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Hydrological restoration of abandoned aquaculture ponds in North Kalimantan, Indonesia

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Abstract. *Basyuni M, Rouf RA, Amelia R, Aznawi AA, Mubaraq A, Wiyono EB. 2025. Hydrological restoration of abandoned aquaculture ponds in North Kalimantan, Indonesia. Asian J For 9: 232-250.* The widespread conversion of mangrove forests to aquaculture ponds in North Kalimantan, Indonesia, has disrupted tidal hydrology, altering salinity and habitat complexity, ultimately threatening coastal biodiversity and essential ecosystem functions. This study implemented a data-driven hydrological restoration strategy, using high-resolution tidal inundation, current, and salinity data collected from 21 mini buoy stations at three locations in North Kalimantan: Salimbatu Village, Liagu Village, and Tanjung Selor, to classify hydrological zones and guide restoration interventions precisely. The tidal inundation duration ranged from 34 to 535 minutes per cycle, depicting distinct hydrological classes supporting various mangrove groups, including *Sonneratia alba*, *Rhizophora apiculata*, *Bruguiera gymnorhiza*, and *Nypa fruticans*. Restoration priorities were based on Normalized Difference Vegetation Index (NDVI) mapping, with low NDVI areas (<0.3) targeted for direct planting, medium NDVI areas (0.3-0.7) for Assisted Natural Regeneration (ANR), and high NDVI areas (>0.7) indicating ongoing recovery. Restoration resulted in a 25-40% increase in NDVI, salinity regulation within the range of 10-16 ppt, and the recovery of five dominant mangrove species: *Rhizophora apiculata*, *R. stylosa*, *Avicennia marina*, *S. alba*, and *Xylocarpus granatum*. Restoration efforts included the installation of sluice gates and excavation of tidal channels with pond–mangrove reconnection, which increased tidal inundation depth by 25-35 cm in 953.61 ha of active and abandoned fish farms. The restoration program plan implemented in Salimbatu and Liagu Villages used three schemes: direct planting (524 ha), silvofishery (324.81 ha), and ANR (104.8 ha), which resulted in clear signs of ecological recovery, including the natural regeneration of key mangrove species. This integrated approach demonstrated that hydrology-based restoration, when combined with adaptive vegetation management, silvofishery, and community governance, is effective in rehabilitating degraded mangrove landscapes while enhancing ecological resilience and livelihoods. This data-driven strategy offers a scalable and climate-resilient solution aligned with Indonesia's FoLU Net Sink 2030 initiative.

Keywords: Community engagement, hydrological connectivity, mangrove restoration, NDVI, silvofishery

Abbreviations: CCB: Carbon, Community, Biodiversity, FoLU: Forestry and Other Land Use, KUPS: Social Forestry Business Groups, LPDH: Village Forest Management Institution, NDVI: Normalized Difference Vegetation Index, REDD+: Reducing Emissions from Deforestation and Degradation, + referring to additional forest-related activities that protect the climate, RTK GPS: Real-Time Kinematic Global Positioning System, UAV: Unmanned Aerial Vehicle

INTRODUCTION

Hydrological disturbances in aquaculture ponds, especially abandoned ponds, pose critical challenges to restoring mangrove ecosystems in Indonesia. Mangroves provide essential ecological functions, including shoreline stabilization, carbon sequestration, aquatic habitat provision, and support for local livelihoods through fisheries and forestry products (Das et al. 2022). Across Southeast Asia, particularly Indonesia, mangrove areas have declined by approximately 40% due to aquaculture expansion, infrastructure development, and hydrological disturbances (Liew et al. 2020; Akram et al. 2023; Anggoro et al. 2025). Abandoned ponds obstruct tidal flows, compromising ecosystem services and decreasing long-term survival rates of mangrove seedlings to 10-20% (Primavera and Esteban 2008; Duncan et al. 2016). Adequate restoration of tidal flow is vital to supplying sediments that elevate land surfaces and stimulate mangrove recovery within ponds previously isolated by pond walls.

Large-scale mangrove restoration projects in Indonesia have often failed to achieve sustainable outcomes because they prioritize direct mangrove planting without restoring critical hydrological connectivity (Sidik et al. 2025). The Ecological Mangrove Restoration (EMR) framework emphasizes restoring hydrological functions first—reconnecting ponds to mangroves via sluice gates and tidal channels, recalibrating flood frequency, and re-establishing elevation gradients before planting begins (Van Loon et al. 2016; Djamaluddin et al. 2019; Lewis et al. 2019). For example, restoration involving tidal channel excavation and sluice gate installation has increased tidal inundation by 30 cm, reopened connectivity over 150 hectares, and raised natural mangrove seedling density by over 70% within two years (Lewis et al. 2019).

Building on Watson's (1928) foundational work on species-site matching according to tidal inundation and salinity gradients, recent advances have refined species zonation models. Species such as *Avicennia* and *Sonneratia* are adapted to low-lying zones with frequent inundation (Class 2), while *Lumnitzera* and *Phoenix* grow better in higher zones with less frequent tidal exposure (Class 4+) (Bishop-Taylor et al. 2019; Islam et al. 2019; Kathiresan 2021). In North Kalimantan, Indonesia, Sidik et al. (2025) used mini buoys and salinity probes to precisely classify tidal frequency, flood duration, and salinity gradients. This data-informed targeted tidal infrastructure installation yielded a 45% increase in tidal connectivity and a 60% improvement in seedling survival over 18 months. Complementing this, Basyuni et al. (2022a) used real-time monitoring and macrozoobenthic indicators to validate restoration success.

Little attention has been granted to interactions between ponds, adjacent forest ecosystems, landscape-level hydrology, and community-based forestry management. This gap restricts a comprehensive understanding of how pond degradation affects regional biodiversity, hydrology, and socio-economic livelihoods dependent on forest landscapes. Restoration best practices advise ensuring suitable hydrological conditions prior to planting, avoiding nursery establishment, and restricting planting to areas currently without mangroves (Lewis 2005; Djamaluddin et al. 2019).

Targeted hydrological restoration interventions, such as re-excavating abandoned creeks, reconnecting ponds to mangroves, and installing sluice gates, have improved carbon sequestration and biodiversity indices (Murdiyarso et al. 2010; Indrajaya et al. 2022). Hydrological restoration is central to forest landscape programs aligned with REDD+ and FoLU Net Sink 2030 climate targets (Murdiyarso et al. 2019). Increasingly, policies in Kalimantan promote multifunctional landscapes that integrate hydrological restoration with reforestation to enhance ecosystem services, biodiversity, and community well-being (Indrajaya et al. 2022; IUCN 2022). This integrated approach aligns with global initiatives like the UN Decade on Ecosystem Restoration and Sustainable Development Goals, advocating cross-sectoral collaboration and inclusive restoration.

This study evaluates a community-based hydrological restoration initiative in Salimbatu and Liagu Villages, as well as Tanjung Selor Village, North Kalimantan. The project restored tidal connectivity by installing sluice gates and excavating channels to achieve tidal inundation depths of 25-35 cm across 953.61 hectares of active and inactive ponds. Objectives included (i) characterizing tidal and salinity regimes using mini buoys, (ii) applying NDVI for vegetation monitoring and site prioritization, and (iii) assessing the ecological response of dominant mangrove species. The approach combined hydrological rehabilitation with community-led planning and silvofishery integration, resulting in a 50% increase in seedling growth and establishment within 18 months. Collaboration with Village Forest Management Institutions (LPHDs) further integrated ecological restoration with sustainable silviculture and fisheries development, enhancing ecological and socio-economic outcomes. These findings underscore the importance of data-driven, site-specific hydrological restoration combined with community engagement for sustainable mangrove recovery in Indonesia (Djamaluddin et al. 2019; Basyuni et al. 2022a; Sidik et al. 2025).

MATERIALS AND METHODS

Study area

This study was conducted in May 2025 in the Villages of Salimbatu 3°04'49″N 117°30'33″E, Liagu 3°16'33″N 117°27'27″E, and Tanjung Selor 2°50'57″N 117°22'08″E, Bulungan District, North Kalimantan, Indonesia (Figure 1). This study specifically focused on potential restoration areas in various mangrove cover that had been converted into special ponds in Salimbatu Village and Liagu Village, along with a reference site in Tanjung Selor Village. The management of mangrove land and ponds in Tanjung Selor, North Kalimantan, emphasizes the rehabilitation and protection of mangrove ecosystems. These ecosystems have important ecological functions such as preventing abrasion, high carbon storage, and providing habitats for marine biota. The government, through the forestry service and the mangrove working group in this area, is fully committed to accelerating mangrove rehabilitation. It is also establishing social forestry business groups (KUPS) for silvofishery (a combination of mangrove and pond cultivation), training human resources, and establishing environmentally friendly ponds. The status of this area as a village forest area within a watershed plays a crucial role in maintaining ecological stability and conserving biodiversity in the region. This location is highly suitable for forest restoration.

The conversion of forest land to shrimp ponds has caused significant forest degradation due to anthropogenic activities that have occurred over the past decade. In Liagu and Salimbatu Villages, approximately 1,000 hectares of mangroves have been prioritized for hydrological and ecological restoration interventions, making them core sites for demonstrating measurable community-based ecosystem recovery. Both sites have experienced varying degrees of mangrove degradation due to aquaculture expansion, making them critical locations for hydrological and ecological restoration. These two locations cover a combined forest area of 8,961 hectares (Liagu: 4,836 ha; Salimbatu: 4,125 ha), as officially recognized through village forest permits granted by the Indonesian Ministry of Environment and Forestry. Salinity was measured at each location using a salinity refractometer.

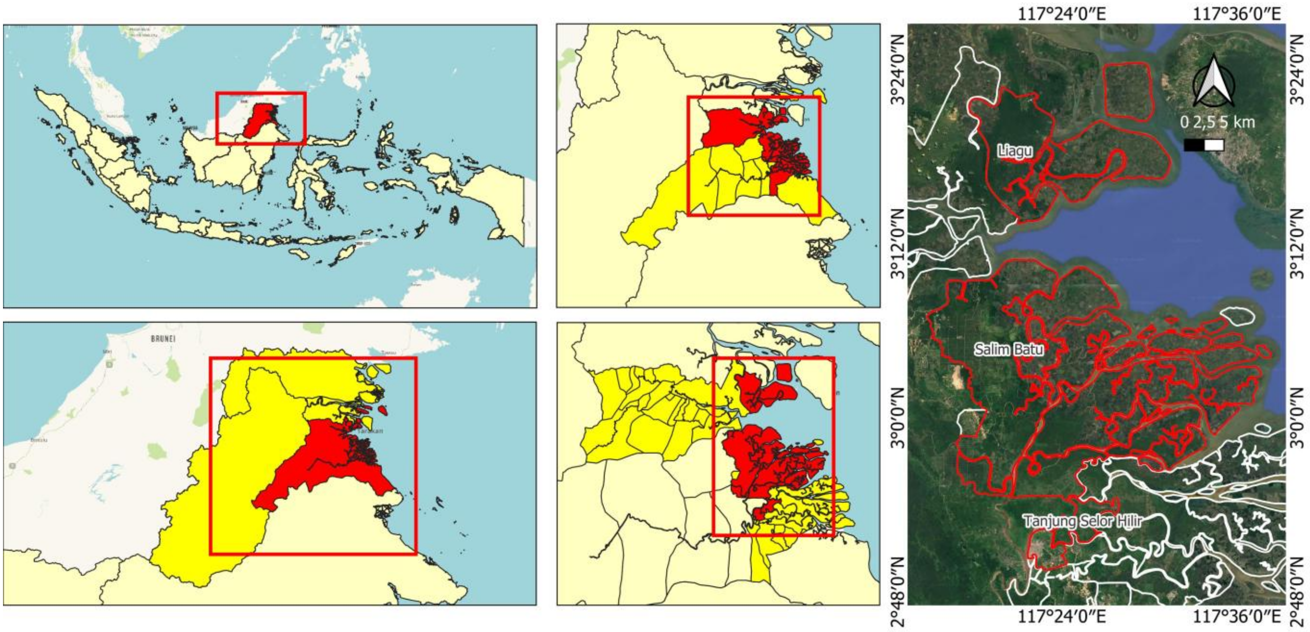

Figure 1. Study area showing Salimbatu, Laigu, and Tanjung Selor villages, North Kalimantan, Indonesia

Land use in Salimbatu and Liagu Villages is generally used as ponds to support the community's livelihood. The change in land cover from forest to ponds is one of the anthropogenic factors that greatly influences the degradation of forest ecosystems, especially mangrove forests. In this case, a restoration plan was implemented to restore the ecological function of the forest by using the village forest boundary as a reference in restoring ponds located near forest areas and river basins. The concept of a buffer zone is important in this conservation effort, as it serves as a transition area between areas used by the community and the protected core forest area. The existence of a buffer zone in mangrove ecosystems is crucial for reducing direct pressure on the core area and maintaining the sustainability of ecological functions, such as coastal protection, carbon sequestration, and habitat for aquatic biota. Therefore, the establishment and management of appropriate buffer zones, taking into account the biophysical and socio-economic aspects of the surrounding community, is a key strategy in the sustainable restoration and conservation of mangroves (Sriwahyuni et al. 2022).

Identification of mangrove forest types in Salimbatu and Liagu Villages

The observation method used in this study was the plot sampling technique. Plot locations were determined by purposive sampling, with each plot measuring 10×10 meters. In each observation plot, a comprehensive inventory of all plant species with a Diameter at Breast Height (DBH) ≥10 cm was conducted. This technique allows for systematic and measurable data collection, thus facilitating biodiversity analysis in Salimbatu and Liagu Villages. Species identification was carried out using botanical classification books and mangrove species identification books (Kitamura et al. 1997; Noor et al. 2006).

Hydrological monitoring

A total of 21 monitoring stations were established in Salimbatu (8 stations), Liagu (7 stations), and Tanjung Selor (6 stations). At each station, a mini buoy device (MSR 145B4A data logger) was installed to collect real-time hydrological data, including tidal inundation duration (minutes), current velocity (m/s), and wave orbital velocity (m/s), following the protocol of Balke et al. (2021), as depicted in Figure 2. Installation was carried out during low tide to ensure device stability and data collection accuracy. Data collection took place over four consecutive days (3-7 May 2025), recording the spring and neap tidal cycles. Mini buoy placement at each station was stratified based on tidal influence and the abandoned status of the ponds. For Liagu Village, mini buoys were installed along restored riverbanks and tributaries. For Salimbatu Village, mini buoys were installed along the canal boundary, the outermost planting zone. At Tanjung Selor, a mini buoy was installed near the estuary. As a low-lying coastal area fed by several estuaries and large tributaries, the area has a complex landscape with strong tidal influences and freshwater input from the mainland. These conditions make it a strategic location for measuring water quality, such as salinity, pH, and temperature, which significantly affect mangrove growth and the presence of aquatic biota.

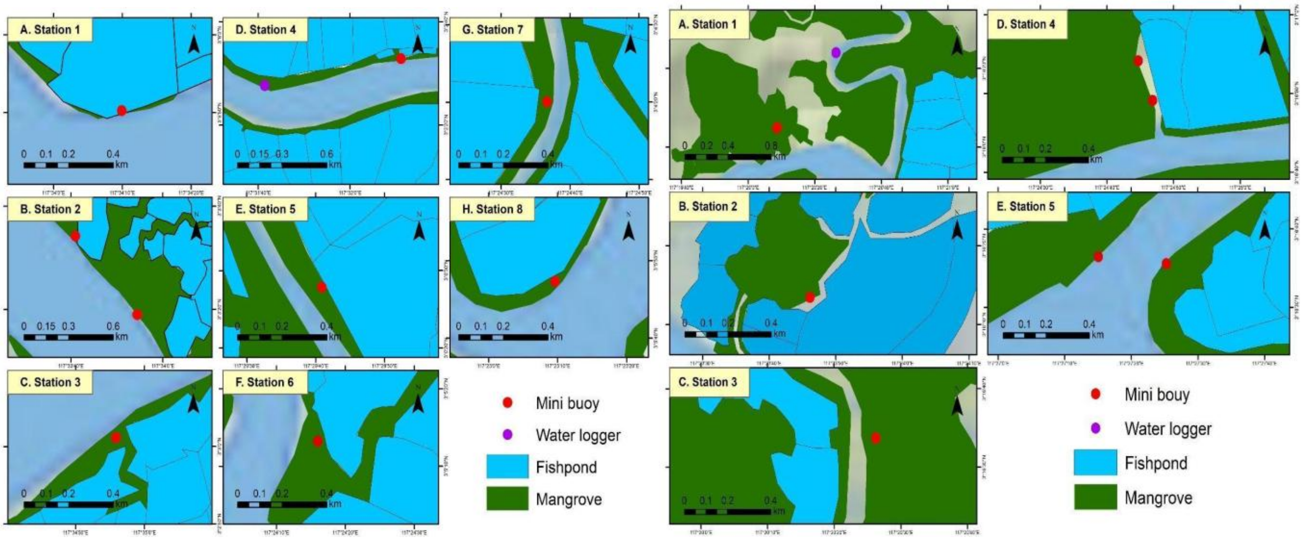

Figure 2. Mini buoy and water logger measurement installation in Salimbatu and Liagu, North Kalimantan, Indonesia

Normalized Difference Vegetation Index (NDVI) analysis

Multispectral satellite imagery with red (R) and near-infrared (NIR) spectral channels, such as Landsat 8 and Sentinel-2, is used to obtain NDVI values. After calculating the NDVI at each pixel, a classification is carried out based on the range of NDVI values to identify the level of greenness or vegetation density. Validation of NDVI data is carried out by taking field data points that are adjusted to the NDVI classes resulting from satellite image classification. Field sampling was conducted using stratified random sampling, ensuring that each NDVI class is represented proportionally (Pettorelli 2013; Almalki et al. 2022).

$$NDVI = \frac{NIR - RED}{NiR + RED}$$

Where:
NIR: Near Infrared channel reflectance value
Red: Red channel reflectance value

Field validation was carried out using stratified random sampling at sites representing different NDVI classes. A confusion matrix was employed to evaluate classification accuracy, following the methods of Deliry et al. (2021) and Almalki et al. (2022). NDVI values were categorized into three groups: low (<0.3), medium (0.3-0.7), and high (>0.7) vegetation density. These categories informed restoration prioritization strategies. Additionally, the vegetation measurements taken in the field were verified with a confusion matrix to determine the accuracy of the NDVI classification. This method is essential to ensure the NDVI values accurately reflect actual field conditions, thereby improving the reliability of vegetation cover analysis (Ozyavuz et al. 2015).

Community engagement and socio-economic data

Qualitative data on local pond management, land use, and restoration perceptions were collected through key informant interviews with village authorities and members of the Village Forest Management Institutions (LPHDs) as previously reported (Boa et al. 2024). The interviews were semi-structured and conducted on 5 May 2025. The socio-economic context was also assessed using a problem-tree analysis to identify the drivers and consequences of deforestation and degradation, guiding integrated restoration planning.

Data analysis

Data and statistical analyses were performed using the statistical program R version 3.4.4 (Hornik and The R Core Team 2024). Pearson correlation analysis was performed to assess relationships between variables using SPSS 25. The correlation coefficient (r) and associated significance level (p-value) were calculated to determine statistical power and significance. The Kolmogorov-Smirnov test was performed to test for normality, and a least squares transformation was applied to the data prior to statistical analysis if necessary. To visualize differences in mangrove species between locations in the mangrove forests of Salimbatu, Liagu, and Tanjung Selor Villages, ggplot2 was used, utilizing the ggplot function with geom boxplot and geom point to overlay point data, along with facet grid or facet wrap to separate panels. Furthermore, it provides insights into underlying ecological interactions and spatial patterns (Sugiyono 2017; Zhang et al. 2025). This integrative approach, combining visualization and correlation analysis, facilitates a comprehensive understanding of spatial variability in mangrove ecosystems across the study sites.

RESULTS AND DISCUSSION

The presence of dominant species and the physical parameters of the waters

Liagu and Salimbatu Village are among the locations with well-maintained mangrove ecosystems in the coastal area of North Kalimantan. Dense vegetation cover and the dominance of species such as *Sonneratia alba* indicate environmental stability and a high level of natural regeneration (Table 1). Physical water parameters show a pH range of 6.2 to 6.8, with relatively low salinity levels of 0-16%, reflecting the influence of freshwater from the mainland and supporting the optimal growth of various coastal mangrove species.

This situation presents both challenges and opportunities to develop an adaptive restoration approach, with appropriate species selection and hydrological management to support the regrowth of mangrove vegetation (Numbere 2021; Das 2022). The identified parent trees have an average height of 10-12 meters with a trunk diameter of about 30 cm, indicating a level of vegetation maturity suitable for propagule collection and genetic preservation. Species such as *Rhizophora apiculata, Nypa fruticans, S. alba,* and *Xylocarpus granatum* were also found in both Salimbatu and Liagu Villages, providing important species diversity for natural regeneration-based restoration strategies. Surface salinity was relatively low (0-2%) in the freshwater-influenced Salimbatu zone, while Liagu recorded higher salinity (14-16%), indicating a brackish-estuary gradient that supports mixed species recovery. These salinity levels align with the hydrological species-class recommendations proposed by Van Loon et al. (2016) and Sidik et al. (2025).

Salimbatu Village, which historically had extensive mangrove areas, is now experiencing changes in its ecosystem structure due to surrounding land use activities. Based on the ecological characteristics of each location, restoration strategies in Liagu and Salimbatu should focus on strengthening the role of local mother trees as sources of natural regeneration and propagation material. In Liagu, a conservation approach combined with the propagation of pioneer species such as *S. alba* can support sustainable vegetation cover. Meanwhile, in Salimbatu, several areas still maintain healthy vegetation communities and show potential for recovery. The dominance of species like *X. granatum* characterizes this area. Restoration efforts can aim to restore habitat structure by improving water quality and utilizing productive mother trees such as *R. apiculata*, *S. alba,* and *X. granatum*, which are present in both villages and can serve as a foundation for vegetation rehabilitation (Table 2). This locally based approach is expected to promote successful, sustainable mangrove restoration and is deeply rooted in the ecological potential of each area.

Hydrological zonation and inundation dynamics

In Salimbatu Village, eight mini buoy devices were installed, spread from stations 1 to 8. Table 3 presents the results of observations using a mini buoy in Salimbatu, specifically the average inundation duration, which was 401 minutes per inundation. The longest inundation occurred at station 1, lasting 524 minutes. The lowest inundation was at station 4, with a duration of 183 minutes. The dominant species in Salimbatu Village are *Avicennia alba*, *Avicennia marina*, *Bruguiera gymnorhiza*, *Lumnitzera racemosa*, *N. fruticans*, *R. apiculata*, *Rhizophora mucronata*, *S. alba*, and *X. granatum*.

According to Van Loon et al. (2016) and Sidik et al. (2025), when the duration of inundation is between 450 and 600 days, the characteristic species are *S. alba* and *A. alba*, observed at stations 1,3, 5, and 6. When the duration of inundation is between 200 and 450 days, the characteristic species is *Avicennia* sp., which is observed at station 7. When the duration of inundation is between 100 and 200, the characteristic species are *R. apiculata* and *X. granatum*, depicted at station 4 (Table 3).

Table 2. Composition of mangrove species

Species	Salimbatu	Liagu
Avicennia marina	√	-
Avicennia alba	-	√
Bruguiera gymnorhiza	√	-
Lumnitzera racemosa	-	√
Nypa fruticans	√	√
Rhizophora apiculata	√	√
Rhizophora mucronata	√	-
Sonneratia alba	√	√
Rhizophora stylosa	-	√
Sonneratia caseolaris	√	-
Xylocarpus granatum	√	√

Note: √: Present, -: Absent

Table 1. Species dominant in Liagu dan Salimbatu Villages, Bulungan District, North Kalimantan, Indonesia

Location	Dominance species	Status	Description
Liagu	*Sonneratia alba,* *Rhizophora stylosa,* *Bruguiera sexangula,* *Xylocarpus granatum,* *Rhizophora apiculata,* *Lumnitzera racemosa*	Natural, slightly disturbed forest	The mangrove ecosystem is relatively healthy, characterized by dense vegetation cover. pH 6.6-6.8 and salinity 14-16%. Dominant species show strong adaptation to high salinity. The average mother tree is 10-12 meters tall, with a diameter of approximately 30 centimeters.
Salimbatu	*Xylocarpus granatum,* *Rhizophora apiculata,* *Bruguiera gymnorhiza,* *Sonneratia alba,* *Avicennia marina*	Active and abandoned ponds.	The area is highly degraded due to land conversion for the construction of ponds. pH is 6.2-6.4, and salinity is low (0-2%). Some parent trees can still be utilized for restoration, particularly in areas where residual vegetation remains.

As shown in Table 4, the highest current velocity value is at station 7, which is 0.80 m/s, and the lowest is at station 3, which is 0.10 m/s, with an average current velocity value of 0.57 m/s. The highest wave orbit velocity value is at station 2, which is 0.85 m/s, and the lowest is at station 4, which is 0.10 m/s, with an average wave orbit velocity value of 0.45 m/s.

In Liagu Village, eight mini buoy devices were installed, spread from stations 1 to 8 (Table 4). Table 4 presents the results of observations on the use of the mini buoy in Liagu, indicating that the average inundation duration was 297 minutes per inundation. The longest inundation, however, occurred at station 5, lasting 494 minutes. The lowest inundation was at station 6, with a duration of 34 minutes. The dominant species in Liagu Village are *A. alba, A. marina, B. gymnorhiza, L. racemosa, N. fruticans, R. apiculata, R. mucronata, S. alba*, and *X. granatum*.

According to Van Loon et al. (2016) and Sidik et al. (2025), when the inundation period is between 450-600 tide/min, the characteristics are the *S. alba* type as seen at stations 4 and 5, when the inundation period is between 200-450 tide/min, the characteristics are the *Bruguiera* sp., *Rhizophora* sp. types, as seen at stations 1 and 8. When the inundation period is <50 species, the characteristics are the *B. gymnorhiza* and *L. racemosa*, as depicted at station 6.

The highest current velocity value is at station 7, which is 0.80 m/s, and the lowest is at station 3, which is 0.10 m/s, with an average current velocity value of 0.53 m/s. The highest Wave orbit velocity value is at station 2, which is 0.80 m/s, and the lowest is at station 1, which is 0.00 m/s, with an average Wave orbit velocity value of 0.35 m/s.

In Tanjung Selor, 6 mini buoy devices were installed, spread from stations 1 to 6. Table 5 presents the results of observations using a mini buoy in Tanjung Selor, indicating that the average inundation duration was 282 minutes per inundation. The longest inundation, at station 6, lasted 360 minutes. The lowest inundation was at station 2, with a duration of 221 minutes. The dominant species in Tanjung Selor Village are *A. alba*, *A. marina*, *B. gymnorhiza, L. racemosa, N. fruticans*, *R. apiculata*, *R. mucronata*, *S. alba*, and *X. granatum*.

Table 3. Hydrological dynamics and inundation data in Salimbatu Village, Bulungan District, North Kalimantan, Indonesia

Station	Species	High tide duration (tide/min)	Current velocity (m/s)	Wave orbital velocity (m/s)
1	*Avicennia alba, Sonneratia alba*	524	0.78	0.41
2	*Rhizophora apiculata, Nypa fruticans, Lumnitzera racemosa*	313	0.75	0.85
3	*Sonneratia alba, Rhizophora apiculata*	535	0.10	0.30
4	*Rhizophora apiculata, Xylocarpus granatum*	183	0.60	0.10
5	*Avicennia alba, Rhizophora mucronata*	465	0.60	0.60
6	*Avicennia alba, Nypa fruticans*	494	0.60	0.50
7	*Avicennia marina, Sonneratia alba*	411	0.80	0.30
8	*Bruguiera gymnorhiza, Nypa fruticans, Rhizophora apiculata*	281	0.30	0.50
	Min	183	0.10	0.10
	Max	535	0.80	0.85
	Mean	401	0.57	0.45
	Standard Deviation	129	0.25	0.23

Table 4. Hydrological dynamics and inundation data in Liagu Village, Bulungan District, North Kalimantan, Indonesia

Station	Species	High tide duration (tide/min)	Current velocity (m/s)	Wave orbital velocity (m/s)
1	*Rhizophora apiculata, Sonneratia alba*	316	0.7	0.0
2	*Rhizophora mucronata, Sonneratia alba*	137	0.4	0.8
3	*Bruguiera gymnorhiza, Xylocarpus granatum*	173	0.1	0.2
4	*Avicennia alba, Sonneratia alba*	465	0.6	0.6
5	*Avicennia alba, Sonneratia alba*	494	0.6	0.5
6	*Bruguiera gymnorhiza, Lumnitzera racemosa*	34	0.3	0.3
7	*Avicennia alba, Sonneratia alba*	411	0.8	0.3
8	*Avicennia marina, Nypa fruticans*	344	0.7	0.1
	Min	34	0.1	0
	Max	494	0.8	0.8
	Mean	297	0.53	0.35
	Standard Deviation	166	0.24	0.27

Table 5. Hydrological dynamics and inundation data in Tanjung Selor Village, Bulungan District, North Kalimantan, Indonesia

Station	Species	High tide duration (tide/min)	Current velocity (m/s)	Wave orbital velocity (m/s)
1	*Rhizophora apiculata, Rhizophora mucronata*	227	0.3	0
2	*Avicennia marina, Bruguiera gymnorhiza, Rhizophora apiculata*	221	0.4	0.1
3	*Avicennia alba, Rhizophora mucronata, Sonneratia alba*	304	0.6	0.2
4	*Avicennia alba, Rhizophora apiculata*	225	0.6	0.3
5	*Rhizophora apiculata, Xylocarpus granatum*	360	0.5	0.5
6	*Lumnitzera racemosa, Nypa fruticans, Rhizophora apiculata*	360	0.3	0.5
	Min	221	0.30	0.00
	Max	360	0.60	0.50
	Mean	282	0.45	0.27
	Standard Deviation	62	0.13	0.19

In Van Loon et al. (2016) and Sidik et al. (2025) reported that the inundation duration ranged from 200 to 450 days, and the characteristics of the species were *Rhizophora* sp., and observed at all stations. The highest current velocity values were recorded at stations 3 and 4, with values of 0.60 m/s, and the lowest was at station 1, with a value of 0.30 m/s, resulting in an average current velocity of 0.45 m/s. The highest wave orbital velocity value is at stations 5 and 6, which is 0.50 m/s, and the lowest is at station 1, which is 0.00 m/s, with an average wave orbital velocity value of 0.27 m/s.

Tidal monitoring via mini buoys revealed wide hydrological variability between sites (Figure 3). In Salimbatu, tidal inundation ranged from 183 to 535 minutes per cycle (mean: 401 minutes), with many zones corresponding to hydrological classes 2*-3, suitable for *S. alba, R. apiculata*, and *B. gymnorhiza*. Liagu exhibited a broader range (34-494 minutes; mean: 298 minutes), with some Class 4 sites being favourable for the establishment of *L. racemosa* or *N. fruticans* (Van Loon et al. 2016; Sidik et al. 2025).

Sonneratia alba has a unique root system consisting of cone-shaped roots (pneumatophores) that emerge above the sediment surface and allow the tree to breathe in muddy, oxygen-poor environments (Kitamura et al. 1997; Noor et al. 2006). This adaptation is essential for surviving the frequent and prolonged saltwater inundation of the coastal intertidal zone (Hogarth 2015). This species also has a high salinity tolerance, superior to some other *Sonneratia* and *Rhizophora* species. For example, *S. alba* has been found to grow optimally in areas with salinities of around 15-31 ppt, even up to 34 ppt, which is common in highly submerged intertidal areas (Liu et al. 2025).

Recommendations for carrying out restoration

Recovery Prioritization using mini-buoy and tidal data to identify dry or hydrologically obstructed areas requiring intervention. Maintenance planning to detect sediment buildup, stagnant flow, or restricted tidal prisms due to pond embankments or vegetation disturbance. Resilience to sea level rise: Identify and install long-term water level loggers to track trends (projected rise of +0.5-0.7 m over the next 30-50 years in North Kalimantan).

The buffer zone at the research site is more open but still under management control, where some forms of use are still permitted on a limited basis. For example, active ponds are planned to implement a silvofishery system, which is the integration of fish farming and mangrove planting, to maintain land productivity while supporting conservation efforts. Meanwhile, abandoned ponds will be fully restored through the replanting of mangrove vegetation. The primary function of this vegetation buffer zone is to protect the core area of the village forest from activities that could potentially disrupt the rehabilitation process. Mukherjee et al. (2024) emphasise that buffer zones in mangrove forest landscapes are areas rich in socio-ecological dynamics, where land use often poses a dilemma between community economic needs and conservation objectives (Figure 4). Therefore, it is important to design adaptive buffer zones that consider long-term sustainability, local community involvement, and flexible land management strategies such as silvofishery, so that they not only serve as physical buffers but also as spaces for compromise between conservation and the subsistence needs of surrounding communities.

The vegetation zoning approach in the restoration programs is planned by considering the dominant species that already exist and the presence of parent trees as a source of natural regeneration of mangrove seeds and seedlings (Figure 5). This strategy allows restoration to be carried out in a more adaptive manner to local ecological conditions, particularly in supporting the sustainability of local species populations. In addition, land use and land cover in this area show the dominance of ponds located in proximity to village forest areas, with some even located within zones that should function as buffers.

This condition poses challenges in land management, especially since the conversion of mangrove land into ponds has caused ecological degradation, including disruption to soil structure and increased risk of erosion in the watershed area. The vegetation buffer zone will function not only as a protector of the main forest area but also as an ecohydrological buffer to reduce runoff, soil erosion, and maintain sediment balance. The importance of mangrove management planning that considers stakeholder involvement, local context, and integration between conservation zones and utilization zones is crucial for effective and inclusive restoration (Christensen et al. 2008). Meanwhile, high-resolution mapping, as presented by Liu et al. (2024), can be used to accurately assess changes in mangrove cover, determine buffer zone boundaries, and monitor restoration success over time. This spatial-based approach is crucial for data-driven and adaptive planning and implementation of restoration efforts in response to changes in coastal landscapes.

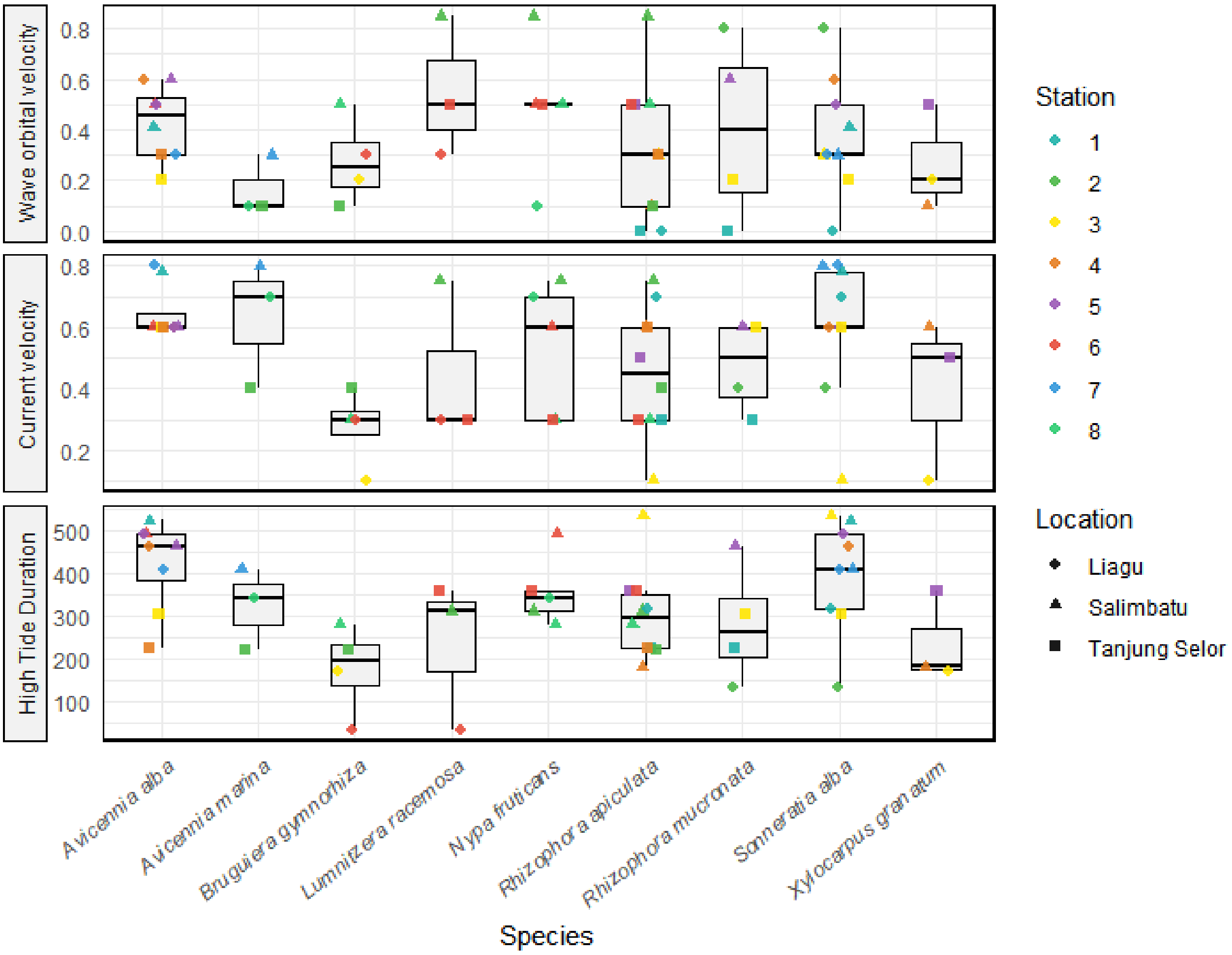

Figure 3. Mini buoy observations at the Salimbatu, Liagu, and Tanjung Selor stations of Bulungan District, North Kalimantan, Indonesia, showing tidal duration, current, and wave of tidal. Note: *: Denotes the significance of the assessment at a 95% confidence level

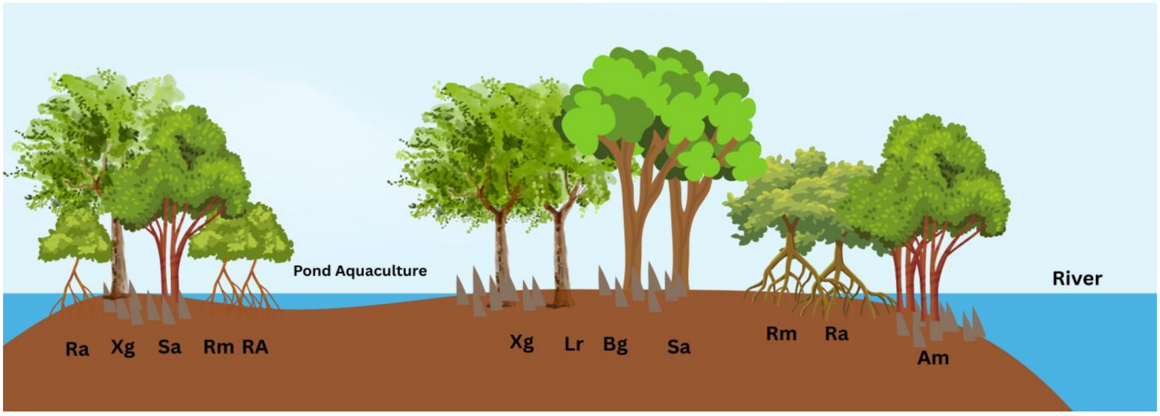

Figure 4. Mangrove buffer zone in Salimbatu and Liagu Villages, Bulungan District, North Kalimantan, Indonesia. Note: Ra: *Rhizophora apiculata*, Rm: *Rhizophora mucronata*, Sa: *Sonneratia alba*, Xg: *Xylocarpus granatum*, Lr: *Lumnitzera racemosa*, Bg: *Bruguiera gymnorhiza*, Am: *Avicennia marina*

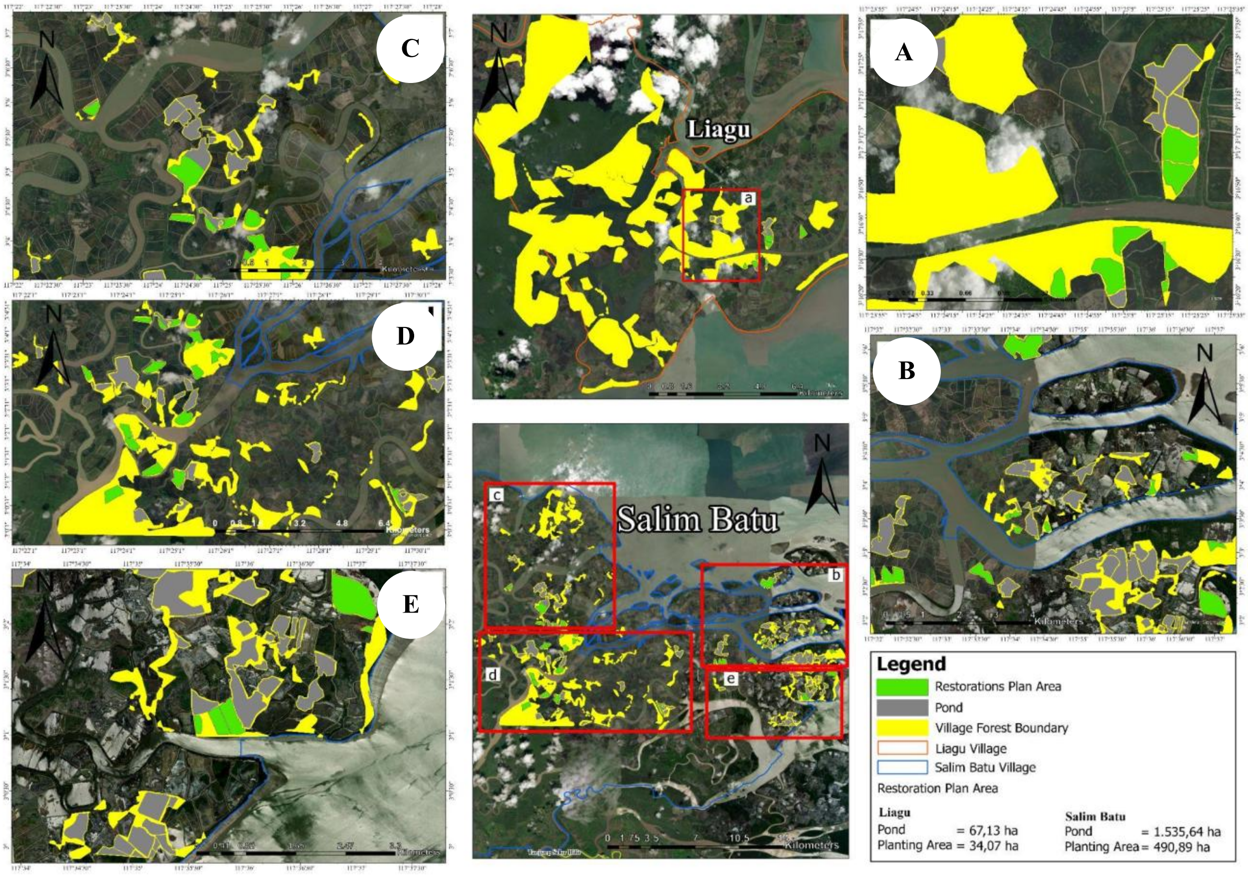

Figure 5. Restoration plan area in Bulungan District, North Kalimantan, Indonesia

In support of sustainable mangrove ecosystem restoration efforts, it is recommended that a sustainable pond model be implemented that integrates ecohydrological principles and a silvofishery approach (Figure 6). This model prioritizes a balance between aquaculture productivity and environmental conservation by maintaining mangrove vegetation in buffer zones and regulating water channel systems to support natural circulation (Basyuni et al. 2022a; Marpaung et al. 2022). The implementation of this model is expected to minimize land degradation, enhance long-term pond productivity, and contribute to the restoration of ecological functions in coastal areas (Chamberlin et al. 2025).

To demonstrate how this approach can be practically applied, we focus on climate change and human activities, noting that similar reasoning could also be used for political instability or resource exploitation (Figure 6). The expected changes in land cover and reforestation efforts in the village of Samlimbatu include a significantly warmer climate, redistribution, increased rainfall, habitat shifts based on altitude, changes in vegetation distribution, habitat homogenization, and a higher risk of flooding and landslides (Frietsch et al. 2023). Combining these potential changes with the four pond models mentioned above results in specific activities that can be incorporated into restoration projects to improve their adaptive capacity. It should be emphasized that these activities are only examples. Ideally, a joint group of scientists, local practitioners, and policymakers should develop suitable activities through a collaborative process.

The restoration plan will be implemented in two villages, namely Salimbatu Village and Liagu Village, with three schemes, namely direct planting with an area of 524 ha, silvofishery divided into 4 locations, and Assisted Natural Regeneration (ANR) planting (Table 6). The direct planting method is effective in accelerating mangrove cover and stabilizing sedimentation, especially in areas with favorable environmental conditions (Chowdhury et al. 2020; Amelia et al. 2023). However, this method requires intensive care to prevent seedling mortality, especially in the early stages of planting. The advantage of direct planting is that it can immediately rehabilitate critical areas and rapidly increase coastal protection. Its limitations are its dependence on the availability of quality seedlings and the need for early protection from external disturbances such as erosion and human activity. Silvofishery is an integrated cultivation system that combines mangrove planting with aquaculture activities such as fish, shrimp, or crab cultivation (Sitiningrum 2025). In land area data, silvofishery is reflected in types such as Traditional Parit Pond Silvofishery and Kao-Kao Pond Silvofishery, with varying areas (e.g., 36.08 ha and 118.17 ha in Salimbatu). This system serves the dual purpose of conservation and production, with mangroves acting as natural biofilters that absorb waste, improve water quality, and simultaneously provide a natural habitat for cultivated organisms (Royna et al. 2024). Silvofishery has been shown to reduce the use of antibiotics and probiotics in cultivation, which improves business sustainability and lowers the risk of production failure. ANR is a mangrove restoration method that relies on the natural regeneration of mangrove seedlings while protecting and controlling disturbances. Data on ANR areas in Salimbatu and Liagu reached 45.60 ha and 59.20 ha, respectively. This method reduces reforestation costs because it optimizes natural processes by supporting environmental conditions for the growth and development of wild mangrove seedlings (Kamali and Hashim 2011). ANR is particularly effective in areas with sufficient natural seed dispersal potential and minimal disturbance. Ecological restoration of mangroves. It has been reported that mangrove forests worldwide can repair themselves or successfully undergo secondary succession over a period of 15-30 years if: (1) normal tidal hydrology is not disturbed and (2) the availability of water-borne mangrove seeds or seedlings (propagules) from adjacent stands is not limited or hindered (Lewis 2005).

As part of data-driven coastal restoration planning efforts, spatial digitalization has been carried out to identify priority zones in Salimbatu and Liagu Villages that are recommended for the implementation of silvofishery and adaptive natural restoration patterns (Figure 7). The determination of these zones takes into account hydrological data, such as tidal flow, water depth, and connectivity, as well as water retention potential, which greatly influence the success of restoration and the sustainability of cultivation. A study of the potential composition of local mangrove species revealed ecological differences between the two villages, with Liagu Village having better vegetation cover and a more stable mangrove community structure. At the same time, Salimbatu Village showed higher degradation due to land conversion into intensive fish ponds. Based on this information, this spatial approach serves as the basis for determining adaptive and sustainable restoration locations, taking into account ecological suitability and environmental carrying capacity in each village.

Table 6. Restoration plan to be implemented in Salimbatu and Liagu Villages, Bulungan District, North Kalimantan, Indonesia

Restoration plan		**Location (ha)**		**Total (ha)**
		Salimbatu	**Liagu**	
Direct planting (ha)		490.90	34.07	524
Silvofishery	Traditional Ditch Pond	36.08	7.73	43.81
	Adjacent Pond (B)	90.86	-	90.86
	Kao Kao Pond (B)	118.17	12.73	130.9
	Open Pond (D)	59.24		59.24
Assisted Natural Regeneration (ANR)		45.60	59.20	104.8
Total		839.95	113.66	953.61

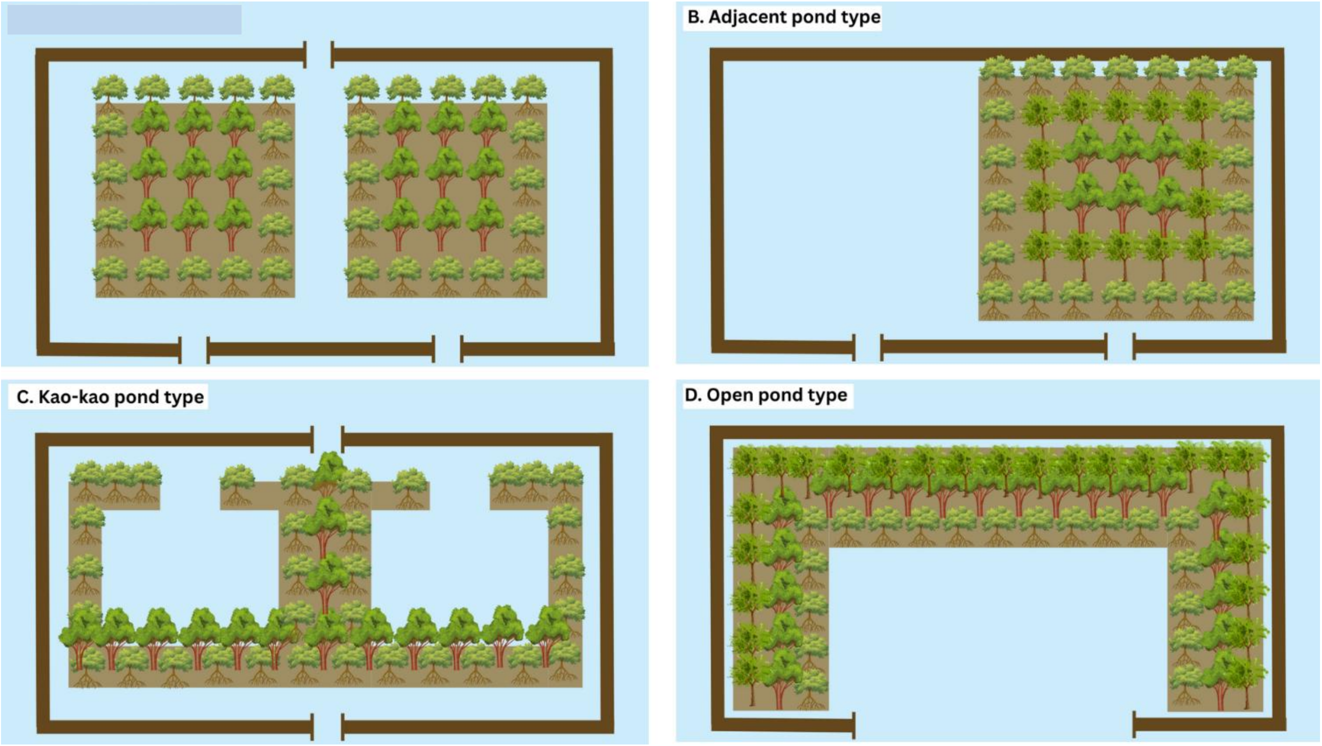

Figure 6. Modelling of ponds in Salimbatu and Liagu Villages, Bulungan District, North Kalimantan, Indonesia

Vegetation response and natural regeneration

This section integrates field data from Region 3 with findings from recent studies, including those by Van Loon et al. (2016), Balke et al. (2021), Basyuni et al. (2021) and Sidik et al. (2025), to guide mangrove restoration based on hydrological classification and tidal inundation regimes. Restoration activities are designed to align with tidal regimes and water level fluctuations that are essential for the growth of *N. fruticans*, as well as for co-restored species such as *A. marina, S. alba, R. apiculata, Rhizophora stylosa*, and *X. granatum*. In the context of restoration monitoring and evaluation, the use of technologies such as mini buoys has proven to be cost-effective and technically effective. Mini buoys are low-cost sensors that can monitor tidal and current hydrological characteristics in mangrove areas in real time. This technology facilitates the assessment of ecological conditions, which is essential for proper restoration planning and monitoring long-term restoration success. Mini buoys provide accurate hydrological spatial data at a much lower cost than conventional methods, making them an essential tool for efficient and sustainable mangrove restoration management in Indonesia (Balke et al. 2021; Siddik et al. 2025).

Species-specific regeneration patterns are evident. Sites with semi-diurnal flooding and salinity levels between 10 and 25 ppt support natural colonization by *A. marina, N. fruticans*, and *S. alba* (Table 7). Areas with higher elevations and lower inundation support *L. racemosa* and *Excoecaria agallocha*. Rehabilitated areas in active ponds also show promising establishment of *R. apiculata*, especially where hydrological modifications have increased tidal flushing, as shown in Table 8 (Watson 1928; Van Loon et al. 2016; Sidik et al. 2025).

Species-specific regeneration patterns are evident. Sites with semi-diurnal flooding and salinity levels between 1–2.5 ppt support natural colonization by *A. marina, N. fruticans*, and *S. alba* (Patel et al. 2010; Kimera et al. 2024; Wang et al. 2024; Hastuti and Prihastanti 2025). Areas with higher elevations and lower inundation support *L. racemosa* and *E. agallocha*. Rehabilitated areas in active ponds also show promising establishment of *R. apiculata*, especially where hydrological modifications have increased tidal flushing (Table 9).

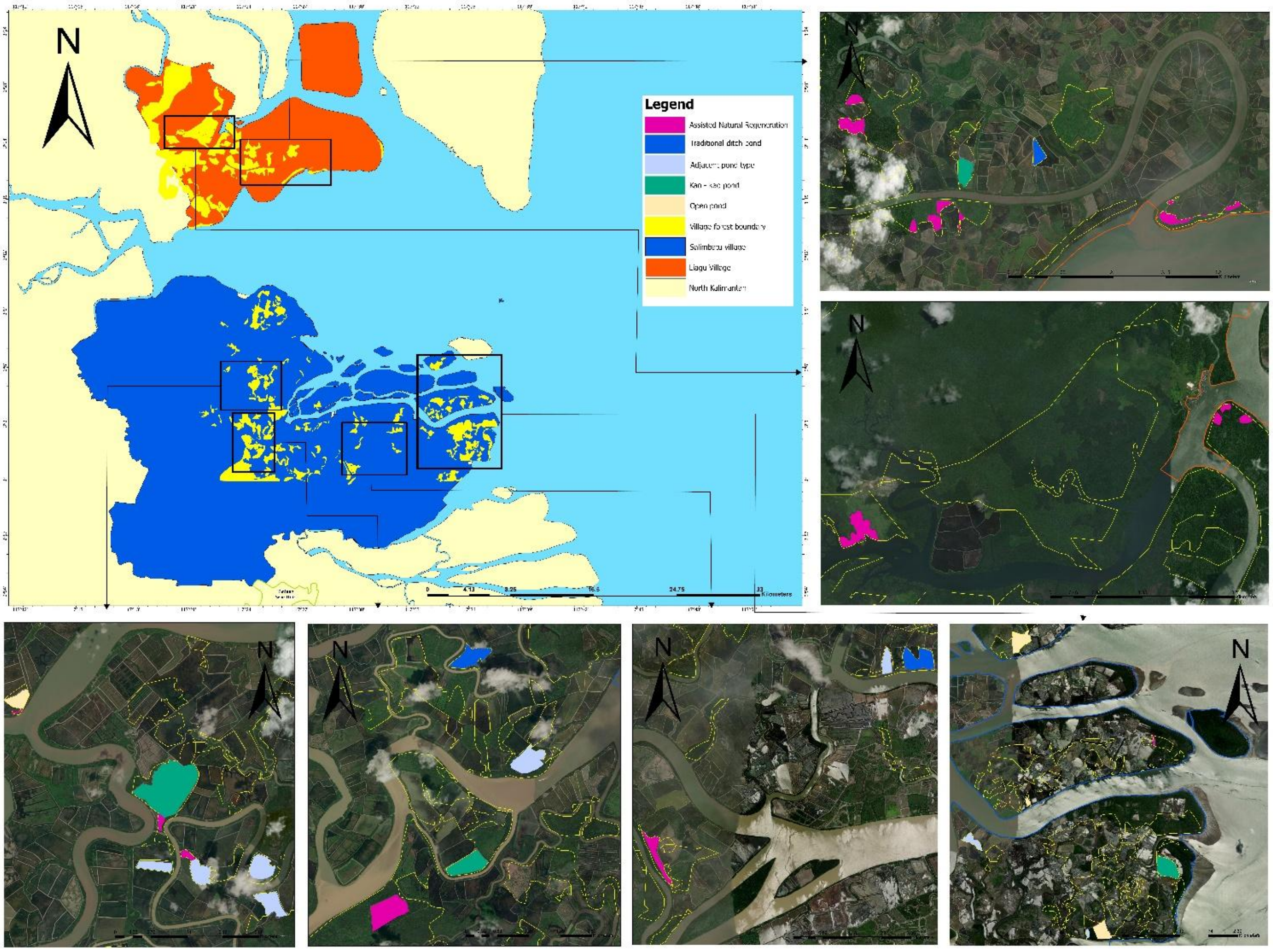

Figure 7. Determination of pond area and assisted natural regeneration

The restoration sites in Tanjung Selor highlight the important role of hydrological suitability in mangrove rehabilitation. This study's results align with Sidik et al. (2025), who emphasize that even in similar regional areas, mangrove species respond differently to micro-hydrological changes, requiring specific restoration approaches. Using Van Loon et al.'s (2016) hydrological classification in planning allowed for precise zoning of species across tidal zones, which helps prevent planting failures (Balke and Friess 2016). This contrasts with conventional monospecific Rhizophora planting methods, which often overlook elevation and inundation class, leading to low seedling survival (Sidik et al. 2025). Species diversity was strongly linked to salinity and inundation classes, indicating that restoration plans must consider site-specific gradients (Houck 2025).

The integration of silvofishery in active ponds following best practices outlined in the SoW for East Kalimantan projects—enabled socio-ecological synergy, balancing carbon sequestration goals with local economic benefits (Harefa et al. 2022). This finding supports the VM0033 methodology under Verra's Verified Carbon Standard, highlighting the co-benefits of restoration activities. However, challenges remain. As documented in Percut Sei Tuan by Basyuni et al. (2022a), persistent flooding or inadequate drainage in former ponds can hinder seedling establishment, even in areas with suitable salinity levels. Therefore, pre-planting hydrological assessment using simple tools, such as mini buoys, remains essential for site success.

Finally, this study contributes to an emerging consensus that hydrology-based, community-engaged restoration models—validated by ecological indicators such as macrozoobenthic diversity offer scalable and resilient pathways for mangrove rehabilitation in Indonesia and beyond. This study highlights the significance of hydrological suitability in determining the success of mangrove restoration, particularly in degraded pond systems where previous top-down efforts have been unsuccessful. The results are consistent with findings from Lewis and Gilmore (2007), Yang et al. (2013), and Van Loon et al. (2016), which emphasize that accurate measurement of tidal inundation, duration, and salinity is essential for identifying the right species for restoration zones.

Table 7. Hydrological targets for restoration

Indicator	**Optimal range/Goal**	**Relevance to *Nypa***
Tidal inundation frequency	1-2x daily (semi-diurnal)	Supports natural seed dispersal and root aeration
Water level range	40-120 cm fluctuation from the mean level	Ideal for *Nypa fruticans* growth and productivity
Soil salinity	10-25 ppt	Compatible with *Nypa*, *Avicennia*, *Sonneratia*
Hydroperiod duration	~2-6 hours per tide cycle	Promotes detritus turnover and nutrient delivery
Surface elevation (RTK GPS)	+0.4-1.2 m relative to mean sea level	Used to zone out planting elevations for tidal resilience

Note: RTK GPS: Real-Time Kinematic Global Positioning System

Table 8. Hydrological classification and suitable mangrove species based on inundation frequency and duration

Hydrological class	**Inundation frequency (times/month)**	**Typical duration per tide (minutes)**	**Suitable species**	**Notes**
Class 1	56-62	>540	None	Too wet for mangrove colonization
Class 2	45-56	450-540	*Avicennia marina*, *Sonneratia alba*	Pioneer species, high inundation tolerance
Class 2*	30-45	350-450	*Nypa fruticans*, *Sonneratia caseolaris*	Suited for brackish and estuarine zones
Class 3	20-30	250-350	*Rhizophora* spp., *Bruguiera* spp.	Optimal for silvofishery and plantation
Class 4	2-20	150-250	*Lumnitzera racemosa*, *Xylocarpus granatum*	Higher elevation and less tidal impact
Class 5	<2	<150	*Phoenix paludosa*, *Acrostichum aureum*	Occasionally inundated terrestrial fringe

Table 9. Summary of hydrological and salinity data in restoration sites

Parameter	**Salimbatu (abandoned ponds)**	**Liagu (active/managed ponds)**
Elevation range (m asl.)	+0.4-+1.8 m	+0.2-+2.0 m
Inundation duration (min/tide)	183-535 (Mean = 401)	34-494 (Mean = 298)
Tidal classification	Mostly Class 2*-3	Class 2-4
Salinity range (ppt)	0-2	14-16
Dominant natural species	*Sonneratia alba*, *Nypa fruticans*	*Rhizophora apiculata*, *Avicennia marina*
Restoration suitability	Passive and active planting zones	Silvofishery and mixed rehabilitation

The successful establishment of species such as *N. fruticans* and *S. alba* in frequently flooded zones, along with *Rhizophora* and *Bruguiera* species in areas with moderate hydroperiods, highlights the importance of the hydrological classification system originally proposed by Watson (1928) and refined by Van Loon et al. (2016). The development of mini buoys and RTK GPS in this study enabled high-resolution mapping of elevation and hydroperiod, addressing a common data gap that often hampers adaptive restoration planning. Moreover, macrozoobenthic indicators, as shown by Basyuni et al. (2022a), proved valuable for early assessment of restoration progress. The reappearance of native gastropods such as *Nerita balteata* in rehabilitated sites supports their use as low-cost, biologically relevant indicators of improved ecological function.

The integration of community-driven silvofishery strategies in Liagu and Salimbatu reflects the increasing need for socially inclusive restoration practices. In alignment with the scope of integrated mangrove-aquaculture systems, this approach not only rehabilitates ecosystem services but also restores livelihood opportunities (Susilo et al. 2018). Active pond users and local LPHDs were directly involved in selecting species and designing the planting schedule, ensuring a blend of scientific and traditional ecological knowledge in decision-making. Nonetheless, despite positive ecological signs, full recovery is likely to be a gradual process. As observed in Percut Sei Tuan (Basyuni et al. 2022a), hydrologically restored ponds often face challenges such as prolonged waterlogging or hypersaline conditions, which can still inhibit early seedling development and natural recruitment (Lopez-Portillo et al. 2017).

NDVI data

NDVI data were obtained from Landsat 8 and Sentinel-2 multispectral satellite imagery for the period from 2005 to 2025 (Figure 8). Field validation was conducted using the stratified random sampling method, adjusted to the NDVI class resulting from satellite image classification, as recommended by Almalki et al. (2022), as depicted in Figure 9.

Trend interpretation

The data shows an interesting pattern in the dynamics of vegetation cover. Between 2005 and 2015, there was a significant increase in healthy vegetation, from 51.43% to 67.54%. During the period 2015-2025, there was a gradual decline in healthy vegetation to 58.70% as shown in Table 10.

This percentage indicates the quantitative change in the area covered by healthy vegetation. A positive (+) value indicates an increase in healthy vegetation, indicating restoration or replanting of green areas. A negative (-) value indicates a decrease in healthy vegetation, which could be caused by deforestation, land conversion, or environmental degradation. Between 2010 and 2015, healthy vegetation cover increased by 23.79%, indicating a significant expansion or restoration of green areas. However, between 2020 and 2025, there was a decrease of -10.59%, indicating a reduction in green areas that require attention. This change in healthy vegetation cover reflects the condition of the ecosystem and environmental quality (Table 11). A decrease in green cover can negatively impact biodiversity, air quality, and climate change mitigation. Conversely, an increase indicates good conservation and land management efforts (Akram et al. 2023; Aransiola et al. 2024)**.**

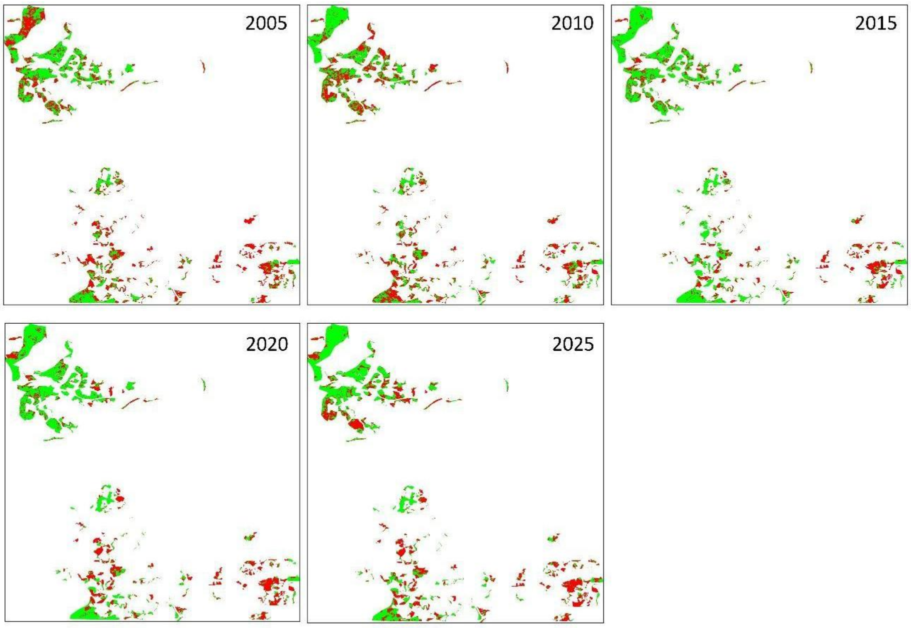

Figure 8. NDVI distribution of Tanjung Selor, Bulungan District, North Kalimantan, Indonesia, from 2005 to 2025. Healthy vegetation (NDVI > 0.7) is shown in green, and non-vegetation areas (NDVI ≤ 0.7) are shown in red

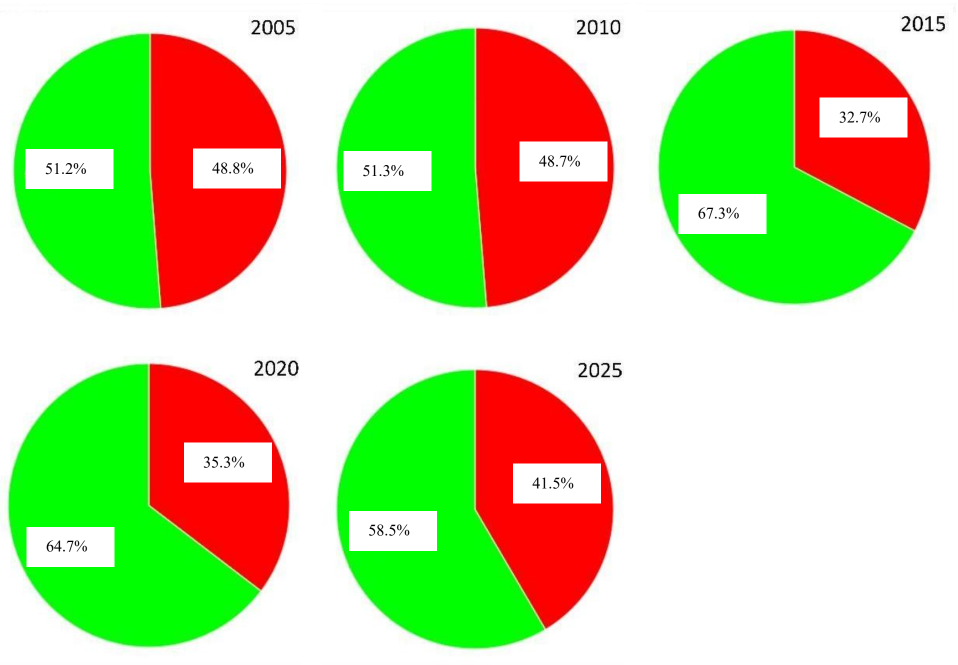

Figure 9. Healthy vegetation distribution. Green: Vegetation. Red: Non vegetation

Table 10. Vegetated and non-vegetated areas

Years	Non-vegetation		Healthy vegetation		% Forest cover change
	Area (ha)	Percentage (%)	Area (ha)	Percentage (%)	
2005	4,390.27	48.92	4,615.03	51.43	-
2010	4,386.19	48.88	4,619.11	51.47	+0.09%
2015	2,944.21	32.41	6,061.10	67.54	+23.79%
2020	3,180.88	35.45	5,825.95	64.92	-4.04%
2025	3,739.01	41.67	5,267.84	58.70	-10.59%

Table 11. Correlation of healthy vegetation with forest cover change

		Forest cover change
Healthy Vegetation	Pearson Correlation	0.551
	Sig. (2-tailed)	0.449

The correlation analysis between healthy vegetation and forest cover change yielded a Pearson correlation coefficient of r=0.55, indicating a moderate positive relationship. However, the correlation was not statistically significant, as reflected by the two-sided significance value of p=0.449, which exceeds the conventional alpha level of 0.05. This suggests that the observed relationship may be due to random variation, rather than a definitive linear relationship. This moderate, non-significant correlation is consistent with findings in ecological and environmental studies where spatial-temporal variability of vegetation indices can influence statistical significance (Creswell 2014; Sugiyono 2017).

Correlation of NDVI with hydrological parameters

Based on mini-buoy data installed at 21 monitoring points (8 stations in Salimbatu, eight stations in Liagu, and six stations in Tanjung Selor), there is a correlation between NDVI values and duration of tidal inundation: Average 401 minutes in Salimbatu, 298 minutes in Liagu. Salinity: 0-2‰ in Salimbatu, 14-16‰ in Liagu. Current speed: 0.57 m/s in Salimbatu, 0.49 m/s in Liagu. Ecological Zoning Based on NDVI, the analysis results show different species distributions according to hydrological class (Van Loon et al. 2016):

Class 2: *Sonneratia alba*, *A. marina* (High NDVI in flooded zone)

Class 3: *Rhizophora* spp., *Bruguiera* spp. (Moderate NDVI in transition zone)

Implications for restoration

NDVI-based strategy, NDVI mapping allows for the identification of restoration priority zones: Low NDVI areas (<0.3) require (i) Priority for direct planting. (ii) Medium NDVI areas (0.3-0.7): Suitable for assisted natural regeneration (ANR), and (iii) High NDVI areas (>0.7):

Focus on conservation and protection. Adaptive monitoring, Monitoring systems using time series NDVI can detect: (i) Restoration success through increasing NDVI values, (ii) Early degradation through decreasing NDVI values, and (iii) Effectiveness of silvofishery in increasing ecosystem productivity.

Validation and Accuracy: Validation using a confusion matrix showed a reliable level of NDVI classification accuracy for vegetation cover analysis (Deliry et al. 2021). Field data showed good correspondence between NDVI values and actual vegetation conditions in the field. According to the results of the Temporal Dynamics Analysis above, it is evident that there was a fluctuation in vegetation cover, with a peak in 2015 (67.54%) and a decline until 2025 (58.70%). Spatial variability, as indicated by the NDVI distribution, correlates with hydrological and salinity gradients, as well as restoration potential. Areas with low NDVI have great potential for active restoration (Van Loon et al. 2016; Perez-Ceballos et al. 2020; Kaskoyo et al. 2023; Wang et al. 2023). This analysis supports a science-based hydrological restoration approach to increase the success of mangrove restoration programs in Salimbatu Village and Liagu Villages, North Kalimantan.

Existing social conditions

The root causes of deforestation and forest degradation occurring in the mangrove forest ecosystems in Salimbatu and Liagu villages have been presented in a problem tree analysis (Figure 10). At the core of the problem are several contributing factors, including low income and community awareness, limited community knowledge of the laws and functions of mangrove forests, the need for mangrove wood for building houses and boats, limited monitoring by the Village Forest Management Institution, and the presence of maritime transportation activities. All of these factors drive uncontrolled extraction of natural resources to meet demand. These activities have caused issues at the second level, such as informal settlements, the opening and expansion of fish ponds, timber harvesting, and the removal of sand and gravel, leading to deforestation and forest degradation.

The consequences of deforestation and forest degradation include the loss of important vegetation, such as endemic trees in the villages of Liagu and Salimbatu, coastal erosion, and the destruction of mangrove habitats, which are key species in the ecosystem. The impacts of deforestation and forest degradation are systemic and interrelated. For example, increased sedimentation affects water quality and impacts organisms living around the mangrove ecosystem. Additionally, there will be a decline in wildlife populations, a direct result of the reduction in forest area. At the highest level, this will disrupt the natural functions of mangrove forests and ultimately reduce the livelihoods of communities that depend on these natural resources. Therefore, the causal framework of this problem tree analysis highlights the importance of preserving mangrove ecosystems to maintain their functions and services.

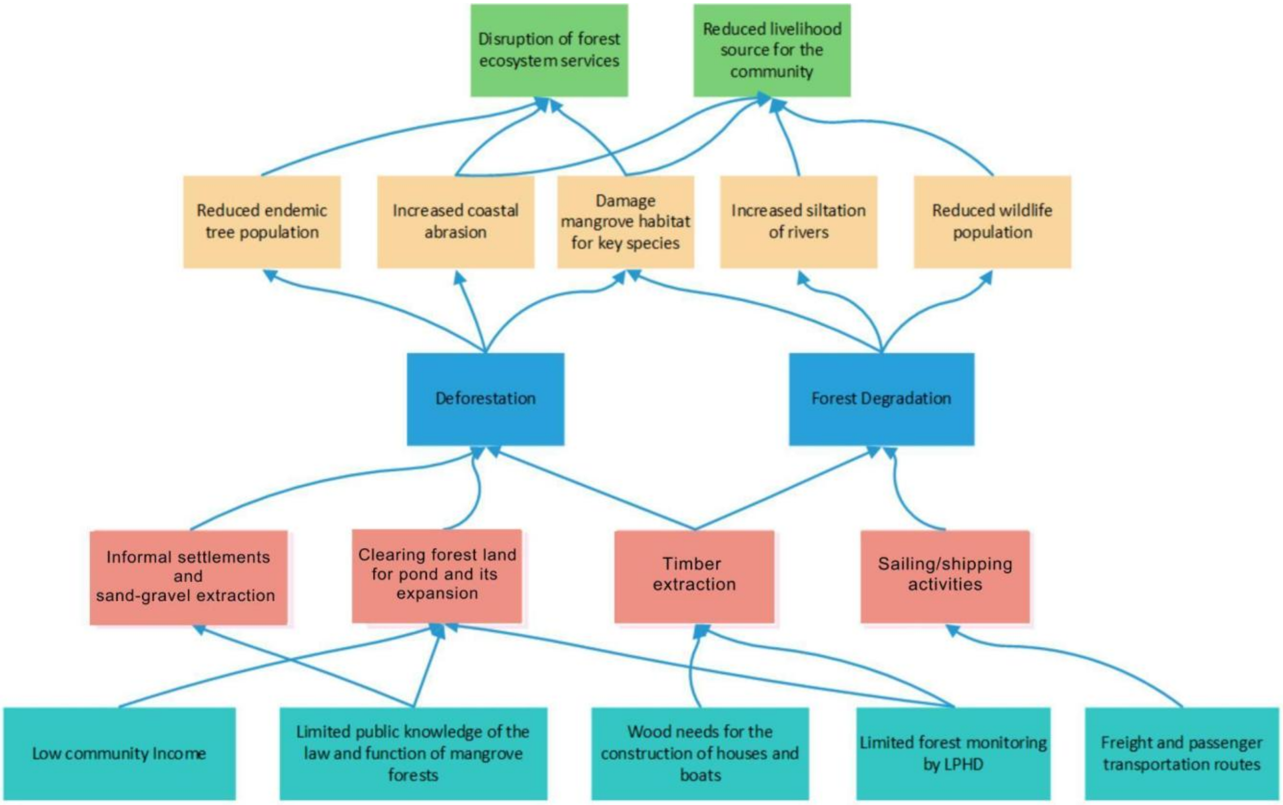

Figure 10. Tree analysis to propose that deforestation and degradation occurred in both sites

Challenges of mangrove restoration policy integration in Indonesia

Mangrove restoration in Indonesia faces significant challenges due to the lack of strong integration with broader regional policies, such as the 2030 Net Sequestration of Forestry and Other Land Use (FoLU) target. This limitation results in weak synergy between mangrove restoration planning and implementation and comprehensive climate change mitigation and natural resource management policies at the national and regional levels. Consequently, the effectiveness of achieving restoration and carbon sequestration targets is less than optimal. Therefore, cross-sectoral and regional policy integration is crucial for sustainable mangrove management (Subambang et al. 2024). Studies demonstrate the need for intensive collaboration between the central government, regional governments, local communities, and NGOs to align mangrove restoration planning and implementation effectively. Synchronized regulations and the active participation of various stakeholders are key to ensuring the sustainability of mangrove ecosystems and supporting the 2030 Net Absorption of FoLU target. In Indonesia, collaborative platforms such as the Mangrove Ecosystem Restoration Alliance (MERA) play a crucial role in integrating mangrove governance at the village, district, and provincial levels. MERA facilitates the synergistic implementation of mangrove protection and management policies and avoids overlapping policies. Community-based restoration approaches, particularly Community-Based Mangrove Ecological Restoration (CBEMR), encourage active community involvement in planning and implementation, thereby strengthening restoration governance and sustainability. However, policies need to be continuously harmonized and improved to support comprehensive synergies across sectors and regions.

Top-down (central-to-regional) mangrove restoration approaches in Indonesia often fail due to a lack of attention to local ecological conditions and minimal local community involvement. Many projects employ mass planting methods without proper hydrological surveys and site selection, resulting in low success rates and substantial cost overruns (Van Loon et al. 2016; Balke et al. 2021; Siddiq et al. 2025; Sidik et al. 2025). This approach also neglects the social and economic aspects of coastal communities, resulting in minimal local support. In contrast, community-based restoration approaches with locally adapted techniques and active community involvement, such as CBEMR, have demonstrated better and more sustainable results. The failure of monoculture mangrove restoration projects and the resulting limited ecosystem function are often attributed to top-down approaches that lack contextualization and participation (Basyuni et al. 2022b).

An example of a failed mangrove restoration project in Indonesia is the initiative of the Peatland Restoration and Mangrove Rehabilitation Agency (BRGM), which focused too much on planting one primary mangrove species, particularly *Rhizophora*, without considering the diversity of other mangrove species more suited to local conditions, such as *Avicennia* spp. or *Sonneratia* (Koral 2023). This method was chosen because of how easy it is to obtain and grow *Rhizophora*, but it doesn't always fit the local ecological conditions, leading to low success rates in restoration. Additionally, many projects fail because they don't consider the proper hydrological and ecological factors. Planting often occurs in unsuitable locations, such as below sea level or in inappropriate habitats, which makes mangrove growth difficult and often results in death. Failures are also caused by land ownership issues that have altered land use and a lack of understanding of the ecological needs of mangroves (Paino 2022). Another example is the restoration project in the Banten 3 Lontar PLTU area, which was suboptimal due to inappropriate location and selection of mangrove species, resulting in low growth rates and high mortality rates (Fauzi et al. 2022).

Limitations and way forward

Despite the promising outcomes observed in this study, several limitations must be acknowledged that may influence the interpretation and generalizability of the results. Firstly, the temporal limitation of the monitoring period (6-12 months) restricts our understanding to short-term ecological responses. Mangrove ecosystems typically require several years to fully re-establish structural complexity, sediment stability, and biotic interactions. As such, some observed changes—especially in vegetation establishment and macrozoobenthic community dynamics—may not represent stable long-term trends. Secondly, the spatial scale of hydrological data collection was constrained by resource availability. While the use of mini-buoys offered valuable insights into tidal inundation and elevation gradients, the resolution of data collection may not have captured micro-topographic variability within pond systems, especially in areas with remnant levees or disconnected sub-basins. These localized features can substantially affect hydroperiods and seedling survival, as previously noted by Van Loon et al. (2016) and Balke et al. (2021). Thirdly, while macrozoobenthic fauna were used as functional indicators of restoration progress, other critical components—such as benthic microbial assemblages, fish larvae, and crustaceans—were not monitored. These groups play vital roles in biogeochemical cycling and trophic linkages, and their responses could further elucidate ecological recovery trajectories. Socio-economic dimensions, although qualitatively considered, were not evaluated using structured tools or indicators. Factors such as changes in household income, employment diversification, gender participation, or governance roles of LPHDs in silvofishery activities were not quantified. This condition highlights a missed opportunity to evaluate co-benefits from restoration in accordance with the Climate, Community, and Biodiversity (CCB) standards. To address these gaps, future research should adopt a longitudinal approach, ideally covering multiple tidal cycles and seasonal extremes, to assess both ecological and socio-economic sustainability. Combining remote sensing tools (e.g., UAV photogrammetry, Sentinel-2 NDVI) with field-based hydrology will enhance the spatial assessment of restoration suitability. Expanding biological monitoring to include fish, invertebrates, and microbial indicators, along with participatory livelihood assessments, will offer a more comprehensive view of restoration outcomes. Additionally, restoration design should be incorporated into national and provincial mangrove strategies, especially within the framework of Indonesia's FoLU Net Sink 2030 and the National Mangrove Map (Peta Mangrove Nasional). Financial incentives from carbon credit mechanisms like Verra's VM0033 methodology could provide a pathway to scale up silvofishery-linked restoration while encouraging community stewardship. Technical support and policy alignment are essential to ensure that hydrological restoration results in sustained ecological function and community resilience.

The perspective that immediate restoration measures, such as direct planting, can yield rapid benefits is valid, particularly in terms of generating public interest and creating visible canopy cover. Such approaches can accelerate vegetation recovery in the short term and demonstrate progress to stakeholders, which is important for maintaining momentum in restoration initiatives (Primavera and Esteban 2008).

However, without healthy hydrological conditions, these benefits are often short-lived. Hydrological connectivity ensures tidal flushing, salinity balance, and sediment dynamics necessary for long-term ecosystem resilience (Lewis 2005; Balke et al. 2021). Integrating direct planting into a broader framework of hydrological restoration provides both immediate visibility and sustainable ecological outcomes, creating lasting benefits for biodiversity and local communities (Lewis et al. 2019).

In conclusion, this study provides empirical evidence that hydrologically based restoration of pond systems connected to forests directly supports landscape-scale mangrove rehabilitation in both abandoned and active aquaculture ponds in Tanjung Selor, North Kalimantan. By aligning restoration interventions with site-specific tidal and salinity conditions, using NDVI-based monitoring, and incorporating real-time hydrological measurements and species-specific zoning models, the project demonstrated increased restoration success and early ecological recovery, including colonization of suitable mangrove species and the return of indicator macrobenthos. The participatory approach, involving Village Forest Management Institution (LPHD) and integrating silvofishery practices, further illustrates how ecological objectives can be aligned with local livelihood strategies to enhance ecosystem resilience and sustainable community benefits. Integrating restoration efforts into forest hydrology for national policy objectives such as FoLU Net Sink 2030, Community-Based Forest Management (CBFM), and community engagement offers a scalable, nature-based solution for tropical deltas. However, this study highlights the need for long-term monitoring, high-resolution spatial data, and comprehensive biotic and social indicators to evaluate restoration outcomes thoroughly. As Indonesia works toward achieving ambitious restoration and climate mitigation goals, this evidence-based integrated strategy provides practical guidance for effective mangrove management. It emphasizes the potential of hydrological and community-based restoration to reverse ecosystem degradation and enhance the socio-ecological resilience of coastal communities.

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