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Monitoring Pilot Study of Temporary Permeable Structures for Mangrove Restoration

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Abstract: Temporary permeable structures of bamboo and brushwood have been implemented for mangrove restoration along retreating coastlines worldwide. However, deriving lessons from previous studies is inhibited by their lack of morphodynamic context, with missing bathymetric data or control comparisons. In this paper, we present a low-tech, low-cost, data collection methodology to support morphodynamic system understanding and modeling of mangrove coastlines. This method was applied to monitor a mangrove restoration project featuring temporary permeable structures of bamboo and PVC, installed in late 2021 on the subsiding muddy coast of Demak, Indonesia. Seabed level changes were regularly tracked with bathymetric surveys and monitoring poles across structures and at a nearby control site. Structures were positioned landward of a chenier, at −0.7 m to −0.9 m relative to mean sea level (MSL), and 30–70 m seaward of the mangrove fringe. Measurements from August 2021 to December 2022 revealed seabed erosion (−0.33 m to −0.4 m) seaward of the structures, with mixed responses landward: two sections eroded (−0.04 m to −0.05 m), one remained stable, and a creek-adjacent section eroded by −0.43 m. At the nearby control site, chenier migration and vertical growth promoted landward accretion, though elevations remained below MSL and thus unsuitable for mangrove colonization. The bathymetric and monitoring pole measurements presented in this study constitute valuable datasets for modeling studies aiming to unravel the dominant processes driving morphodynamic changes. Such models could also inform integrated approaches to mangrove restoration in subsiding coastlines, considering sediment supply, subsidence management, and structure integrity.

Keywords: mangrove restoration; brushwood structures; temporary permeable structures; nature-based solutions; building with nature

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1. Introduction

Mangroves protect coastal communities worldwide from flooding and sea level rise [1–3], while providing valuable economic services such as food and timber provision [4]. Yet, despite their contribution to nearby communities, mangrove ecosystems have degraded across the globe for urbanization and farming [5,6]. Deforestation, in combination with activities that reduce sediment sources, like river damming, or activities that constitute sediment sinks, such as sand mining or subsidence due to groundwater extraction, can exacerbate flooding and coastline retreat. To address erosion problems and aid mangrove recovery, temporary permeable structures made of bamboo and brushwood have been applied for mangrove restoration at coastlines of Guayana, Indonesia, Suriname,Thailand, and Vietnam, among other countries [7–9].

Bamboo and brushwood structures, also referred as permeable structures, dams or fences, emulate the effect of the lost mangrove vegetation, by dampening waves while enabling sediment influx by tidal currents, promoting net mud sedimentation and fostering return of mangroves [8]. For successful mangrove establishment, accretion must raise the seabed to suitable elevations, typically between mean sea level (MSL) and mean high water (MHW), with specific thresholds depending on the mangrove species. Bamboo and brushwood structures commonly consist of two rows of vertical bamboo poles filled with bundled brushwood. Typical structure lengths (alongshore) reach 35 m to 100 m, with (cross-shore) widths around 0.4 to 0.6 m [10] (between the landward and seaward bamboo poles, center to center). The structures are built of bamboo and brushwood with the idea that they should induce sufficient accretion for mangrove colonization within m, and shelter mangroves while they are growing for another 3–5 years [11]. After this period, the materials are expected to degrade naturally, allowing for the construction of new structures further seaward to progressively extend the coastline. However, in some cases remnants of brushwood structures have caused debris accumulation along the shore, highlighting the potential need for waste management strategies to mitigate this issue [12], and to remove any non-biodegradable structure components.

Previous studies indicate that structure performance varies considerably depending on the local conditions, especially depending on wave exposure. In Guyana, structures placed at a site sheltered by a visible offshore mud bank, and previously experiencing accretion, had greater potential to trap sediments and increase elevation [13]. Other sheltering morphodynamic features, like cheniers (coarse-sediment deposits over mud layers that shelter the coastline from waves and foster mangrove establishment [14]), could also influence, and perhaps favor, structure performance while they are present. Conversely, high-energy environments with large waves or strong currents often reduced efficacy within efforts in Vietnam, leading to erosion and undermining structure stability [10]. Failures were often aggravated by structural damage due to barnacle infestation or shipworm attack on wooden and bamboo poles.

Deriving conclusions from past studies is not straightforward because of the limited published data on the topic. Some studies provide accretion rates during the first months after structure construction [7,13,15], but do not specify spatial variations, nor standard deviations. Moreover, contextualizing accretion rates in a morphodynamic framework is hindered by the lack of reported bathymetric data. In line with this lack of contextualization, some studies report successful implementations at already accreting coastlines [13], without conducting measurements at control locations. Finding suitable controls for morphodynamics is challenging (and often unfeasible) at complex coastlines, but understanding permeable structure performance requires evaluating the behavior of the system without interventions. Although system behavior may vary at the control site due to the heterogeneity of coastal processes, monitoring data from areas without structures remains crucial for developing and validating morphodynamic models under both natural and altered conditions.

In this study we therefore monitor a mangrove restoration pilot project featuring temporary permeable structures in Demak, Indonesia, between 2021–2022, by measuring bed level changes at fixed monitoring poles, and surveying monthly bathymetries across structure transects and across a nearby location without structures. The presented approach constitutes a low-tech, low-cost, data collection methodology to acquire valuable datasets that support system understanding and morphodynamic models. Additionally, we provide a descriptive analysis of bed level changes observed at the pilot site, which could be further explored through follow-up statistical analyses and morphodynamic models. Our work also includes costs of structure construction, monitoring, and maintenance, lessons learned, and discusses structure performance within the context of subsiding mangrove coastlines.

2. Materials and Methods

2.1. Site Description

The pilot structures were installed in the Fall of 2021, 500 m north of the village of Timbulsloko, in the regency of Demak (North Java, Indonesia) (Figure 1). The region of Demak mostly consists of aquaculture ponds, many of which have been flooded by the sea, and rice fields, delimited by Semarang city in the south and by the Wulan river delta in the north (Figure 1a). The coastal system is mostly muddy but cheniers are frequently observed migrating along and across the system [14,16]. Chenier dynamics are sensitive to the timing of waves and tides-they tend to propagate towards the shore due to wave action, with most transport taking place during high water levels that fully submerge the chenier [16]. In the long term, landward migration can be counteracted by tidal phase lags (due to tidal flooding of subsided hinterland), which leads to a dynamic equilibrium of these sandy features [17]. This dynamic equilibrium is unique of Demak, whereas other locations with cheniers often experience continuous onshore or alongshore migrations. Chenier presence promotes mangrove establishment, especially when they remain at their position over more than one year [14].

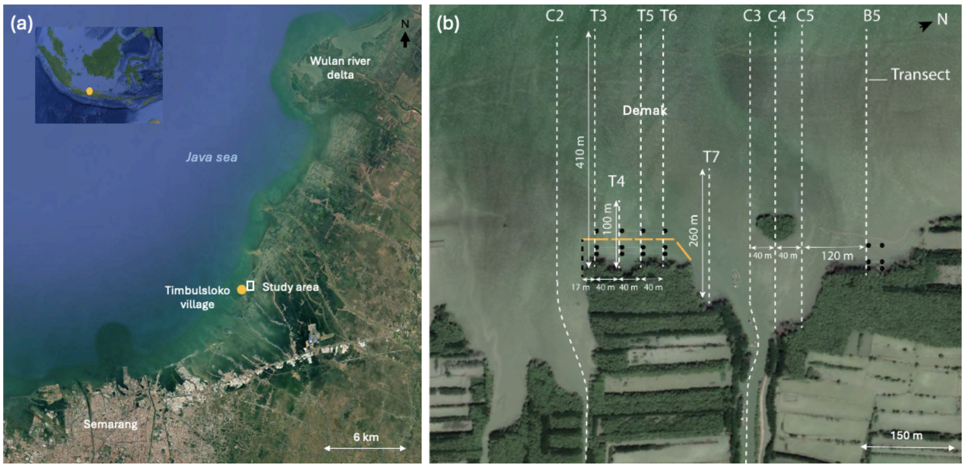

Figure 1. (**a**) In the upper corner, location of Demak in northern Java, Indonesia, within the broader Indonesian archipelago. The larger picture shows the region of Demak, covered by aquaculture ponds, many of which have been inundated by the sea, and rice fields, bordered by Semarang City to the south and the Wulan River delta to the north. (**b**) Map showing the location of temporary permeable structures of the 2021–2022 pilot study (yellow lines) and the measurement set up. PVC pipes (black dots) were used for monitoring. Monitoring poles were placed 10 m seaward from the structures, 10 m just landward from the structures, and 20 m landward from the structures. At the control site, the monitoring poles were placed at equivalent distances from the coastline. White dashed lines show transect locations where bathymetries were collected, across permeable structures (T3–T6), creeks (C2 and C3), and the control location (B5)

Despite mangrove establishment having been observed in unusually calm years without storms, or locally behind sheltering cheniers [14], mangrove presence in Demak is threatened by subsidence [18], caused by groundwater extraction in the neighbouring city of Semarang [19]. Subsidence rates reach up to 0.19 m/year at the city [20,21], and gradually decrease further away, reaching between 0.05–0.1 m/year at the location of the pilot project [18]. Mangroves have shown several mechanisms to temporarily counteract subsidence, such as accumulating sediment within forest stands, growing longer pneumatophores to survive higher water levels or developing new, higher root mats when pneumatophores cannot stretch any longer [18]. A monitoring study over 2 years showed that locally mangroves were able to keep up with approximately 0.04 m/year [18]. Nevertheless, the forest edge retreated in the long term, as trapped sediments came from the eroding foreshore, exposed to increasingly larger waves due to subsidence, resulting in cliff formation and falling trees [18].

Several variations of temporary permeable structures made of bamboo, brushwood, and PVC poles, were regionally implemented between 2014–2020. The structures were built to reduce wave action and enhance sediment accretion, in order to elevate the ground elevation at flooded aquaculture ponds present along the coastline. The first structure induced 0.5 m of accretion [22], and posterior structures induced 0.2 m to 0.3 m of accretion on average during their first stormy season [23]. Despite some instances of mangrove establishment behind structures, none of them led to long-term mangrove recovery. Accretion levels could only compensate for subsidence during the structure lifetime, and structures failed to elevate the seabed to or above mean sea level—the critical threshold for the establishment of the local pioneer species, *Avicennia marina*. Moreover, structures required frequent maintenance due to loss of the brushwood filling or due to their collapse during storms, which was exacerbated by shipworm damage to the bamboo poles.

Locally, most storms occur during the rainy and stormy north-west (NW) monsoon, between November and March. Past field campaigns indicated that the largest waves observed during the NW monsoon reached a height of H_{m0} = 2 m, with periods of T_p = 6 s during a storm in 2018, where storm surge increased water levels by approximately 1 m [14]. During the relatively calmer south-east (SE) monsoon, between June–August, significant wave heights remain below 0.3 m, with wave periods of a few seconds [14]. Over the year, the tidal range varies between 0.5 m (neap tides) and 1 m (spring tides), corresponding with a microtidal coastal system with mixed semidiurnal tides [16].

2.2. Pilot Study

Temporary permeable structures made of bamboo and PVC were installed in the Fall of 2021 at a water depth of −0.7 m to −0.9 m with respect to mean sea level (MSL) or −0.2 m to −0.4 m below mean low water (MLW), positioned 30 m to 70 m seaward of the mangrove fringe. Mangroves had been retreating at this site since 2018, and fallen trees were present along the vegetation edge. Structures consisted of 2 to 3 rows of poles with a shore-normal spacing of 5 m. Two types of pole arrangements were implemented-rows of vertical bamboo poles (dashed lines in Figure 2a), and horizontal bamboo beams attached to PVC poles filled by concrete (yellow lines in Figure 2a). Brushwood fillings were not used since previous restoration efforts in this region showed frequent damages of the brushwood bags, which were often pierced or floated away, causing large maintenance costs. Shore-parallel structure sections had a length (alongshore) of 35 m with 5-m gaps in between. To the north, a 43-m-long section consisted of two rows angled at 45 degrees from the vegetation edge to facilitate shipping. Lastly, to the south there was a 100 m long row of bamboo poles.

2.3. Data Collection

Ten transects were monitored from August 2021 to December 2022. These included five transects at locations with structures, four near channels, and one at a control site without channels. Monitoring poles were installed both (10 m) seaward and (10 m and

20 m) landward of the structures to track changes in the distance between the top of the poles and the seabed over time (Figure 1b), since this monitoring method provided valuable data for previous pilot structures in the region [23]. The poles were made of PVC filled with concrete, drilled ∼1 m deep into the mud. Their top elevation was initially 1.2 m with respect to the seabed. Over time, erosion and accretion processes would modify the distance between the pole top and the sea bottom, and such changes were recorded in regular field surveys. Since the monitoring poles were only drilled one meter into the soil, they subsided with their surrounding area, and pole measurements therefore provide information about erosion, accretion and consolidation, but not about shallow subsidence. For context, past studies indicated that subsidence rates at nearby villages varied between 0.05–0.1 m/year [18]. Bed level changes at monitoring poles were recorded between December 2021 and December 2022.

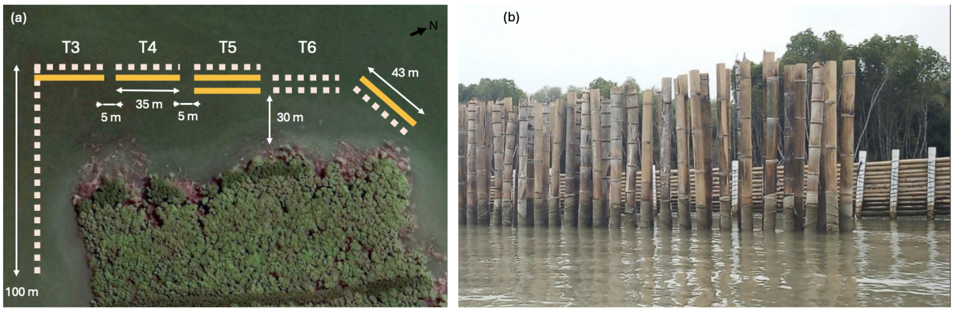

Figure 2. Layout of the structures built in the pilot project. (**a**) Overview of the arrangement of structures consisting of rows of vertical bamboo poles (white dotted lines), and horizontal bamboo beams attached to PVC poles filled with concrete (yellow lines). (**b**) Close-up details of a row of vertical bamboo poles (front) and row of horizontal bamboo beams attached to vertical PVC pipes (back).

Bathymetric data along the transects (Figure 1b) were collected between August 2021 to December 2022 by measuring the distance from the water surface to the seabed every 10 m using a measuring pole with a flat ground plate attached. This plate prevented the pole from sinking into the soft sediment. Depth measurements were referenced to the mean sea level for each period, based on data from the tidal station in Semarang [24]. The tidal station stopped working at the end of the Summer of 2022, implying that we could not correct profiles after July 2022, which are therefore excluded from this analysis. For each time period, the bathymetric measurements across a transect were projected on the same shore-normal line, since by walking the bathymetries there was some lateral spread (of a couple of meters) in the measurements. The specific wave conditions during the measurement period from ERA5 [25] are shown in Figure 3.

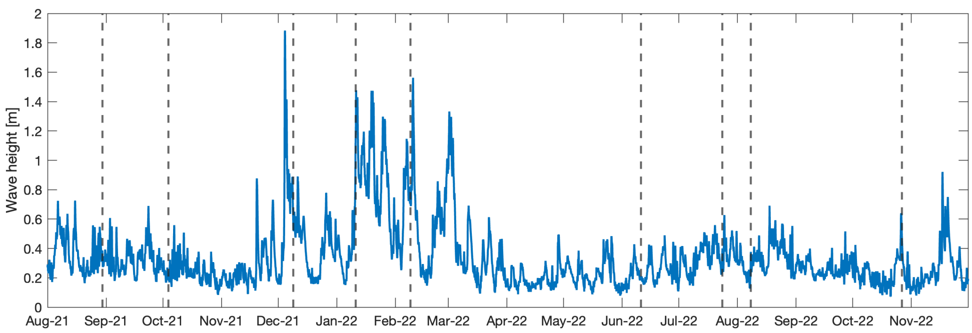

Figure 3. Time series of significant wave height data from ERA5 during the measurement period. Vertical dashed line show dates in which bathymetric data was collected.

3. Results

3.1. Bathymetric Data

The bathymetry reveals two prominent features: a submerged chenier, represented by shallow (yellow) areas in Figure 4, and the drainage creeks extending from the mangrove stands, shown by blue-green dots. Between August 2021 (Figure 4a) and July 2022 (Figure 4b), the most significant large-scale changes include the deepening of several drainage channels and an increase in the crest height of the chenier, which rose above mean sea level, as it migrated onshore. The progression of these features over time is further illustrated in Figure 5, which provides a detailed view of the profile evolution over 10 months after structure construction. The bathymetry also shows that the structures aligned with the edge of an already present drainage channel, which deepened between August 2021 and July 2022 (Figure 4a,b).

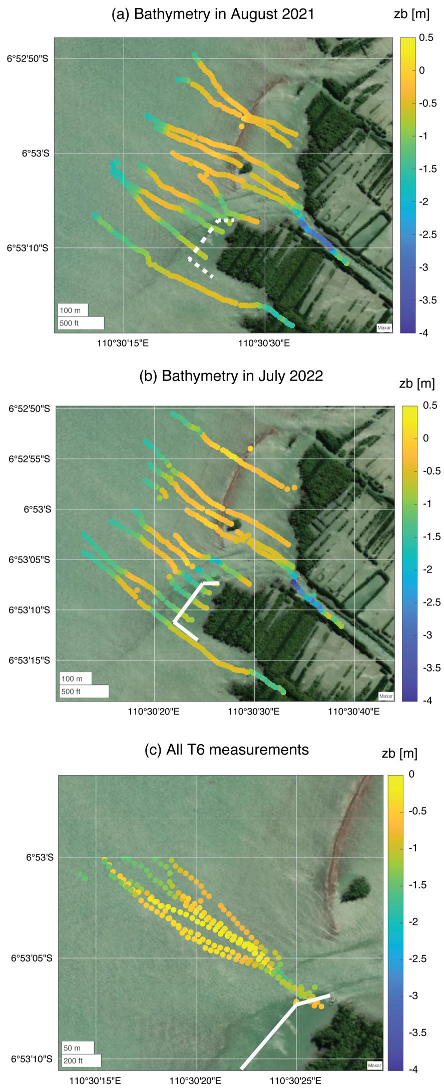

Figure 4. Bathymetric profiles along monitoring transects, where z_b represents the seabed elevation relative to mean sea level (MSL) in meters. (**a**) Bathymetric profiles in August 2021, before the construction of the structures. (**b**) Bathymetric profiles from July 2022, showing the seabed elevation 10 months after structure construction. (**c**) Bathymetric profiles from all time measurements at transect T6, highlighting lateral variability and misalignment among measurements due to spatial differences in transect positioning. The location of the structures is indicated by white lines. In plot (**a**), a dashed white line is used to indicate that the structure had not yet been constructed at that time.

Cross-shore bathymetric profiles show that the chenier was highest in the control transect (Figure 5f), with an initial elevation of −0.1 m with respect to mean sea level, and grew in height over time until reaching a maximum crest elevation of 0.23 m. Bed levels increased behind the chenier up to ∼0.1 m. Despite these accretive effects, the bed level remained at −0.3 m with respect to MSL at the most landward bathymetry measurements, which is below the bed level required for mangrove establishment. Satellite imagery also reveals that both the coastline and the mangrove edge continued to retreat over time (Figure 6). Behind the structures, the bed level response varied, as illustrated in the plots of different structure transects (Figure 5b–d). It is important to note that maintaining exact alignment when walking transects across different measurement periods was challenging (see Figure 4c). Therefore, the bathymetric data offers a broader overview of the site's dynamics, while the monitoring pole data delivers more precise information on vertical bed level changes at specific locations.

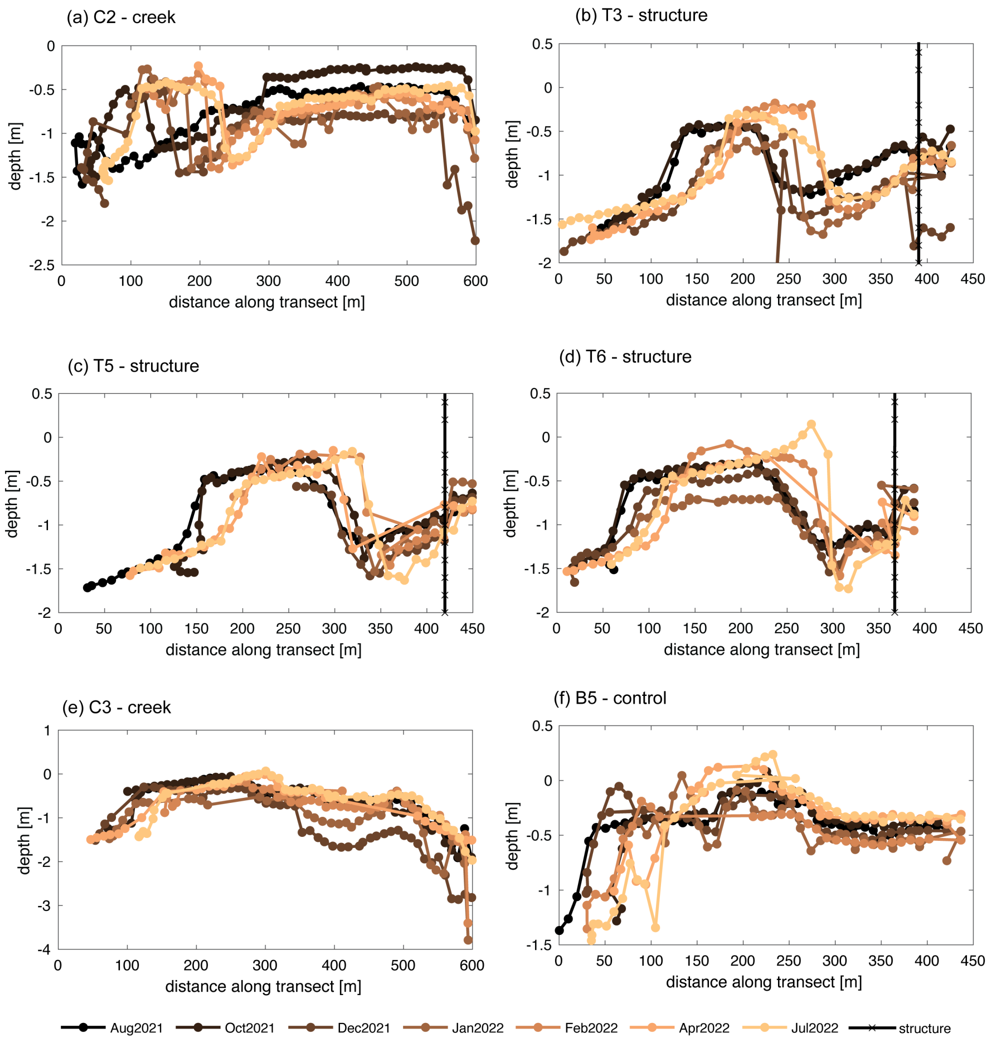

Figure 5. Bathymetric profiles across several transects, representing the water depth relative to mean sea level (MSL) in meters. (**a**) C2, (**b**) T3, (**c**) T5, (**d**) T6, (**e**) C3, (**f**) B5. The most seaward points are shown on the left, and the most landward at the right. Transects T3, T5 and T6 are located across structures, while B5 is situated without a structure. T3 partly collapsed during a storm in January 2022, wheras T5 and T6 remained intact. C2 and C3 are located along creeks. Different lines represent bathymetry data collected at various times between December 2021 and July 2022, illustrating the migration of a chenier across the transects over time.

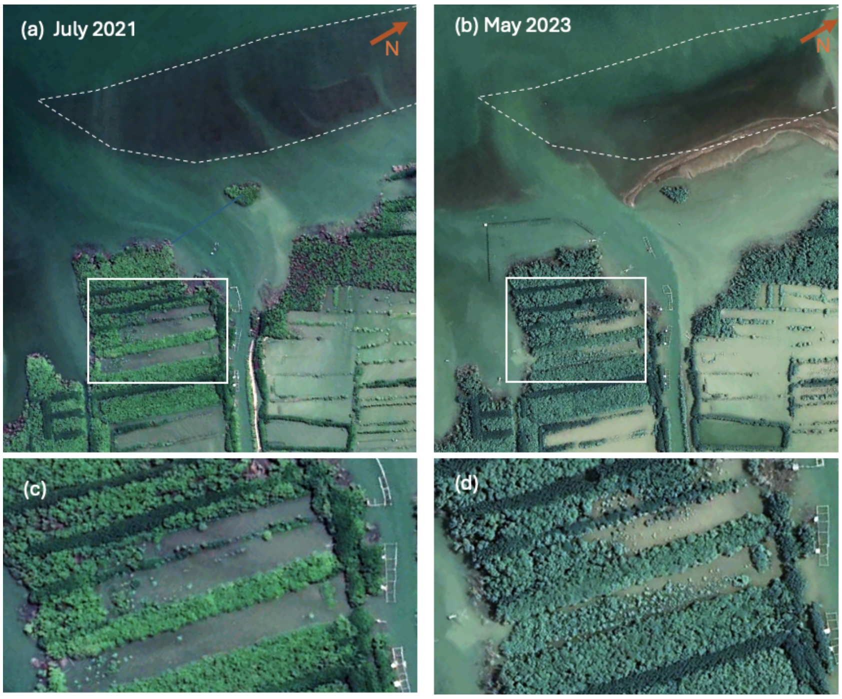

Figure 6. Satellite imagery from Google Earth depicting the study area in (**a**) July 2021, and (**b**) May 2023. The chenier outline from (**a**) is overlaid as a white dashed line in (**b**) for comparison. The landward migration of the chenier can be observed between (**a**,**b**). The white rectangles enclose areas with increase in mangrove cover between 2021–2023, with close ups for (**c**) July 2021 and (**d**) May 2023.

3.2. Monitoring Poles

The comparison of average bed level changes at monitoring poles between December 2021 and December 2022, from structure and control transects is shown in Figure 7. At the control transects (no structures), monitoring poles showed consistent sediment accretion. Mean bed level changes between both control transects reached accretion values of 0.01 m on the most seaward pole, 0.08 m landward, and 0.13 m further landward. At the structure transects, on average, considerable erosion is measured seaward from the structures (mean change = −0.38 m), with slight erosion just landward of the structure (mean change = −0.03 m), and larger erosion further landward (mean change = −0.05 m). Standard deviations at these points were relatively high, particularly further landward (standard deviation = 0.2 m), indicating substantial spatial variability in sediment dynamics within the structured area, as also shown in Figure 7b.

Erosion seaward of the structures likely resulted from a combination of processes, including creek development along the structures, sediment stirring and scouring caused by wave reflection [26], as well as landward sediment influx due to wave height reductions across the structures [27]. Wave reflection and transmission likely varied for different structures, considering variations in designs [26] and differing levels of damage during the northwest monsoon (Figure 3), with T3 and T4 heavily damaged by mid-January, while T5 and T6 remained intact. Despite differences in structure stability, and possibly in performance, during storms, the relatively uniform erosion observed along all sections suggests that creek development may have played a significant role in driving erosion on the seaward side of structures. Landward of the structures, responses varied: T3 and T4 experienced erosion, T5 remained stable, and T6—adjacent to a creek—showed initial accretion near the structure (0.07 m) but substantial erosion (−0.43 m) farther landward (Figure 7).

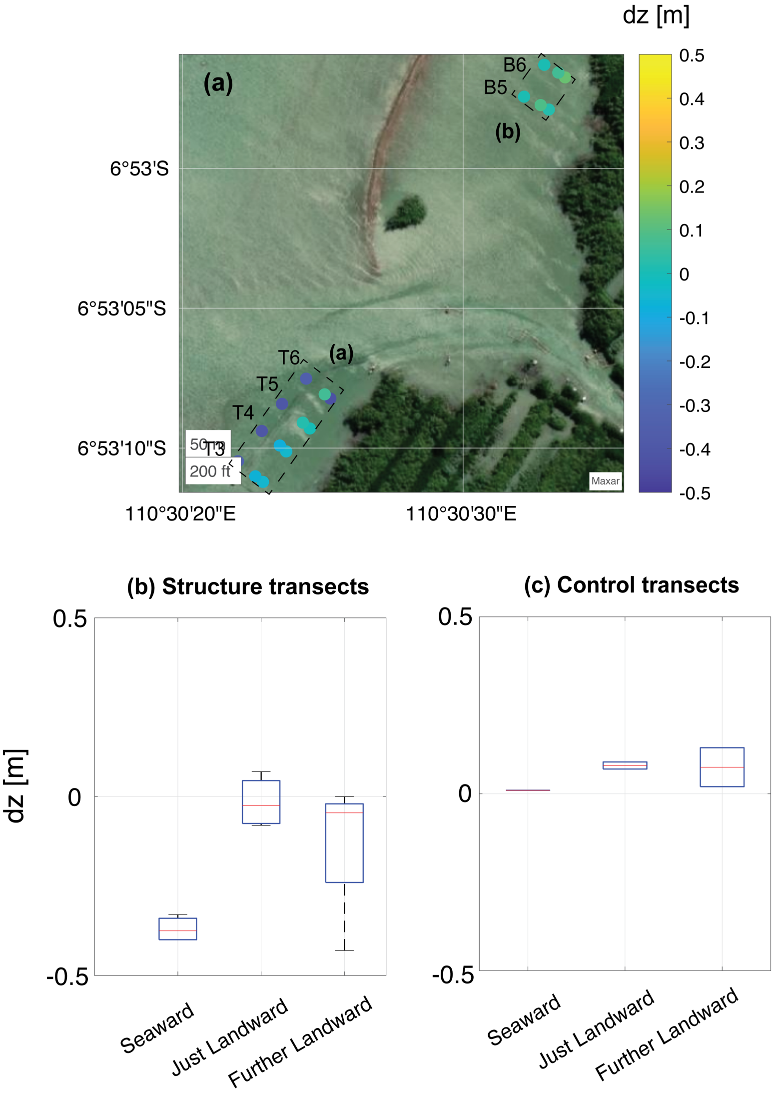

Figure 7. (**a**) Map depicting bed level changes (denoted as dz, in meters) between December 2021 and December 2022 for both structure and control transects. (**b**) Boxplot illustrating bed level changes at structure transects for monitoring poles located 10 m seaward, 10 m (just) landward, and 20 m (further) landward from the structure. (**c**) Boxplot for control transects, showing bed level changes at poles placed at equivalent distances from the shore.

Seaward erosion occurred mainly within the first two months (Figure 8a,b), continuing into subsequent months as the area deepened significantly by June (Figure 8c) before stabilizing between June and December (see Figure 9). Behind T3 and T4, mild erosion persisted throughout the year. At T5, the bed level raised by 0.1 m between January and February 2022, perhaps due to sedimentation during storms within this period (see consecutive storms in January in Figure 3) but this sediment had eroded again by June. At T6, significant erosion occurred at the most landward point during the first month (Figure 8a), while bed level changes elsewhere were minor. The severe erosion observed at the seaward pole of T6 appears influenced by creek development, supported by the deepening of creek C3 in December 2021 (Figure 5e).

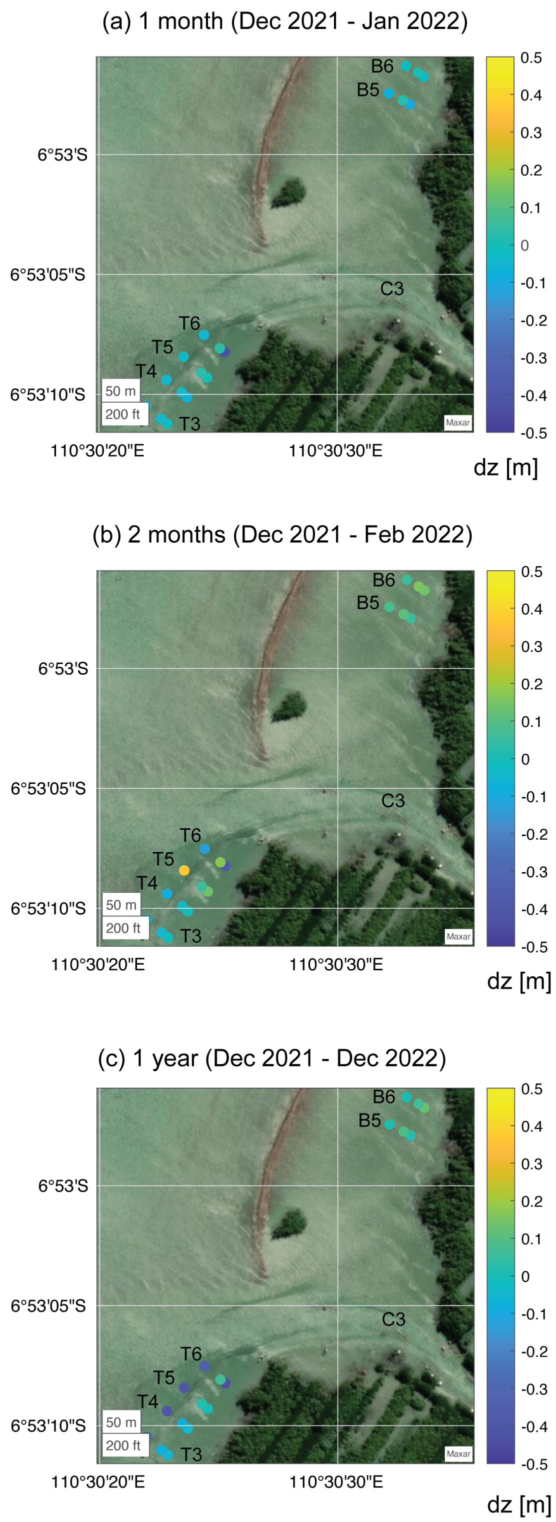

Figure 8. Bed level changes measured at monitoring poles across structure transects (T3–T6) and control locations (B5–B6). (**a**) Changes observed between 9 December 2021, and 11 January 2022, highlighting erosion and localized accretion patterns. (**b**) Bed level changes between 9 December 2021, and 9 February 2022, showing continued accretion near structures and minimal changes at control sites. (**c**) Bed level changes over the longer term, from 9 December 2021, to 10 December 2022, illustrating overall erosion in front of the structures and variable accretion and erosion behind them.

The control transect, where the chenier height was larger, exhibited complex dynamics: erosion in December, significant accretion in January, followed by erosion in February, minimal changes until June, and further accretion (up to 0.08 m) from June to December, when wave conditions were relatively milder (Figure 3). Accretion during calm wave conditions may have occurred in periods of elevated tidal levels, when submersion of the chenier top enables even small waves to generate significant morphodynamic changes [16]. The time series of a structure transect and a control transect are shown in Figure A1 of the Appendix A.

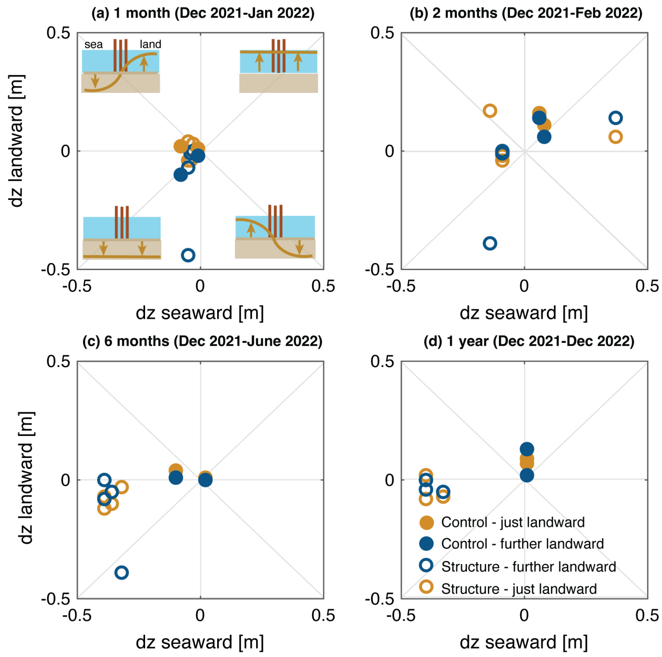

Figure 9. Seabed level changes (dz in meters) measured both landward (vertical axis) and seaward (horizontal axis) of a temporary permeable structure (empty dots), and at a control transect (filled dots) across four different time periods. The diagonal represents equal magnitude of the changes in the seaward and landward points. (**a**) December 2021–January 2022, representing one month during the Northwest monsoon season; (**b**) December 2021–February 2022, covering two months of the Northwest monsoon season; (**c**) December 2021–June 2022, representing a six-month period; and (**d**) December 2021–December 2022, capturing a full year. These plots illustrate sediment accumulation or erosion patterns in proximity to the temporary permeable structures compared to sites without structures. Sketches illustrating the erosion patterns for different combinations of bed level changes seaward and landward are shown in plot (**a**).

4. Discussion

4.1. Structure Damage During Storms

A field survey revealed that the landward rows of T3 and T4 had collapsed due to storms by mid January 2022 (see Figure 10b). The damaged sections consisted of horizontal bamboo beams attached to vertical poles, which were destabilized and tilted by wave loads. The damaged sections included 12 m (∼30%) of the back row of T3 and the entire back row of T4. The greater damage observed in T3/T4 compared to T5/T6 may be attributed to higher wave exposure, though variations in construction quality and soil conditions cannot be ruled out. In contrast, the front (seaward) rows, made of vertical bamboo poles embedded in the seabed, remained stable (see Figure 10a). Repairs were carried out in March–April 2022, involving the retrieval of the fallen section from the seabed and the construction of additional support structures behind the fences (see Figure 10c). The delay between the collapse and repair indicates that the structure's performance at T3 and T4 could have been compromised for two months, which could have contributed to the higher erosion measured landward of the structures at these two transects, compared to T5. Our observations indicate that ensuring structural stability requires reinforcing horizontally beamed fences with support structures to prevent tilting. Additionally, structures built using only vertical bamboo poles proved to be more stable, as all elements were securely drilled into the soil. To further enhance future implementations, stability models for bamboo structures should be developed.

Figure 10. Photographs documenting the repair process of the damaged temporary permeable structure during early 2022: (**a**) the first row, consisting of vertical bamboo poles embedded in the muddy seabed, remained stable throughout the storm season; (**b**) the second row, originally constructed with horizontal bamboo poles supported by vertical poles, collapsed in January 2022 due to insufficient stability to withstand wave loads. The damaged sections had a length of 12 m (∼30% of the back row) of T3 and 35 m (entire back row) of T4; (**c**) the structure was repaired between March and April 2022, with the collapsed components lifted and additional support structures added to enhance stability.

4.2. Limitations of Permeable Structures at Subsiding Coastlines

Accretion rates behind structures were highest at T5, potentially due to its relatively better condition during the pilot study and its design, which included three rows instead of two, providing greater wave damping. However, local sedimentation levels were not sufficient to enhance mangrove recovery, as the water depth remained at −0.7 m with respect to MSL at the most landward pole. Although subsidence may have constrained structure performance—given that maximum accretion levels (0.1 m) are comparable the expected annual subsidence (0.05–0.1 m)—the structure at T5 would have needed to generate significantly higher sedimentation levels (∼0.7 m) to support mangrove establishment at the fringe. The mangrove fringe continued to retreat at both structure and control transects.

The limitations of the structures in inducing sufficient accretion may stem from the pilot's specific location, and in hindsight, a monitoring period of at least 6–12 months prior to construction could have been beneficial. Such monitoring might have identified potential challenges posed by the chenier and creek, which likely affected the structures' efficacy. However, considering that previous pilot projects using bamboo and brushwood structures in the Demak coastal system—across varying conditions such as the presence or absence of cheniers, differing water depths, and distances from the shoreline—have similarly failed, the broader limitations of these structures likely arise from insufficient protection against hydrodynamic forces and/or the need for more long-lasting and resistant designs to support mangrove recovery on subsiding coastlines.

Despite the challenges faced by seaward mangrove fringes, mangrove establishment has been locally observed along the coast over the past decade. In Demak, Google Earth imagery reveals long-term mangrove colonization and growth at the seaward edge behind a stable chenier that has persisted in front of the coastline since 2015 (2 km north of Timbulsloko village), as well as behind a concrete seawall constructed in 2012 in Timbulsloko. These observations demonstrate the feasibility of mangrove restoration on subsiding coastlines and emphasize the potential need for longer-lasting or even permanent interventions in regions affected by subsidence. Degraded mangrove systems along subsiding coastlines, such as the one in Demak, arise from the interplay of multiple factors, including landscape-level processes like subsidence rates and sediment supply, as well as localized abiotic features such as cheniers and tidal channels. Effective mangrove restoration at the seaward fringe requires a comprehensive, long-term intervention strategy, which could involve temporary permeable structures, sediment nourishments, permanent structures, or combinations thereof, as done in dune-dike hybrid coastal protection systems.

The choice of restoration techniques will depend on factors such as the rate of subsidence and sediment availability. Temporary permeable structures may be effective in areas with relatively low subsidence rates and adequate sediment supply. For regions experiencing higher subsidence rates, permanent structures can facilitate mangrove recovery, provided they allow sufficient sediment influx through adequate openings. However, the effectiveness of these structures is constrained by sediment availability, and their presence limits the seaward expansion of vegetation. Cheniers could be nourished to extend their stability and functionality, serving as a more adaptive solution to evolving boundary conditions. While sand nourishment would require a local sand supply, it could provide a more dynamic approach to supporting mangrove restoration in subsiding environments.

Integrated design approaches can be informed by morphodynamic models based on bathymetric datasets such as the one presented in this study. These models could assess the performance of potential solutions in erosion mitigation and mangrove habitat restoration. Additional monitoring pilot studies for various interventions—such as permeable structures, nourishments, or hard structures—would provide valuable data for the validation of modelling frameworks. As previously discussed, identifying control locations with comparable morphodynamic behavior in highly degraded and complex coastal systems—such as the one studied here—can be challenging. However, monitoring data from areas without interventions remains essential for validating the modeled morphodynamic behavior of the system in its natural state.

Lastly, although this study focused on mangrove restoration at the seaward fringe, additional opportunities can be found further landward. Previous studies in Demak found that mangrove restoration in abandoned aquaculture ponds further inland was relatively more successful than along the seaward fringe, where higher wave exposure driven by regional subsidence posed greater challenges. At this site, mangroves did colonize abandoned aquaculture ponds located 100 m landward from the fringe at structure transects, and at variable distances from the fringe at the control transect, (Figure 6) but such colonization cannot be directly attributed to shoreline dynamics, given that the vegetation edge continued to retreat over time.

4.3. Costs of Construction, Monitoring and Maintenance

The costs of the construction of the pilot in 2021 were equal to 27,000 euros or 429,330,000 IDR for 466 m of structures, with costs between 30–60 euros per meter of structure (500,000–1,000,000 IDR per meter of structure). Transects were monitored monthly, corresponding to costs of 230 euro/month or 3,847,900 IDR/month (2760 euro/year or 46,174,800 IDR/year). During this pilot, several lessons learned from previous projects were applied to reduce maintenance costs, such as avoiding using brushwood filled nets (which often broke or floated away) and protecting bamboo poles to avoid shipworm damage (which increases their lifetime from less than a year to two years). However, by using dense horizontal arrangements of bamboo, the high forces acting on the poles resulted in partial collapse of one section of the structure during the NW monsoon season. For subsequent years, support structures were added behind the bamboo poles, but fixing the damages of the first NW monsoon of 2022 was as expensive as building the structures from scratch. Damages from waves impact, combined with shipworm damage in locations where brushwood structures are submerged for a long time, have also resulted in large damage in Vietnam [10]. In the structures of this pilot, the structures were −0.7 to −0.9 m with respect to MSL, or −1.2 to −1.4 m with respect to MHW, exceeding the recommendation that the bed level should not be lower than MHW −0.70 to −0.80 m, based on experiences in Vietnam [10], which could have led to excessive wave exposure and wood submergence. Nevertheless, due to the considerable erosion experienced by this region, it was difficult to find shallow foreshores fronting vegetation stands.

5. Conclusions

Temporary permeable structures were installed at the subsiding coastline of Demak and monitored for a year, at a site with retreating vegetation fronted by a submerged chenier. Erosion occurred seaward from structures, while landward responses varied, with some areas showing mild accretion and others significant erosion. In comparison, a control area, where the chenier was relatively higher, experienced relatively larger accretion. Temporary permeable structures faced significant challenges, including damage during the northwest monsoon and unintended interactions with existing geomorphic features like cheniers and drainage creeks.

Overall, bed elevations remained below the threshold needed for mangrove seedling establishment, both landward from structures and at the control location. Locally, net mangrove expansion over decade has been observed behind a chenier that remained relatively stable for 10 years at 2 km north of Timbulsloko, and behind a concrete structure at the Timbulsloko village, suggesting that long-term mangrove restoration in highly dynamic and subsiding environments may require durable, high-performing interventions combined with strategies that minimize subsidence and ensure sufficient sediment supply. Overall, the bathymetric and monitoring measurements provided in this study form a unique dataset that could inform future modeling studies on integrated approaches for mangrove restoration in subsiding and eroding mangrove fringes.

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Conflicts of Interest: Author Tom Wilms was employed by the company. Witteveen en Bos. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

The time series of bed level changes for the structure transect T5 and the control transect B5 are shown in Figure A1.

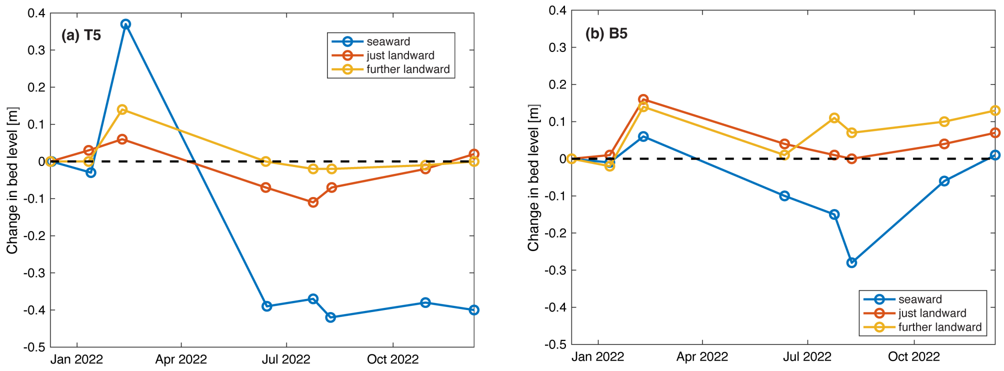

Figure A1. Time series of bed level changes from monitoring poles at T5 (**a**) and B5 (**b**). Each subplot shows three lines representing measurements taken at different locations: seaward, landward, and further landward.

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