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Historical Analysis of Mangrove Ecosystems Changes in Tidal Disasters-Prone Areas Using Remote Sensing

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ABSTRACT

Mangrove ecosystems are vital for human livelihoods, but ongoing exploitation and natural disturbances have led to significant land use and cover changes. Therefore, this study aimed to identify trends regarding land cover (LC) changes in mangrove ecosystems using remote sensing. LC changes from 1988 to 2024, as observed using remote sensing techniques. Satellite imagery from Landsat 5 TM, Landsat 7 ETM+, Landsat 8 OLI/TRIS, and Landsat 9 OLI/TRIS was analyzed using the Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), and a newly developed Combined Mangrove Recognition Index (CMRI). The results revealed four distinct phases of LC change over the study period (1988–2024), starting from 1988 to 1989, during which 12.14 ha of mangrove forest were documented. The second phase, spanning from 1990 to 1994, witnessed the onset of anthropogenic disturbances in pond area expansion, totaling 41.04 ha. The third phase, which spanned from 1995 to 1998, featured abrasion, resulting in 11.56 ha reduction in the area covered. Natural ecosystem recovery began in 1998 and continued with human intervention in the fourth phase from 2008 to 2024, resulting in an increase in mangrove forest LC by 62.57 ha. The study demonstrates the utility of remote sensing in documenting ecological changes over time and provides critical insights for sustainable coastal management and policymaking in vulnerable urban coastal zones.

Introduction

Mangrove forests are located in the intertidal zone and are frequently influenced by tides [1], whereas constituent trees grow in wetlands and tolerate varied salinity levels. Furthermore, roots grow above the soil surface to obtain oxygen because of the wetness of the site [2], and the forest provides economic, social, and ecological benefits. The community gains economically from mangrove forests because of their application as an aquaculture site [3] for shrimp farming. Regarding the social aspect, mangroves have a spiritual meaning for Indonesians because they are connected to their customs and culture [4]. At the same time, ecological benefits include the use of marine biota as a habitat and food source. Mangroves play a significant ecological role in mitigating climate change owing to their carbon storage capacity. Compared to other land cover (LC) types, including rainforest, peat forest, salt marshes, and seagrass meadows, it can store 956 Mg of carbon per ha [5]. Mangrove forests can counteract sea level rise by 7 mm/year by trapping sediment and building peat, absorbing carbon, and reducing global warming [6].

During development, mangrove ecosystems tend to be damaged by natural or anthropogenic disturbances, leading to negative effects on their functions. Abrasion is a disturbance caused by nature that can occur due to anthropogenic activities [7]. Examples of anthropogenic human activities that disrupt ecosystems include converting mangrove forests into settlements, industries, ponds, and agricultural land [8]. The conversion of mangrove forests into ponds leads to significant carbon stock loss, especially in the soil, where excavation depths range from 0.5 to 2.5 meters [9]. This exacerbates the release of stored carbon into the atmosphere,

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thereby contributing to climate change. The coastline of Semarang City has changed over 45.72 km since 1972, resulting from 165.95 ha of accretion and 46.77 ha of abrasion [10]. The most common areas experiencing abrasion include eastern Genuk, western Tugu, and the north Semarang Subdistrict [11]. Abrasions can damage facilities as well as other land uses, leading to a loss in the area along the coast. The occurrence of abrasion is also attributed to the function of mangrove forests, with their inability to withstand sea waves properly, which promotes easy tidal flooding [12]. The impacts of deforestation can be detrimental to the economy and welfare of communities when left unaddressed, thereby reducing ecosystem sustainability [13,14].

Following the occurrence of abrasion, mangrove forests experience ecosystem recovery that is supported by the addition of land (accretion) to facilitate planting in affected sites. According to previous studies, sediment movement parallel to the shore and current patterns are the main causes of the accretion tendency primarily observed in the western part of Semarang City [15], where the accretion incidence started to increase between 1991 and 2001 [16]. This ecosystem recovery occurs in two ways: natural tree growth and through human assistance. In the meantime, communities, non-governmental organizations (NGOs), the government, academics, and commercial areas engage in rehabilitation activities as part of human restoration efforts. The implementation of a silvofishery system that combines ponds with mangrove plants is another way to repair ecosystems. Silvofishery has been believed to be a community-based strategy that considers both conservation and commercial benefits [17–19].

Long-term assessment of LC can promote learning from the historical loss and gain of mangrove vegetation as well as the provision of warnings about potential damage. This activity includes LC monitoring to prevent damage that exceeds the recovery ability of ecosystems. Information regarding changes in land use and land cover (LULC) can be obtained from long-term assessments. Managers can use LULC data to assess and monitor future sustainable mangrove forest LC, specifically in natural conservation efforts [20]. According to previous studies, assessment activities provide information about LC change trends [21], which can be used to enhance ecosystem management [22]. The land area covered by both lost and gained mangrove forests is a key indicator of ecosystem sustainability and preservation. The suppression of anthropogenic activities that disrupt mangrove ecosystems is an effective means of ensuring the sustainability and preservation of these ecosystems. Long-term assessment of changes in mangrove landscape trends, natural factors, and anthropogenic disturbances will provide scientific support for mangrove ecosystem conservation and restoration [23].

An alternate method for conducting long-term assessments is remote sensing, which is commonly used to monitor alterations in geographical scope and clarify the reactions of mangrove forest areas to climate change and the impacts of human activities [24]. Managers also use it to collect a wide range of data over an extended period in hazardous areas with challenging terrain for human safety, and to identify and measure LC loss initiated by anthropogenic activities [25]. Landsat satellite imagery is applied as important data in long-term assessment due to possessing a temporal dimension of more than 40 years [26]. Therefore, this study aimed to identify LC change trends in mangrove ecosystems using remote sensing. The results should provide insights into trends that can support decisions on sustainable management to preserve ecosystems and benefit both the present and future generations.

Material and Method

Study Area

This study was conducted in a mangrove forest located in Mangunharjo Village, Tugu District, specifically in the western area of Semarang City, north of the Java Sea (Figure 1). Mangunharjo Village is geographically located between 6°56’10”–6°58’20” S and 110°17’50”–110°19’40” E with a total area of 435.95 ha and a coastline of 3.5 km^2, where mangrove rehabilitation is performed in Indonesia [27]. The community manages ponds through a silvofishery system that combines ponds and mangrove plants to preserve the forest. The air temperature ranged from 20 to 30 °C, with an average temperature of 27 °C.

Material

The Landsat series, including Landsat 5 TM, Landsat 7 ETM+, Landsat 8 OLI/TRIS, and Landsat 9 OLI/TRIS, with a spatial resolution of 30 × 30 m, was used as medium-resolution satellite imagery. Landsat satellite images offer long-term imagery, thereby providing a useful tool for assessing vegetation over time [28]. Google Earth Engine (GEE) was used to gather and classify Landsat series imagery. GEE is the most recent platform capable of readily managing vast amounts of satellite data [29]. Top-of-atmosphere (TOA) reflectance images were selected to perform geometric and radiometric corrections.

Figure 1. An outline of a mangrove forest located in Mangunharjo Village, Tugu District, Semarang City.

Method

Imagery Classification

Three stages of vegetation index calculation, including the normalized difference vegetation index (NDVI), normalized difference water index (NDWI), and combined mangrove recognition index (CMRI), were used to conduct the picture classification process. The NDVI index used to detect vegetation in the study area incorporated the Near Infra Red (NIR) and red bands (Equation 1). According to the NDVI principle, the radiation of the red band is absorbed by chlorophyll, and the leaf structure reflects it through the mesophyll tissue [30]. The NDWI index, implementing both the green and NIR bands (Equation 2), was used to define wetlands and exclude any area comprising soil and terrestrial vegetation [31]. NDVI and NDWI can be combined using the recently developed CMRI index (Equation 3), which is effective for differentiating mangrove and non-mangrove vegetation [32,33].

$$NDVI = \frac{Band\ NIR - Band\ red}{Band\ NIR + Band\ red} \quad (1)$$

$$NDWI = \frac{Band\ green - Band\ NIR}{Band\ green + Band\ NIR} \quad (2)$$

$$CMRI = NDVI - NDWI \quad (3)$$

The index calculation results were classified into five LC classes: seawater, mangroves, ponds, vacant land and buildings, and non-mangrove vegetation (Table 1). This classification was determined by modifying the studies performed by Gupta et al. [32] to adjust field conditions. The LC classes used by Gupta et al. [32] were water dominance, mangrove dominance, non-mangrove vegetation, and non-vegetation, including barren land, settlement, and muddy and sandy soil. The process of integrating remote sensing to identify trends in LC changes in mangrove ecosystems could be seen in Figure 2.

Table 1. LC definitions in this study are based on modified SNI 7645-1:2014.

No.	LC Classification	Definition
1.	Seawater	All types of marine waters, including deep and shallow waters.
2.	Mangrove	Wetland forest impacted by tides with a muddy and brackish appearance.
3.	Ponds	A constructed body of water located on the coast has access to seawater and freshwater. Ponds are typically defined by bund-like barriers, a modest pond size, and the use of aquaculture.
4.	Vacant land/ buildings	This classification describes open land whose surface has undergone pavement or structural reinforcement, including mixed buildings, i.e., settlement and associated buildings of other functions.
5.	Non-mangrove vegetation	This classification refers to dry land covered by non-mangrove vegetation, such as agriculture and grasses.

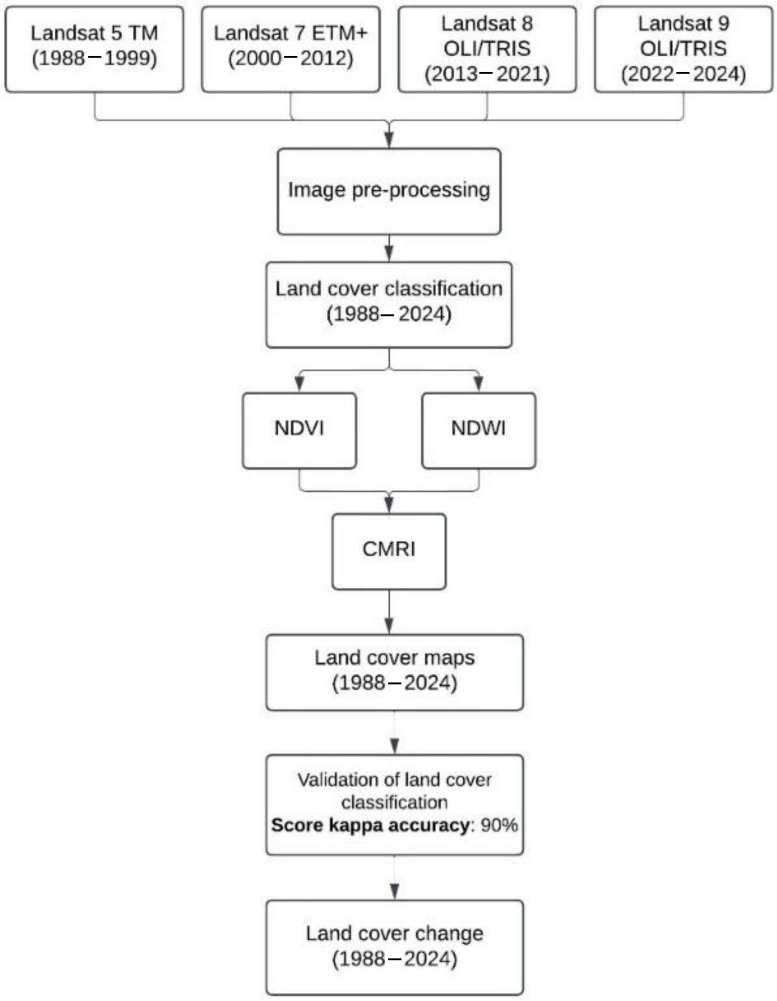

Figure 2. Research flowchart integrating remote sensing to identify trends in LC changes in mangrove ecosystems.

Validation

Validation was performed by comparing the classification results from the 2024 Landsat imagery to the appearance of objects in the field. The Landsat classification of the images prior to 2024 was validated using the 2024 pixel value range. This assumes that the land cover of seawater, mangroves, ponds, vacant land/buildings, and non-mangrove vegetation before and after 2024 will have the same pixel range. This featured 45 samples selected from locations determined using purposive sampling methods based on certain considerations such as ease of access and user certainty during classification. The validation process included determining the values of kappa, user, and producer accuracies. Kappa accuracy was computed with the Fultriasantri and Fajrin [34] formula (Equation 4), while the formulas stated by Islami et al. [35] were used to calculate user and producer accuracy, as shown in Equations 5 and 6, respectively.

Kappa Accuracy = $[(\sum_{i=1}^{r} X_{ij} - \sum_{i=1}^{r} X_i X_i)/(\sum_{i=1}^{j} X_i X_i) \times 100\%$ (4)

User accuracy (UA) = $\frac{x_{ii}}{R_i}$ (5)

Producer accuracy (PA) = $\frac{x_{ii}}{C_i}$ (6)

X_i : Number of Samples in the i-th Row

X_{ij}: Diagonal Value of the I-th Row and i-th Column Contingency Matrix

x_{ii} : Number of correctly classified pixels in each category

R_i : Total number of reference pixels in the category (total rows)

C_i : Total number of reference pixels in the category (column total)

Result

Validation

The kappa accuracy values show that the 2024 image classification is usable, where 90% (Table 2) signifies nearly perfect agreement [36]. The kappa accuracy score reflects the level of agreement between the satellite image classification results and ground conditions. The level of agreement increased with the kappa accuracy score. Furthermore, the 2024 LC classification serves as a guide for calculating the types of LC existing before 2024, assuming that the LC on seawater, mangroves, ponds, and vacant land/buildings all have the same pixel range. Meanwhile, the NDWI detected non-mangrove vegetation LC between 1988 and 2010.

Table 2. The accuracy test in 2024 uses a confusion matrix.

Confusion matrix		Groundcheck						
		Seawater	Ponds	Vacant land/building	Mangrove	User total	User accuracy (%)	Producer accuracy(%)
Landsat 2024	Seawater	2	2	0	0	4	50.00	100
	Ponds	0	11	1	0	12	91.67	85
	Vacant land/building	0	0	10	0	10	100	91
	Mangrove	0	0	0	20	20	100	100
	Producer total	2	13	11	20	46	-	-

Land cover change from 1988 to 2024

The analysis results of 1988–2024 images showed changes in mangrove forest LC, which were divided into four phases (Figure 3). During the first phase, from 1988 to 1989, 12.14 ha of mangrove forest still remained on the coast of Mangunharjo Village (Figure 3a). Land use in the form of ponds remained safe and was subsequently seen as a viable enterprise by the community. This led to the second phase from 1990 to 1994, when the community in the study area expanded to windu shrimp ponds (Figure 3b). Abrasions in the study area were observed in the third phase, which occurred from 1995 to 1998 (Figure 3c). After the abrasion described in the third phase, various actors tried to recover mangrove forest ecosystems naturally or through human intervention. This recovery process is described in the fourth phase between 1999 and 2024 (Figure 3d).

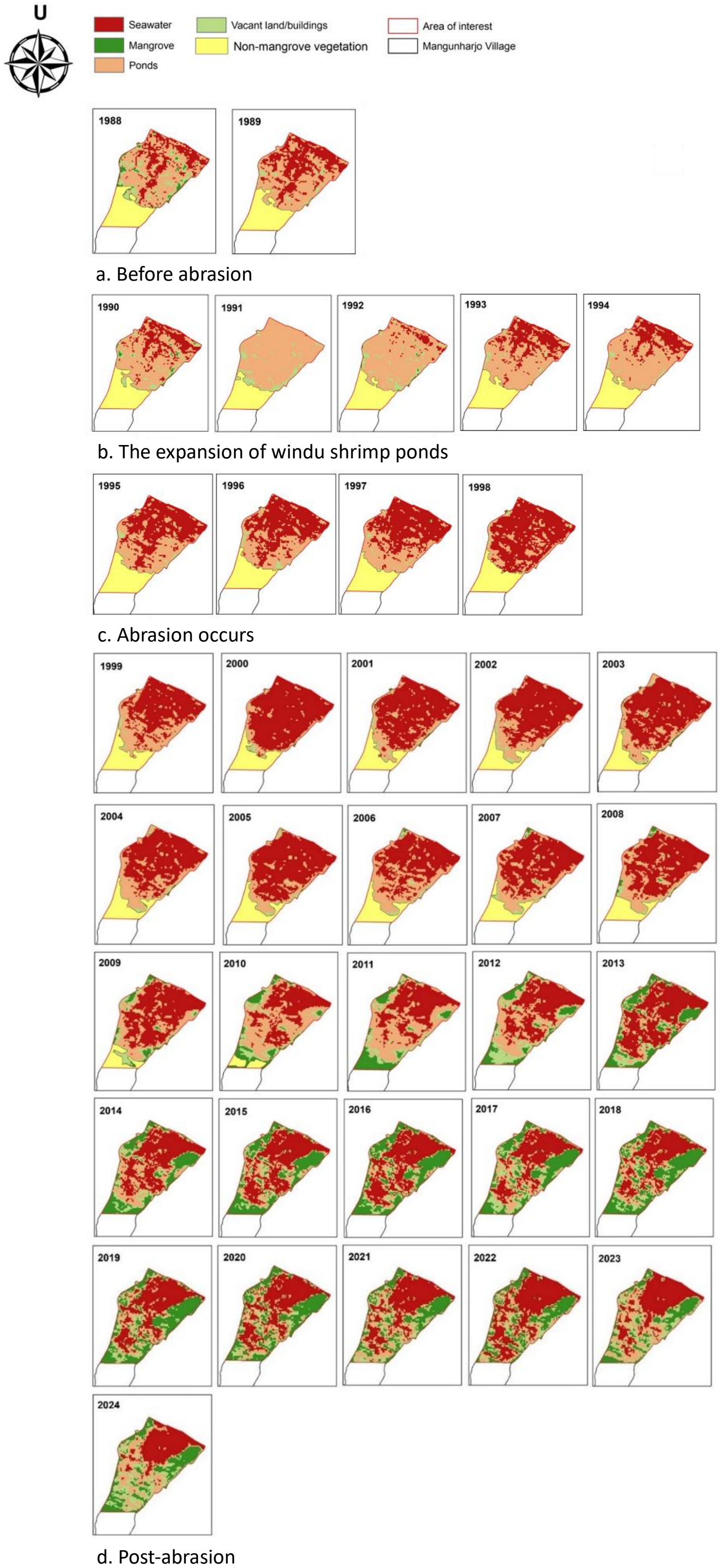

Figure 3. Mangrove forest LC changes in Mangunharjo Village, (a) Before abrasion in 1988–1989, (b) The expansion of windu shrimp ponds in 1990–1994, (c) During abrasion in 1995–1998, (d) Post-abrasion in 1999–2024.

Following the abrasion, the Mangunharjo Village community became more aware of the importance of protecting mangrove forest ecosystems. They began collaborating by planting mangrove plants in their ponds, using a technique known as silvofishery. The silvofishery systems followed a komplangan pattern, but three different silvofishery patterns were occasionally combined in each pond. The first, second, and third patterns used mangroves planted at the edge of the pond (Figure 4a), in the alley (Figure 4b), and in the center of the pond, respectively (Figure 4c). The entire record of monitoring LC changes from 1988 to 2024 is provided as stacked bars, showing that observation of the growth in the mangrove forest ecosystem LC started in 2008 (Figure 5). However, in 2010, a decrease in land covered by non-mangrove vegetation was detected, signifying that more people were aware of the need to increase the area of mangrove forest LC.

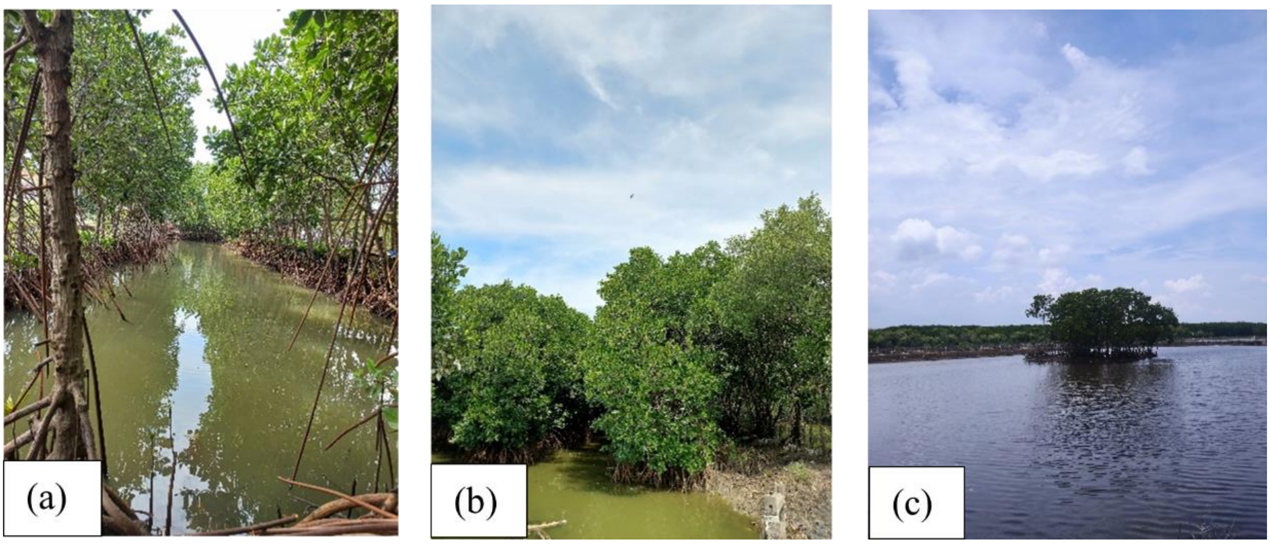

Figure 4. Farmers who integrate mangrove plants into their pond land utilize a variety of silvofishery patterns, such as (a) mangroves planted at the edge of the pond, (b) mangroves planted in the alley, and (c) mangroves planted in the center of the pond.

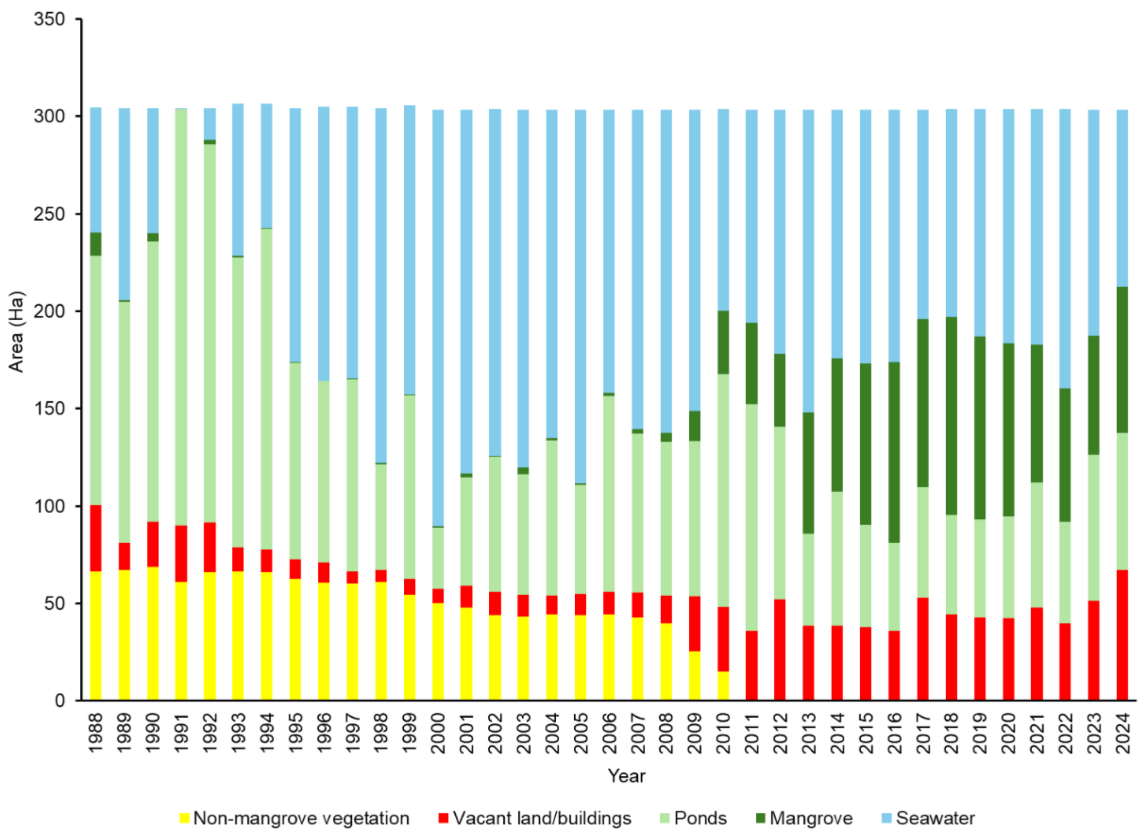

Figure 5. Mangrove forest LC change trends at Mangunharjo Village from 1988 to 2024, depicted as stacked bars.

Discussion

Changes in mangrove forest LC in this study were divided into four phases (Figure 3). From 1988 to 1989, there were still 12.14 ha of mangrove forests on the coast of Mangunharjo Village. This was the initial phase of the mangrove forest LC (Figure 3a). The development of the second phase, which occurred from 1990 to 1994, was triggered by community activities to expand the windu shrimp ponds (Figure 3b). This was because of the community's view of the windu shrimp pond as a viable business. The rise in pond activities caused a decrease in LC, which initiated damage to the mangrove forest ecosystems. This was consistent with Hadiyanto et al. [37], who attributed the loss of mangrove forest area in Mangunharjo Village to land conversion into ponds and illegal logging.

The existence of dense mangroves helps to minimize seawater waves through bottom friction [38]. When the extent of the LC decreases, there is no defence against sea waves, thereby leading to abrasion. According to Da Costa et al. [39], damaged mangrove forest ecosystems cause abrasion and a decrease in biodiversity. In accordance with the findings of the study, the loss of mangrove LC caused abrasion in the study area during the third phase, from 1995 to 1998 (Figure 3c). This abrasion leads to a 50% loss of mangrove forest ecosystems in Mangunharjo Village [37]. The abrasion process begins when wind-driven waves approach the beach, generating turbulence that moves debris from the bottom or causes beach sand erosion [40]. The absence of mangrove forests to safeguard the beach will initiate settlement collapse and damage public infrastructure [41].

Abrasion disasters have led to efforts by various actors to recover mangrove forest ecosystems. In Mangunharjo Village, the mangrove forest ecosystem is recovering both naturally and through human intervention. This recovery process, which is depicted in the fourth phase (Figure 3d), occurred between 1999 and 2024, during which the mangrove forest LC increased by 62.57 ha. The onset of natural recovery occurred in 1998 when mangrove trees in Mangunharjo Village started growing naturally. Furthermore, human-assisted recovery began with public awareness of the environment, specifically mangrove ecosystems. In 2002, the planting of *Avicennia* sp. and *Rhizopora* sp. was commenced as evidence of environmental awareness. The community plays an active role in mangrove rehabilitation because of the importance of maintaining ecosystems to prevent environmental damage capable of decreasing human quality of life [42], and settlements began to flood. Additionally, rehabilitation activities in Mangunharjo Village were conducted by the community, academics, NGOs, and local governments [43]. This will promote a continuous increase in the area covered by mangrove forests until 2024, while the deflection of river currents will contribute to planting success. Previous investigations have shown that accretion or land gain occurring largely between 1991 and 2001 [17] in the western area of Semarang City was caused by current patterns and sediment movement parallel to the coast [16].

The entire record of monitoring LC changes from 1988 to 2024 is provided as stacked bars, showing that observation of the growth in mangrove forest ecosystem LC started in 2008 (Figure 4). However, in 2010, a decrease in land covered by non-mangrove vegetation was detected, signifying that more people were aware of the need to increase the area of mangrove forest LC. A substantial expansion in LC is the outcome of efforts by the community and other stakeholders to enhance the environment. Mangrove forest LC in Mangunharjo Village can be increased through community-based management (CBM). According to Hasani et al. [44], community-based and multistakeholder management are successful strategies. Porter-Bolland et al. [45] also found lower deforestation rates in tropical forests managed by communities than in those protected by the state.

Increased LC has positive consequences for mangrove forest ecosystems in Mangunharjo Village. A study by Khairunnisa [46] showed that rehabilitation success in Mangunharjo Village impacts physical, biological, and social aspects. The physical condition of the mangrove forest in Manguharjo Village experienced additional sedimentation following rehabilitation activities. Biological conditions include increased LC area, mangrove density, and biodiversity. This area expansion will improve environmental quality and promote its use as a habitat for aquatic biota. According to Retnaningdyah et al. [47], the success of restoration is reflected in mangrove vegetation expansion, improved physical and chemical quality of the environment, and diversity of macrozoobenthos, including crustaceans and gastropods, which serve as bioindicators. In addition, increasing the mangrove forest LC may be beneficial to the community. Forest ecosystems can protect settlements from high sea waves and tidal floods by trapping sediment particles to slow water movement through buffering from sedimentation and mangrove formation. Mangrove stems, roots, pneumatophores, and animals inhabiting aboveground parts can increase water friction to achieve slower movement [48]. Long-term monitoring of mangrove ecosystems using remote sensing can assist managers in tracking the conditions of these ecosystems, including whether the mangrove area has grown. According to studies [49], conducted in Bangladesh's Harinbanga and Baleshwar rivers, which similarly use remote sensing for long-term monitoring, there is a tendency toward less mangrove cover as a result of anthropogenic human activity.

Mangrove forest LC continually increases until 2024 owing to silvofishery implementation, an alternative to sustainable pond development that does not reduce community welfare while contributing to ecosystem conservation [19]. By applying the silvofishery system by farmers, combining ponds with mangrove plants can expand the forest area (Figure 3). According to several studies, applying silvofishery with a 60% mangrove and 40% pond ratio will balance the economic and ecological conditions. This implies that community welfare can be improved by preserving mangrove ecosystems [50–54]. The application of silvofishery can reconcile biodiversity benefits with aquaculture productivity [4]. In addition to land used as ponds, farmers plant mangroves to protect them from environmental damage. The silvofishery systems followed a komplangan pattern, but three different silvofishery patterns were occasionally combined in each pond. The first, second, and third patterns used mangroves planted at the edge of the pond (Figure 3a), alley (Figure 3b), and center of the pond, respectively (Figure 3c).

Conclusion

In conclusion, this study highlights four distinct phases of land cover change in Mangunharjo Village, offering valuable insights into the dynamics of mangrove ecosystems under human and natural influences. The first occurred between 1988 and 1989, during which 12.14 ha of mangrove forest LC was found on the coast of Mangunharjo Village in 1988. Additionally, the second phase ranged from 1990 to 1994, featuring LC disruptions caused by anthropogenic activities, such as the expansion of the windu shrimp pond community, which led to an LC increase of 41.04 ha. The third phase, spanning from 1995 to 1998, showed an 11.56 ha LC decrease caused by abrasion due to increased pond activities. The fourth phase (1999–2024) marks the recovery of the ecosystem, largely driven by community-based conservation efforts, which led to an increase of 62.57 ha of mangrove forest. These findings highlight the importance of monitoring mangrove ecosystems to assess growth. As a result, a long-term monitoring policy for mangrove ecosystems is required in rehabilitation activities to determine the success of rehabilitation in mangrove ecosystems.

Authors Contributions

AVYP: Conceptualization, Methodology, Investigation, Writing; **RS:** Conceptualization, Review, Editing, Supervision; and **EP:** Conceptualization, Review, Editing.

Conflicts of interest

There are no conflicts to declare.

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