

Types of Mangroves	Salinity Maximum (ppt)	Salinity (ppt)
Rhizophora mucronata	40	8-33
Rhizophora apiculata	60	8-15
Sonneratia alba	32	11-20
Bruguiera cylindrical	50	8-34

4. Tidal range

Tidal patterns in coastal areas, including their timing and intensity, are highly localized and influenced by various factors. These factors include the relative positions of the Earth, Sun, and Moon, deep-sea tidal patterns, specific coastline shapes, and water depth (Hubbard, 2000; Talley et al., 2011). Unsurprisingly, these variations in tides significantly impact the health and condition of coastal mangroves (Ellison, 2015). Mangroves in micro-tidal conditions will be more vulnerable than mangroves in meso-tidal conditions (Xie et al., 2022).

These parameters were then analyzed using a GIS-based weighted overlay. The results of the overlay were then categorized based on the following classification:

Table 4. Score of Tidal Range

Score	1	2	3	4	5
Tidal Range	Very low MVI <1m	Low MVI 1-1.5m	Moderate MVI 1.5-2m	High MVI 2-3m	Very high MVI >3m

Table 5. Classification of MVI

MVI	Score
Low	3 ≤ x > 7
Modetate	7 ≤ x > 11
High	11 ≤ x > 15

RESULTS AND DISCUSSION

Analysis of Sentinel-2A satellite imagery showed the spatial distribution of mangroves in the study area, located in the Delta Comal region of Pemalang Regency. The mangroves exhibit a clustered and elongated pattern, primarily situated on pond embankments and directly bordering the beach. Their density varies, with some areas exhibiting denser and taller growth than others. This variation suggests differing levels of vulnerability among the mangrove populations.

1. Mangrove Density

Sentinel 2A processing using NDVI obtained values in the range of 0.84-0.2. The data processing results show that mangroves in the Comal Delta are in the high-density to low-density class. Mangrove density and vulnerability are inversely correlated: denser mangrove forests are generally more resilient and less vulnerable to threats like coastal erosion and storm surges. In contrast, lower-density areas are more susceptible to damage (Sagala et al., 2024).

Figure 2 shows that high-density mangroves primarily dominate the Comal Delta. This is particularly evident in the formerly developed Kawasan Ekonomi Esensial (KEE) located north of the Comal River. Although damage from abrasion in early 2021 forced the abandonment of the KEE in the past two years, most of the mangroves in this region remain healthy. Field surveys confirmed that only the northern part of the KEE suffered significant damage.

Strong waves in early 2021 caused severe abrasion in the Comal River estuary. This damaged public facilities in the northern part of the KEE, destroyed fish and shrimp ponds, and even broke branches and trunks of some mangrove trees. However, the central KEE fared much better. The mangroves remain healthy and thicken and continue supporting diverse plant and animal life. Notably, the density and overall condition of the mangroves in the northern delta (including the damaged area) classify them as having low vulnerability based on their density.

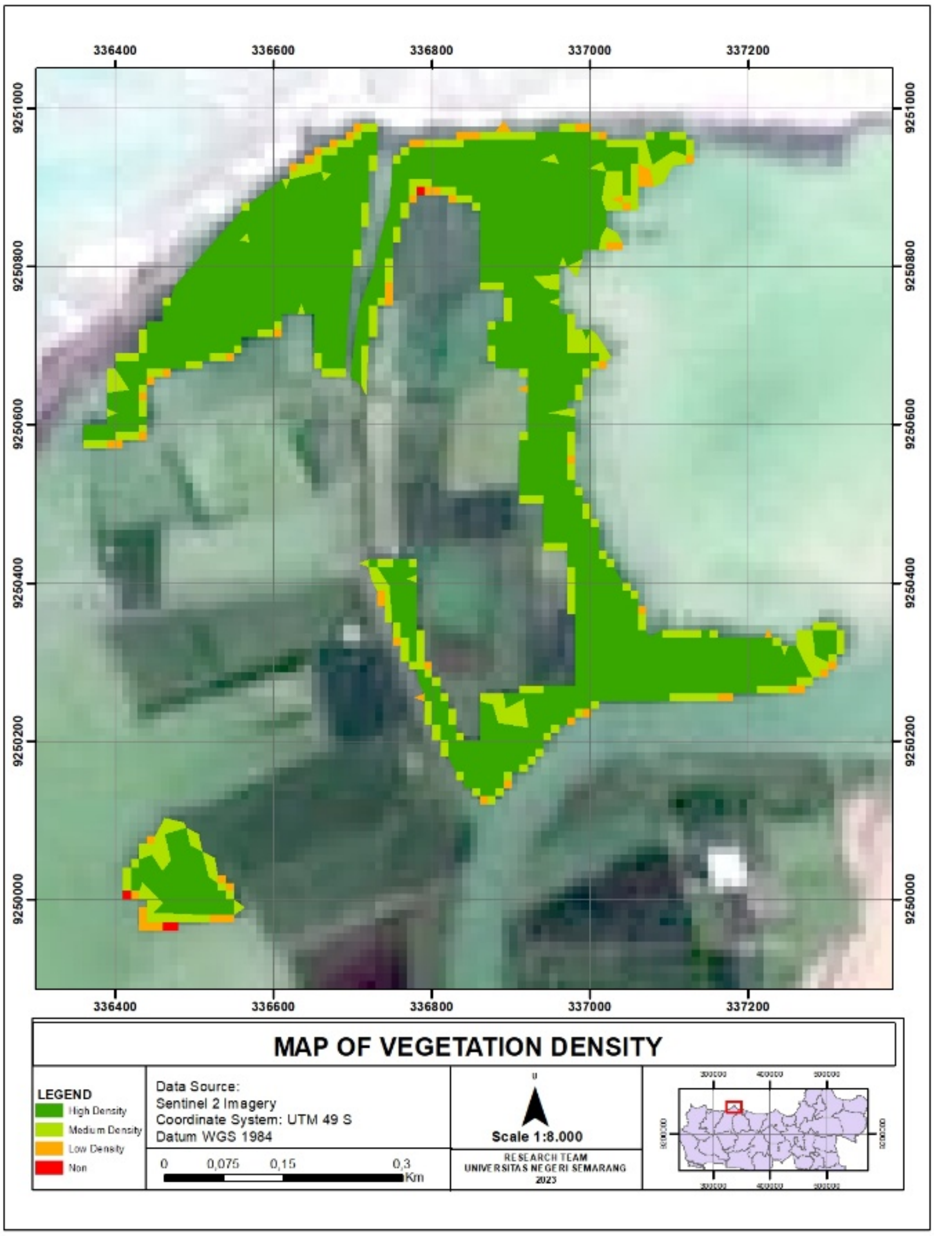

Figure 2. Mangrove Density Map (Source: Data Processing, 2025)

2. Distance from coastline

Distance from the shoreline is another important factor influencing mangrove vulnerability. Mangroves act as a natural buffer, weakening the force of waves before they reach the coast. This distance also influences the types of mangrove species that can thrive in a particular location. Areas closest to the coastline experience higher salinity and stronger wave action. These harsh conditions typically favor Avicennia mangroves, a species well-adapted to such environments.

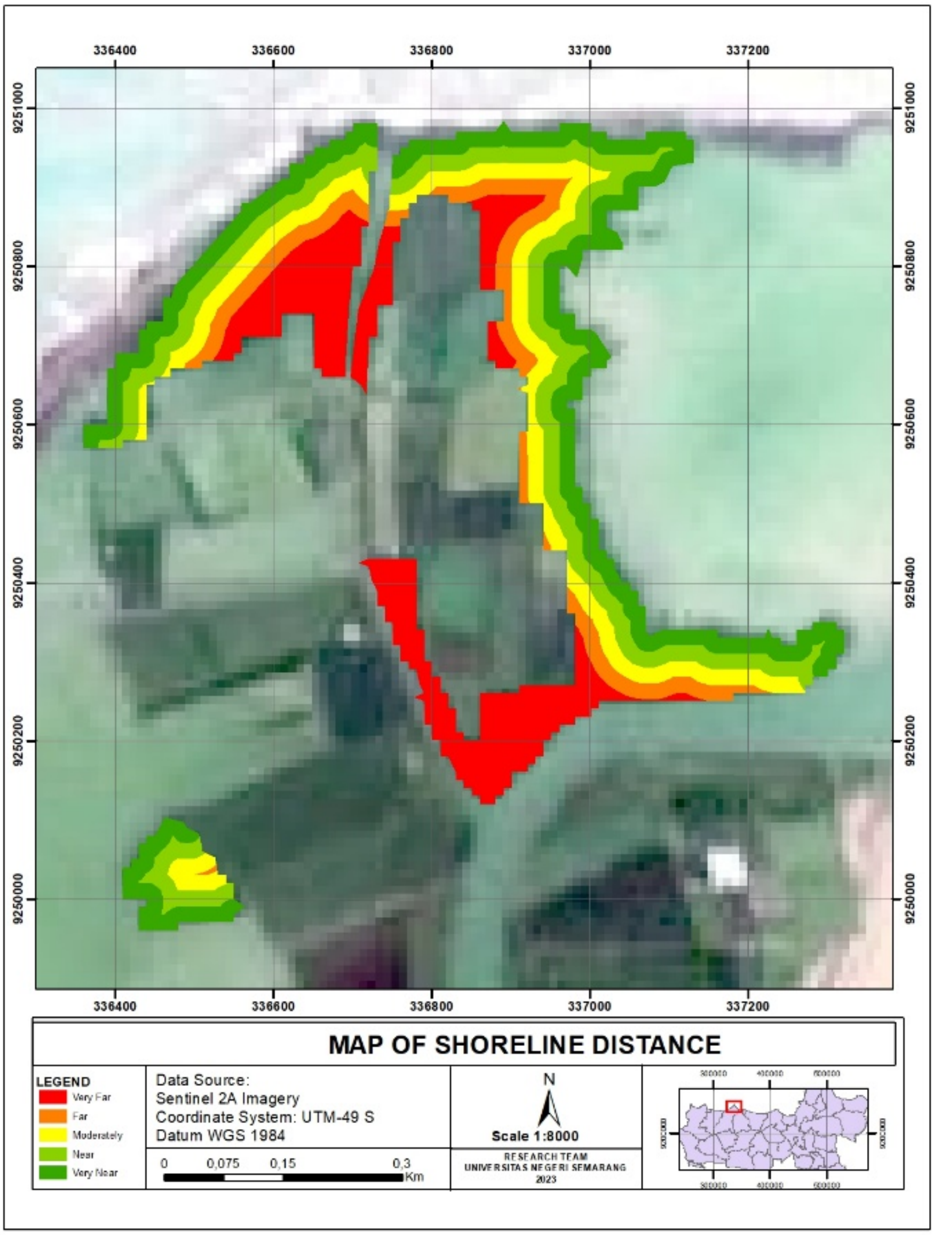

Figure 3. Distribution Map of Distance from Coastline (Source: Data Processing, 2025)

3. Salinity

Salinity levels were measured directly in the field using a refractometer. The study classified salinity into just two categories: low and normal. This classification considers the varying salt tolerance of different mangrove species. For instance, Avicennia mangroves can tolerate higher salinity compared to Bruguiera. The analysis revealed that nearly all areas of the Comal Delta mangroves have salinity levels considered normal for their respective species. This normal salinity contributes to a lower overall vulnerability for the mangroves in the delta. There are different classes in this salinity parameter because the salt tolerance of each species is very broad. So if it is more than the salt tolerance threshold of the species, it is declared as a low class, or if it is related to the scoring analysis that will be compiled, then the category is highly vulnerable, and vice versa.

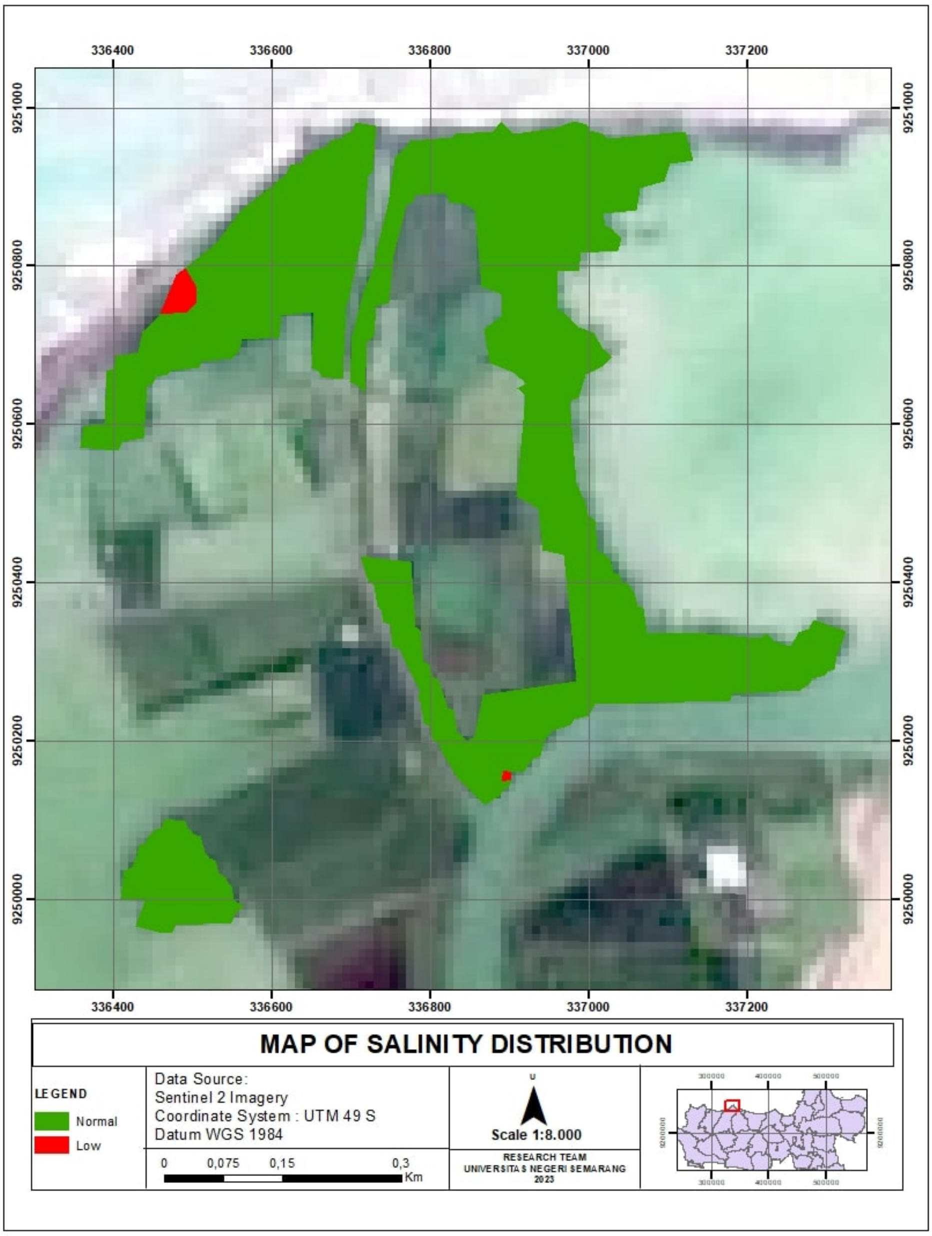

Figure 4. Salinity Distribution Map (Source: Data Processing, 2025)

4. Tidal Range

The final parameter assessed is the area submerged by tidal waters. Mangroves thrive in brackish to salty environments, relying on tides to bring seawater inland and maintain these conditions. However, excessively high tides (over 3 meters) can negatively impact mangrove health. This is because prolonged submergence in seawater can occur in areas experiencing such high tides.

Tides influence salinity levels and the physical health of mangroves. Higher wave energy associated with high tides can increase vulnerability. Figure 5 illustrates the results of tidal data analysis. The KEE and surrounding areas show low vulnerability due to tides typically less than 1 meter high. Conversely, the eastern region directly exposed to ocean waves experiences high tides, making it more vulnerable. This area was the most impacted by the high waves in early 2021, damaging mangroves and residents' ponds.

The four parameters (density, distance, salinity, and tidal range) were combined using a scoring system to generate a final mangrove vulnerability map (Figure 6). This map reveals variations in vulnerability across the Comal River Estuary. The northern estuary exhibits moderate vulnerability, the central KEE area shows low vulnerability, and the eastern portion facing the ocean has very high vulnerability

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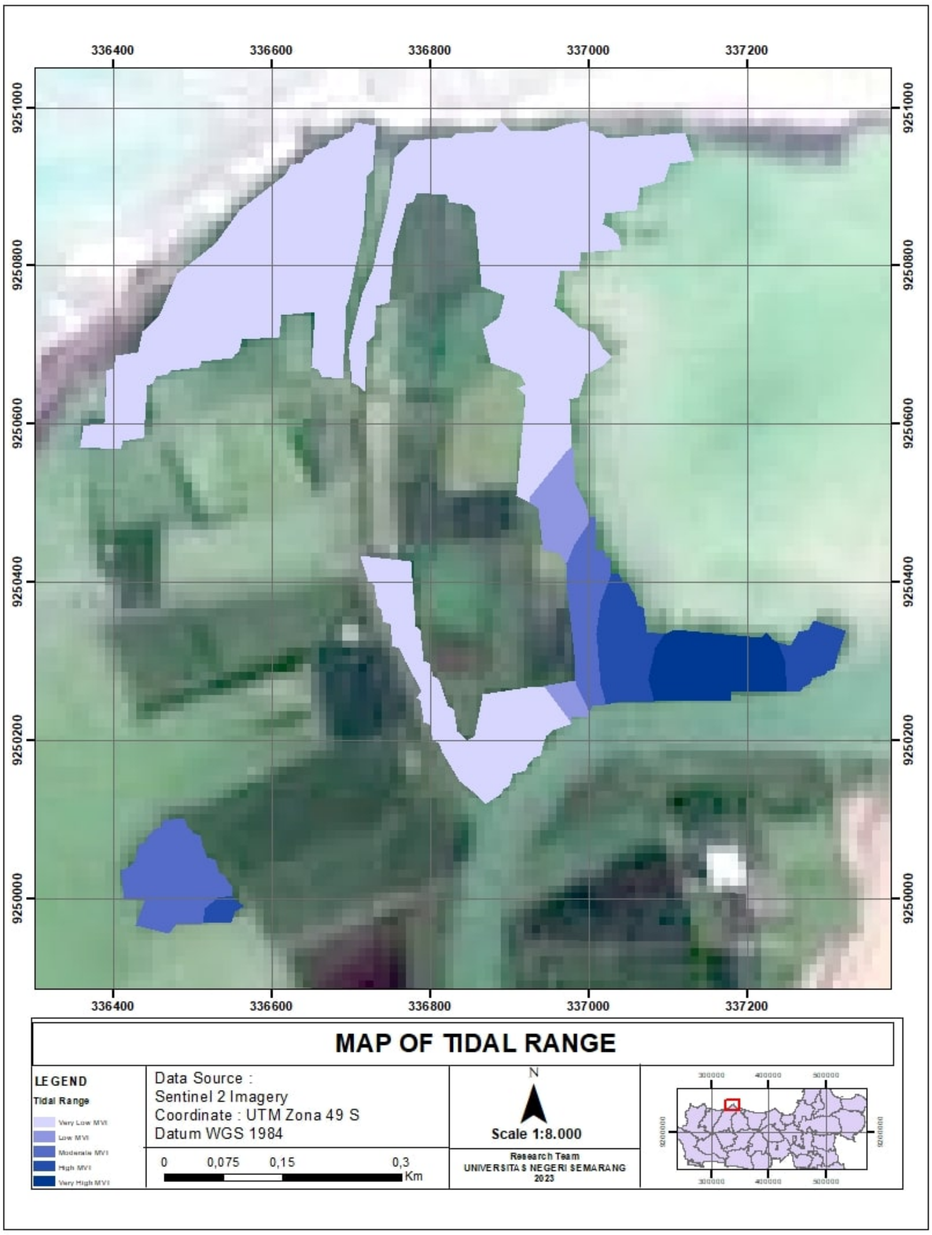

Figure 5. Tidal Range Map (Source: Data Processing, 2025)

Analysis of the four key factors - mangrove density, salinity, distance to the coastline, and tidal range - revealed a high vulnerability score for the eastern region. As a result of the scoring analysis, the Comal Delta has a 6 - 18 score divided into Low Vulnerable to High Vulnerable classes. According to Figure 9, the largest area with a highly vulnerable class is in the eastern part. This area is particularly susceptible due to high tides and proximity to the coastline. Field observations confirmed this vulnerability, with some mangrove areas directly exposed and damaged by strong waves.

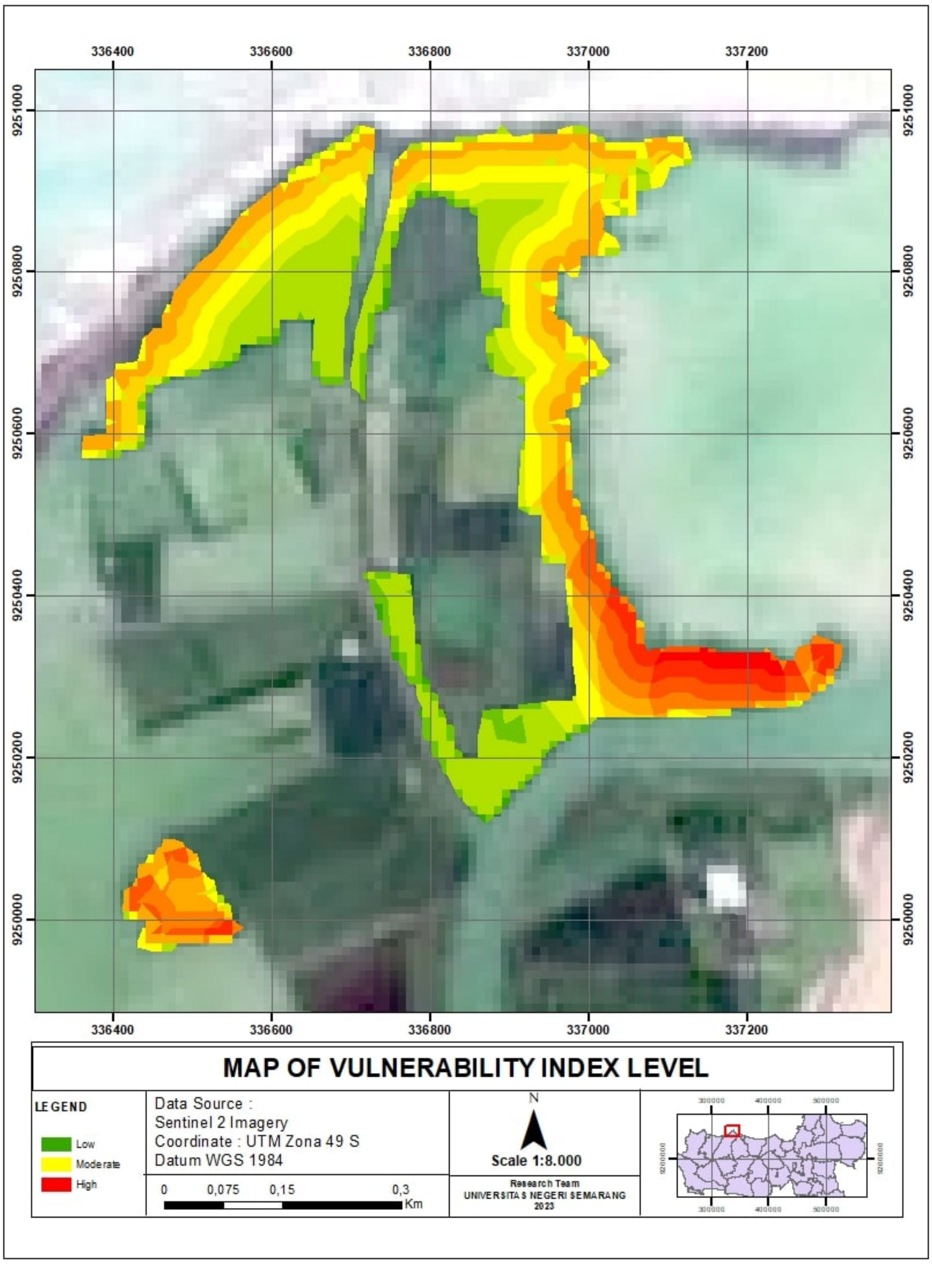

Figure 6. Mangrove Vulnerability Map (Source: Data Processing, 2025)

Strong waves are the primary culprit behind mangrove damage in the Comal River Delta. The biggest wave abrasion happened in 2021; most of the fish ponds in that area were destroyed by waves, and farmers no longer used them. In addition, mangroves that function as pond barriers have also been damaged, making it impossible for farmers to repair the entire fish pond that has been damaged.

Field observations also point to substrate type as a contributing factor. Since coastal ecosystems are highly dynamic and susceptible to change due to natural processes, some areas exhibit Rhizophora trees growing in sandy substrates. This is problematic because Rhizophora thrives in muddy environments and struggles to grow optimally or survive in sand. Furthermore, pollution and the presence of garbage likely play a role in exacerbating mangrove death and damage.

During this research, discussions were also held with relevant stakeholders, including the Pemalang Regency Fisheries Office and mangrove and pond activists. The results of these discussions show that the community understands the importance of protecting mangroves. Many Corporate Social Responsibility (CSR) programs have been implemented, but not all have shown good results. The biggest cause of unsuccessful mangrove planting programs is the destruction of mangroves after planting. Strong waves and the unsuitability of the species of mangrove planted dominate the damage. This is influenced by the lack of knowledge about the region's condition of mangroves. Based on this research, we suggest stakeholders implement innovation for mangrove sustainability in Delta Comal.

For the wave abrasion problem, the researcher suggested building a wavebreaker before the newly planted mangrove seedlings. Wave breakers function to reduce the energy that reaches the mangrove seedlings. Mangrove seedlings still do not have strong roots, so they are vulnerable to strong waves. Previously, the community had made a wave breaker in the form of a concrete barrel, but the wave breaker was easily damaged when the waves were too strong, so it could still not protect the mangrove seedlings. PT Pertamina Hulu Energi has patented an innovative wavebreaker that has a shark tooth formation. The shark tooth formation resembles a shark's tooth, in the form of a zigzag sequence composed of units in the form of a 3-dimensional structure of isosceles, triangles made of wood and bamboo embedded in the substrate/soil. Within the shark tooth units, mangrove saplings are planted tightly in clumps. With this formation, it has been proven that mangrove seedlings can grow well without too much wave energy (PT Pertamina Hulu Energi Offshore North West Java (PHE ONWJ), 2023). This method has never been applied in Pemalang, so for the next period, wave breakers will be tried as one of the steps for mangrove conservation.

CONCLUSION

The vulnerability of mangroves in the Comal estuary is not uniform. The northern part faces moderate vulnerability, the central KEE area has low vulnerability, and the eastern region experiences very high vulnerability. Tidal factors significantly influence these vulnerability levels. Strong waves associated with high tides can damage mangroves, causing broken branches and trunks and eroding coastal areas, altering the substrate.

This study leverages the efficiency and effectiveness of remote sensing technology. Two of the four parameters to assess vulnerability were obtained remotely, while the other two required direct field measurements. It is important to note that traditional vulnerability assessments consider three parameters: hazard, biological, and physical. Here, the focus was solely on the biological parameter (mangrove condition). The vulnerability values aligned well with field observations despite using only one parameter. However, incorporating physical and hazard parameters in future research would yield more accurate results.

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