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Effectiveness of community-based mangrove management for coastal protection: A case study from Central Java, Indonesia

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A R T I C L E I N F O

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A B S T R A C T

Management and restoration of mangrove forests to protect coasts are promoted in many countries, including Indonesia. Indonesian mangrove forests are actively restored and managed by local communities for their ecosystem services, including coastal protection. Whether community-based mangrove management (CBMM) is effective is still debated. Our study analysed the effectiveness of different CBMM practices in four Central Javan communities by analysing the capacity of their mangrove forests to protect against coastal hazards. We used complementary interviews, field assessments and literature reviews to collect the necessary information.

The overall CBMM performance and success significantly differed for each community's mangrove rehabilitation effort and the resulting coastal protection service. Of the four communities, Bedono performed best in terms of mangrove coverage, forest structure and restored coastal protection service. This is explained by multiple factors, such as application of long-term and integrated CBMM approaches, involving appropriate maintenance and additional measures to reduce wave energy. Our results can help governments, practitioners and communities to better understand the factors that contribute to CBMM's success and failure when restoring and managing mangrove forests and protecting coasts.

1. Introduction

Mangroves increase resilience to coastal disasters and climate change. Their protective capacity to reduce the impact of coastal hazards such as high waves, storms, storm surges, tsunamis, erosion and sea level rise, is widely acknowledged (Marois and Mitsch, 2015; Sandilyan and Kathiresan, 2015; Dasgupta et al., 2019). The structural configuration of mangrove tree trunks, aerial roots and pneumatophores create a drag force that dissipates wave energy and reduces wave height (Dahdouh-Guebas et al., 2005; Mazda et al., 2006; Mclvor et al., 2012; Spalding et al., 2014). This also influences hydrodynamics and sediment deposition within the mangrove forest, thus slowing erosion and improving soil cohesion (Spalding et al., 2014; Quartel et al., 2007). Removal of mangroves from the coast accelerates erosion and increases vulnerability to coastal hazards (Marois and Mitsch, 2015; Guleria and Edward, 2012; Akber et al., 2018, 2018van Wesenbeeck et al., 2015; Winterwerp et al., 2005). Therefore, maintaining the coastal protection services of mangroves is crucial for the safety of millions of coastal inhabitants worldwide (Mclvor et al., 2012, 2012van Zelst et al., 2021).

Currently, the use of mangrove forests to increase coastal resilience is increasingly promoted in many countries (Mclvor et al., 2012, 2012van Wesenbeeck et al., 2017), including Indonesia. This vital role of mangroves in protecting lives and properties from coastal hazards is also recognised by Indonesian authorities and local communities (Badola and Hussain, 2005; Setyawan and Winarno, 2006; Meilasari-Sugiana, 2012a, 2012b). This stimulated numerous mangrove-rehabilitation efforts throughout Indonesia (Setyawan and Winarno, 2006; Kusmana, 2011; Ilman et al., 2016) and culminated in the recent 600,000ha mangrove rehabilitation program enacted in the Presidential Decree number 120/2020 (Peraturan President No and Indonesia, 2020).

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These rehabilitation efforts are implemented by engaging local communities in the management activities of their local mangroves. Such community-based mangrove management (CBMM) is considered the most effective approach to achieve sustainable results (Erftenmeijer and Bualuang, 2002; Walters, 2004; Biswas et al., 2009). It accentuates local participation in decision making related to mangrove rehabilitation and management (i.e. resource identification, setting development priorities and selection and adaptation of technologies for sustainable management practices) (Datta et al., 2012). However, whether the rehabilitation and management strategies selected by local communities effectively restore mangrove protection services is rarely assessed.

Our study analysed the effectiveness of different CBMMs in four villages in Central Java to achieve their rehabilitation and management objective of restoring mangrove coastal protection service. We first assessed the extent of damage caused by coastal hazards occurring between 2011 and 2015, then we looked into communities' adaptation strategies to these hazards, and their perception of the ability of mangroves to mitigate these hazards. We then identified the CBMM characteristics and strategies applied in each village. In addition, we assessed the forest structure and estimated the capacity of mangroves managed by communities to provide coastal protection. Lastly, we analysed the impact of the applied rehabilitation and management strategies on the extent and structure of the rehabilitated mangroves in each village and the subsequent protection services delivered by these ecosystems. Our study helps governments and practitioners to ensure the involvement of local communities in restoring and managing mangrove forests to protect coasts.

2. Study area

The study was conducted in four Indonesian neighbouring coastal villages (i.e. Sriwulan, Bedono, Timbulsloko and Surodadi) in Sayung,

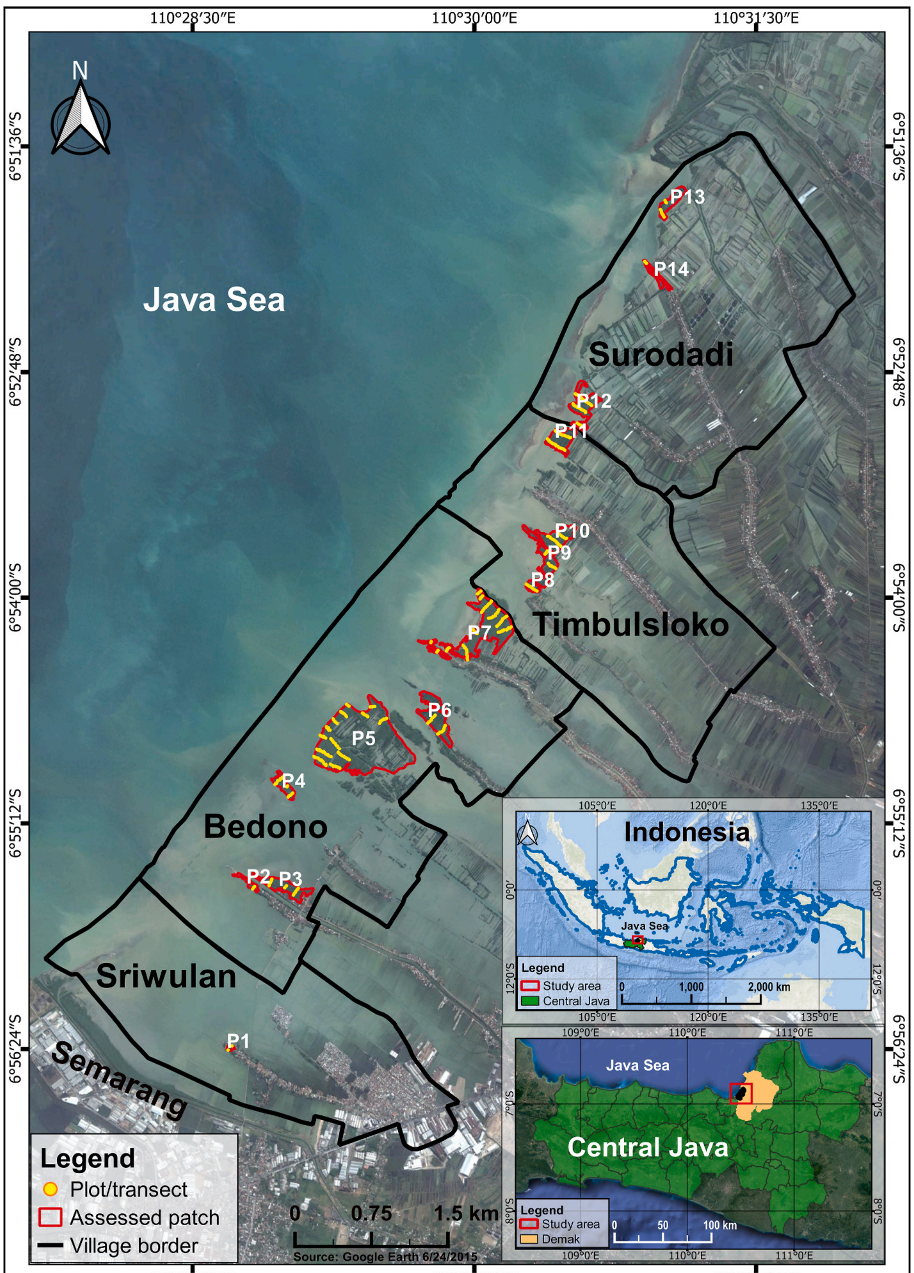

Fig. 1. Map of the study area.

Demak District of Central Java (Fig. 1). These villages were selected due to the presence of CBMM, the similar age of mangroves (c. Ten years old or older) and geographical and biophysical similarity (Damastuti et al., 2022).

The four villages are characterised by a flat lowland topography with an elevation between 0 m and 5 m above average sea level (Marfai, 2012; Dewi et al., 2016). These areas are influenced by the monsoon climate with four seasons: one dominated by western winds and rain (i.e. the 'West Monsoon'; December to February), one dominated by calmer eastern winds (i.e. the 'East Monsoon'; June to August) and two transitional seasons (March to May; September to November). The offshore wave height ranges between 0.2 m and 2 m, with a wave period of about 3s–7s (Ginanjar et al., 2021; Alferink, 2022). High waves occur most frequently during the west monsoon season and the second transitional season (Sugianto et al., 2018; Muskananfola and SupriharyonoFebrianto, 2020; Ervita and Marfai, 2017). The dominant nearshore wave height and water level during storms are 0.5 m and 1.5 m, respectively (Alferink, 2022). The tidal characteristics are mixed semi-diurnal, with a daily occurrence of two high tides and two low tides of different heights (Muskananfola and SupriharyonoFebrianto, 2020). The tidal range of neap and spring tide is 0.1 m and 1 m (Muskananfola and SupriharyonoFebrianto, 2020; Pramita et al., 2021). The coastal sediment in the four villages is dominated by silt and clay (Damastuti et al., 2022; Muskananfola et al., 2020). Additionally, all four villages experience sea-level rise of 5.5 mm per year and land subsidence at a rate of 2 cm–3 cm per year at least due to natural compaction, excessive groundwater extraction and construction loads (Chaussard et al., 2012; Taufani et al., 2018; Yuwono et al., 2018; Sarah et al., 2020; Prasetyo et al., 2019).

Originally, the coastal area of these villages was formed by sediment deposition resulting from erosion processes in the Kendeng region, which forms the upper catchment of the Wulan river (Marfai, 2012; Soekmono, 1967). This sedimentation process led to land accretion along the coast, which was converted into farmland, aquaculture ponds and settlements (Marfai, 2012). In the past, mangrove forests that were mainly dominated by *Avicennia* species grew naturally along the coast and sheltered the four villages from storms and waves. However, the coastal landscape was significantly altered over the last two decades due to the excessive use of mangroves for firewood, conversion of mangroves to aquaculture, land subsidence, and harbour development in the nearby city of Semarang (Marfai, 2012; Joseph et al., 2013; Fikriyani and Mussadun, 2014; Winterwerp et al., 2014; Damastuti and de Groot, 2018). As a result, villages were highly affected by coastal erosion (c.-25 m per year), tidal floods and inundations that occurred daily with a depth ranging between 0.1 m and 1 m (Muskananfola and SupriharyonoFebrianto, 2020; Widada et al., 2012; Rahadiati et al., 2022; Afifah and Hizbaron, 2020; Chatarina et al., 2016). Within a decade (2003–2013), these recurring tidal floods destroyed 221 houses and 300ha of aquaculture ponds and turned more than 2000 housing units into slum areas (Asiyah et al., 2015). Storm surge-induced extensive coastal flooding with an average extreme height of 2 m also repeatedly threatened these villages (Muis et al., 2020; Mahya et al., 2021). In 2013, for example, coastal flooding inundated more than 1900ha, including 150ha of residential areas (Nurdyansah et al., 2014; Subardjo, 2015). In 2017, the storm surge returned to these villages along with tropical cyclone Dahlia and caused extensive flooding of 1.5 m high that affected more than 3000 houses (Afifah and Hizbaron, 2020).

3. Materials and methods

3.1. Assessment criteria

We applied seventeen criteria to assess CBMM's effectiveness to protect coastal areas. These were classified under three management components and three impact components. (Table 1). These criteria were selected and developed from various studies, including De Groot et al. (De Groot et al., 2006), Crawford and Ostrom (1995), Maliao and Polohan (2008), UNEP-WCMC (UNEP-WCMC, 2011), Datta et al. (2010), and Bao (2011).

Table 1
CBMM effectiveness assessment criteria.

Components	Criteria/Indicators
Management characteristics	
Community governance	Organisation of local collective action
	Local participation
	Communities' bargaining power in decision making
Shared strategies	Mangrove rehabilitation strategies
	Post-planting management strategies
Supporting local regulation	The attribute of the regulation
	Appropriation and prohibition
	Sanctions
Management impact	
Mangrove coverage	Size of mangrove area
	Width of mangrove area
	Survival rate
Mangrove structure	Species
	Height
	Density
	Canopy closure
Coastal protection capacity	Actual protection capacity based on community perception
	Actual protection capacity based on mangrove structure

We selected indicators assuming that community governance's characteristics (e.g. collective action, local participation, and decision-making process) determine the decision on rehabilitation and post-planting management strategies. These strategies (e.g. rehabilitation scale, site and species selected for rehabilitation, planting technique and time, monitoring, maintenance and other technologies) and supporting local regulations affected rehabilitated mangrove ecosystems in terms of their coverage and structure. Mangrove coverage (their size and width) and structure, particularly species, height, density and canopy closure, determine mangroves' capacity to protect the communities. We also related this protective capacity to communities' perceptions to understand how they benefit from restored mangrove coastal protection service.

3.2. Data collection

We incorporated various methods to gain the necessary information for our analysis. These methods include participatory resource mapping (PRM), semi-structured interviews, questionnaire-based interviews, vegetation assessment and literature review. The information was gathered within two periods: October 2014 to January 2015 and May to November 2015. The first period was used to collect preliminary information on coastal changes and CBMM characteristics through PRM and semi-structured interviews. The second period was used to gather detailed information on mangrove characteristics through vegetation assessment and impact of coastal hazards and perception on mangrove protection service using observation and questionnaire-based interviews. Within both periods, we also collected information from local and regional governments, community organisations and research organisations.

PRM was applied in the villages Bedono and Timbulsloko to estimate the extent of coastal changes and vulnerable areas and identify actors that were involved in CBMM. These two villages were selected based on the relatively larger mangrove areas on the seaside than in Sriwulan and Timbulsloko. The PRM was conducted through seven formal meetings and some additional informal meetings that involved twenty-five villagers who represented different parts of their community (i.e. associations, quarters or roles). The PRM information formed the basis for the semi-structured and questionnaire-based interviews. The semi-structured interviews provided information on the different management characteristics in the four villages. We interviewed 16 actors that represent local CBMM leaders, governments and NGOs. The questionnaire-based interviews provided information on local adaptation strategies, communities' perceptions of the mangroves' importance as coastal defence systems, relevant socio-economic conditions, and observed impacts by coastal hazards. The questionnaires were pre-tested with trial household interviewees to identify potential problems during the actual interviews. We applied snowball samplings to select 500 household interviewees (125 per village) for the questionnaire-based interviews (Biernacki and Waldorf, 1981). This sample size represents 10% of the total number of the 5092 households (5092) of the four villages.

Field measurements provided information on the different mangrove-forest structures in the four villages. This information quantified the protective capacity of mangroves, particularly to attenuate waves. Over recent years, the mangroves in the four villages were fragmented into many smaller patches instead of forming a continuous greenbelt (Fig. 1). We, therefore, selected mangrove patches on the seaside, particularly those located adjacent to the residential or aquaculture pond areas (Fig. 1). Mangroves that were scattered within the residential area or around the aquaculture ponds were not considered. In addition, we applied a transect plot method (English et al., 1997) to assess the mangrove's species composition and structure. The transects were randomly located, and most of them were oriented perpendicular to the seaside towards the land (c.f. Fig. 1). In total, 438 plots of 10 m by 10 m along these transects were measured. Two different sub-plots were made within each plot to assess the saplings (5 m × 5 m) and seedlings (1 m × 1 m) (English et al., 1997). Within each plot and sub-plots, we identified and counted the mangrove species and measured the tree height using Suunto clinometer and the tree girth at breast height (GBH 1.3 m) using diameter phiband. Additionally, we gathered information on waves, tides, and water depths from literature, representative for an average storm in the studied area.

3.3. Data analysis

Following Lichtman (2014), the answers from the semi-structured interviews were transcribed and classified into themes (i.e. organisation of local collective action, local participation, communities' bargaining power in decision making, Mangrove rehabilitation strategies, and post-planting management) to determine the different CBMM characteristics. Both quantitative and qualitative information on local socio-economic conditions, damages adaptation strategies, communities' perceptions and impacts by coastal hazards were analysed using descriptive statistics.

The mangrove structural composition (i.e. diameter at breast height (cm), tree density (tree per ha) and important value index (%)) was analysed based on English et al. (1997). The important value index was estimated by summing relative density, frequency, and dominance. The model used to analyse the vegetation is provided in Appendix A. We applied the exponential equation model for non-uniform mangrove stands (Bao, 2011) to quantify the wave attenuation capacity of mangroves in the four villages:

$$W_h = a \bullet e^{b \bullet B_w} \qquad \text{Equation 1}$$

where W_h is the wave height behind the mangrove forest [cm]; B_w is the width between the sea and land sides of a mangrove patch [m]; a is a coefficient for the initial wave height, and b is the coefficient for canopy closure, height and density. The a coefficient is defined as:

$$a = 0.9899 \bullet I_{wh} + 0.3526 \qquad \text{Equation 2}$$

where Iwh is the initial wave height (cm). For our calculation, we assumed water levels of 1,5 m and incoming wave heights at the start of the mangrove forest of 0,5 m. These conditions are representable for an average storm in the four villages (Alferink, 2022). The b coefficient is determined by:

$$b = 0.048 - 0.0016 \bullet H - 0.00178 \bullet \ln(N) - 0.0077 \bullet \ln(CC) \qquad \text{Equation 3}$$

where H is the average tree height [m], N is the tree density [ind ha^{-1}], and CC is the canopy closure [%]. In our calculation, we included trees and saplings with a diameter at breast height (DBH) equal to or more than 5 cm. We assumed that the canopy closure of dense (≥1500 ind. ha^{-1}) *Rhizophora* and *Avicennia* dominated mangrove forests is 80% based on an estimate in a neighbouring village Betahwalang by Purnama et al. (2020).

Furthermore, the inversion of the b coefficient defines the forest structure index (V = -b), which expresses the configuration of the mangrove's structural condition (tree height, forest density and canopy closure). The insertion of Equations 2 and 3 into Equation (1) thus estimates the wave-height reduction of the original wave height on the basis of mangrove-forest structure.

Based on the derived information from the Bao (2011) equation, We determined the wave attenuation capacity (W_{ac}) by calculating the percentage of reduced wave height. We truncated the negative value as the minimum W_{ac} can not be lower than zero:

$$W_{ac} = MAX\left(0, \frac{Iwh - Wh}{Iwh} \bullet 100\right) \qquad \text{Equation 4}$$

4. Results

4.1. Impact of coastal hazards on local communities

The studied communities have been threatened by repeated occurrences of coastal hazards. Nearly all interviewees (97%) experienced at least one out of four types of coastal hazards, floods, erosion, storms and storm surges (Fig. 2). Coastal flooding was most frequently experienced in Sriwulan, Timbulsloko and Surodadi, followed by storms in Bedono, Timbulsloko and Surodadi. Flooding was only experienced by half of the interviewees in Bedono, but they all experienced storms. Additionally, storm surges (locally known as '*unju-unju*') were only experienced by interviewees in Sriwulan and Bedono who lived less than 1 km from the coastline.

Between 2011 and 2015 the recurring floods, storms and erosion events caused substantial losses to more than two-thirds of all interviewees. Over 90% of losses involved destruction or damage to houses and aquaculture ponds, and the remainder involved losses or damage of other properties (i.e. boats, fishing gears and electronic devices). The total losses (Fig. 3) in this period were US$578500[1] (n = 367), which averaged to US$1570 per household. The average annual loss per household is, therefore, US$310, which accounted for 12%–16% of the yearly household income (Table 2). The highest losses were recorded in Timbulsloko, where the aquaculture ponds were especially hard hit (Fig. 3), followed by Sriwulan, Bedono and Surodadi. The loss and damage of aquaculture ponds resulted in a socio-economic response of occupational shifts in all four villages. The response was most prominent in Timbulsloko, where almost a quarter of the interviewees shifted from fish farming to fishing or manual labour (Table 2) (see Table 3).

Despite the damage to their residential houses, none of the interviewees was willing to move to other places. Their motivation included, particularly, their occupation (30%) and attachment to their birthplace (25%) and their families (12%). To deal with the repeated occurrence of coastal hazards, almost all interviewees allocated additional budget to elevate their houses (Fig. 4), except in Surodadi, where only half applied this strategy. A few interviewees in Sriwulan, Bedono and Surodadi also built simple stone or sand dikes around their houses to increase flood protection (Fig. 4). Each of the affected households in the

[1] The conversion was based on the average currency rate released by Indonesia's Central Bank in 2015: 1 US$ equals to 13514 IDR.

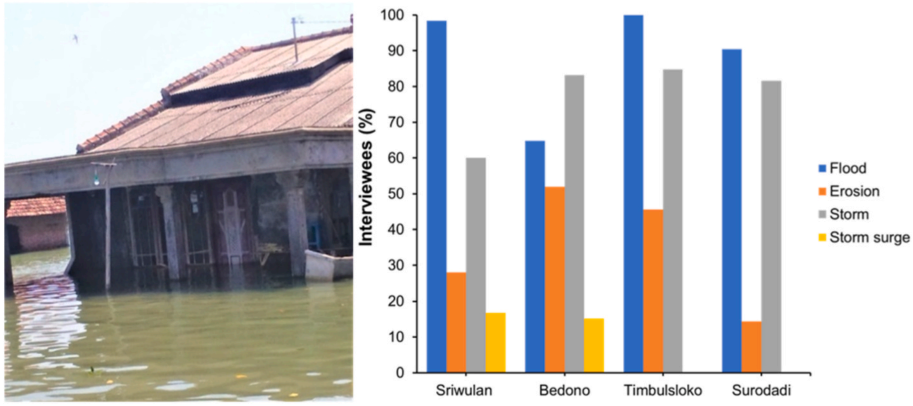

Fig. 2. Coastal flooding in Sriwulan (left) and experience of coastal hazards in the four villages (right).

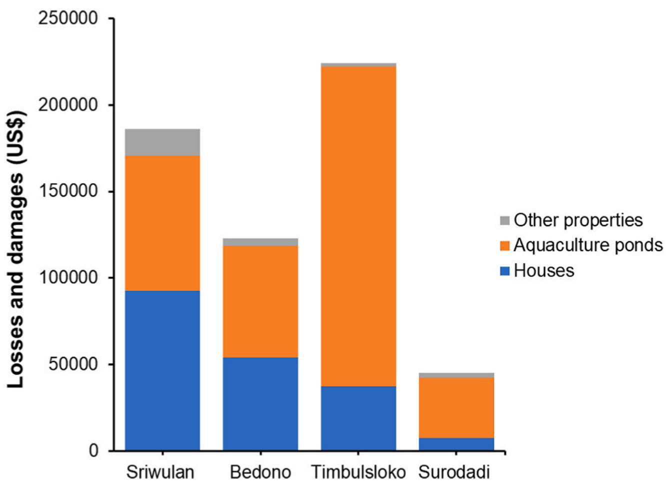

Fig. 3. Losses and damages caused by coastal hazards from 2011 to 2015 (367 interviewees) Other properties refer to boats, boat engines, fishing gear, electronic devices, cars and motorcycles.

four villages spent between 15% and 30% of their income in 2014 on house renovation (c. US$750) and adaptation (c. US$400).

Aside from these adaptation strategies, various other coastal defence measures were implemented, ranging from constructing breakwater systems (i.e. concrete, stone, bamboo, rubber and semi-permeable structures to enhance sedimentation and stimulate mangroves' natural regeneration) to active rehabilitation of mangrove forests. Among these measures, mangrove forest rehabilitation was most commonly applied in all four villages, whereas the others were mainly applied in Bedono and Timbulsloko.

4.2. Mangrove-forest establishment and management in the four villages

The effort to rehabilitate mangrove forests as a coastal defence strategy in Sayung was first implemented in 1993 by the farmer association Karya Makmur in Surodadi. This association wanted to protect their aquaculture ponds from erosion. In the late 1990s, the Demak Environmental Office simultaneously began its rehabilitation activities in the four villages, and this marked the first regional government involvement in these villages. Since 2004, numerous mangrove rehabilitation projects have been initiated and implemented by the government, NGOs, and private enterprises, in the four villages. Most projects that were implemented by the government were part of national mangrove-rehabilitation programs. The strongly committed Organisation for Industrial, Spiritual and Cultural Advancement (OISCA), for example, only implemented their projects in Bedono.

Table 2
Socio-economic characteristics of the households in the four villages in 2015.

Criteria	Unit	Sriwulan	Bedono	Timbulsloko	Surodadi
Household size	Person	3.9	4.3	4.1	3.6
Type of houses					
Bamboo	%	1	1	0	0
Wood	%	9	21	15	10
Brick	%	77	48	48	63
mix	%	14	30	37	26
Properties					
land/living area (median)	m^2	90	72	83	100
House (median)	$	740	1480	1480	3700
pond	%	24	20	37	63
Boat	%	21	76	29	28
Livestock	%	16	24	18	33
Other properties	#	10	20	12	11
Main occupation					
Aquaculture farmer	%	18	8	33	58
Fisher	%	26	80	42	34
Labourer	%	33	5	10	4
Other occupations	%	21	7	10	3
Unemployed	%	2	0	6	0
Secondary occupation	%	21	30	20	34
Occupational transition	%	7	10	24	6
Gross family income[a]	US$	1980	2486	1998	2575

[a] The gross family income refers to the income received from all members of the household and additional money that is regularly received from other family members who do not live in the same house.

Similarly, PT Kubota and PT Askes implemented and financed rehabilitation projects in Bedono. Contrarily, Sriwulan received the least support and had the smallest rehabilitation projects. External institutions were reluctant to implement projects there because of a perceived lower chance of success caused by more significant hazards, relatively smaller rehabilitation areas, and limited responsiveness and cooperation from the local communities.

Nearly all rehabilitation and post-planting management activities in the four villages engaged local communities. Their involvement was coordinated by locally or externally initiated mangrove associations. Multiple associations existed in Bedono (6), Timbulsloko (5) and Surodadi (2) but only one in Sriwulan. These associations were important in fostering decisions on mangrove forest rehabilitation and management. Some of these associations (e.g. Mangrove Bahari in Bedono; Rejeki Makmur in Timbulsloko; Karya Makmur in Surodadi; and Makmur Tani in Sriwulan) carried out larger rehabilitation activities compared to the other associations and thus strongly determined the CBMM

Table 3
House renovation and adaptation costs per household in 2014.

Village	Losses and damages		Renovation		Adaptation	
	Households (%)	Cost (US$)	Households (%)	Cost (US$)	Households (%)	Cost (US$)
Sriwulan	77	1939	57	1041	58	633
Bedono	74	1335	50	586	39	442
Timbulsloko	76	2361	33	549	61	212
Surodadi	67	539	36	722	41	272

Note: The costs of house renovations were related to the damage caused by floods, storms, and erosion from 2011 to 2015.

Fig. 4. Adaptation strategies through floor elevation (top-left), total house elevation (top-right), stone dike (bottom-left) and sand dike (bottom-right).

characteristics in these villages (Damastuti et al., 2022; Damastuti and de Groot, 2017).

4.2.1. Community governance

Despite the proximity of the study areas, each village had different dominating governance characteristics, which can be described by three characteristics (Damastuti and de Groot, 2017).

1. **Bottom-up decision making**, with voluntary participation and self-mobilised collective action in Surodadi;
2. **Partnership decision making**, with participation limited by projects in Bedono; and
3. **Top-down decision making**, with manipulative participation in Sriwulan and Timbulsloko

The formation of the Karya Makmur association and its initiative to rehabilitate the mangrove in Surodadi was the only self-mobilised collective action identified in the four villages. This association and its members made collective decisions on mangrove rehabilitation and management strategies. Membership and extended community participation were voluntary, based on similar occupations and/or interests to protect the aquaculture ponds and other assets from erosion. Most of the association's activities were carried out independently and based on the collaborative system of *'gotong royong'*, a long-standing Indonesian cultural value system of working together or mutual assistance (Simarmata et al., 2020) until the arrival of externally funded rehabilitation projects that introduced direct incentive mechanisms. Community support also started to wane after a leadership transition in 2010.

Contrarily, the collective actions in Sriwulan and Timbulsloko were mainly initiated by external governmental institutions. Decision making was dominated by an association's leader and/or funding organisations, whereas participation was mainly a formality or limited to hired labour. The presence of capable leadership in Timbulsloko did, however, attract external institutions to implement their projects in this village and stimulated positive responses from villagers. Such leadership was absent in Sriwulan. Furthermore, in Bedono, decisions were made in partnership with Mangrove Bahari and the OISCA. Nevertheless, also these decisions were often limited by agenda and budget availability.

4.2.2. Rehabilitation, monitoring and maintenance strategies

All associations in the four villages implemented similar planting techniques, including direct planting using propagules or seedlings and the use of bamboo stakes for protection and involving a similar spacing distance of 1 m–2 m. Site selection was based on funding requests or area availability rather than thoroughly assessing site suitability. In Surodadi, the sites were selected in relation to the aim of protecting the aquaculture ponds. Although all villages used predominantly *Rhizophora* seedlings, Bedono and Surodadi also used *Avicennia marina and Sonneratia caseolaris* seedlings, but this was hampered by the high cost of those seedlings. The size of the areas targeted by rehabilitation efforts in the four villages differed. Of the 5.7 million propagules and/or seedlings planted in the Sayung District between 1999 and 2014, 45% was planted in Bedono, 24% in Timbulsloko, 25% in Surodadi and only 6% in Sriwulan. In 2015 a new rehabilitation method, the construction of permeable structures designed to stimulate sedimentation and natural mangrove regeneration, was implemented along the coast of Bedono, Timbulsloko and Surodadi.

Monitoring of the rehabilitated mangrove forests in the four villages was largely conducted voluntarily by members of mangrove associations or done on a project basis by field officers of the supporting government institutions or NGOs. Only Karya Makmur in Surodadi officially appointed one of its members as part of its '*gotong royong*' efforts to regularly monitor the mangroves but without an obligation to provide written reports or monitoring records. Furthermore, only the Mangrove Bahari association in Bedono conducted regular maintenance with support from OISCA, involving the replacement of dead or lost seedlings with new ones. Maintenance activities in other villages were generally project-based. In Surodadi, each pond owner was responsible to maintain mangroves planted around their aquaculture ponds.

4.2.3. Village regulations

Each village regulated the management and protection of the coastal and rehabilitated mangrove areas. These contain: 1) boundaries of the regulated area; 2) subjects of the regulation; 3) actors responsible for the supervision, protection, management and monitoring; 4) tasks and responsibilities of the appointed managers; 5) prohibited actions; and 6) sanctions. The rules related to mangrove-protection services implied that efforts must be taken to protect the rehabilitated mangrove forests from logging and the damages caused by destructive fishing or livestock herding. Each village applied different sanctions for illegal mangrove logging. For example, Surodadi severely sanctioned the cutting down of a single mangrove tree with the obligation to plant at least one thousand trees, without an option to replace the sanction with a fine. In Bedono, logging one tree was punished by the requirement to plant 300 trees, but in Sriwulan and Timbulsloko the requirement was planting of only one hundred trees. Fishing activities that damaged the mangroves were subjected to gradual sanctions ranging from warnings to confiscation of fishing gear. Despite the presence of these sanctions, logging activities occurred inside the protected mangrove areas in Bedono and nobody was punished. Clearcutting of mangroves was recorded around some ponds in Surodadi, and this incident was resolved through both replanting and financial compensation by the violators.

4.3. Impact of CBMM on mangrove coastal protection services

4.3.1. Mangrove coverage

The implementation of numerous mangrove rehabilitation activities in the four villages resulted in sparse to dense patches of new mangrove forests, covering larger portions of the shore (Table 4). The width of these patches varies from c.60 m–340 m (Table 6). Narrow scattered belts of mangroves were also present around the ponds and houses (Table 4). We estimated that with over five million planted seedlings (10,000 seedlings per ha), the rehabilitation projects covered at least 560ha. While Rhizophora seedlings died in many places, natural regeneration of *Avicennia* stands occurred in between, augmenting the numbers of seedlings (van Bijsterveldt et al., 2020). However, the total rehabilitated mangrove area in the four villages covered less than half of the intended area (Table 4), indicating a low survival rate of plantings. This was most apparent in Sriwulan, where less than 10% of the seedlings appeared to have survived. Inappropriate timing of planting was a likely significant contributing factor to this low rate of success, as well as unfavourable conditions for the survival of planted seedlings and the absence of additional measures to protect newly planted seedlings from natural disturbance (Damastuti et al., 2022, van Bijsterveldt et al., 2020). The presence of breakwaters and permeable structures, natural beach ridges (cheniers) and lower subsidence rates in Bedono and Timbulsloko, were likely contributing factors to a higher mangrove survival rate (van der Lelij et al., 2021; Akbar et al., 2017). The higher success rate in Surodadi may be caused by lower subsidence and coastal erosion rates compared to the other villages, a better site selection including the river and pond banks with less wave exposure, the higher elevation of the intertidal area and higher sediment deposition.

Table 4
Mangrove cover in the four studied villages (Pramita et al., 2021).

Description	Unit	Sriwulan	Bedono	Timbulsloko	Surodadi
Total number of planted propagules/ seeds	thousand	350	2540	1350	1430
Estimated mangrove area planted	ha	35	254	135	143
Total mangrove area present (natural and planted)	ha	4	111	52	74
Seaside	ha	1	61	21	12
Ponds and settlement	ha	3	50	31	62

4.3.2. Mangrove structure

The majority of the assessed mangrove patches in the four villages were approximately ten years old or older. These patches consisted of eight species including *Avicennia marina*, *Avicennia alba*, *Rhizophora mucronata, Rhizophora apiculata, Rhizophora styloza, Sonneratia caseolaris, Xylocarpus mollucensis* and *Excoecaria agallocha* (Table 5). The tree and sapling densities were highest for *A. marina,* particularly in Bedono (Patches 2 to 7), followed by *R. mucronata* (Patches 1 and 14) and *A. alba* (Patches 6, 9 and 12). Their height ranged between 1 m and 15 m. A lack of natural regeneration occurred in Sriwulan, where only *R. mucronata and R. apiculata* were present in the last one ha mangrove patch on its coast (Tables 4 and 5). This originated from planting efforts. Successful natural regeneration of *A. marina* was observed in Bedono, where this species replaced the initially planted *Rhizophora* sp. *A. alba* dominated or co-dominated most mangrove patches in Timbulsloko and Surodadi.

4.3.3. Coastal protection capacity of mangroves in the four villages

After the mangrove forests were restored in the four villages, almost 90% of the interviewees in Sriwulan and more than 95% in Bedono, Timbulsloko and Surodadi experienced reduced impact of coastal hazards. Most interviewees (98%) perceived mangroves as important to extremely important to protect their village. However, they argued that mangrove alone is not enough to protect them from recurring tidal floods and storms. Most interviewees desired additional measures such as embankments and breakwaters (Fig. 5). In Sriwulan, house and floor elevation were also considered an important measure due to the worsening impact of tidal floods and inundation that threatened this village.

Table 6 lists the wave attenuation capacity of the different mangrove patches. More than half of the patches have attenuated 20%–95% of the incoming 0.5 m wave height. The protective capacity of Bedono's patches was higher compared to those of the other villages. Patches 3, 5, 6 and 7 in this village reduced over 50% of the incoming wave height. These patches were relatively wide (>200 m) compared to the other two patches with low W_{ac} (Patches 2 and 4). Similarly, Patches 1, 8, 9, 12 and 13 with the lowest wave attenuation capacities (<20%) had either a narrow coverage area (<150 m) and/or a lower stand density (i.e. less than 1600 individuals per ha with DBH $\geq$ 5 cm). The high protective capacity (88%) of Patch 14 in Surodadi resulted from higher stand density and wider coverage area compared to the other patches in this village. Changes in canopy closure substantially decrease or increase the total amount of wave reduction capacity (Table *B.1)*.

4.4. Synthesis

Our analysis showed different outcomes from CBMM implemented in the four villages regarding their success in restoring mangrove protection capacity. Our results highlighted three types of dominating CBMM governance implemented in the four villages: Bottom-up, Partnership and Top-down governance (Table 7). These CBMMs were particularly

Table 5
Mangrove structure in all studied mangrove patches (*Avicennia marina: Am, Avicennia alba: Aa, Rhizophora mucronate: Rm, Rhizophora apiculata: Ra, Rhizophora styloza: Rs, Sonneratia caseolaris: Sc, Xylocarpus mollucensis: Xm and Excoecaria agallocha: Ea;* IVI is the important value index*)*.

Village	Patch no	Species	Tree (dbh ≥10 cm)			Sapling (dbh 2cm–9.9 cm)			Seedlings (dbh<2 cm)	
			Height (m)	Density (ind.ha^{-1})	IVI (%)	Height (m)	Density (ind.ha^{-1})	IVI (%)	Density (ind.ha^{-1})	IVI (%)
Sriwulan	P1	*Rm*	11	475	100	5	2,400	62	145,000	100
		Ra	–	–	–	4	2,300	38	–	–
Bedono	P2	*Am*	8	875	100	5	4,500	100	–	–
	P3	*Am*	8	362	100	4	4,672	88	75,000	93.5
		Rm	–	–	–	5	362	10	133	6.54
		Sc	–	–	–	13	19	2	–	–
	P4	*Am*	8	716	100	5	1,537	100	16,316	71.3
		Rm	–	–	–	–	–	–	5,789	28.7
	P5	*Am*	7	547	100	5	2,739	78.8	42,149	80.1
		Aa	–	–	–	8	10	0.5	–	
		Rm	–	–	–	3	1,100	20.8	902	19.9
	P6	*Am*	9	55	49	6	2,700	75	11,000	40.7
		Aa	9	60	51	6	80	5	–	–
		Rm				4	920	20	21,500	59.3
	P7	*Am*	9	62	90	4	6,131	76	25,053	75.6
		Aa	9	1	2	6	67	3	–	–
		Rm	10	5	8	4	1,448	18	5,474	24.4
		Rs	–	–	–	4	168	3	–	–
		Ra	–	–	–	5	34	1	–	–
Timbulsloko	P8	*Am*	8	8	23	4	1,933	41	–	–
		Aa	8	33	77	5	1,800	44	–	–
		Rm	–	–	–	4	767	14	–	–
	P9	*Am*	10	7	51	4	2,213	41	43,333	65
		Aa	7	7	49	4	1,760	42	4,667	6.8
		Rm	–	–	–	3	453	5	–	–
		Rs	–	–	–	3	613	12	8,000	28.2
	P10	*Am*	7	13	26	5	3,983	59	12,500	38.8
		Aa	7	75	74	5	867	21	–	–
		Rm	–	–	–	6	1,000	18	25,000	53.6
		Rs	–	–	–	5	67	2	4,583	7.62
	P11	*Am*	9	56	92	5	1,949	50	3,333	14.2
		Aa	–	–	–	7	1,056	36	17,949	30.1
		Rm	7	10	8	6	267	8	17,179	36.8
		Rs	–	–	–	6	205	6	7,692	18.9
Surodadi	P12	*Am*	8	68	45	5	2,039	49	114,634	33.4
		Aa	8	83	53	6	859	31	–	–
		Rm	7	2	2	5	712	16	23,659	55.9
		Rs	–	–	–	6	107	4	6,829	
	P13	*Am*	7	144	83	5	956	27	4,444	16.4
		Aa	8	22	17	6	1,578	40	–	–
		Rm	–	–	–	4	1,067	20	15,556	57.4
		Rs	–	–	–	6	511	13	5,000	21.3
		Ra	–	–	–	–	–	–	556	4.93
	P14	*Am*	7	33	39	–	–	–	13,636	30.2
		Rm	9	300	61	7	3,733	40	24,773	57.7
		Rs	–	–	–	4	400	7	6,364	9.74
		Ra	–	–	–	7	800	18	–	–
		Xm	–	–	–	5	1,867	21	909	2.38
		Ea	–	–	–	3	1,867	14	–	–

distinct in their organisation of local collective action, how decisions were made and how the communities were involved in the decision-making process and rehabilitation and management activities. The different governance characteristics resulted in different decisions related to the applied rehabilitation and management strategies (i.e. the rehabilitation scales, selected species and rehabilitation sites, and maintenance of the rehabilitated mangrove ecosystems) as synthesised in Table 7. These strategies partially affected the rehabilitated mangrove ecosystems' size, structure and sustainability and, subsequently, their coastal protection capacity.

5. Discussion

Over the past two decades, Indonesian rehabilitation and post-planting management schemes have increasingly adopted community participation as a central approach (Brown et al., 2014; Banjade et al., 2017). This approach has been implemented with various strategies and results. A comparison of these different strategies and their subsequent impact on the restored mangrove protective capacity illustrates how to engage community members and improve the rehabilitation strategies to protect people's assets and livelihood. Although our study was designed to be robust and covers four adjacent villages in a similar biophysical setting, some limitations and uncertainties exist. These are presented and discussed in this section.

5.1. Challenges in estimating the damage to houses and other losses caused by coastal hazards

Estimating the damage to houses and other losses was challenging due to frequent coastal hazards and the emigration of households severely affected by the hazards. The satellite imagery (Fig. 1) clearly illustrates the higher erosion and inundation severity experienced in Sriwulan and Bedono compared to Timbulsloko and Surodadi. These hazards caused severe destruction in Sriwulan and Bedono that culminated in the forced emigration of more than 200 households from two sub-villages (P4 and P5, Fig. 1) in 2006. Asiyah et al. (2015) also

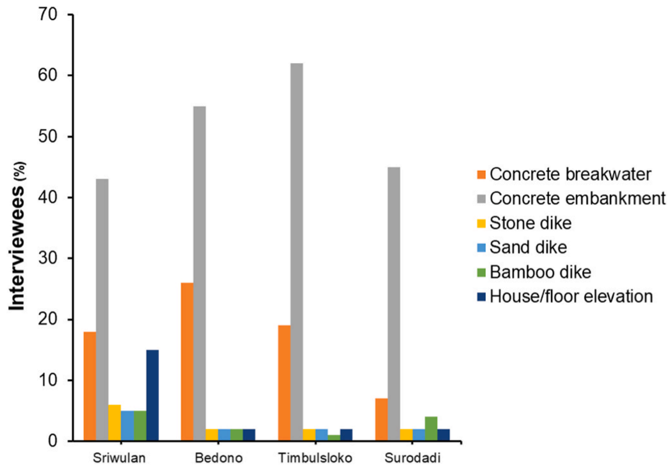

Fig. 5. Additional coastal defence strategy to complement mangroves.

reported the loss of 17 houses in Sriwulan and 127 houses in Bedono from 2003 to 2009. However, our results revealed that from 2011 to 2015, the damages and losses in Timbulsloko were the highest among all villages. This was due to the vast destruction of remaining aquaculture ponds located in the southwestern part of the village. Ismail et al. (Ismail and HeriyantoSuharini, 2012) reported that the flooding and erosion between 2008 and 2012 destroyed 70% of the aquaculture ponds in Timbulsloko. Umami et al. (2018) also provided evidence on the 884 m coastline retreat in Timbulsloko from 2014 to 2015, which was the maximum erosion that occurred in sub-district Sayung since 2006. These findings validate our results on the higher losses in Timbulsloko during the referred period.

5.2. Challenges in quantifying the protective service of mangroves

Studies on protective services by mangroves indicate that the rate of wave height reduction depends on the configuration of factors including forest width, forest structure, and mangrove tree morphology relative to water depth, topography (slope of seabed and land) and wave height (Bao, 2011; Das and Crépin, 2013; Hashim and Catherine, 2013; World Bank et al., 2016). Maza et al. (2021), for example, used process-based mathematical modelling to estimate the attenuation capacity of *Rhizophora*-dominated mangrove forest using several variables, including water level, incoming wave height, incoming wave period, tree age, tree density, forest width and root structure. Similarly, Lee et al. (2021) also applied such variables to calculate the wave damping in disturbed mangrove forests dominated or co-dominated by *Avicennia* sp.

Mangrove roots present considerable resistance to water flow (McIvor et al., 2012). During shallow-water level conditions, they perform as obstacles to incoming waves (Mazda et al., 2006; McIvor et al., 2012). Therefore, the root structure variables (type, density, diameter, and height) may have impacted wave reduction capacity during such events but were excluded in our empirical model. Our schematisation of wave attenuation was based on other key factors, such as the number of trees, tree height, leaf cover, wave height, and cross-shore width. This provides a preliminary estimate to compare different patches, but some specific factors are ignored, such as vegetation drag exerted by mangrove roots, bottom slopes, water depth and wave reflection. Different bottom slopes cause variation in water depth and shoaling, breaking and reflection characteristics and, subsequently, the wave height. A mild bottom slope, according to KG and Bhaskaran (KG and Bhaskaran, 2017), could substantially reduce the wave height as waves loose energy for longer distances over mildly sloping foreshores (KG and Bhaskaran, 2017). Water depth affects the attenuation rate relative to the distance in mangrove and vegetation structures (McIvor et al., 2012; Horstman et al., 2014). Lee et al. (2021) explained that as the water level increases, the cross-sectional area varies and changes the amount of vegetation drag deployed on water flow. Additionally, the waves reflected by vegetation structure affect the hydrodynamic around and within the mangroves and can potentially retain some wave energy (Lee et al., 2021; Horstman et al., 2014; Yanagisawa et al., 2009). As our studied patches had relatively similar water depths and consisted primarily of young mangroves, ignoring these factors probably does not affect our results.

Despite using a parsimonious empirical model, our results are similar to Maza et al. (2021) and Lee et al. (2021), who included more complex vegetation characteristics. Maza et al. (2021) estimated that the wave attenuation rate of 50 m-wide *Rhizophora*-dominated mangrove forests is less than 50%. They argued that only a forest width of at least 300 m reduces incoming 0.2 m–0.9 m wave heights by more than half. Two out of fourteen assessed mangrove patches in our study area were dominated by *Rhizophora mucronata* (Patches 1 and 14). Patch 1 was slightly wider than 50 m, and its wave attenuation was indeed less than 50%. Similarly, Patch 14, which was 300 m-wide, reduced wave heights by over 50%. Furthermore, Lee et al. (2021) outlined the capacity of 90 m to 250 m-wide *Avicennia*-(co)dominated mangrove forests to damp up to 80% of wave heights during storm conditions (0.2 m–0.9 m). Our analysis also showed the ability of 90 m to 290 m-wide and dense (0.2 ind.m^{-1} to 0.4 ind.m^{-1}) *Avicennia-(co)*dominated mangrove patches to reduce the height of incoming 0.5 m high waves by up to 85%.

Most patches in the four villages were dominated by small 1 m to 15 m-high *Avicennia trees* (Table 5). Unlike *Rhizophora* stilt roots that can extend to above 1 m in height, *Avicennia*'s root systems feature narrow and short pneumatophores ranging between 20 cm and 30 cm (McIvor

Table 6
Wave attenuation capacity of mangrove patches in the four villages.

Village	Patch number	Dominant species	Height	Density	Width	*a*	*b*	*V*	*Wh*	*Wac*
			m	ind.ha^{-1}	m				m	%
Sriwulan	P1	*Rm*	6.6	2775	66	0.8	−0.010	0.010	0.43	14
Bedono	P2	*Am*	7.6	3875	89	0.8	−0.013	0.013	0.28	44
	P3	*Am*	5.1	2267	213	0.8	−0.008	0.008	0.17	67
	P4	*Am*	6.8	1874	77	0.8	−0.010	0.010	0.39	22
	P5	*Am*	5.7	2363	292	0.8	−0.009	0.009	0.07	86
	P6	*Am, Aa*	5.8	2215	264	0.8	−0.009	0.009	0.08	83
	P7	*Am*	4.0	2308	238	0.8	−0.006	0.006	0.21	58
Timbulsloko	P8	*Aa, Am*	4.5	2075	107	0.8	−0.007	0.007	0.42	16
	P9	*Am, Aa*	3.8	1560	149	0.8	−0.005	0.005	0.41	19
	P10	*Aa, Am*	5.4	3071	174	0.8	−0.009	0.009	0.19	62
	P11	*Am, Aa*	5.8	1985	173	0.8	−0.009	0.009	0.19	61
Surodadi	P12	*Am, Aa*	4.2	1900	129	0.8	−0.006	0.006	0.40	20
	P13	*Am, Aa*	5.4	2100	69	0.8	−0.008	0.008	0.49	2
	P14	*Rm, Am*	6.1	4200	342	0.8	−0.010	0.010	0.02	95

Note: The density includes trees and saplings with DBH ≥5 cm. We used constant value for CC and Iwh of 80% and 0.5 m, respectively.

Table 7
Effectiveness of CBMM for coastal protection.

Criteria	Sriwulan	Bedono	Timbulsloko	Surodadi
Management characteristics				
Community Governance	Government initiated collective actions, dominated by top-down decision-making and manipulative participation	NGO and government initiated collective actions dominated by partnership decision-making limited by project	Government initiated collective actions, dominated by top-down decision-making and manipulative participation	Community and government initiated collective action dominated by bottom-up decision-making and self-mobilised participation
Shared strategies				
Rehabilitation Scale	±350,000	±2,540,000	±1,350,000	±1,430,000
Species selected for planting	*Rhizophora* sp.	*Rhizophora* sp., *Avicennia marina*, *Sonneratia caseolaris*	*Rhizophora* sp.	*Rhizophora* sp., *Avicennia marina*
Site selection	Based on funding	Based on funding	Based on funding	Based on necessity & funding. Mostly along the river and around the ponds
Planting Technique	Direct planting of seedling/ propagules using bamboo stakes, with 1m–2 m spacing distance	Direct planting of seedling/ propagules using bamboo stakes, with 1m–2 m spacing distance	Direct planting of seedling/ propagules using bamboo stakes, with 1m–2 m spacing distance	Direct planting of seedling/ propagules using bamboo stakes, with 1m–2 m spacing distance
Monitoring	No scheme & records Activities are voluntary or based on project by appointed officials	No scheme & records Activities are voluntary or by appointed officials from NGO/Government	No scheme & records Activities are voluntary or based on project by appointed officials	Monitoring by appointed individuals. No recorded monitoring results
Maintenance	Irregular, based on project	Regular maintenance for OISCA's funded projects	Irregular, based on project	Maintenance by individuals for mangroves around the ponds, based on projects for mangroves on the seaside.
Additional strategy[a]	–	Breakwaters	Breakwaters	–
Supporting local regulation related to coastal-protection service				
mangrove logging	Logging 1 tree sanctioned by planting 1000 trees.	Logging 1 tree sanctioned by planting 300 trees	Logging 1 tree sanctioned by planting 100 trees	Logging 1 tree sanctioned by planting 100 trees
Destructive fishing	Gradual sanction	Gradual sanction	Gradual sanction	Gradual sanction
Livestock herding	warning	warning	warning	warning
Management Impact				
Mangrove coverage				
Ponds and settlements(ha)	3	50	31	62
seaside (ha)	1	61	21	12
Width of mangrove patches on the seaside (m)	66	89–238	107–173	69–342
Mangrove structure[b]				
Dominant species	*Rm*	*Am, Aa*	*Am, Aa*	*Am, Aa, Rm*
Tree height (m)	6.6	4–7.6	3.8–5.8	4.2–6.1
Tree density (ind.ha^{-1})	2775	1874–3875	1560–3071	1900–4200
Canopy closure (%)[c]	80	80	80	80
Coastal protection capacity				
Community perception (% of interviewees experienced the reduced impact of storms)	<90	>95	>95	>95
Wave attenuation capacity (%)	14	44–86	16–62	2–95

[a] The breakwater constructions were implemented through separated projects initiated by external institutions.
[b] The mangrove structure includes small trees and saplings with DBH ≥ 5 cm on the observed mangrove patches.
[c] Canopy cover based on a constant value of 80%.

et al., 2012). Furthermore the significant wave height in the four villages during storms was higher than the pneumatophores (0.5 m, water level 1.5 m), with the highest heights of recent waves reaching 2.7 m (Ginanjar et al., 2021; Alferink, 2022). In such a situation, according to Mazda et al. (2006), the attenuation rates by mangrove pneumatophores become smaller. Lee et al. (2021) showed evidence that under storm conditions when the water depth is higher than the roots, trunk contribution to vegetation drag in *Avicennia*-(co)dominated mangrove forest increased substantially (up to 35%). Mazda et al. (2006) also highlighted a 100% increase in wave reduction per 100 m width of mangrove forests when the water reached the thicket of leaves. Therefore, we assumed that the absence of root variables from the model employed in this study did not affect the robustness of the results since the wave attenuation in the assessed mangrove patches mainly resulted from the cross-shore width and forest's vertical structure (density and canopy). Applying vertical forest structure variables (Bao, 2011) is, therefore, sufficient to get a preliminary estimate of the relative coastal protection performance of mangrove patches dominated by small *Avicennia* trees of which (part of) the canopy was flooded (Horstman et al., 2014).

5.3. Factors influencing mangrove protective capacity against storm surge and flooding

Despite being located in the same geographical area, the nearshore bathymetry of the studied villages differs. According to Muskananfola et al. (Muskananfola and SupriharyonoFebrianto, 2020), the water depth in Sriwulan and Bedono is deeper (>2 m) than in the other villages. Likewise, estimations of annual soil subsidence also varied, with Sriwulan ranking highest (3.1 cm), followed by Bedono and Timbulsloko (both 2.8 cm) and Surodadi the lowest (1.7 cm) (Yuwono et al., 2018). The deeper nearshore water level combined with a higher subsidence level in Sriwulan and Bedono resulted in higher and stronger waves. This explained that more interviewees experienced storm surges in Sriwulan and Bedono compared to the other two villages. In addition, communities closer to Semarang, such as Sriwulan and Bedono may have been affected more by subsidence compared to Timbulsloko and Surodadi. In view of the fact that subsidence in the vicinity of large industrial areas has been more profound due to higher levels of gound water extraction (Abidin et al., 2010) implying a larger total relative sea level rise in these areas.

Storm events sometimes cause abnormally high seawater levels and storm surges onto the land, especially when they coincide with spring tides (Mclvor et al., 2012; Bertin, 2016). Mangroves attenuate storm surges and subsequent inundation by reducing the surge height and slowing the flow of water (Zhang et al., 2012; Krauss et al., 2009). Storm surge attenuation by mangroves is influenced by several factors, including forest structure characteristics, spacing during planting, structural complexity (i.e. roots, stems, branches, and foliage) of dominant species, physical characteristics (i.e. bathymetry and topography of the area and the presence of channels and pools), storm characteristics (i.e. size and wind speeds of the storm), and tides (Dasgupta et al., 2019; McIvor et al., 2012). Krauss et al. (2009) and Zhang et al. (2012) pointed out that the presence of inland channels and pools in the mangrove areas that interconnected water bodies decrease mangrove forests' ability to reduce the peak water level. These inland channels and pools allow the surge to pass easily and quickly through the landscape and penetrate further inland.

Most settlements in the four villages were concentrated along the rivers and creeks that traverse through the mangrove areas (Fig. 1). These villages were also affected by soil subsidence and sea-level rise (Chaussard et al., 2012; Taufani et al., 2018; Yuwono et al., 2018; Prasetyo et al., 2019). The location of the rivers and the soil subsidence combined with sea-level rise allowed surges and tidal floods to move further inland and triggered more frequent and extensive flooding and deeper inundation (McIvor et al., 2012; Zhang et al., 2012; Krauss et al., 2009). This underlines interviewees' doubts about mangrove protective capacity against recurring tidal floods and storms and their comments on needing additional measures such as embankments to complement the flood attenuation services of mangroves. Dasgupta et al. (2017) and Takagi (2017) also highlighted the need for such built infrastructure alongside mangrove planting to increase the protection of densely populated storm-prone areas that experience land subsidence and sea-level rise. Referring to Takagi (2017), such infrastructure has to be carefully designed and integrated with mangrove rehabilitation and management activities to avoid systems failure and maximise mangroves' long-term protection service.

5.4. Impact of rehabilitation and management strategies on mangroves' protective capacity

Our analysis showed that variations in forest width and structure resulted in different protective capacities of mangrove forests in the four villages. We show that these variations were affected by local environmental factors (i.e. different coastal erosion rates), forest maturity, and rehabilitation and management strategies (i.e. pre-rehabilitation studies, rehabilitation scale, maintenance, planting time and additional protection in response to natural disturbance) applied in each village.

The erosion rates in Sriwulan, Bedono and the western part of Timbulsloko are higher compared to Surodadi and the eastern part of Timbulsloko (Muskananfola and SupriharyonoFebrianto, 2020). However, Sriwulan's high erosion rates did not lead to applying additional protection measures or interventions to raise the success of mangrove restoration efforts. The absence of such measures in Sriwulan combined with limited rehabilitation activities, irregular maintenance, and inappropriate seasonal timing of planting, resulted in high mortality rates and narrow mangrove patches. Contrarily, the presence of various breakwaters combined with larger rehabilitation efforts, possible lower subsidence rates, regular and long-term maintenance and construction of embankments probably contributed to higher survival rates and larger and wider mangrove patches in Bedono. Young mangrove patches in Timbulsloko (Patches 8 and 9; see Table 6) located on the western side of the village experienced higher erosion rates than the eastern side (Muskananfola and SupriharyonoFebrianto, 2020). The permeable structures located on the foreshore seem to have sheltered these two patches and enable natural regeneration. This is illustrated by the abundant seedlings and saplings of both *A. marina* and *A. alba* in between planted *R. mucronata* and *R. stylosa* (Table 5) (Damastuti et al., 2022).

Planting mangroves on highly disturbed shorelines as the four studied villages, is challenging due to harsh physical conditions (Matsui et al., 2012). The survival of newly planted seedlings or saplings in such areas is constantly threatened by wave action, erosion and inundation (Matsui et al., 2012; Yuanita et al., 2021). Numerous studies emphasise the need for additional protective measures or specific techniques (e.g. soil amendments, construction of breakwaters, geo bag dike or permeable structures) when planting mangroves in such areas to mitigate high seedlings' mortality (Akbar et al., 2017; Matsui et al., 2012; Yuanita et al., 2021; Jati and Pribadi, 2017). Such measures require high investment (Akbar et al., 2017) and are sometimes unaffordable for local communities. Nevertheless, requests from communities for such protection measures are often neglected, as shown in Sriwulan or not integrated with rehabilitation efforts, as shown by the construction of various breakwaters in Bedono and Timbulsloko. This lack of synergy between breakwater construction and mangrove planting, according to Akbar et al. (2017), reduces the effectiveness of the efforts to protect the coast. Additionally, areas with new intertidal space for mangroves, sufficient sediment input and good mangrove protection may in the short run, be the most successful for mangrove recovery and restoration of coastal protection services. Therefore, an integrated approach combining knowledge of the coastal structure in mangrove rehabilitation planning and management, supported by scientific, technical, and financial assistance from relevant institutions, is imperative to achieve sustainable mangrove ecosystem rehabilitation and the desired coastal protection objective (Akbar et al., 2017; Hashim et al., 2010).

5.5. Governance and strategic collaboration to protect the coast

Severe coastal flooding and erosion events have stimulated the communities, local governments and other institutions to rehabilitate mangroves in the studied villages. These rehabilitation efforts were often implemented without proper pre-rehabilitation studies of the environmental variables and reflection on how to reduce heavy coastal erosion, wave energy and land subsidence. Such studies and reviews are crucial to develop effective tailor-made rehabilitation and management strategies for each situation. However, their implementation is probably hampered by a lack of knowledge, resources, support from external agents (i.e. scientists) and appropriate governance structures (Ellison et al., 2020).

Datta et al. (2012) and Ellison et al. (2020) highlighted that communities' involvement and inclusion of local knowledge in the selection and adaptation of vital activities and technologies are among the factors that determine the success of mangrove rehabilitation and management. Our results showed that such selection, adaptation and inclusion are strongly influenced by the characteristics of collective action, local communities' participation and communities' bargaining power in decision making. The '*gotong royong*'-based association in Surodadi, for example, determined its own strategies focused on protecting the aquaculture ponds, and selection of species, planting techniques and timing were based on local knowledge and/or adopted from rehabilitation practices elsewhere.

In Bedono, local communities partnered with external institutions to determine their strategies. Such inclusive planning applied in Surodadi and Bedono stimulated greater acceptance, support and commitment of the people involved. This is important to achieve successful mangrove rehabilitation. The top-down approach of Sriwulan, on the other hand, restrained the communities' ability to communicate their knowledge on, for example, local weather seasonality and related coastal currents to determine the right time for planting, as well as their motivation to deal with high coastal erosion and seedling mortality. Consequently, local support was reduced, and this probably caused scepticism, discouragement and even rejection (Damastuti and de Groot, 2017).

Regardless of the top-down or bottom-up approaches, the presence of capable local leadership in Timbulsloko was decisive in obtaining assistance and collaboration from external institutions while also providing the opportunity for strong community engagement in planning and implementation. Indonesian traditional communities, and notably the Javanese, are characterised by a paternalistic culture with high reliance on capable 'father-figure' leaders (Irawanto and Ramsey, 2011). Such leadership is proven effective to stimulate collective action but also susceptible to conflict of interest, and this likely contributed to social envy and division in the community and eventually to less support (Meilasari-Sugiana, 2012a, 2012b; Irawanto and Ramsey, 2011).

Additionally, Ellison et al. (2020) outlined the unequal and weak or asymmetric relationship (i.e. differences in capacity, power or ideology) between stakeholders involved in mangrove rehabilitation and management. This relationship leads to gaps in policies, project design and implementation, as observed in the four villages. Such asymmetric relationship, referring to Ellison et al. (2020), can be overcome through long-term commitments to funding and monitoring, resolution of conflicts between bottom-up (local) environmental initiatives and top-down (governmental) legislation, strategic collaboration and alignment of goals and objectives of external institutions (i.e. government, funding bodies, NGOs, research institutions) and local communities.

6. Conclusions

Our study examined the effectiveness of different CBMMs for coastal protection by comparing different types of community governance, the associated rehabilitation and management strategies, and the resulting protective capacity of mangroves in the coastal communities of Sriwulan, Bedono, Timbulsloko and Surodadi. The comparison of management performances between the four villages showed large differences in mangrove rehabilitation success. The most effective CBMM in terms of wider mangrove coverage on the seaside and higher average forest structure index was found in Bedono. This resulted in enhanced mangrove coastal protection services. Timbulsloko ranked second with a larger extent of mangroves on the seaside and more protective capacity than Surodadi and Sriwulan. Despite the larger extent of total restored mangroves in Surodadi, most of its mangroves were located around ponds. Only a few small patches (12 ha) fortified the village from the sea with an average protective capacity equal to Timbulsloko. Sriwulan had the smallest and narrowest coverage, and this resulted in the lowest protection of all villages.

The differences in the success of the CBMM were influenced by several factors, including larger rehabilitated areas; longer-term and more integrated and inclusively designed projects and strategies; more regular maintenance; and the presence of additional measures to reduce wave energy. Despite geographical similarities, the water depth in Sriwulan, Bedono and western part of Timbulsloko is higher than in Surodadi and the eastern part of Timbulsloko. This resulted in higher wave energy and erosion rates that threatened sustainability of the rehabilitated mangrove ecosystems in these areas. Our results highlighted the necessity of additional protection measures or interventions to increase the CBMM's success when rehabilitating mangroves in rapidly eroding coastal areas. Furthermore, our study showed the importance of substrate suitability and natural variability when selecting rehabilitation sites, species and planting techniques and follow-up maintenance. We also demonstrated the importance of integrating local knowledge in mangrove rehabilitation and management.

Our results showed that community-led governance efforts stimulated genuine participation through mutual assistance. These efforts also facilitated independent collective decisions and considered local knowledge when selecting rehabilitation and management strategies (i.e. scale, sites, species, timing, maintenance and monitoring). However, rehabilitating mangroves in eroding coastal areas requires additional knowledge, technologies and support from external organisations (i.e. scientific, financial, governmental and non-governmental organisations). Collaborative efforts between communities and supporting organisations within a partnership-based decision-making process proved effective to restore mangroves and the subsequent protective services. Our study demonstrated the critical role of capable local leaders to stimulate collective action and gain support from external organisations. In addition, local regulations can substantially support the sustainability of mangrove management and its potential to protect coastal communities from coastal hazards.

Finally, we showed that strategic collaboration between community members and external organisations, and inclusive and integrated planning and management with a long-term implementation scope, leads to more sustained, larger scale and more effective coastal protection. This should be considered by the Indonesian government when initiating new mangrove rehabilitation programs.

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Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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References

Abidin, H.a.Z., et al., 2010. *Studying Land Subsidence in Semarang (Indonesia) Using Geodetic Method* in *FIG Congress 2010, Facing The Challenges-Building The Capacity*. Sydney, Australia.

Afifah, S., Hizbaron, D.R., 2020. Vulnerability Assessment of Residential Buildings to Tidal Flood Hazards in Sriwulan Village, Sayung District, Demak Regency, 200. E3S Web Conf., 01008

Akbar, A.A., et al., 2017. The role of breakwaters on the rehabilitation of coastal and mangrove forests in West Kalimantan, Indonesia. Ocean Coast Manag. 138, 50–59.

Akber, M.A., et al., 2018. Storm protection service of the Sundarbans mangrove forest, Bangladesh. Nat. Hazards 94 (1), 405–418.

Alferink, M., 2022. Wave transmission through permeable structures in Demak Indonesia: a design study with numerical model SWASH. In: Geoscience and Engineering. Delft University of Technology, The Netherlands, p. 105.

Asiyah, S., Rindarjono, M.G., Muryani, C., 2015. Analisis perubahan pemukiman dan karakteristik permukiman kumuh akibat abrasi dan inundasi di pesisir kecamatan Sayung, Kabupaten Demak tahun 2003-2013. Geo 1, 83–100.

Badola, R., Hussain, S.A., 2005. Valuing ecosystem functions: an empirical study on the storm protection function of Bhitarkanika mangrove ecosystem, India. Environ. Conserv. 32 (1), 85–92.

Banjade, M.R., et al., 2017. Governing Mangroves: Unique Challenges for Managing Indonesia's Coastal Forest. Bogor, Indonesia CIFOR, Washington DC. USAID Tenure and Global Climate Change.

Bao, T.Q., 2011. Effect of mangrove forest structures on wave attenuation in coastal Vietnam. Oceanologia 53 (3), 807–818.

Bertin, X., 2016. *Storm surges and coastal flooding: sttaus and challenges* La Houille Blanche-Revue Internationale de l'eau. EDP Sciences, pp. 64–70.

Biernacki, P., Waldorf, D., 1981. Snowball sampling: problems and techniques of chain referral sampling. Socio. Methods Res. 10 (2), 141–163.

Biswas, S.R., et al., 2009. A unified framework for the restoration of Southeast Asian mangroves—bridging ecology, society and economics. Wetl. Ecol. Manag. 17 (4), 365–383.

Brown, B., et al., 2014. Community based ecological mangrove rehabilitation (CBEMR) in Indonesia. Sapiens 7, 53–64.

Chatarina, M., Setya, N., Singgih, P., 2016. Impact of coastal erosion and tidal flood to land loss at Sriwulan village, Sayung, Demak, central Java province. In: Proceedings of the 1st International Conference on Geography and Education (ICGE 2016). Atlantis Press.

Chaussard, E., Amelung, F., Abidin, H.Z., 2012. Sinking cities in Indonesia: space-Geodetic evidence of the rates and spatial distribution of land subsidence. In: Fringe 2011 Workshop. Frascati, Italy.

Crawford, S.E.S., Ostrom, E., 1995. A grammar of institution. Am. Polit. Sci. Rev. 89, 582–600.

Dahdouh-Guebas, F., et al., 2005. How effective were mangroves as a defence against the recent tsunami? Curr. Biol. 15 (12), R443–R447.

Damastuti, E., de Groot, R., 2017. Effectiveness of community-based mangrove management for sustainable resource use and livelihood support: a case study of four villages in Central Java, Indonesia. J. Environ. Manag. 203 (1), 510–521.

Damastuti, E., de Groot, R., 2018. Participatory ecosystem service mapping to enhance community-based mangrove rehabilitation and management in Demak, Indonesia. Reg. Environ. Change 19, 65–78.

Damastuti, E., et al., 2022. *Effectiveness of community-based manngrove management for biodiversity conservation: a case study from Central Java, Indonesia* Trees. Forests and People 7, 100202.

Das, S., Crépin, A.-S., 2013. Mangroves can provide protection against wind damage during storms. Estuar. Coast Shelf Sci. 134, 98–107.

Dasgupta, S., et al., 2017. *Mangroves As Protection from Storm Surges in Bangladesh* in *Policy Research Working Apper 8251*. World Bank Group.

Dasgupta, S., et al., 2019. Quantifying the protective capacity of mangroves from storm surges in coastal Bangladesh. PLoS One 14 (3), e0214079.

Datta, D., Guha, P., Chattopadhyay, R.N., 2010. Application of criteria and indicators in community based sustainable mangrove management in the Sunderbans, India. Ocean Coast Manag. 53 (8), 468–477.

Datta, D., Chattopadhyay, R.N., Guha, P., 2012. Community based mangrove management: a review on status and sustainability. J. Environ. Manag. 107, 84–95.

De Groot, R.S., et al., Valuing wetlands: guidance for valuing the benefits derived from wetland ecosystem services. Ramsar Technical Report No. 3/CBD Technical Series No. 27 2006, Ramsar Convention Secretariat, Gland Switzerland and Secretariat of the Convention on Biological Diversity, Montreal, Canada.

Dewi, R., et al., 2016. Fuzzy classification for shoreline change monitoring in a part of the Northern coastal area of Java, Indonesia. Rem. Sens. 8 (3), 190.

Ellison, A.M., Felson, A.J., Friess, D.A., 2020. Mangrove rehabilitation and restoration as experimental adaptive management. Front. Mar. Sci. 7 (327).

English, S.A., et al., 1997. In: English, S.A., Wilkinson, C.R., Baker, V.J. (Eds.), Survey Manual for Tropical Marine Resources, second ed. Australian Institute of Marine Science, Townsville, Qld, Australia.

Erftenmeijer, P.L.A. and Bualuang, A. Participation of local communities in mangrove forest rehabilitation in Pattani Bay, Thailand; Learning from success and failure. in 2nd International Conference on Wetlands and Development 2002. Dakar, Senegal: Wetlands International, IUCN, The World Wildlife Fund.

Ervita, K., Marfai, M.A., 2017. Shoreline change analysis in Demak, Indonesia. J. Environ. Protect. 8, 940–955.

Fikriyani, M., Mussadun, 2014. Evaluasi program rehabilitasi mangrove di pesisir desa Bedono Kecamatan Sayung Kabupaten Demak. Ruang 2, 381–390.

Ginanjar, S., et al., 2021. Coastal storm waves detection system design using Beaufort scale standardization and Sugianto wave forecasting method in Timbulsloko, Demak, Central Java, Indonesia. IOP Conf. Ser. Earth Environ. Sci. 893 (1), 012066.

Guleria, S., Edward, J.K.P., 2012. Coastal community resilience: analysis of resilient elements in 3 districts of Tamil Nadu State, India. J. Coast Conserv. 16 (1), 101–110.

Hashim, A.M., Catherine, S.M.P., 2013. In: A laboratory study on wave reduction by mangrove forests, 5. APCBEE Procedia, pp. 27–32.

Hashim, R., et al., 2010. An integrated approach to coastal rehabilitation: mangrove restoration in Sungai Haji Dorani, Malaysia. Estuar. Coast Shelf Sci. 86 (1), 118–124.

Horstman, E.M., et al., 2014. Wave attenuation in mangroves: a quantitative approach to field observations. Coast. Eng. 94, 47–62.

Ilman, M., et al., 2016. A historical analysis of the drivers of loss and degradation of Indonesia's mangroves. Land Use Pol. 54, 448–459.

Irawanto, D.W., Ramsey, P.L., 2011. Paternalistic leadership and employee responses in Javanese culture. Gadjah Mada Int. J. Bus. 13 (2), 185–203.

Ismail, C.S., Heriyanto, Suharini, E., 2012. Pengaruh abrasi terhadap tingkat pendapatan petani tambak di kecamatan Sayung, kabupaten Demak. Geo Image 1 (1), 57–61.

Jati, I.W., Pribadi, R., 2017. In: Penanaman mangrove tersistem sebagai solusi penambahan luas tutupan lahan hutan mangrove Baros di pesisir Pantai Selatan Kabupaten Bantul, 14. Proceeding Biology Education Conference, 1, 1487-153.

Joseph, V., et al., 2013. Occupational transitions in three coastal villages in Central Java, Indonesia, in the context of sea level rise: a case study. Nat. Hazards 69 (1), 675–694.

Kg, P., Bhaskaran, P.K., 2017. Wave attenuation in presence of mangroves: a sensitivity study for varying bottom slopes. Int. J. Ocean Clim. Syst. 8 (3), 126–134.

Krauss, K.W., et al., 2009. Water level observations in mangrove swamps during two hurricanes in Florida. Wetlands 29 (1), 142.

Kusmana, C., 2011. Management of mangrove ecosystem in Indonesia. Jurnal Pengelolaan Sumberdaya Alam dan Lingkungan 1 (2), 152–157.

Lee, W.K., et al., 2021. Potential short wave attenuation function of disturbed mangroves. Estuar. Coast Shelf Sci. 248, 106747.

Lichtman, M., 2014. Qualitative Research for the Social Sciences. SAGE Publications, Inc.: 55 City Road, London.

Mahya, M., et al., 2021. Economic Assessment of Subsidence in Semarang And Demak, Indonesia. Deltares, The Netherlands.

Maliao, R.J., Polohan, B.B., 2008. Evaluating the impacts of mangrove rehabilitation in cogtong bay, Philippines. Environ. Manag. 41 (3), 414–424.

Marfai, M.A., 2012. Preliminary assessment of coastal erosion and local community adaptation in Sayung coastal area, Central Java, Indonesia. Quaestiones Geographiceae 31, 47–55.

Marois, D.E., Mitsch, W.J., 2015. Coastal protection from tsunamis and cyclones provided by mangrove wetlands – a review. Int. J. Biodivers. Sci. Ecosyst. Serv. Manag. 11 (1), 71–83.

Matsui, N., Songsangjinda, P., Keiyo, M., 2012. Mangrove rehabilitation on highly eroded coastal shorelines at samut sakhon, Thailand. Int. J. Ecol. 2012, 1–11.

Maza, M., Lara, J.L., Losada, I.J., 2021. Predicting the evolution of coastal protection service with mangrove forest age. Coast. Eng. 168, 103922.

Mazda, Y., et al., 2006. Wave reduction in a mangrove forest dominated by Sonneratia sp. Wetl. Ecol. Manag. 14 (4), 365–378.

McIvor, A.L., et al., 2012. Storm surge reduction by mangroves. Natural Coastal Protection Series: Report 2. Cambridge Coastal Research Unit Working Paper 41. The Nature Conservancy and Wetlands International, p. 35.

Mclvor, A.L., et al., 2012. Reduction of wind and swell waves by mangroves. Natural coastal protection series: report 1. Cambridge coastal research unit working paper 40. The Nature Conservancy and Wetlands International, p. 27.

Meilasari-Sugiana, A., 2012a. Collective action and ecological sensibility for sustainable mangrove governance in Indonesia: challenges and opportunities. J. Political Ecol. 19, 184–201.

Meilasari-Sugiana, A., 2012b. Community dynamics and ecological sensibility for sustainable mangrove governance in Sinjai Regency, South Sulawesi, Indonesia. Asian J. Agric. Dev. 9, 77–98.

Muis, S., et al., 2020. A high-resolution global dataset of extreme sea levels, tides, and storm surges, including future projections. Front. Mar. Sci. 7.

Muskananfola, M.R., Supriharyono, Febrianto, S., 2020. Spatio-temporal analysis of shoreline change along the coast of Sayung Demak, Indonesia using digital shoreline analysis system. Reg. Stud. Mar. Sci. 34, 101060.

Muskananfola, M., Purnomo, P., Sulardiono, B., 2020. Impact of environmental factors on macrobenthos distribution and abundance in mangrove ecosystems on the Northern Coast of Java. AACL Bioflux 13, 2745–2756.

Nurdyansah, R., Subardjo, P., Helmi, M., 2014. Luas area genangan banjir pasang pada kawasan pemukiman di Kecamatan Sayung, Kabupaten Demak. *Provinsi Jawa Tengah* Oseanografi 3, 574–581.

Peraturan President No, 2020. In: Indonesia, R. (Ed.), *Badan Restorasi Gambut dan Mangrove* P. Kementrian Sekretariat Negara Republik Indonesia Jakarta, Indonesia, 120.

Pramita, A.W., Syafrudin, S., Sugianto, D.N., 2021. Effect of seawater intrusion on groundwater in the Demak coastal area Indonesia: a review. IOP Conf. Ser. Earth Environ. Sci. 896 (1), 012070.

Prasetyo, Y., et al., 2019. Impact of land subsidence and sea level rise influence shoreline change in the coastal area of Demak. IOP Conf. Ser. Earth Environ. Sci. 280, 012006.

Purnama, M., Pribadi, R., Soenardjo, N., 2020. Analisa tutupan kanopi mangrove dengan metode Hemispherical Photography di desa Betahwalang, kabupaten Demak. J. Mar. Res. 9 (3), 317–325.

Quartel, S., et al., 2007. *Wave attenuation in coastal mangroves in the Red River Delta, Vietnam.* J. Asian Earth Sci. 29 (4), 576–584.

Rahadiati, A., Sutrisno, D., Munawaroh, 2022. Management of coastal flood impact in rural area (Case study in Sayung District). IOP Conf. Ser. Earth Environ. Sci. 1095 (1), 012006.

Sandilyan, S., Kathiresan, K., 2015. Mangroves as bioshield: an undisputable fact. Ocean Coast Manag. 103, 94–96.

Sarah, D., et al., 2020. Natural compaction of Semarang-Demak alluvial plain and its relationship to the present land subsidence. Indones. J. Geosci. 7 (3), 273–289.

Setyawan, A.D., Winarno, K., 2006. Pemanfaatan langsung ekosistem mangrove di Jawa Tengah dan penggunaan lahan di sekitarnya: kerusakan dan upaya restorasinya. Biodiversitas 7, 282–291.

Simarmata, N., et al., 2020. Gotong Royong in Indonesian History, 5. Digital Press Social Sciences and Humanities, 00006.

Soekmono, R., 1967. A geographical reconstruction of Northeastern central Java and the location of medang. Indonesia 4, 2–7.

Spalding, M.D., et al., 2014. The role of ecosystems in coastal protection: adapting to climate change and coastal hazards. Ocean Coast Manag. 90, 50–57.

Subardjo, P., 2015. Genangan banjir pasang pada kawasan pemukiman di kecamatan Sayung. *Kabupaten Demak-Provinsi Jawa Tengah* Jurnal Kelautan Tropis 18 (1), 07-12.

Sugianto, D., et al., 2018. The effect of wave run-up on environmentally friendly coastal protection buildings to mitigate erosion in the coast of Demak Regency. Int. J. Civ. Eng. Technol. 9, 1457–1470.

Takagi, H., 2017. Design considerations of artificial mangrove embankments for mitigating coastal floods – adapting to sea-level rise and long-term subsidence. Nat. Hazards Earth Syst. Sci. Discuss. 1–19, 2017.

Taufani, A., Pardo, M.d.L., Wesenbeeck, B.v., 2018. Ecosystem-based Adaptation at Scale through Building with Nature: towards Resilient Coasts in Indonesia. Deltares, The Netherlands.

Umami, K., et al., 2018. *Aplikasi Citra Lansat Dalam Analisa Perubahan Garis Pantai* in *Seminar Nasional Geomatika 2018: Penggunaan Dan Pengembangan Produk Informasi Geospasial Mendukung Daya Saing Nasional*. Geospatial Information Agency of The Republic of Indonesia.

UNEP-WCMC, 2011. Developing Ecosystem Service Indicators: Experiences and Lessons Learned from Sub-Global Assessments and Other Initiatives, in CBD Technical Series. Secretariat of the Convention on Biological Diversity, Montreal, QU, Canada.

van Bijsterveldt, C.E.J., et al., 2020. How to restore mangroves for greenbelt creation along eroding coasts with abandoned aquaculture ponds. Estuar. Coast Shelf Sci. 235, 106576.

van der Lelij, A.C., et al., 2021. Ecological Mangrove Restoration with Permeable Structures: Monitoring Report. Deltares, The Netherlands.

van Wesenbeeck, B.K., et al., 2015. Aquaculture induced erosion of tropical coastlines throws coastal communities back into poverty. Ocean Coast Manag. 116, 466–469.

van Wesenbeeck, B.K., et al., 2017. Coastal and riverine ecosystems as adaptive flood defenses under a changing climate. Mitig. Adapt. Strat. Gl. 22 (7), 1087–1094.

van Zelst, V.T.M., et al., 2021. Cutting the costs of coastal protection by integrating vegetation in flood defences. Nat. Commun. 12 (1), 6533.

Walters, B.B., 2004. Local management of mangrove forests in the Philippines: successful conservation or efficient resource exploitation? Hum. Ecol. 32 (2), 177–195.

Widada, S., Rochaddi, B., Endrawati, H., 2012. Pengaruh arus terhadap genangan rob di Kecamatan Sayung Kabupaten Demak. Buletin Oseanografi Marina 1, 31–39.

Winterwerp, J.C., Borst, W.G., de Vries, M.B., 2005. Pilot study on the erosion and rehabilitation of a mangrove mud coast. J. Coast Res. 2005 (212), 223–230.

Winterwerp, H., et al., 2014. A Sustainable Solution for Massive Coastal Erosion in Central Java: towards Regional Scale Application of Hybrid Engineering. Deltares and Wetlands International.

World Bank, 2016. In: Beck, M., Lange, G. (Eds.), Managing Coasts with Natural Solutions: Guidelines for Measuring and Valuing the Coastal Protection Services of Mangroves and Coral Reefs, Wealth Accounting and the Valuation of Ecosystem Services Partnership (WAVES). World Bank, Washington, D.C.

Yanagisawa, H., et al., 2009. The reduction effects of mangrove forest on a tsunami based on field surveys at Pakarang Cape, Thailand and numerical analysis. Estuar. Coast Shelf Sci. 81 (1), 27–37.

Yuanita, N., et al., 2021. A physical model simulation of combination of a geo-bag dike and mangrove vegetation as a natural coastal protection system for the Indonesian shoreline. Appl. Ocean Res. 108, 102516.

Yuwono, B.D., Prasetyo, Y., Islama, L.J.F., 2018. Investigation of potential landsubsidence using GNSS CORS UDIP and DinSAR, Sayung, Demak, Indonesia. IOP Conf. Ser. Earth Environ. Sci. 123, 012005.

Zhang, K., et al., 2012. The role of mangroves in attenuating storm surges. Estuar. Coast Shelf Sci. 102, 11–23.