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Managing erosion of mangrove-mud coasts with permeable dams – lessons learned

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ABSTRACT

Mangrove-mud coasts across the world erode because of uninformed management, conversion of mangrove forests into aquaculture ponds, development of infrastructure and urbanization, and/or extraction of groundwater inducing land subsidence. The accompanied loss of ecosystem values, amongst which safety against flooding, has far reaching consequences for coastal communities, exacerbated by sea-level rise. To halt erosion various nature-based solutions have been implemented as an alternative to hard infrastructure sea defenses, including mangrove planting and erection of low-tech structures such as bamboo fences, permeable brushwood dams, etc. These structures have been designed on the basis of best-engineering practice, lacking sufficient scientific background. This paper investigates the use and success of permeable dams over a period of about 15 years, describing their application in Guyana, Indonesia, Suriname, Thailand and Vietnam, summarizing the lessons-learned, and analyzing their functioning in relation to the physical-biological coastal system. Also an overview of relevant costs is given.

The basic philosophy behind the construction of permeable dams is the rehabilitation of mangrove habitat through re-establishment of the (fine) sediment dynamics – we refer to Building with Nature as the overarching principle of this approach. Our main conclusions are that a successful functioning of permeable dams requires (1) a thorough understanding of the physical-biological system and analysis of the relevant processes, (2) patience and persistence, including maintenance, as the natural time scales to rehabilitate mangrove green belts take years to decades, and (3) intensive stakeholder involvement. We give a list of conditions under which permeable dams may be successful, but in qualitative terms, as local site conditions largely govern their success or failure.

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1. Introduction

1.1. Mangrove-mud coasts across the world

Coastal protection is one of the many ecosystem services provided by mangroves. Its economic value is estimated between 2,000 and 9,000 USD per hectare per year (Spalding et al., 2010; UNEP-WCMC, 2006), worth an estimated 65 billion USD per year globally (Menéndez et al., 2020). Evidence suggests that mangroves are able to both reduce the economic impact of coastal hazards and increase the speed at which coastal economies can recover (Horchard et al., 2019). Many countries have therefore adopted green-belt policies to protect mangrove zones along their coast. For instance, by law Indonesia and The Philippines require mangrove green-belt widths of at least 100 m along open water. Yet, mangrove forests continue to be under threat. Worldwide, a total area of 9.736 km^2 (about 7%) of mangrove has been lost between 1996 and 2016, while an estimated 1,389 km^2 of remaining mangrove forests are identified as degraded (Worthington and Spalding, 2018). Mangrove losses continue on every continent, although rates of loss have declined considerably from 1 – 3% in the late 20th century to 0.3 – 0.6% in the early 21st century (Friess et al., 2019). However, Hamilton and Casey (2016) report ongoing high losses in Asia, notably in Indonesia, Malaysia and Myanmar. The main causes of mangrove loss are transformation of forests into economic land use such as aquaculture and agriculture, wood production, and (urban) infrastructure. The future outlook is mixed, with new agricultural drivers of deforestation emerging (Friess et al., 2019), while erosion linked to sea-level rise and subsidence by e.g. ground water subtraction are expected to affect large areas of mangroves over the next century (Lovelock et al., 2015).

Worldwide, numerous rehabilitation efforts were initiated to halt/reverse mangrove losses and to stop further coastal erosion. However, few have been successful, primarily because the biophysical and/or socio-economic conditions were not suitable for mangrove recovery (Lewis III, 2005; Samson and Rollon, 2008; Ellison, 2000; Wodehouse and Rayment, 2019). In the Philippines, for example, over a period of 20 years about 440 million mangrove propagules were planted on 440 km^2 coastal area at a cost of USD 17.6 million, but survival rates were on average 5 – 10% only (Primavera and Esteban, 2008). Survival rates are also low in Sri Lanka, with less than 20% successful replantation efforts (Kodikara et al., 2017). Other efforts to stop erosion have been carried out using more traditional coastal defense structures as well, such as sea walls, groins, (porous) coast-parallel breakwaters, etc. This is very expensive, does not work on the soft soils of muddy coasts (Kempfert and Raithel, 2002), and may lead to maladaptations, or path dependencies – “a response that does not succeed in reducing vulnerability but increases it instead” (IPCC, 2001, p. 857; Barnett and O’Neill, 2010). Furthermore, these structures are generally reflective, scouring the seabed locally (e.g. Winterwerp et al., 2005, 2013; Anthony and Gratiot, 2012). Therefore, appropriate and site-specific approaches to coastal protection become increasingly important, which should involve the re-establihment of healthy mangrove green belts, as these trees are important ecosystem engineers controlling sedimentation processes and coastal protection (Gutiérrez et al., 2011).

Disturbance of the fine sediment balance is a major, yet overlooked, root cause of the poor success of rehabilitation efforts on eroding coastlines (Winterwerp et al., 2005; Anthony and Gratiot, 2012; Besset et al., 2019). In these studies, the changes in sediment dynamics and bathymetry, which form the root cause of erosion, were also found to prevent mangrove re-establishment, and resumption of their coastal protection services. Hence, mangrove degradation may cause accreting/stable coastlines to flip towards an erosive state (Stanley and Lewis, 2009). Mangrove green-belt restoration can be realized through managed retreat, such as reconversion of cultivated land into mangrove forests. This has major socio-economic consequences, though, and is generally not popular. Therefore, Winterwerp et al. (2005, 2013) proposed to install non-reflective permeable dams along the eroding coasts of Demak, Indonesia with the objective to stop erosion, and potentially regain lost land. More or less simultaneously, GIZ (Albers and Schmitt, 2015) introduced this approach in Vietnam, while similar experiments were carried out in Suriname, Guyana and Thailand, and in coastal Louisiana (USA).

The objective of this paper is to present and discuss more than a decade of experience with the design, construction, maintenance and success of permeable dams along tropical mangrove-mud coasts. Chapter 2 presents, in alphabetical order, an overview of coastal rehabilitation/protection projects throughout the world using permeable dams. All projects have been based on best-engineering practice, as little scientific evidence was available on effectiveness of this method for erosion control in tropical (mangrove) environments. This best-practice is based on qualitative analyses of the functioning of salt-marsh works in NW-Europe, deployed since centuries – these are therefore briefly discussed below. In this paper, theory and lessons-learned are presented with the aim to provide knowledge and know-how for better informed designs in the future, discussing under which conditions this approach may be feasible, or not. These lessons include constructive aspects, the physics of the hydro-sedimentological system, the need for monitoring, and, last but not least, the socio-economic conditions required for success.

1.2. The history of permeable dams in NW Europe

Managing authorities base their decisions on proven technology, and the best examples constitute the salt marsh works in NW-Europe. As early as the Roman era, small ridges of 0.1 – 0.2 m height were built in Europe around mean high water (MHW) on the lower supratidal marshes facing the North Sea (Lascaris and De Kraker, 2013). These dams probably functioned to reduce current velocities and wave impact at high tide, enhancing deposition of fine sediment. These ridges were built with sediment excavated from the surroundings, thereby probably creating ditches to dewater the reclaimed land during falling tide. In the first century BC, 1 m high and up to 14 m wide summer dikes were built from marsh sods on the middle intertidal marshes (Bazelmans et al., 1999). These restricted flooding to once or twice a year, fertilizing the land which thus became suitable for agriculture (Lascaris and De Kraker, 2013). Yearly winter storms, overtopping the dikes, provided fertile mud and nutrients to the land while submergence with salt water killed nematodes, improving crop health and productivity. In these zones, dwelling hills were often built, allowing permanent housing. This configuration of dams, dikes and dwelling hills constitutes one of the first examples of salt marsh works in the world.

In the north of The Netherlands dyke building on a larger scale started around the 10th to 11th century and became common practice in the 12th and 13th century (Acker Stratingh, 1866; Andreae, 1881; Rienks and Walther, 1955; Edelman, 1974). Where accretion occurred, additional dykes were erected seaward, built on the higher salt marshes of the upper supratidal zone. Since Medieval Times accretion was stimulated by earthen or stone dams and dewatering ditches, sometimes in rectangular patterns. In some cases brushwood was placed between these permeable dams (Vierlingh, 1577; Esselink, 2000). Since the 18th century, land-reclamation works were carried out more systematically and at larger scale in the Wadden Sea in Germany, The Netherlands and Denmark (Probst, 1996; Bakker et al., 2002), using earthen dams and drainage channels in front of the dykes (Brahms, 1767; Stratingh and Venema, 1979; Verhoeven et al., 1980; Probst, 1996; Esselink, 2000). Then, in the first decades of the 20th century new standards for salt-marsh creation were developed in Northern Germany and implemented in The Netherlands in 1930 (Dijkema et al., 1988; Esselink, 2000; Van Duin et al., 2007). These schemes consisted of three rows of interconnected sedimentation basins in front of the higher intertidal flats, each measuring circa 200×200 m^2 (and, in the Netherlands first 400x400 m^2 and later 400x200 m^2; De Glopper, 1986; Dijkema et al., 1988; Bakker, 2014). Each basin was surrounded by permeable dams

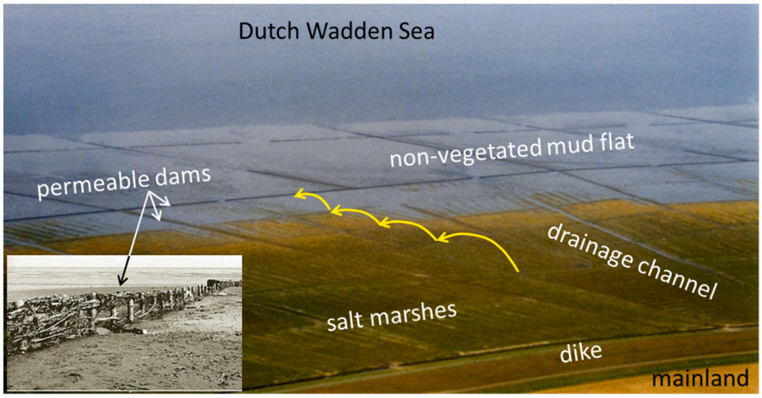

Fig. 1. Example of sedimentation basins and permeable dams in the Wadden Sea (The Netherlands) with details in inlay; yellow arrows indicate subsequent installment of dams over time.

emerging about 0.3 m above MHW, consisting of brushwood and held in place by vertical poles. Furthermore, a dense system of draining ditches, consisting of main channels and secondary drains was maintained.

It is mainly the brushwood that dissipates waves. When sedimentation has reached a specific level, new basins are erected in front, thus building out into the sea, while vegetation starts to develop in the back, in the older basins (Fig. 1). Much of the contemporary salt marshes at the mainland of the Netherlands and Germany developed as result of this design, termed the Schleswig-Holstein method.

1.3. Permeable dams for coastal restoration

The basic philosophy behind permeable dams is to restore mangrove habitat by restoring the net sediment balance. The restoration of sediment dynamics is being increasingly advocated as a pre-requisite for ecological restoration (Paola et al., 2011; Edmonds, 2012). The net sediment balance results from the difference between gross deposition and erosion rates, the latter two being orders of magnitude larger than the net effect (Winterwerp et al., 2013). A relatively small intervention in the coastal zone may therefore flip the net balance, initiating erosion or accretion. Permeable dams decrease wave activity, reducing wave-induced erosion, while enhancing gross sedimentation rates by trapping sediment-laden flows in their sedimentation basins. Dams are meant to be temporary and may become obsolete after mangrove rehabilitation. Their construction can be relatively cost-effective and low-tech, implying that they can be built and maintained by local coastal communities, provided they have the basic training. This nature-based adaptive approach can be regarded as an example within the Building with Nature (BwN) framework, applying natural forces in an integrated manner (De Vriend and Van Koningsveld, 2012; De Vriend et al., 2014), in concert with local communities to serve their socio-economic needs as well.

Fig. 2 depicts the definitions used for this BwN-approach in this paper. A permeable dam may have an opening and/or side walls, or not. Unless stated otherwise, all permeable dams consist of vertical poles supporting horizontally oriented elements, often brushwood. The area behind a dam is referred to as the sedimentation basin, also when side walls are absent. The (tidal) current makes an angle ϕ with the coastline, and the waves an angle θ. Incoming waves are partly reflected, partly dissipated within the dam and partly transmitted. Mangrove habitat is generally found between MHW and high-high water spring (HHWS), though under very calm conditions mangroves may be found around mean sea-level (MSL) as well. Mudflat slopes are generally mild, i.e. of the order of 1:1000.

2. Examples of coastal rehabilitation projects

2.1. Guyana

The coastline of Guyana measures about 370 km. Ninety percent of the Guyana population lives in its low coastal plain, concentrated in the coastal area between the Essequibo and Berbice Rivers. This part of the coastline is mainly protected by earthen dams and concrete seawalls. The Guyana coastal system is characterized by a semi-diurnal tide with a 1 – 3 m range at neap and spring tide, respectively. In conjunction with the Guyana current, alongshore velocities towards the west of 0.2 – 0.5 m/s are induced. The climate is tropical and dominated by northeasterly Trade Winds. Also waves come from this direction, with periods between 8 and 10 s, and heights between 1 and 1.7 m, the higher values in the months November – March (Gratiot et al., 2007).

The stability of the Guyana coast is governed by the about 30 km long mud banks migrating alongshore, colonized by mangroves at their landward side. Under the pressures of economic development, much of the mangrove-bearing coastal zone of Guyana has been transformed into settlements, agricultural land and aquaculture estates protected by coastal dikes. These defence structures are less effective in dissipating wave energy than mud banks. They also hinder the consolidation and subsequent mangrove colonisation of these banks, notably by enclosing mature mangrove forests and preventing propagule transport from these forests to mud banks (Anthony and Gratiot, 2012). East of the Berbice River and west of the Essequibo River, the mangrove-mud coast is generally in good condition, at locations more or less pristine. However, along the 80 km between these two rivers, in particular around Georgetown, mangrove forests have virtually disappeared, though may temporarily recolonize the coast when a mudbank approaches (Figure 3).

The management and rehabilitation of mangroves in the coastal system falls under NAREI, the National Agriculture Research and Extension Institute. As a follow-up on the Mangrove Restoration Project, the Guyana Mangrove Restoration and Management Department was integrated within NAREI. Various rehabilitation projects were initiated, amongst which: 1) Planting of mangrove and *Spartina* grass, 2) Construction of sediment traps, permeable dams and breakwaters, 3) Construction of restrictive gates and fences to reduce the impact of anthropogenic activities, 4) Community based mangrove management and livelihood initiatives such as tourism and beekeeping and 5) Extensive public awareness and education. Based on data from the most successful sites and comparison with the natural forest, NAREI has established a guideline for planting *Avicennia germinans* at 2.3 - 2.7 m above chart datum. During 2010-2018 over 500,000 seedlings were produced in community nurseries and planted along the coastline.

Permeable dams were constructed with local, resilient bamboo, which has a life time of about 3 – 7 years. The construction of the dams

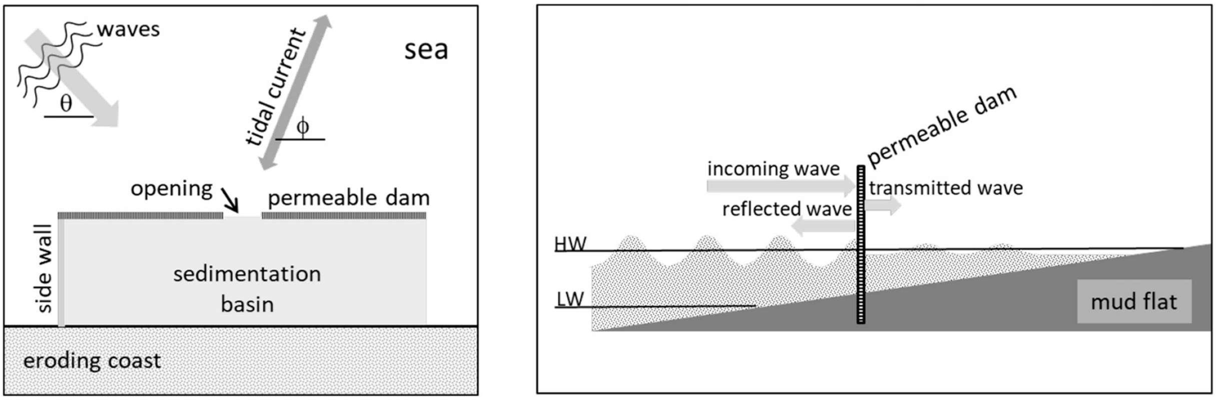

Fig. 2. Definitions used for the BwN approach, with (a) plan and (b) side view.

was similar to the descriptions in Section 4. Figure 4 shows an aerial photo of some of the dams erected near Georgetown. The dams near Georgetown did not have durable results. However, along the left bank of the Essequibo River (Anna Regina and Devonshire Castle, west of Georgetown) 1.5 – 2 m siltation was monitored behind a 100 m long dam between 2013 and 2016. The higher siltation rate yielded bed levels a bit higher than the optima for mangrove rehabilitation. Part of the mangrove planting took place on these deposits.

2.2. Indonesia

Loss of mangrove habitat on the Indonesian islands is a major concern, as the archipelago depends largely on marine resources, thus on the ecosystem services provided by mangroves. Table 1summarizes these losses on four islands, based on 2010-data from the Indonesian Ministry of Forestry and Environment and 2015-data from the Indonesian Geospatial Data. Though considerable areas of mangroves were gained on Sumatra and Kalimantan, and to a lesser degree on Sulawesi, net losses are significant. Data from the Indonesian Ministry of Marine Affairs and Fisheries (MMAF) show that on Northern Java, more than 80% of the mangrove forests are damaged, directly affecting coastal stability: almost 750 km (44%) of the total 1690 km coastline is eroding, and in 2014 almost 130 km^2 mangrove habitat was lost, affecting more than 30 million people on Java alone. Though the majority of coastal erosion occurs in rural areas, the annual economic losses involved are estimated at 2.2 billion USD (MMAF, 2017a; Hendra and Muhari, 2018). Losses are attributed to urbanization, industrialization, conversion to aquaculture ponds, and subsidence. This rapid mangrove loss and degradation creates a strong imperative to restore mangrove forests and the ecosystem services they provide to coastal populations.

In conjunction with national and local authorities, a first BwN-pilot in Indonesia for coastal rehabilitation with permeable dams was carried out in 2013 in Bogorame, a small village in Demak, central Java. Coastal erosion in Demak is severe, with land losses up to 100 m/yr as a result of wide-spread aquaculture in the one-time dense mangrove forests, and because of subsidence. This coastal system is characterized by a diurnal tide with a few 0.1 to about 1 m tidal range, including a small semi-diurnal component. Wind, rain and waves follow seasonal patterns with the NW-monsoon from about November through April, with December through February being the wettest months. During these months, waves of about 5 s with offshore heights of typically 1.5 m erode the vulnerable coast further. This monsoon also drives an anti-clockwise residual current of 0.1 – 0.2 m/s in Demak coastal waters. The rest of the year, shorter waves are induced by a sea-land breeze, occurring in particular in the afternoons (MMAF, 2012).

Two sedimentation basins were created by erecting permeable dams on the lost lands at the head of Bogorame, as this part of the village was severely at risk to erosion and flooding. Fig. 5 shows the remnants of the bunds previously forming the now-lost aquaculture ponds. The

Fig. 4. Mangrove recolonization along Guyana coast, east of Georgetown, 2019.

Fig. 3. Mangrove recolonization along the Guyana coast synchronizing with a migrating mudbank (dotted white ellipse).

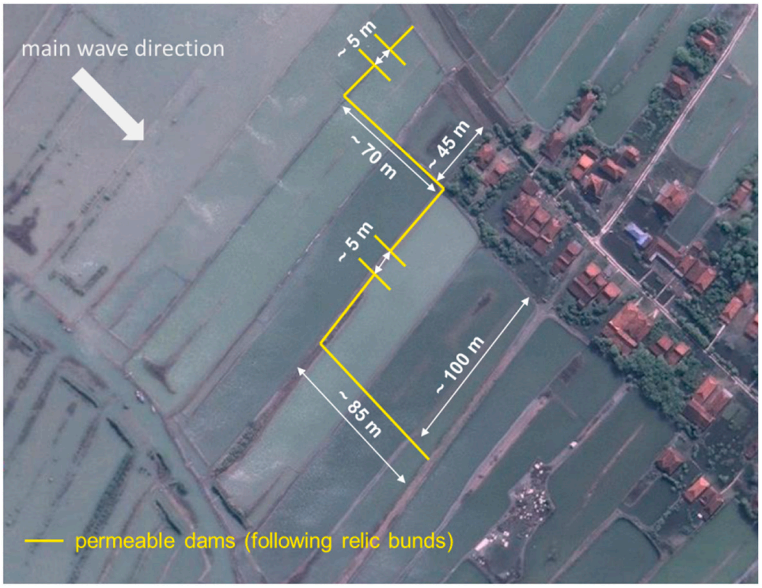

Fig. 5. First permeable dam pilot project in Indonesia in 2013, Bogorame, Demak.

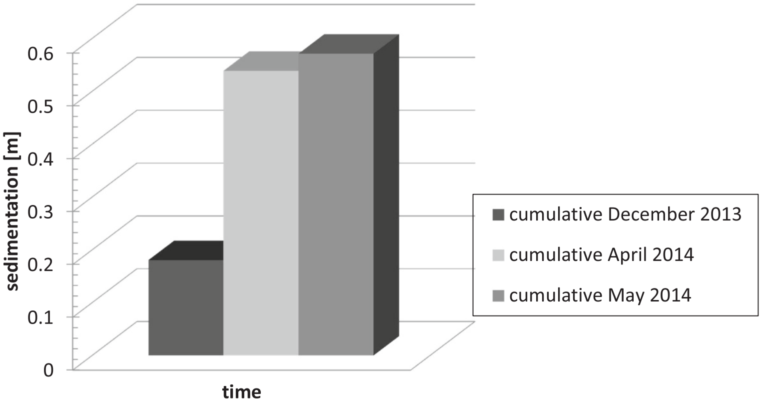

Fig. 6. Measured sedimentation rates 2013 pilot, Bogorame, Demak, Java, Indonesia.

permeable dams were placed on top of these remnants, as they form a stable underground, reducing the risks of local scour. Construction of the dams was finished in November 2013. Fig. 6 presents the measured sedimentation volumes in the two sedimentation basins, showing a mean sedimentation rate of about 0.5 m in the four most dynamic months, whereas elsewhere erosion continued. Based on these promising results, many more dams were constructed in Demak coastal area with a total length of more about 13.5 km, built and funded by various partners, with slightly modified designs, while still based on best engineering practices. Simultaneously, an extensive monitoring and basic research program was set up, in conjunction with a socio-economic development program with the local stakeholders (see Section 5).

Initially, these permeable dams trapped considerable amounts of sediment and overall, bed levels behind the dams raised. At some locations spontaneous mangrove colonization was observed. Also, local communities planted *Rhizophora* in several sedimentation basins. Fig. 7 shows some photographs of the sedimentation patterns observed. First observations of longer term monitoring results indicate initial sedimentation behind the dams, but on the longer term sedimentation rates reduced considerably. More thorough analysis of these long-term results was on-going at the time this paper was written. Over longer times, mangroves survived in only a few of the most protected sedimentation basins. Elsewhere, juvenile mangroves disappeared after one or two years, most likely because the relative bed level dropped below mean sea level again. Apart from consolidation of the deposits, subsidence probably played a role, which was initially underestimated. Observational evidence and water-loggers revealed that subsidence rates of large parts of the coasts must be 0.05 m per year, or higher (Van Bijsterveldt et al., 2020c. Basically this implies that, over the project lifetime, the first dams, initially emerging above MHW, have subsided by 0.25 m or more, and are disappearing below MSL. These dams thus become less effective, and maintenance costs become higher, requiring more efforts to keep the dams in place.

In spite of these uncertainties and gaps in knowledge, the BwN-approach of coastal rehabilitation was adopted by the Indonesian government (MMAF, 2016 & MMAF, 2017b), and 6.3 km of permeable dams were constructed in 2017 at various locations on Java, and 1.7 km dam at Meranti (Sumatra). In 2018, another 3 km on Java, and 2 km permeable dams near Banyuasin (Sumatra) and 1 km near Penajam Paser Utara (Kalimantan). In 2019, another 1.5 km was built in Demak, and 9.5 km permeable dam at various locations in Sulawesi. As an example, Fig. 8 shows the permeable dams built in East Java.

Prior to the construction of permeable structures, a 150 m long seawall was built in Timbul Sloko using concrete cylinders. This seawall is locally known as the APO (Fig. 9), located along the original, pre-erosion coastline. Sedimentation behind the APO up to MSL took place in about two years, and one year later the first *Avicennia* seedlings were

Fig. 7. 2019 sedimentation patterns, Bogorame, Demak, Java, Indonesia, photos December 2019 and January 2020.

observed. After that, the local community planted *Rhizophora* as well. In 2020, a mature, many meter high mangrove canopy has developed with both species, as shown in Fig. 9. As the APO is highly reflective, considerable scour took place in front, prohibiting seaward extension of the mangrove forest. Moreover, the APO is becoming unstable over time and some of its supporting structures have already collapsed. It is however a question whether a complete collapse of the APO would be problematic. The pile of concrete rubble would continue to dissipate wave energy, and the mangroves behind may well survive. If integrated with the coast behind, the construction of temporary hard structures, collapsing in a managed way, may therefore form an option in heavily degraded coastal systems, where waters are too deep for the application of permeable dams. Seaward extension of the coastline would then, of course, no longer be possible.

2.3. Suriname

Suriname is part of the same coastal system as Guyana, together with French Guiana, and is characterized by the same hydro-sedimentological processes described in Section 2.1. The major part of the Suriname mangrove-mud coast is more or less pristine and in good condition. At large scale, the mangrove-mud coast alternatively accretes and retreats by many kilometers with a periodicity of about 20 – 30 years (Augustinus, 1978, Augustinus, 2004; Anthony et al., 2010, 2019; see also Winterwerp et al., 2013). These dynamics synchronize with the migration of mudbanks along the coast: coastal reaches protected by a mudbank accrete rapidly, whereas in between the banks, the coast retreats. Over longer time scales, the majority of the coast accretes. However, at two locations, i.e. north of Paramaribo and further west, near Coronie, ongoing erosion occurs, likely as a result of mangrove conversion for agriculture and housing development (Winterwerp et al., 2013). In particular the erosion in the vicinity of “Weg naar Zee”, north of Paramaribo is problematic, as shown in Fig. 10.

Therefore a coastal rehabilitation plan was initiated in 2015, and a series of permeable dams were constructed, as shown in Fig. 11, the locations of which are indicated in Fig. 10. Next to these constructions, a small-scale mangrove replanting program was executed in 2018. This work was mainly aimed at involving local stakeholders in mangrove rehabilitation efforts, and no systematic monitoring program was executed.

Fig. 9. APO, concrete seawall at Timbul Sloko, Demak, Indonesia (courtesy COREM-UNDIP) with natural colonization by *Avicennia* (high vegetation) and planted *Rhizophora* (low vegetation).

2.4. Thailand

The approximately 3,000 km shoreline of Thailand consists of about 1600 km sandy coasts, 330 km rocky coasts, over 1000 km muddy

Fig. 8. Example of permeable dams in Gresik Regency, close to Solo River, Java, Indonesia (photo by MMAF early 2019).

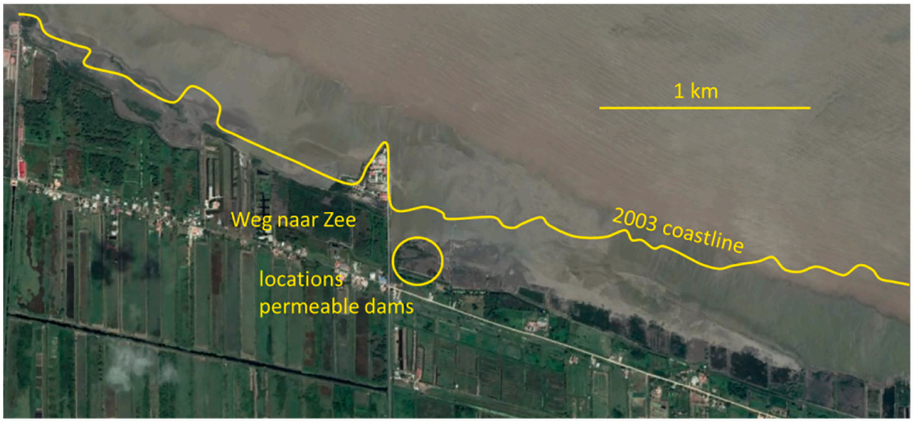

Fig. 10. Coastal erosion around Weg naar Zee, Paramaribo, Suriname (Google Earth, 2019).

Fig. 11. Permeable dams constructed near Weg naar Zee, north of Paramaribo, Suriname (photos by E. Van Lavieren).

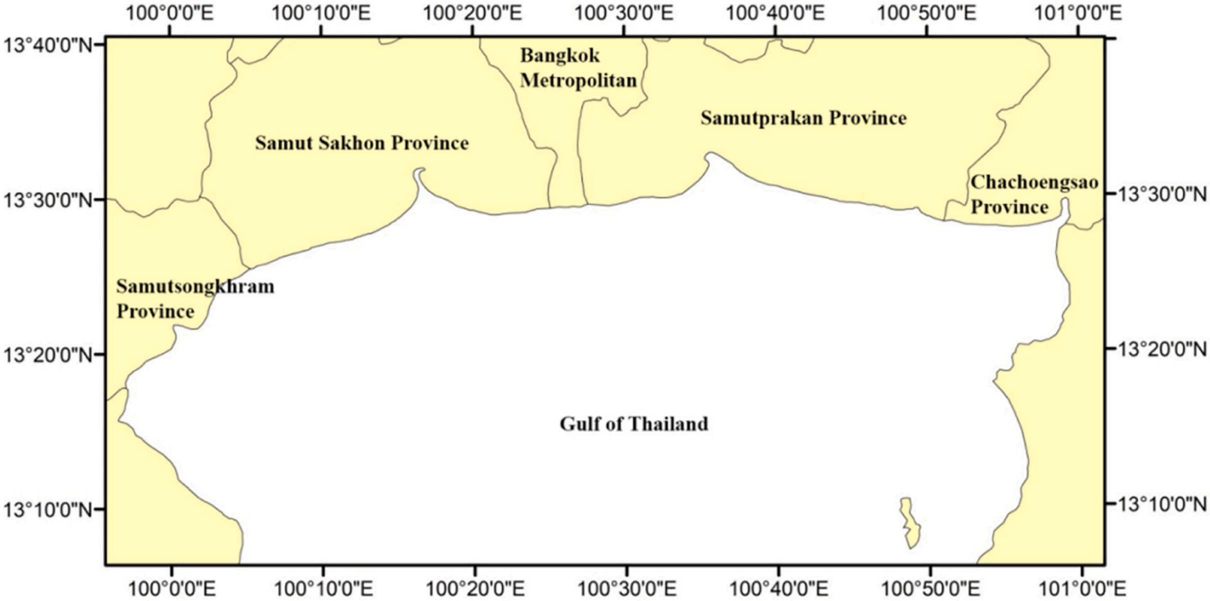

Fig. 12. Five provinces with muddy coastline along the Upper Gulf of Thailand.

coast, and the rest are other features such as inlets and estuaries (Department of Marine and Coastal Resources, 2017). For many decades, coastal erosion is one of the chronic problems in the country. Along the upper Gulf of Thailand (GoT), coastal erosion up to 30 m/yr has been observed at some locations (Winterwerp et al., 2005). This coastline is mostly muddy and mangrove forest used to be abundant, but has been converted largely into aquaculture ponds. Five provinces along the GoT, i.e. Samutsongkhram Province, Samut Sakhon Province, Bangkok Metropolitan, Samutprakan Province, and Chachoengsao (Fig. 12) have struggled to stop erosion. Wave conditions are generally mild in the GoT, as follows from a hindcast of 20 years of wind data by the authors using the JONSWAP method (Hasselmann et al., 1973; Kamphuis, 2010). Yet, offshore significant wave heights up to 2.5 m are predicted occasionally, in particular along the central part of the GoT around Bangkok Metropolitan and Samutprakan Province. Samutsongkhram province and Samut Sakhon Province experience a milder wave climate with calm conditions for 90% of the time.

Coastal erosion along the upper GoT has been addressed by installing low-crested revetments, sediment-filled geotextiles ("sand sausages") and bamboo fences (Saengsupavanich, 2013). The latter constitute of single rows of vertically placed densely spaced bamboo poles (Fig. 13). Bamboo fences are functionally similar to permeable dams,

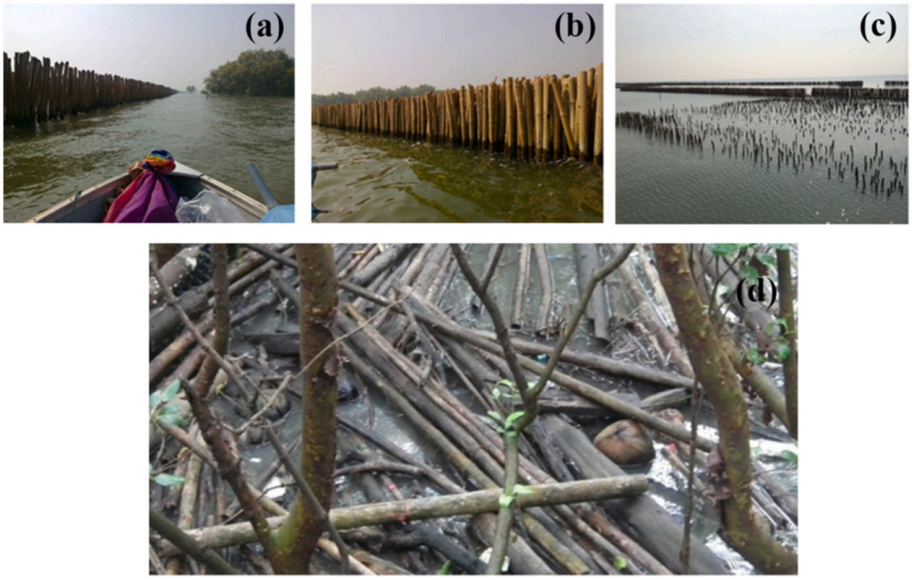

Fig. 13. a), (b), and (c) Bamboo fences along Bangkok Metropolitan coastline (d) drifted bamboo debris.

dampening waves and creating calm hydrodynamic conditions where sediment can settle.

During 1989 – 1993, at some locations Chachoengsao Province experienced coastal erosion rates > 70 m/yr. The local Sub-district Administration Organization (SAO) attempted to stop erosion by placing sand sausages and bamboo fences, but was not successful due to the severity of the problem and limited budget. Later other governmental departments, including the Marine Department and the Department of Marine and Coastal Resources, have also placed sand sausages and bamboo fences. Again, the results were not satisfactory because the sand sausages sank into the soil. Experience with the bamboo fencing was not favorable as well, because (a) the bamboo lasted for two to three years, after which it decomposed into debris, (b) this debris drifted into the GoT, obstructing navigation and damaging the sand sausages placed elsewhere, and (c) part of the bamboo poles remains within the soil, wounding local fishermen collecting cockles and krill (Saengsupavanich, 2013; Pranchai et al., 2019). Debris can also damage the stems of landward mangrove vegetation, leading to observable degradation of the surrounding forest (Pranchai et al., 2019). From that time onwards, the SAO has hardly supported the construction of bamboo fences, but continued placing low-crested rock revetment. This technique proved more successful, while the growth of mangroves proved possible behind these revetments.

During 1995 – 2008, the average erosion rate at Bangkok Metropolitan's coastline was about 8 m/yr. From 2008 to present (2020), Bangkok Metropolitan continued placing bamboo fences to stop further erosion (Fig. 13). However, here this technique also was not successful , and during 2008 – 2011, erosion rates of 9 m/yr were experienced, despite the maintenance of the bamboo fences. During 2011 – 2013, erosion continued at rates up to 14 m/yr. Learning from the literature and Chachoengsao province's experience, the Bangkok Metropolitan decided in 2014 to change their strategy and implement low-crested breakwaters instead. Thai law, however, requires to undertake an environmental impact assessment (EIA) for every type of breakwater, prior to construction. This EIA process is complicated in Thailand and took five years to complete, eventually being approved in February 2019.

Bamboo fencing appeared to be more successful though in Samutsongkhram and Samut Sakhon Provinces, and siltation rates up to 0.5 m in 28 months were reported anecdotally (Sukhothai Thammathirat Open University, 2013). Five years after the placement of the fences, the Department of Marine and Coastal Resources reported evident mangrove growth behind the bamboo fences (Phiriyayatha, 2013). The department also elaborated on the proper selection of the bamboo, and how to involve local SAO and coastal communities in participatory construction (Sukhothai Thammathirat Open University, 2013).

Further south, along the west coast of Thailand, the coastal community of Ban Klong Prasong, located on Klang Island in the Krabi River Estuary facing the open Andaman Sea has been impacted by coastal erosion and storm damage for many years (Enright and Nakornchai, 2015). The erection of a concrete seawall in 2003 by the Department of Public Works and of the Town and Country Planning, and its heightening a few years later did not resolve flooding problems, but instead enlarged problems by water logging. Also replanting of mangroves (first *Rhizophora* and later *Avicennia marina*) failed, with survival rates of about 10% only. Therefore, under a previous Raks Thai project, community members started to erect a 50 m long bamboo fence in April 2013, placed 50 m in front of the previously built seawall. Eight months later, about 0.15 m of sediment accumulated behind the fence (Fig. 14) The community planted *Avicennia marina* seedlings, of which 80% survived the first year. A double fence of 500 m length has been projected in the area, but no long-term information is available.

2.5. Vietnam

The coastal zone of the Mekong Delta in Vietnam faces cumulative challenges such as urbanization, development of infrastructure, unsustainable use of natural resources, population growth and increasing consumption. These challenges are exacerbated by the impacts of climate change, i.e. (relative) sea-level rise, increased intensity of storms, and flooding, which ultimately result in erosion of the muddy coastlines (Carew-Reid, 2007; Schmidt-Thome et al., 2014; Schmitt and Albers, 2014; Joffre and Schmitt, 2019). Permeable dams were erected at various locations in the Mekong Delta. Their T-shaped design was based on experiments with a variety of configurations (Albers and von Lieberman, 2011), consisting of a long-shore and cross-shore part (Fig. 15), forming sedimentation basins of about 50×50 m^2. The long-shore dam dampens incoming wave energy (Fig. 16), while the cross-shore part is meant to reduce long-shore currents. In the longshore dams, openings of approximately 20 m were made to secure drainage and entrance of sediment-laden flow into the sedimentation basins. Flow velocities in the sedimentation basins are small, allowing the fine sediment to settle and consolidate – the latter is important for

Fig. 14. Sedimentation and *Avicennia marina* behind the bamboo fence on Klang Island, Thailand.

increasing stability against erosion and one parameter to assess the success of the measure (Albers et al., 2013).

Thus a total of 7,500 m of permeable T-shaped bamboo dams were installed on the east coast of the Lower Mekong Delta in Soc Trang and Bac Lieu Provinces (Fig. 15). In addition, 925 m of permeable dam was installed at the edge of the intertidal in Ca Mau Province between 2015 and 2016 (Fig. 16). The dams were about 1.4 m high, with their crest at MHW.

Two designs were tested in Soc Trang, a double row of bamboo fences filled with soft and another filled with stiff brushwood bundles. Wave measurements to quantify wave transmission through the permeable dams were carried out over a period of approximately six months to cover various storm and tidal conditions. Pressure transducers were used to measure wave heights at two positions on the seaward and landward side of the bamboo dam, each about 5 m from the dam. The wave data were analysed and summarised in significant wave heights of 15-min periods (Schmitt et al., 2013), see Section 3.3 for the results. Flexible bundles were found more efficient in damping waves than stiff bundles; these can induce up to 80% reduction of the incoming wave height.

Also the impact of these dams on floodplain restoration was monitored (Albers and Schmitt, 2015). For instance, in Bac Lieu Province a sedimentation rate of approximately 0.17 within seven months was measured. The reduction of wave action within the sedimentation basins also accelerates the consolidation of the deposited mud, thus increasing its stability against erosion. This is well demonstrated from mud density measurements at Soc Trang Province and photos of the landscape formed (Fig. 17). The colour of the mud and the natural regeneration of *Avicennia alba* indicate consolidation of sediment, developing from the back of the sedimentation basins. On November 2012 the coast parallel elements of the permeable dams are still visible (Fig. 17). In February 2013 the beginning of sedimentation is observed. In November 2013 consolidation of sediments has started and natural regeneration of *Avicennia* occurred. The photo taken in January 2015 shows the growth of mangroves, which are no longer disturbed by wave action, owing to the elevation of the intertidal flats. Local stakeholder involvement also protects these mangroves from further anthropogenic effects.

Fig. 16. Wave dampening effect of bamboo T-dams in Ca Mau Province, Viet Nam (courtesy R. Sorgenfrei, 2016).

3. Physical considerations

Before any detailed designs for construction can be made, as discussed in Section 4, a conceptual design and long-term vison have to be setup. These should include the considerations in the following sections.

3.1. System understanding

A key element for a successful application of permeable dams or any other intervention in coastal systems, is a good understanding of the geological, hydrological/hydrodynamic, morphological, sedimentological and ecological elements, i.e. the natural system. On the basis of available data and a general understanding of coastal processes, a conceptual picture of the local sediment dynamics has to developed. Tidal ranges, direction and magnitude of tidal and residual currents,

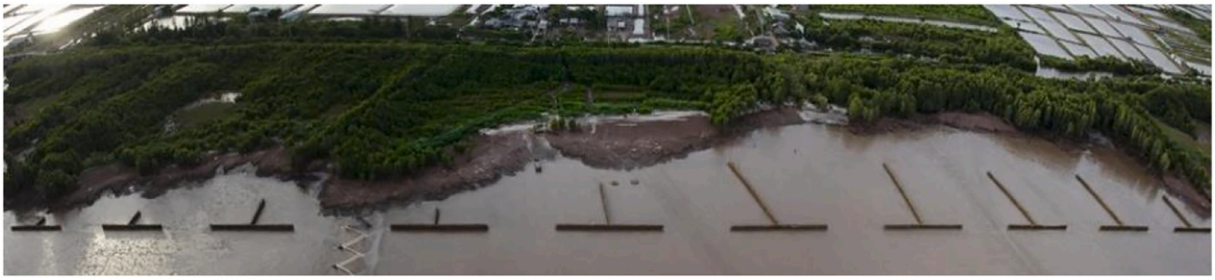

Fig. 15. Placement of T-dams in Bac Lieu Province, Viet Nam (courtesy Cong Ly and G.E. Wind, 2013).

Fig. 17. Natural regeneration of Avicennia on restored floodplains in Soc Trang Province from the construction of the T-fences in October 2012 until January 2015 (Photos: GIZ Soc Trang, R. Sorgenfrei).

direction, period and height of waves, and their recurrence are obvious parameters to be collected, in conjunction with coastal geometry and bathymetry, and sources and properties of (fine) sediment. Sediment availability in particular is of major importance in setting up a coastal rehabilitation plan, as this is a prerequisite for the rehabilitation of minerogenic mangrove habitats. In general, four sources of sediment in the coastal system can be identified:

1. Relic deposits from geological and biological processes. Geological deposits can be huge, providing a major source of coastal sediment. Examples are the Gulf of Bangkok, fed by sediments from the Chao Praya and minor Thai rivers, and the north coast of Java formed by terrestrial erosion of its many volcanos. Calcareous and marly muds, which are largely generated by marine organisms, are found in Florida, the Cayman Islands, Jamaica, Belize, the islands of the Great Barrier Reef, the coral islands of the west Indian Ocean, Yukatan and East Africa (Sauer, 1982),
2. Contemporary riverine input, local or remote. Though the majority of sediment has originally been brought to the coast by rivers, their contribution at the time scales of coastal erosion/rehabilitation is often small. For instance, only in the vicinity of larger rivers on Java (such as the Wulan, Demak), sediment input is considerable, initiating local delta formation. Exceptions are huge rivers, such as the Amazon in Brazil and the Fly River in Papua Guinea.
3. Longshore transport of sediment from riverine input or coastal erosion. Longshore transport of fine sediment is often small along muddy coasts. A major exception are the mud banks along the Guiana coastal system, dispersing Amazon sediment up to Venezuela.
4. Coastal erosion. With the erosion of mangrove-mud coasts, large amounts of fine sediment become mobilized, part of which remains in the coastal system for prolonged periods of time.

As many mangrove-mud coasts are under-researched, detailed hydro-sedimentological data are generally scarce. However, many free and/or global datasets exist that can be used to approximate coastal hydro-sedimentological dynamics. Appendix A provides some basic information on this. Next to these abiotic data, information on the local species of mangroves and their spatial distribution is required, together with data on the availability of propagules and their transport paths (Lewis III, 2005).

Of equal importance to the understanding of the natural system is insight into the causes and conditions of coastal erosion. Frequently encountered causes are:

- subsidence, i.e. relative sea-level rise,
- conversion of mangrove forest into e.g. aquaculture ponds,
- urbanization and infrastructure, such as roads,
- coastal infrastructure, such as jetties and seawalls,
- water logging and/or loss of fresh water sources, and
- unsustainable wood harvesting.

Though actual erosion events may occur under storm conditions, the issues above generally reduce the resilience of a coastal system, and are therefore the root causes of coastal erosion.

3.2. Design philosophy and long-term vision

A major advantage of the erection of permeable dams along eroding mangrove-mud coasts is that these can be built offshore, i.e. there where land has been lost by erosion. If the dams function properly, (some) lost land may be regained through sedimentation. When the elevation has increased to a level where tidal inundation is below the threshold tolerance of mangrove species (Balke et al., 2011; Ball, 1988), the sedimentation basins are suitable for colonization by mangroves, and a next sedimentation basin in front can be installed by constructing new permeable dams further offshore (Fig. 1). Mangrove vegetation will then take over the role of the permeable dams and their maintenance becomes obsolete. However, this is only possible if scour in front of the dams is limited, enabling regular sedimentation patterns in the basins without risks of water logging and/or too deep water unsuitable as mangrove habitat.

From a physical point of view, wave damping within a sedimentation basin does not have to be complete. Wave energy has to be reduced to a point where sediment is no longer or only little remobilized during storms. Currently, we have no rules on how much wave energy has to be dissipated by the dams, though the conceptual “Windows of Opportunity” by Balke et al. (2011) may give some guidelines, providing stresses which mangrove seedlings may survive.

Generally, coastal erosion is the result of decades of uninformed or even mis-management of the coastal system. Then, it is unlikely that rehabilitation can be achieved within a few years, even if the causes of coastal degradation have been stopped or reversed. This implies that patience and persistence is required by all parties involved (see also Chapter 5), requiring a long-term vision on the development of the coastal system, accounting for the physical constraints of the coastal system (e.g. sediment availability and pathways) and anticipating on the expected coastal developments, including further extensions seaward in due time, as in Fig. 1. Such a plan should include prioritizing of the locations of dam construction:

- protection of life, housing and livelihood,
- protection of infrastructure, such as roads, service systems (water, sewage, …),
- protection of remaining fringes of mangroves.

With respect to the latter, it may be an efficient strategy to try and built out from resilient stretches of mangroves, and/or from locations which are more or less stable, or accrete already. Of course, planning also requires securing stakeholder involvement, funds and possibly other boundary conditions over longer periods – we only touch shortly on stakeholder involvement in Section 5.

3.3. Wave damping by permeable dams

Waves approaching a permeable dam will be partly reflected, partly dissipated within the confines of the dam, and partly transmitted, as formalized by the following energy balance:

$$E_\infty = E_r + E_d + E_t \tag{1}$$

where E_∞ is the energy of the incoming wave ($E_\infty \equiv \rho g H_{s,\infty}{}^2/8$), with ρ is water density, g is acceleration of gravity, H_s the significant wave height, and E_r, E_d and E_t are the reflected, dissipated and transmitted wave energy (see also Fig. 2). A few experimental studies on wave damping through permeable dams have been reported in the literature, e.g. Mai et al. (1999); Sayah (2006); Haage (2018); and Jansen (2019). However, no generic design rules exist at present for dimensioning these permeable dams, though research is being carried out. Therefore, the formulation for wave attenuation by coastal vegetation by Dalrymple et al. (1984); Mendez and Losada, 2004 is used, assessing the work done by the wave-induced drag, integrated over water depth, neglecting vertical forces, and in which plants are schematized as vertical cylinders:

$$E_d = \frac{2}{3\pi}\rho C_d D \frac{N}{k}\frac{\sinh^3\{kh\} + 3\sinh\{kh\}}{3\cosh^3\{kh\}}\left(\frac{gk}{2\omega}H_s\right)^3 \tag{2}$$

where E_d is the wave energy dissipation [W], k and ω are wave number and frequency, h is water depth, N is number of elements, D is the characteristic diameter of cylinders/elements with effective drag coefficient per element C_d. Note that the porosity of this configuration reads $\varepsilon = 1 - \pi N D^2/4$, where n is number of elements per unit area. However, the filling of brushwood structures consists of horizontal elements which may also exert drag in vertical direction to the flow. This is accounted for by Suzuki et al. (2019) by adding a vertical component to the dissipation term. As permeable brushwood dams are typically deployed close to the coast at small water depths, even the shortest waves behave as shallow water waves (i. e. $c = \sqrt{gh}$) characterized by small to neglible vertical velocity components. Then the orientation of the elements is no longer relevant, see also Section 7. Thus, assuming negligible vertical drag forces, a relative damping rate can be derived by dividing Equ. (2) by $(2g^2/3\pi)\rho C_d D N (H_s/2)^3$. This relative damping rate is plotted in Fig. 18 as function of water depth and wave period, showing that sensitivity to the wave period, thus length is not very large.

The rate of energy loss by wave dissipation is given by:

$$\frac{\mathrm{d}Ec_g}{\mathrm{d}x} = -E_d \tag{3}$$

where c_g is the group velocity of the waves. Integration and some manipulation (see Dalrymple et al., 1984) gives the transmission coefficient $H_{s,t}/H_{s,\infty}$:

$$k_t = \frac{H_{s,t}}{H_{s,\infty}} = \frac{1}{1 + \frac{4}{9\pi}c_{D,b}DNH_{s,\infty}k\frac{(\sinh kh)^3 + 3\sinh kh}{(\sinh 2kh + 2kh)\sinh kh}L_{tot}} \tag{4}$$

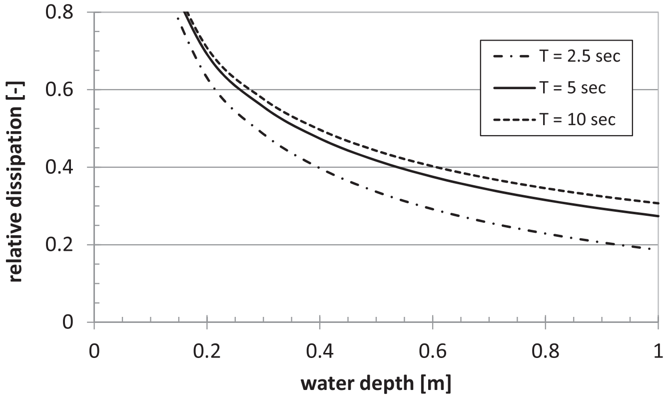

Fig. 18. Dependency of relative wave damping as function of water depth and wave period, according to Dalrymple, Equ. (2).

where L_{tot} is the thickness of the dam, $H_{s,t}$ is the wave height transmitted through the dam, whereas $H_{s,\infty}$ is the incoming significant wave height. Equ. (4) allows assessment of the wave dissipation that can be attained with a specific dam design, provided C_d is known, which is also a function of the wave period. For isolated cylinders, the drag coefficient depends on (1) the ratio between wave excursion and cylinder diameter (Keulegan and Carpenter, 1958), denoted as the Keulegan-Carpenter number $\mathrm{K_C}$ ($\equiv U_\infty T/D = \lambda_w/D$) or on (2) the Reynolds number $\mathrm{Re_D}$ ($\equiv U_\infty D/\nu$), where U_∞ is the amplitude of orbital velocity of incoming waves with period T and wave length λ_w, and ν is the viscosity of water. A number of studies have reported a reduction in drag coefficient for groups of cylinders under uniform flow, owing to a reduction of velocity and delayed flow separation from the elements (Nepf, 1999; Liu et al., 2008; Bokaian and Geoola, 2008). Heideman and Sarpkaya (1985) and Suzuki and Arikawa (2010) suggest that for multiple elements under waves, the ratio between wave excursion and element spacing determines the degree at which the flow approaching an element is hindered by the presence of surrounding elements, referred to as sheltering. In more detail, modelling results by Etminan et al. (2019) suggest that sheltering only plays a role for element densities smaller than 0.016. When the element density increases, flow acceleration in between the elements yields narrower wakes and higher drag coefficients than in the case of isolated cylinders – the flow is blocked, and velocities in between the elements increase. Discerning whether sheltering or blockage governs the drag is essential to find the optimum element density for wave dissipation. At large $\mathrm{K_C}$, the sensitivity of C_d to T decreases, and one may conclude that brushwood dam designs applicable under conditions of locally generated waves (e.g. Demak, Indonesia) are also suitable to more open coastal systems, characterized by swell, as in Vietnam. From an engineering point of view, optimizing permeable dam design implies maximizing the overall drag coefficient with a minimum of dam material, hence construction costs. However, it is stressed that the exact relations are not yet understood, and more research is required for reliable predictive formulations.

In Vietnam, wave damping over flexible and stiff brushwood was measured in-situ over a period of six months, including storms with high waves. Fig. 19 presents the measured transmission coefficient k_T in comparison to wave flume experiments, as a function of the ratio between the freeboard of the dams R_c (see Fig. 31) and the incoming significant wave height H_s. The transmission coefficient k_T is defined as the ratio of the mean transmitted wave height and of the incoming wave height (equ. (4)). The solid lines in Fig. 19 represent the best-fit through the measured values. The black triangles represent physical modelling data while the red squares and blue crosses in-situ measurements. Flexible bundles lead to smaller wave transmission coefficients than stiff bundles, and thus have a larger wave dampening effect. On average, about 35% reduction of the initial wave height was measured.

Finally, large blockage enhances the forces on the structures, increasing construction and maintenance costs, which is subject of Section 4 (see also Pranchai et al., 2019).

Waves along the direction of permeable dams are not hindered. It follows that the damping coefficients are reduced by a factor $\sin\{\theta\}$, for oblique waves (see Fig. 2).

3.4. Wave reflection

Further to Equ. (1) and Fig. 2, permeable dams do not only dampen waves, but also induce reflection. In the extreme case of a vertical impermeable structure (sea wall), full reflection occurs, and the amplitude of the generated standing wave is twice that of the incoming wave. Bed shear stresses close to the structure then increase by a factor four with high risks of local scour at the foot of the sea wall. This is one reason that ample attention is paid in literature to wave reflection by coastal structures, as scour risks have to be minimized by costly bed

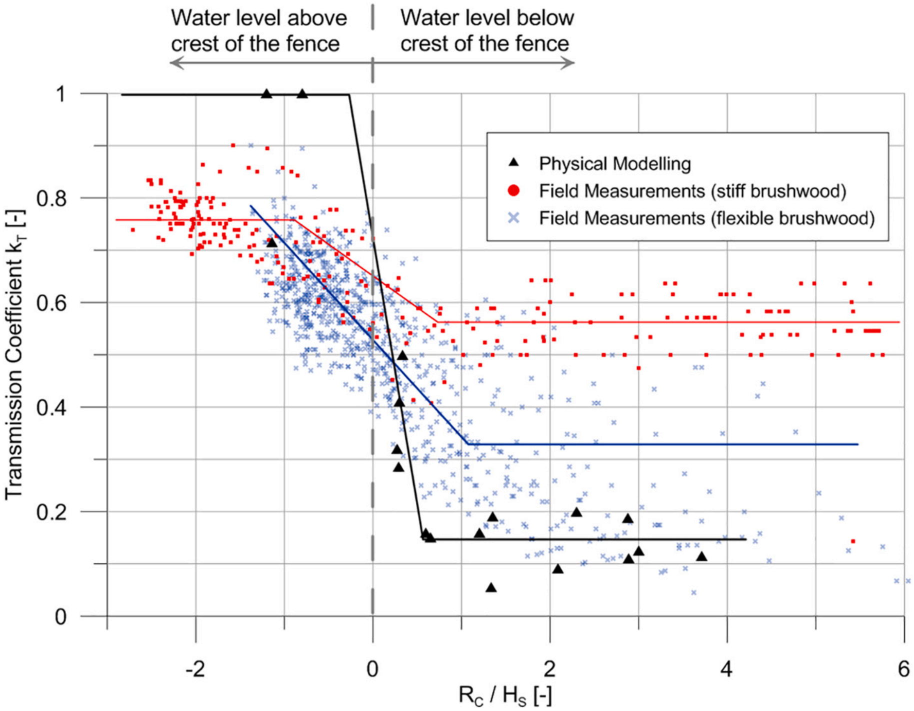

Fig. 19. Wave transmission coefficients of bamboo fences under various hydrological conditions (modified after Albers et al., 2013).

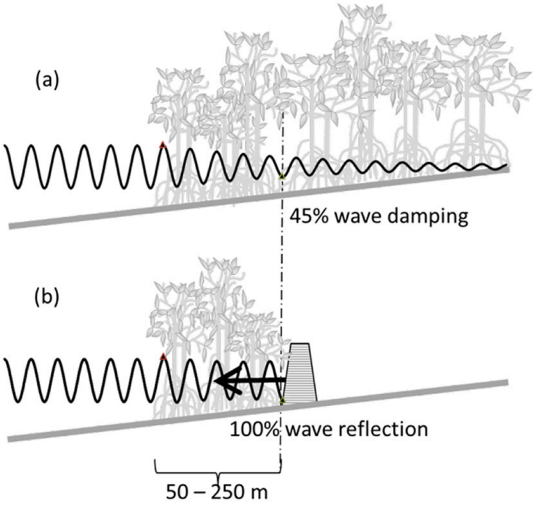

Fig. 20. Schematic of wave amplification by reflection against seawall, a) "pristine" and b) with seawall.

protection. The degree of wave reflection is often given by the ratio of the heights of the reflected and incoming wave. However, we prefer a definition based on the ratio of reflecting and incoming wave energies (e.g. Yu, 1995), as energy is the preserved quantity, thus defining a reflection coefficient $K_r = E_r/E_\infty$, where E_r is the energy of the reflected wave, and E_∞ of the incoming wave.

Relevant for the reflection by brushwood dams is the theoretical work by Dalrymple et al. (1991) on wave dissipation and reflection by vertical porous rubble mound walls. For shallow water conditions, they predict $K_r = 0.2 – 0.4$ for a porosity of $\varepsilon = 0.4$. Also Yu (1995) analyzed wave reflection by thin vertical porous walls and found $K_r \approx 0.5$ for a wide range of wall thicknesses (but all small compared to the wave length) – unfortunately, no information on the porosity of the walls studied was given. Laboratory flume experiments on regular arrays of cylinders were carried out by Haage (2018) for $\varepsilon = 0.7 – 0.9$ and by Jansen (2019) for $\varepsilon = 0.6 – 0.9$ at water depth of a few 0.1 m and wave periods smaller than 2 s showing reflection coefficients of 0 – 0.4; the latter value for the more dense configuration ($\varepsilon = 0.6$). From field observations in Demak, a reflection coefficient of about 0.2 was estimated, at a porosity of about $\varepsilon = 0.54$. Though no detailed information on in-situ porosities of brushwood dams is available, we estimate reflected wave energy at a few ten percent, maximal. Thus little scour in front of the permeable dams is to be expected, and new sedimentation basins in front can be designed efficiently.

Further to Section 3.4, reflection by oblique waves is also reduced by a factor $\sin\{\theta\}$.

Field observations on permeable dams in Demak during mild wave conditions showed wave damping between 20 and 80% (Gijón Mancheño et al., 2020), whereas a healthy mangrove forest may reduce wave heights by 0.2 – 1% per m vegetation (Horstman, 2014; McIvor et al., 2012, 2013). This implies that in sedimentation basins in front of e.g. dykes, wave reflection are likely to occur against these dykes, which may prevent sedimentation land/or mangroves colonization at the back of these basins. For instance, wave heights are doubled against a fully reflective seawall (100% reflection), thus erosive forces, scaling with the square of wave height, increase by a factor four. This implies that when less than 50% of wave energy is dissipated within a mangrove green belt, erosive forces at the back of that belt (in front of the seawall) are larger than at the coastline. This is sketched in Fig. 20, showing the effects of a fully reflective seawall/dyke within a mangrove forest at a location where 45% wave damping would have occurred in the undisturbed forest. As a result, mangrove stands are now attacked also from the back. If this would damage the forest, felling individual trees, wave damping further reduces, and wave attenuation increases further, etc. This sets a minimum green belt width of 50 – 250 m, depending on rate of wave dissipation by the mangrove vegetation for fully reflecting sea defenses. This is one reason that it is very difficult to rehabilitate mangrove habitat along solid dykes, as in some parts of the Guyana coast. Reflection-reducing features on such dykes/seawalls reduces wave attenuation and may thus increase the success of mangrove rehabilitation in these environments.

Finally it is noted that permeable dams also deflect (tidal) currents owing to their hydraulic drag under stationary conditions (Gijón

Mancheño et al., 2020). This implies that fine sediment does not pass through these dams, or in small amounts only, if alternative pathways for the currents exist. Hence, their lay-out should be designed such that sediment can enter a sedimentation basin, as achieved for instance by the openings in the salt marsh works in NW Europe (Fig. 1).

3.5. Sediment trapping by permeable dams

The objective of permeable dams and bamboo fences is to create still (low dynamic) sedimentation basins, suitable for mangrove colonization. In this section, we presume that sediment is carried in suspension by the tidal flow towards these basins. The lay-out of the dams then follows from the local water depth:

- If erected on intertidal areas, water movement, thus sediment transport towards and into the basins is primarily induced by tidal filling, thus by currents perpendicular to the coastline – this is the case in the Wadden Sea in NW Europe (Fig. 1), Indonesia, Solo River (Fig. 8), Thailand (Fig. 13 and 14) and Vietnam (Fig. 15, 16 and 17).
- If erected at deeper water (the basins are initially always submerged), water movement, thus sediment transport towards and into the basins is primarily induced by large-scale circulations, often with a profound component along the coast – this is the case in Demak, Indonesia, Fig. 5 and 7. It is noted, that dams in deeper water, submerged more or less permanently, also increases the risk of shipworm-induced damage (see below).

The dams in Guyana and Suriname have also been erected on intertidal flats, but sediment transport mechanisms are a bit different – see Section 3.6. This dependency of the transport paths of sediment as a function of water depth has profound implications for the configuration of the dams. On intertidal areas, the T-shaped dams (Fig. 1, 14, 15) are most effective as they allow sediment to enter the basins through the openings within the dams, and induce a drainage channel in a natural way, while preventing lateral losses.

In deeper water, one can profit from the large transport capacity by large scale circulations in the foreshore, bringing sediment efficiently towards the calm zone behind a coast-parallel dam, as sketched in Fig. 21. Side-walls (the T-dam configuration) would disturb these circulations, reducing sediment transport towards the sedimentation basin in the calm zone.

Data and modeling results on the sediment transport paths in Demak became available only after a substantial number of dams had been built. In hindsight, their configuration was not optimal as illustrated by the following observations, which exemplifies the need for a proper analysis of the coastal system.

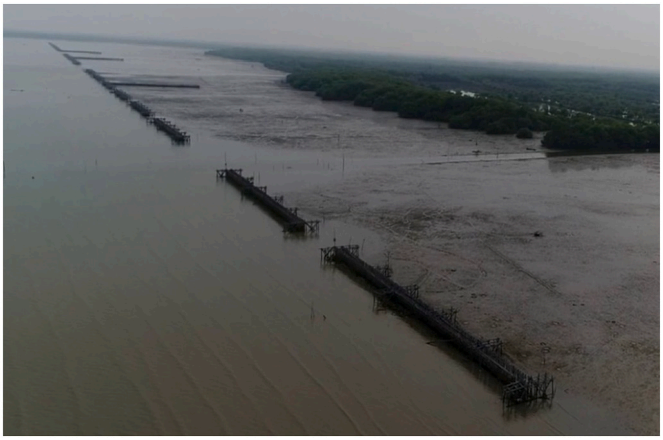

Fig. 21. Permeable dam array constructed by MMAF at Gresik, Gresik Regency, Java, Indonesia (photo MMAF).

3.5.1. Demak, Indonesia: shift from subtidal to intertidal

The strategy of a coast parallel dam in deeper water was followed in Demak, and indeed yielded many 0.1 m of sedimentation in the first monsoon season after construction. However, it was not anticipated that these sedimentation basins would become intertidal, thus blocking the large scale circulation, thereby blocking further feeding of the sedimentation basin. In hindsight, T-dams should have been erected a year after construction around the newly formed intertidal basins allowing further sediment input and the generation of a drainage channel.

3.5.2. Wonorejo, Indonesia: lack of knowledge on current patterns

As an example of optimizing dam layout, the array of permeable dams constructed at Wonorejo, Indonesia, is further analyzed (Fig. 22), using the sedimentation patterns observed a year after their construction. The entire bay left (i.e. west) of the tidal creek depicted in Fig. 22 consists of lost land, previously occupied by aquaculture ponds and historically vegetated by dense mangrove forest. A bit offshore, a small chenier is found (see below). Where possible, permeable dams were erected on the remnants of fish pond bunds for reasons of constructional stability. Our design philosophy was to build out mangrove habitat from existing vegetation, but information on local current patterns was not available at the time. In hindsight, a shorter permeable dam (b), in conjunction with an extra dam between (b) and (c) would allow more sediment trapping between dam (b) and (c). An extra opening halfway dam (c) would allow more sediment transport to the area between dam (c) and (d). Dams (f) and (g) are obsolete, and could better not have been built at all, as these block sediment transport towards the back of the bay.

The source of the sediment is local, i.e. mobile fine sediments stemming from erosion of the coast during previous events. The tidal creek does not bring any significant amounts of sediment to the coast. Its shape remains stable (for the time being) because of the sandy levees previously formed along its banks.

3.5.3. Bogorame, Indonesia: stimulating the formation of channels for drainage of the mangrove forest

The sediment deposits, in particular when becoming colonized by mangroves, will affect the current patterns further. These morphodynamic processes are ideally accounted for in the coastal rehabilitation long-term vision. Fig. 23 shows an example on how to stimulate the formation of channels within the deposits. Upon rehabilitation of the mangrove forest, such channels are required to drain the forest, preventing water logging.

3.5.4. Kien Giang, Vietnam: waves take and give

Next to the transport paths of sediment towards the sedimentation basins, its concentration is important, linearly affecting sedimentation rates. Suspended sediment concentrations are generally larger during storm, as high waves stir up sediment from the seabed. This is illustrated in Fig. 24, showing measured sedimentation rates in five pilot plots in Kien Giang Province, at the very south of Vietnam (Cuong and Brown, 2012). This site faces the open ocean, and sea and swell are both important. At four plots various configurations of permeable dams were installed, closing off the sedimentation basins from the ocean (i.e. without openings in the dam). A fifth plot served as control. In the four pilot plots, about 0.1 m sedimentation was measured during the five months wet, wavy season. The open control plot experienced about 0.3 m sedimentation in the first two months, which was lost again though in the second half of the SW monsoon period.

These observations imply that:

- Sediment transport and associated coastal rehabilitation takes place during the stormy season, as waves then stir up fines from the bed, being carried onshore by the tide,
- As waves also erode, the entire deposit in the control plot was lost

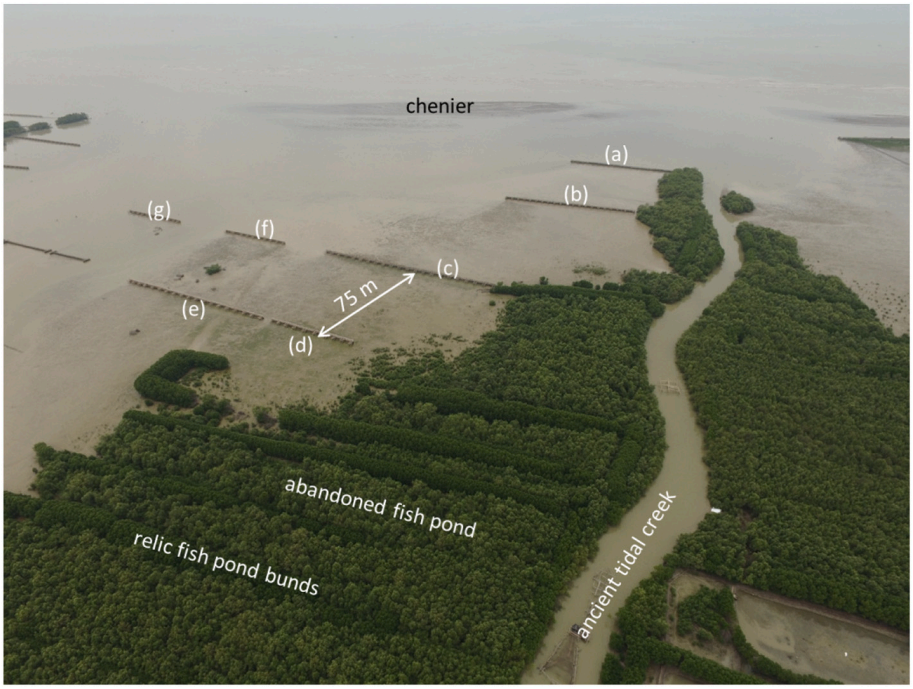

Fig. 22. Arrays of permeable dams at Wonorejo, Demak, Java, Indonesia (WI drone image, 2019).

again, probably because no more sediment was available in the foreshore to be stirred up by waves – thus sediment availability is a crucial parameter,

- Thus waves take (erode) and give (mobilizing sediment), as predicted by Winterwerp et al. (2005) – note that this is in particular true for the higher waves, smaller waves can erode the muddy bed, but mobilize too little sediment for mud flat buildup,
- The permeable dams are not entirely impermeable for sediment, but without openings trapping is less efficient. Thus sediment-laden water may be transported through permeable dams if alternative pathways are not available (water follows the path of least resistance),
- The permeable dams constructed did prevent erosion of sediment deposited behind the dams.

Thus the important conclusion has to be drawn that coastal erosion and coastal accretion both take place during the wet, stormy season mainly, and it is thus the challenge to reduce erosion rates, while maintaining, or enhancing sedimentation rates at the same time (see also Winterwerp et al., 2005).

3.6. *Mud streaming by waves*

Many mud coasts exhibit thicker or thinner layers of soft, fluid mud (e.g. Metha, 2013). Along the Guiana coast in northern South America, fluid mud forms an inherent part of the coastal system and the migration of Amazon-borne mud along the coast in the form of mud banks (Anthony et al., 2010). In Indonesia, soft mud is formed at locations by remobilization and accumulation of eroded coastal sediment, as in Demak. Such soft mud layers are known to dampen waves efficiently by viscous dissipation, e.g. Gade (1958); Wells and Kemp (1986) and Kranenburg et al. (2011). In the direction of wave damping, so-called radiation stresses are induced (Longuet-Higgins, 1953; Sakakiyama and Byker, 1989; Rodriguez and Mehta, 1998), propelling the soft mud (Motohiko and Shintani, 2006) in the direction of wave propagation. This process is known as streaming. Streaming forms one of the major

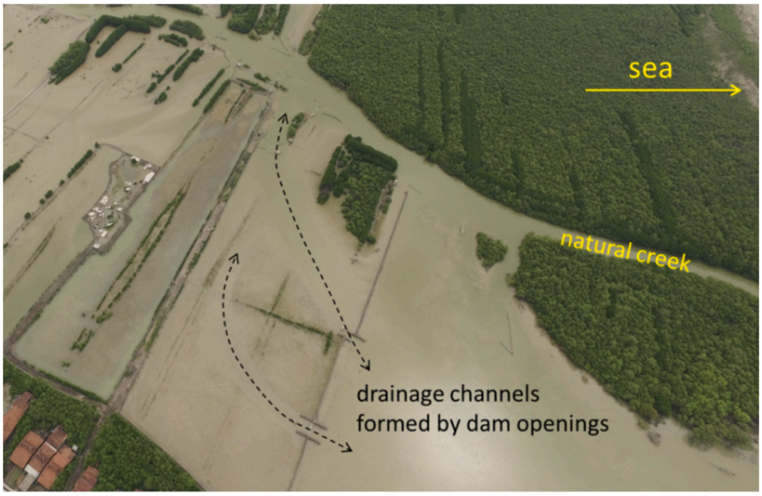

Fig. 23. Arrangement of permeable dams to induce drainage channels, Bogorame, Demak, Java, Indonesia (WI drone image, 2019).

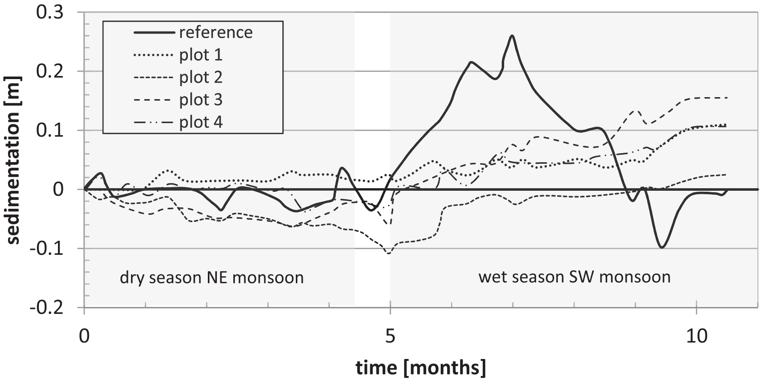

Fig. 24. Measured sedimentation rates in Vietnam pilot plots – from GIZ, Practical Experience from Kien Giang Province, 2012.

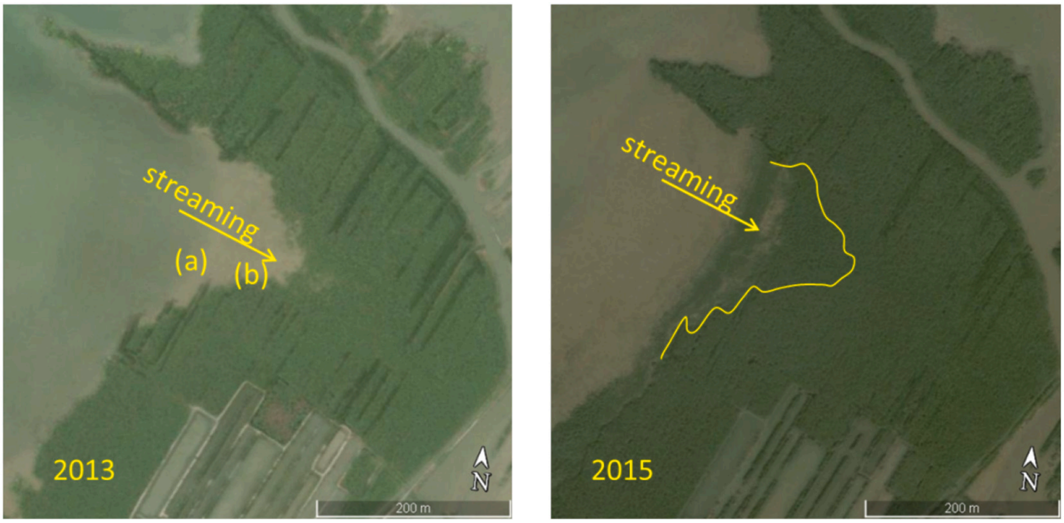

Fig. 25. Example of small scale sedimentation by streaming, Bedono, Demak, Indonesia (Google Earth image).

mechanisms in onshore fine sediment transport at the leeside of the mud banks in the Guiana coastal system.

Fig. 25 shows an example of the large transport rates induced by streaming and the corresponding large sedimentation rates. Mangrove habitat was rehabilitated naturally in about 1.5 year, and rapidly colonized when the conditions became favorable. During a site visit in 2013, fluid mud thicknesses from a few 0.1 m at location (a) to more than a one meter at location (b) were observed.

It is obvious that erecting permeable dams in this area would be counter-productive, killing the onshore sediment transport, as it kills the driving force. This process was unknown and unforeseen at the time of installing a permeable dam some 100 m offshore from location (a), stopping the natural accretion at this location. Borsje (2017) elaborated further on the role and dynamics of streaming in the fine sediment dynamics in Demak coast, and conditions at which streaming may be expected.

3.7. The role of cheniers

Fig. 26 and further inspection of Google Earth images reveals sedimentary ridges along the Demak coastline, the majority at the 2003 pre-erosion coastline. Visual inspection during site visits (Tas et al., 2020) shows that these ridges consists of sand lenses sitting on an otherwise muddy substrate. Particle sizes were estimated at about D_{50} = 200 μm at the windward side to about 100 μm at the ridge leeside. We therefore refer to cheniers (e.g. Augustinus, 1989; Otvos, 2018), which may or may not be attached to the shore. Cheniers are encountered along many coastlines across the world (Holland and Elmore, 2008), such as in Suriname and West Africa, where over time they may form terrestic sand ridges in the landscape. Paramaribo, for instance, was initially built on such ridges.

In the Demak coastal system, cheniers have a width of the order of 100 m, with a top above MSL, commencing below low water. Some of these cheniers are formed from coastal processes on riverine input of sand in the coastal area (Fig. 26, right panel). Other cheniers are likely being formed by local sorting and subsequent self-organization of sediment previously eroded from the coastline (e.g. Augustinus, 1989). Over longer time scales, this sand of course has been brought into the coast system by the various rivers on Java.

As these cheniers are much steeper than the otherwise muddy coast, waves break at their windward side, losing considerable energy. They do therefore play an important role in mudflat development and the protection of the vegetation behind, as shown by the analysis by Van Bijsterveld (2015, Van Bijsterveldt et al., 2020a). Along the coast of Suriname, cheniers form ridges in between the mud banks of many meters height, protecting the hinterland. Note that at the location of Fig. 26 no chenier was encountered where streaming occurs.

The formation and dynamics of cheniers and their migration are largely unknown. Tas et al. (2020) collected data on chenier dynamics, mainly under quiet hydrodynamic conditions (0.2 m waves). They tested some hypotheses with mathematical models, and it is postulated that the large tidal volume behind this chenier presumably augments its dynamics largely. However, no data could be collected during storm conditions. Fig. 27 exhibits the importance of such storm conditions, showing how a cheniers moved about 100 m onshore within one to two weeks. Likely, its further migration is blocked by the permeable dam.

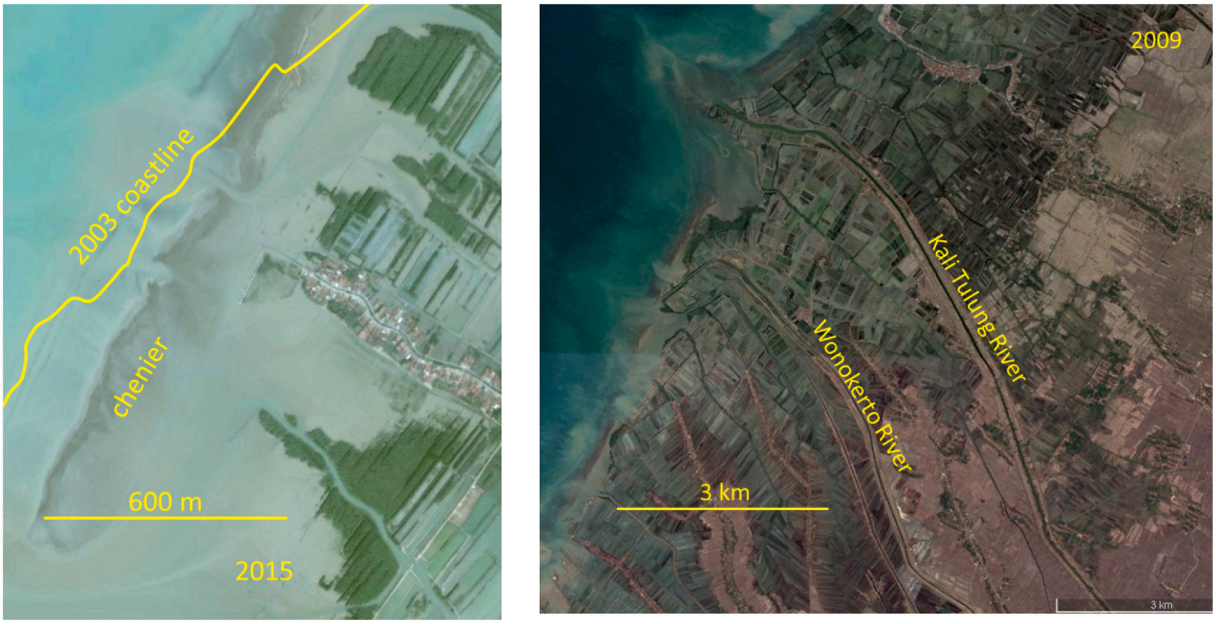

Fig. 26. Example of chenier formation Demak, Indonesia (Google Earth image) by (a) self-organization of eroded coastal sediment and (b) riverine sand input.

At other locations, it was observed that upon landing on the coastline, cheniers suffocated existing mangrove vegetation. On the other hand, mature trees have been found on older sand riches along the coastline. Apparently, mangroves can colonize these more sandy substrates as well, hence forming a sustainable and solid protection of the mangroves behind, as for instance in the Guyana's in South America. However, no detailed information is available on the time scales involved.

Though basic research on the formation and dynamics of the cheniers in Demak is still going on, it is anticipated that these detached cheniers are a temporary phenomenon. If formed from local sorting of eroded sediment, its source will become depleted one day, while previously formed cheniers will have landed on the coastline, as observed with the chenier systems in the Guiana coastal system.

4. On the construction of permeable dams

In the following sections, the lessons-learned on constructing permeable dams in Demak, Indonesia are summarized. Their designs were partly based on the experience gained in Vietnam by GIZ (Von Lieberman, 2012). This section is based on the more comprehensive "Technical Guidelines Permeable Structures" (Wilms et al., 2018). These dams consist of horizontally placed brushwood, which mainly damp the waves, and vertical poles to hold the brushwood, as in Fig. 1. Most of the issues addressed are directly applicable elsewhere. The permeable dams need to stay in place long enough for mangroves to take over, which period is determined by the sediment accretion rate (in Demak, estimated at 2 – 5 years) and rate of mangrove recovery (in Demak, estimated at 3 – 5 years). A crucial aspect appeared the involvement of local stakeholders in construction, inspection, maintenance and repairs. This issue is further addressed in Section 5.

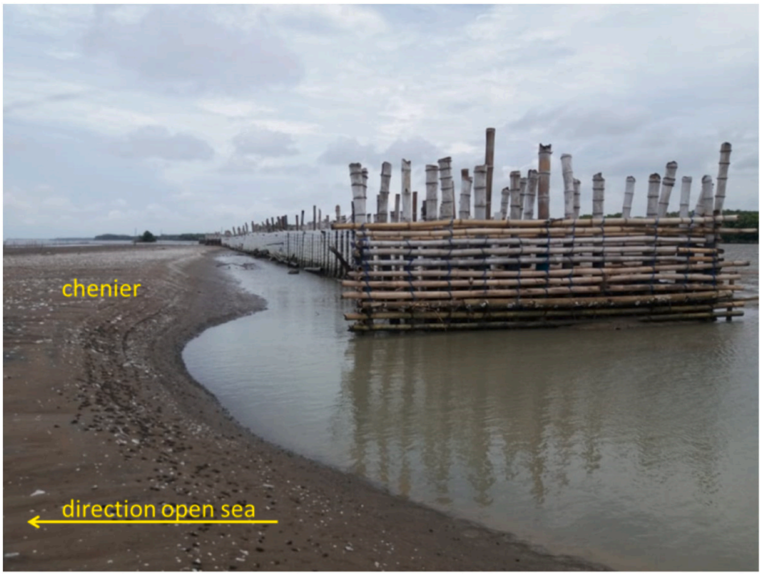

Fig. 27. Chenier approaching permeable dam at Wonorejo, Demak, Java, Indonesia.

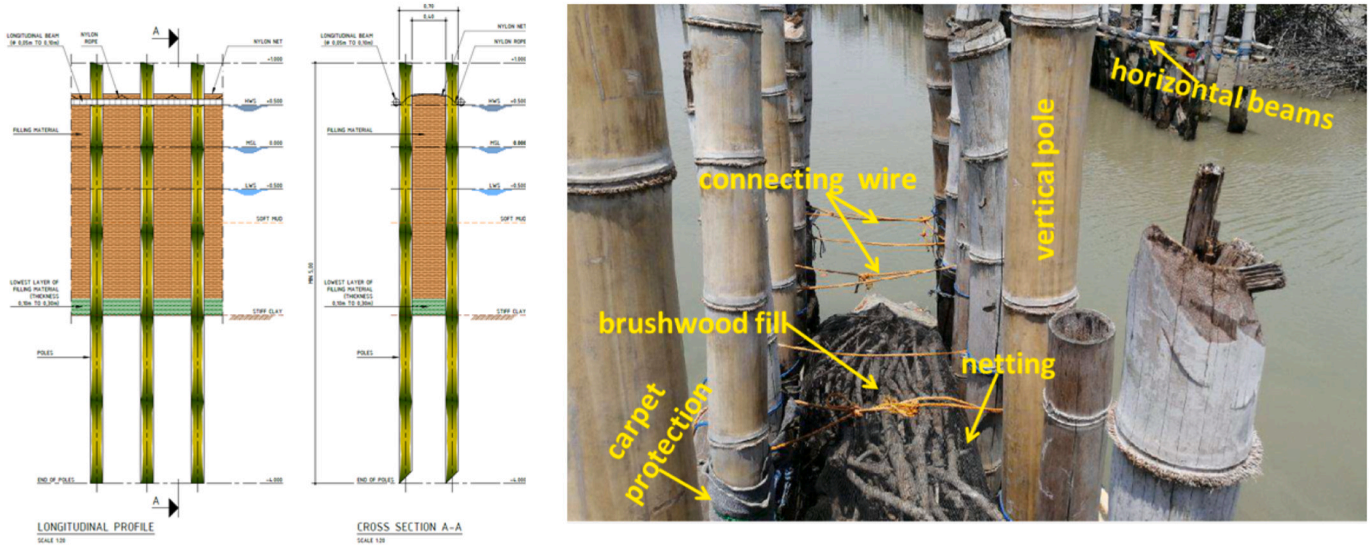

Fig. 28. Schematic of (a) front and (b) side view of permeable dam with brushwood and (c) actual dam.

4.1. Components

Fig. 28 presents the main configuration and components of the permeable dams in Demak. Two rows of vertical poles with a diameter of 0.12 – 0.15 m, spaced at about 0.6 m, form the skeleton of the dams, supporting about 0.4 m thick brushwood bundles. These poles are preferably of natural materials, as the dams are meant to be temporal. Initially, *Melaleuca Cajuputi* (locally known as *Galam*, *Kayu Putih* or *Kayu Galam*) local wood was used, with and without bark, and painted or not. This wood appeared very vulnerable to shipworm and deteriorated within a year. Better results were obtained with bamboo, which was available in a variety of qualities. Bamboo is much cheaper than Gelam, with a life time of less than two years, when permanently submerged. With various types of plastic cover (carpet protection, see Fig. 28), the lifetime of bamboo poles could be increased to a few years, provided the protection remains undamaged. Tests with other reasonably priced wood did not provide favourable alternatives.

Non-natural materials have been used as well, such as PVC pipes filled with concrete. They have a very long lifetime, but are difficult to handle and construction costs are much higher. Additionally, owing to their smooth surface, it is difficult to attach bamboo crossbeams. These non-natural poles might be removed and re-used, which can cut costs for future deployments. At the end of their use, they should be removed not to leave any unnatural materials in the environment.

Brushwood from trees is used as fill material, which is tied in bundles and placed between the rows of poles. The bundles can be kept together with a net, which is easily damaged though by friction or sharp elements in the construction. Atop, the brushwood is to be kept in place firmly by wires to prevent loss. This is a crucial element of the construction, as it untightens easily (Fig. 28). Brushwood decays and compacts rapidly and needs to be refilled regularly. The large quantities of brushwood required form a large part of the total construction costs. Initially, bed protection has been applied. However, the soft bed sediment are washed out easily, making bed protection inefficient. As a result, scour under the brushwood dams occurred generally (Fig. 29), affecting the stability of the brushwood filling further and the sedimentation patterns behind the dams. When constructed on the remnants of bunds, local scour was smaller.

Horizontal support beams are used to stabilize the structure and spread hydrodynamic loads over it. They are placed at HW, LW and sometimes a third row at MSL. Hence, the permeable dams were designed up to around MHW, though a bit lower in practice as the brushwood filling appeared to shrink/lower over time. These beams can be made of bamboo with a diameter of 0.10 m to 0.15 m. An advantage is that they add to wave dissipation, and can be used to fixate the brushwood with durable wire. Nails cannot be used as they split/damage the bamboo, accelerating their decay. Long wires are valuable but unfortunately frequently stolen. Therefore, short, less valuable ropes are used, which however imply more construction work, thus higher costs. On the other hand, shorter ropes are easier to retighten, thereby lowering maintenance costs. Bamboo support structures can be placed at the back of the structures for additional support against wave loading. These supports are generally placed at a spacing of 5 to 10 m, as shown in Fig. 30.

The permeable dams constructed in Vietnam differ only slightly in design and dimensions. These consist of two rows of vertical bamboo poles, placed about 0.3 m apart with a mean diameter of 8 cm and brushwood bundles in between. The spacing between the two rows for coast-perpendicular dams is 0.40 m for and for the long-shore sections 0.50 m. Two rows of crossbeams are attached at each side of the vertical poles. The brushwood bundles consist of small bamboo branches, and everything is tied together with stainless steel wire. The brushwood filing was designed up to MSL. Contrary to the constructions in Demak, scour protection with a double layer of Nypa palm leaves was installed on the bed (Fig. 31). However, scouring could not be avoided completely, requiring sufficient depth of the vertical bamboo poles into the soil to guarantee their stability.

4.2. Construction

The construction cycle below is based on extensive experience in Demak, Indonesia. Structures should be in place during the monsoon period from November to March to be effective as coastal erosion and sediment redistribution primarily takes place in this season. Local stakeholders/communities should be involved during the entire process, including site selection, selection of contractors, choice of materials, construction works, inspection/supervision and maintenance. They are trained as well, enabling them to work on the structures independently (Section 5). This requires time and commitment. Hence, training forms an essential part of construction. A basic outline of activities for a construction cycle is given below:

1. Based on the long-term vision, discussed in Section 3.2, a spatial design is made for the work to be carried out in the next construction cycle (February).
2. On-going stakeholder engagement to explain progress and plans for

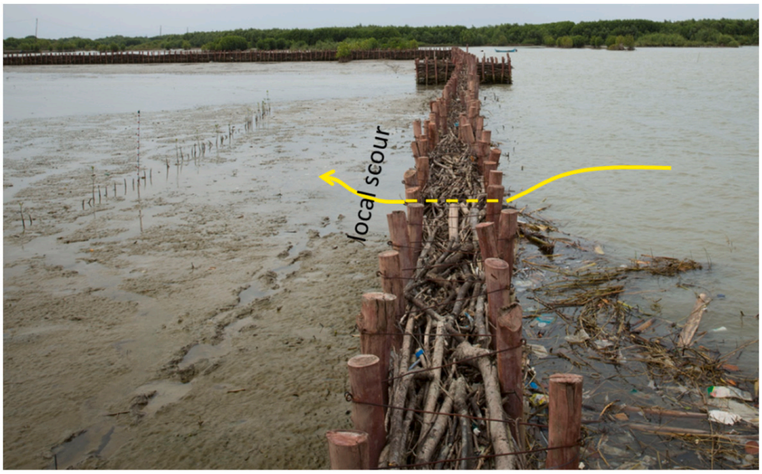

Fig. 29. Example of local scour by near-bed currents underneath loose brushwood, coastal restoration works in Bogorame, Demak, Indonesia.

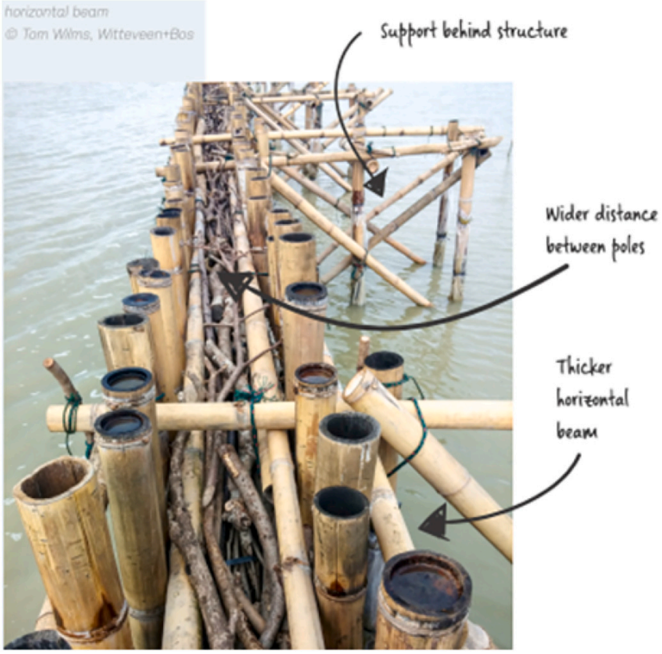

Fig. 30. Permeable dam with support structure, Demak, Java, Indonesia.

the rest of the year (January to May).

3. Discussions of the plans with local communities to guarantee stakeholder participation. Past experience with previous structures (if any) and physical or social constraints at the proposed locations should be incorporated. Site inspection is a necessity for a detailed design, obtaining up-to-date data on depth, physical obstacles, etc. Markers for the actual construction are set to facilitate the execution of the work (March).
4. Permits need to be obtained for construction in the coastal zone – compliance and application of these permits should continuously be checked during the execution of the work.
5. Tender for supervision: prepare documents and allocate budget. When possible involve the supervisor in the tender for construction. Contracts to be signed by April/May.
6. Tender for construction: prepare documents, drawings and allocate budget, also for maintenance (June and July). When ordering materials, provisions should be made for losses due to sub-standard quality, for compaction and decay of brushwood, and volume losses due to local scour.
7. Training for construction, maintenance and monitoring (May and June).
8. Construction and supervision, aimed to be done well before November, to account for delays and unworkable weather (June to September).
9. Monitoring and maintenance starts during the construction work and continues (from July onwards)

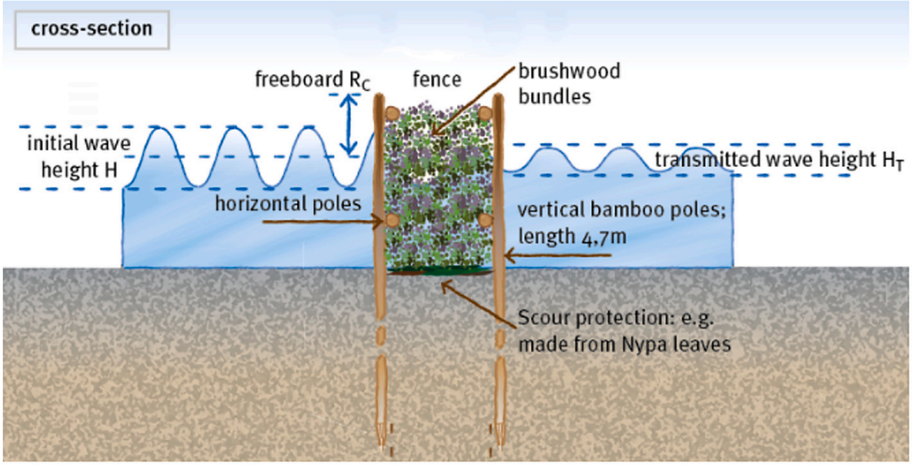

Fig. 31. Design of the permeable bamboo fences and resulting wave transmission.

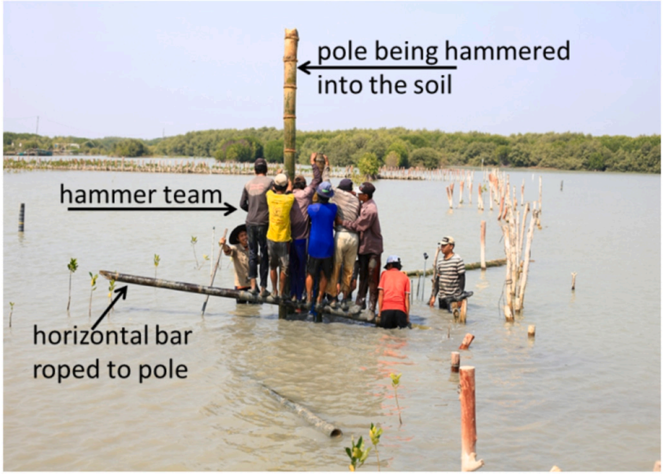

Fig. 32. Hammer team at work to place bamboo pole, Bogorame, Demak, Indonesia.

The foreshore in Demak is characterized by a stiff mud bed with a layer of soft sediment on top with a thickness of several decimetres. Stiffer soil is encountered at the locations of relic aquaculture bunds, which may be favourable to place the structures as it reduces the risk of scour. Remnants of foundations for houses etc. have been encountered in the field as well, which complicate construction.

Bamboo poles have a maximum length of about 6 m – longer poles cannot be handled properly. All poles need to be inspected before use, in particular their finishing to prevent water accumulation at the top end. The poles (and later the brushwood) are brought to site by shallow rafts. When using soil drills or water jets is too laborious, the poles are hammered into the soil. Heavy equipment cannot be used in these shallow areas. Therefore a technique was developed by forming a “hammer team”, which jumps on a horizontal bar connected with a rope to the pole to be put into the soil, as depicted in Fig. 32. For stability, the poles need to be hammered deep enough into the stiffer subsoil, preferably up to 2/3 of their length, but at least 2 m. Of course, the top of the poles should remain well above high water (HW) to allow brushwood to be placed high enough. It takes about 15 minutes to hammer in one pole.

Brushwood bundles are made using rope and old fishing nets. When the rows of bamboo poles are in place, and horizontal support beams connected, these bundles are placed and tied firmly to the construction. The placement of brushwood should be done around low water. This prevents the brushwood from floating; tying down the brushwood properly is almost impossible at higher water. The placement and tying of the brushwood proved to be the most critical part in the entire construction process and needs to be supervised intensively.

Though no heavy equipment is used, safety is an issue, as the bamboo poles are long and heavy, and hammering implies considerable forces on the poles and horizontal bars. Also weather conditions, in particular storm conditions and lightening are important safety issues.

To get an idea on the budgets required, the following costs in USD for materials and construction per unit meter permeable dam are summarized in Table 2 .

It is noted that, due to its massive losses and rapid decay, brushwood filling forms an important part of the overall costs of permeable dams. It is therefore important to appreciate that sufficient wave damping can also be achieved with vertical (bamboo) poles only, as the orientation of the dissipating structures in shallow water is not important (Gijón Mancheño, 2021). This is subject of ongoing research.

Table 1
Loss of mangrove habitat between 2010 and 2015 (MMAF, 2017a).

	2010 – 2015
	net loss [km^2]
Java	1664 (-82%)
Sumatra	1703 (-20%)
Kalimantan	8114 (-56%)
Sulawesi	1164 (-47%)

Table 2
Ranges in construction and maintenance costs (per maintenance cycle) per unit meter permeable dam in USD; Thailand: bamboo fences.

	Construction in USD/m			Maintenance in USD/m		
	Material	Labor	Total	Material	Labor	Total
Demak	60 – 120	20 – 40	80 – 160	38 – 60	12 – 20	50 – 80
Vietnam	40 – 70	10 – 20	50 – 90	10 – 40	10 – 20	20 – 60
Thailand	12 – 85	4 – 17	16 – 110	-	-	-

4.3. Inspection and maintenance

The long-term vision sets the required lifetime of the dams. The dams have therefore to be maintained, likely for a number of years (in Demak, estimated 3 – 5 years, see above). In deeper water, as in Demak, when poles are submerged permanently, the lifetime of the poles is largely determined by shipworm-induced damage. Maintenance should therefore be budgeted, and because of its high costs, this may appear to be an important component in the deployment of permeable dams. Thus regular inspection is crucial, to allow for timely maintenance. Regular maintenance requires a dedicated state-of-mind, for which involvement of local stakeholders is crucial. Inspection is performed at various moments: before and after each rainy season as this period is characterized by intensified wave conditions and more maintenance, weekly during construction, after two months after construction to check proper installation, and finally after storms to check if structures are still intact. All inspection, maintenance and repair work have to be documented with photos and receipts.

Inspection can also lead to new insights to be incorporated into future designs. This learning-by-doing forms a crucial part of the Building with Nature philosophy. In Demak it was found that shipworm reduced the structural strength of the structure. This led to adding: 1) carpet protection; 2) horizontal support structures, and 3) additional horizontal beams for spreading loads. Other lessons-learned are:

- The required maintenance strongly correlates with the intensities of storms,
- New vertical poles are difficult to place in existing rows. When only a couple of poles are weak the section can be strengthened using additional horizontal beams. Experience indicates that when approximately 40% of a section is weakened, it must be replaced entirely, as it cannot be sufficiently strengthened. If poles have to be replaced within the structure, this must be done at the seaside of the existing structures.
- Horizontal beams must be replaced when becoming too weak.
- Damage to the nets is hard to repair. The only feasibly form of maintenance is then to tie additional rope around the top metre of fill material to restore connectivity.
- The tying wire to fixate brushwood to the dam can loosen or get lost, because knots loose hold, fill material lowers, and/or it is damaged or stolen. When wire is damaged, it needs to be replaced. When a wire is too loose, while the top of the fill is still above the horizontal beam, it should be tightened immediately. When a wire is loose and fill material is below the horizontal beam, fill material has to be added (within the net) up to 0.1m above the horizontal beam and the wire has to be tightened over the fill. The tying wire is one of the

major elements to keep the brushwood in place.

- o Fill material needs to be added when its level gets below the highest horizontal beam. Experience in Demak shows that this needs to be done regularly, at about a rate of 50% per year.
- o Broken poles etc. must be removed as its debris may damage mangrove trees elsewhere (Pranchai et al., 2019), hinder navigation, block drainage channels and/or the remaining stumps may endanger local fishermen. This is no longer necessary when the permeable dams become encapsulated within the mangrove forest, as aimed at.

5. Stakeholder involvement and socio-economic aspects

Rehabilitation of mangroves and their habitat is rarely successful without the involvement of local stakeholders. Socio-economic aspects should be included in restoration projects, so that local communities benefit from sustainable mangrove use. It is key to introduce sustainable economic activities alongside mangrove restoration, such as sustainable aquaculture and integrated mangrove-aquaculture schemes, fisheries, eco-tourism and non-timber forest products (Ahammad et al., 2013). In a mangrove based economy, mangrove greenbelts provide coastal safety and the resilience for communities to thrive, providing incentives for sustaining the mangroves they depend on. Prior to mangrove restoration, awareness needs to be raised about their importance, proper management and accompanying sustainable land use practices. Further, land ownership and use rights need to be established and protection needs to be embedded in village, district, provincial and/or national policies (Lovelock and Brown, 2019). Successful projects empower communities, engage local government and ensure that local actions are strengthened by policies and planning throughout the process from design through to implementation.

The Building with Nature activities in Suriname, for example, were mainly aimed at raising awareness and involving local stakeholders in mangrove rehabilitation efforts.

In Demak, the aim was to enhance resilience of 70,000 people by avoiding coastal flooding and erosion, while providing sustainable economic development options Van Wesenbeeck et al, 2015. This was done through integration of mangrove restoration, small scale engineering and sustainable land use, i.e. by adopting a Building with Nature approach. In areas with severe erosion, placement of permeable dams to trap sediment was necessary to enable mangrove recovery, while in other areas aquaculture pond conversion into mangrove was a more adequate approach. Coastal Field Schools (Widowati et al., 2020) were successfully organised in nine coastal villages to raise awareness about the role that mangroves play in coastal safety, and to introduce best (sustainable) aquaculture practices, or alternative livelihoods when aquaculture was no longer possible due to land loss. Best aquaculture practices significantly increased yields of both milkfish and shrimp, and gross financial margins of those farmers stocking shrimp (Widowati et al., 2020). The project further introduced an innovative mixed mangrove-aquaculture pond design, in which part of a pond is scarified to make space for mangroves (Bosma et al., 2014). In this scheme, aquaculture productivity is optimised, while surrounding mangroves purify water and enhance fisheries (Primavera, 2000). Ecosystem services of mangrove forests were quantified through providing funds for services by local communities to the ecosystem. We refer to “bio-rights” (Van Eijk and Kumar, 2009; Wetlands International website), which enabled communities to restore tens of hectares of mangroves along rivers and coasts, while revitalising hundreds of hectares of aquaculture ponds. Fisheries are recovering along with mangrove recovery in the area, providing an extra source of income (Debrot et al., 2020). Simultaneously, communities were empowered to join policy dialogues to ensure sustainability of mangrove and aquaculture measures through the establishment of protected areas and budget allocations. As a result, these communities are now great ambassadors of the Building with Nature approach.

In Thailand, local communities were intensively consulted on methods to stop coastal erosion (Saengsupavanich, 2013). Poor experience with bamboo fences in some provinces along the upper Gulf of Thailand led to a preference to build low-crested revetments instead (see Section 2.4). On the other hand, the local community of Ban Klong Prasong in the south of Thailand took the initiative to erect bamboo fences when the more classical concrete seawall failed to protect the village. In none of these initiatives, a socio-economic component was introduced.

The protection of the coast was recognized by the Vietnamese government as an essential factor to safeguard the (economic) development of the entire Mekong Delta. Therefore an overall plan was developed based on existing evidence from recent studies, and on the assessment of Vietnamese experts, international consultants and provincial government agencies under the mandate of MARD VDMA. This Coastal Protection Plan for the Mekong Delta (CPP) includes online and printed guidance for coastal protection measures and prioritization of investments (http://coastal-protection-mekongdelta.com/#). The CPP considers also the design and construction of bamboo fences and dams, which was inspired by several study tours to Germany and The Netherlands. The main objective of the CPP is to harmonize coastal protection planning at the regional level. Although being a sectoral plan for coastal protection, the approach is based on the integration of water management, forest management and land-use planning in the coastal area. The CPP does not replace official planning documents but is supposed to feed concepts, ideas and solutions into future regional and provincial planning. The coverage ranges over seven provinces from Tien Giang (Eastsea) to Kien Giang (Westsea).

6. To plant or not to plant

Mangroves are lost because of adverse bio-physical and socio-economic conditions (many mangroves are manually removed to convert to fish ponds). For successful restoration, an inventory of limiting biophysical parameters should be made, and restoration efforts should focus on restoring these conditions (Lewis III, 2005). Limiting abiotic conditions typically consist of elevation within the tidal range, wave impacts, fresh water availability, lack of drainage and sediment availability (Balke et al., 2011). Unfavorable biological conditions range from limited seed availability, insufficient seed transport capacity, to predation by crabs and bioturbation by worms, burying small seedlings. However, if abiotic conditions are favorable, mangroves generally recruit spontaneously and grow naturally. This is often preferable to planting, as natural recolonization can be extremely fast if conditions are favorable (see also Fig. 9 and 17), whereas up to 85% of planting efforts fail. However, there is a psychological element as well. Seeing your coast eroding in response to the loss of a protecting mangrove green belt, one is eager to take rapid action, which often implies planting.

Mangrove planting has therefore become highly popular across the world. Local communities may earn from nursery management and planting, financial incentives provided by many governments and international donors. Pride and ownership is connected to these planting efforts, while raising awareness of the important role of mangroves in coastal resilience. Also, many international organizations organize “planting events” and even “planting holidays” for youngsters with a green heart. However, despite good intentions mangroves are often planted at unfavorable locations, too low in the intertidal (Primavera and Esteban, 2008). There, they influence and affect other ecosystems, such as seagrasses and mudflats, and those ecosystems are essential areas for shellfish and fish species, but also for threatened species, such as sea turtles and dugongs. Hence, good intentions that fuel planting efforts may backfire and result in destruction of vital coastal ecosystems (Primavera and Esteban, 2008).

Overall, mangrove replanting is often done with red mangrove propagules, irrespective of habitat suitability (Fig. 33). As a

Fig. 33. *Rhizophora* planted on mud flat.

consequence, planted mangroves are often submerged too long and therefore grow slowly or stay small for years. Also, red mangroves are often not the main pioneer species and planting these first reverts natural forest zonation. Proper techniques for mixed species planting are available and have been tested (Primavera and Esteban, 2008). Such planting yields a richer mangrove community and higher planting success rates, but has to be accompanied by biotic and abiotic surveys, while often requiring hydrological restoration as well (Primavera et al., 2012, 2013; Brown et al., 2014). In the Demak rehabilitation pilot, principles of Ecological Mangrove Restoration (EMR, Lewis III, 2005) are followed. EMR aims at restoring the favorable habitat conditions for mangroves, and generally no planting is done. In this way, EMR strives to achieve a natural zonation and optimized species site matching. This results in fast growth of the forest and high survival rates.

If it is decided to strive for natural recruitment, it is essential that the newly formed mud flats are protected from crab fishing and similar activities, as frequent stirring up the fresh deposits will prevent mangrove recruitment.

When all conditions to rehabilitate mangrove habitat have been met, other local potential stressors may influence recruitment and survival of mangrove vegetation. In South-East Asia, a major stressor is the large quantity of household waste, most notably plastic (Sandilyan and Kathiresan, 2012; Smith, 2012). Plastic getting stucked to seedlings increase the chance of uprooting, and covering pneumatophores causes deformation of the roots, while the tree attempts to outgrow the suffocating material, see Fig. 34. Half-yearly monitoring of litter cover in the mangroves of Demak revealed plastic cover up to 50% of the forest floor, often multiple layers thick (Van Bijsterveldt et al., 2020b). These amounts of plastic can seriously affect mangrove resilience, and should therefore be addressed/mitigated in the designs of mangrove-mud coast rehabilitation. Placement of nets may keep floating plastic out of regained mudflats, but also hinders the ingress of mangrove propagules.

7. Challenges and conclusions

Building with Nature (BwN) initiatives to rehabilitate damaged and eroded mangrove-mud coasts are now being trialed across the world, in many cases using techniques similar to the salt marsh works deployed in NW-Europe, by erecting permeable dams along the coast. The basic philosophy is to restore mangrove habitat by restoring the local sediment balance along eroding coastlines. Some of these applications were more successful than others, but all case studies provide three main lessons for future applications:

1. Patience and persistence. In general, degradation of mangrove-mud coasts occurs over a period of decades, while unfavorable changes in the coastal system may have started well before (Winterwerp et al., 2013). It is naive to assume that rehabilitation may be realized within a few years – rehabilitation obeys the time scales of the natural system. This necessitates a long-term vision for coastal rehabilitation covering a considerable period of time – the BwN-approach advocated here allows for adaptation of the plans through learning-by-doing. The long-term vision should also accommodate for initial failures: this is the essence of learning-by-doing. While construction costs are typically low, it is stressed that maintenance costs can become considerable – yet, maintenance is crucial for long-term success. Preventing the formation of debris and/or its clearing should be included in any maintenance plan.

Fig. 34. Example of root degeneration/deformation in response to suffocation by plastic (Demak, photo C. Van Bijsterveldt).

2. System understanding. This long-term vision should be based on a robust understanding of the biotic and abiotoc coastal system, its long-term development and its long-term response to the interventions planned. The permeable dams proposed herein are relatively cheap and easy to build, hence can be considered as low-tech coastal interventions. However, without a fundamental understanding of the natural system, these interventions may easily lead to disappointments, frustrating the need for patience and persistence.
3. Stakeholder involvement. Local stakeholders and communities should become convinced and motivated that mangrove rehabilitation is necessary, and then that patience and persistence are a required for safeguarding and improving their living conditions. This implies that long-term visions should include short-term incentives, and long-term socio-economic prospects as well. Moreover, local stakeholders and communities should be involved in the planning itself, construction of the dams, and their inspection and maintenance.

In all examples of Section 2, local stakeholder involvement was a key element for implementation of the BwN-approach. However, this necessary condition is not sufficient, as basic understanding of the muddy coastal system at larger scale is generally not available. It is a great challenge to integrate local stakeholder involvement and local knowledge of the coastal system with advanced engineering expertise on the functioning of muddy coasts.

Priorities in a long-term vision should anticipate on early successes, as these will boost motivation. As an example, start with building dams at locations where success is highly likely – this can serve as a show case for further works. Because of the complexity of the physical and socio-economic conditions, experts of multiple disciplines should be involved, such as coastal engineers, ecologists, sociologists and economists.

Permeable dams are meant to create low-dynamic sedimentation basins, dissipating a major amount of the wave energy. However, when large amounts of fine sediment occur in the foreshore, shoreward sediment transport may be driven by streaming, as in the Guiana coastal system and at some locations in Demak. Permeable dams will then frustrate this natural rehabilitation process. Their construction should therefore be synchronized with this natural process, i.e. commenced only when streaming-induced transport becomes small. Further research should shed more light on the conditions under which streaming can be expected.

Many muddy coasts are characterized by the presence of cheniers, shallow lenses of sand atop an otherwise muddy substrate. They may or may not be attached to the shore. When encapsulated in the landscape, they form sand ridges. Though their formation and behavior is not well-understood, self-organization seems to play an important role. In eroding coastal systems, cheniers may be a transient phenomenon. Tas et al. (2020) found that cheniers can be very dynamic, even under relatively calm hydrodynamic conditions. As cheniers can dissipate large amounts of wave energy, they form an important element in the stability of mangrove fringes along the coast (Van Bijsterveldt et al., 2020a).

Permeable dams can only be deployed in shallow water, as mangrove habitat rehabilitation cannot be expected in deep water. Then even locally generated waves behave as shallow water waves, and vertical components of their orbital movements are small: shallow water waves induce orbital movements in horizontal direction only. This implies that the orientation of energy-dissipating elements in permeable dams becomes irrelevant, and equ.'s (2) and (4) can then be used to assess dissipation rates. In other words, wave dissipation by brushwood dams can be achieved also with vertical elements (i.e. poles) only (Gijón Mancheño, 2021). This is a crucial observation, as the problematic construction and maintenance of brushwood can be prevented, and the freedom in configurations becomes much larger. We are currently investigating if zero-reflective pole configurations can be designed, and whether such poles can also serve other ecosystem services (mussel cultures).

The more classical approach for coastal defense consists of the construction of coast-parallel concrete seawalls, breakwaters, or low crested revetments (Thailand), porous or not, at some distance from the coastline. These constructions are generally reflective, inducing scour in front, thereby destabilizing the structures, yielding complete collapse in due time. The degree of reflection is a function of the porosity of the structure. These heavy structures may also sink into the soft mud, losing their function, hence soil improvements and/or foundations are required. However, at some locations, there are no other options than deploying such solid structures, for instance when water depths are too large. When sediment deposits behind such structures a habitat may be formedsuitable for mangroves colonization, planted or natural. It is worthwhile to investigate if designs are possible, allowing for a managed collapse of these structures, forming a more or less permanent coastal defense for the mangrove forest developed behind. It is important not to build such structures too far offshore, as possible sediment deposits behind become immobile, while building out seaward is no longer possible as well.

From a scientific point-of-view, our understanding of the functioning of eroding mangrove mud coasts has increased considerably. Also, many lessons were learned on how to construct and maintain permeable dams to rehabilitate these coasts. Yet, it is not possible to provide unambiguous rules for successful application of this Building with Nature approach, as site-specific conditions are very important. This is why a proper understanding of the natural system is so important. However, at a more qualitative level, a number of criteria for success can be given.

1. Water depth (1). The salt marsh works in NW Europe have always been deployed on intertidal flats, so that the permeable dams always emerged entirely around low water. Our results, in particular in Demak, show that permeable dams may work at deeper water. Though we have no hard data on critical depths beyond which permeable dams can no longer be efficient, it is likely that this depth depends on the sediment transport capacity in the system. We speculate that permeable dams will not be effective if mean water depths exceed the sedimentation rate in one monsoon season. In Demak, sedimentation rates of about 0.5 m during the monsoon season have been measured, which would imply that the critical mean water depth would amount to about 0.5 m – local water depths are indeed not larger.
2. On intertidal flats, sediment transport is mainly due to tidal filling perpendicular to the coastline. Then longshore currents are unfavorable, and cross-shore dams have to be constructed (the T-dams of Vietnam).
3. At deeper water, longshore sediment transport (f.i. in the form of large eddies) often occurs. Then cross-shore dams should not be placed initially. However, when a sedimentation basin becomes intertidal over time, tidal filling becomes the dominant transport mechanism, and the dam configuration may have to be modified locally.
4. Water depth (2). The construction of permeable dams at deeper water has two other consequences: wave-induced hydrodynamic loading becomes larger, requiring stronger constructions, and shipworm problems increase with the duration of submergence of the structures.
5. Subsidence. Increasing water depths by subsidence have unfavorably effects on the functioning of the structures themselves (see 4.) and adversely affect survival rates of mangroves colonizing the tidal flat behind the dams, especially when sediment supply is limited and the bed level cannot be maintained at MSL. We have no data on threshold subsidence rates, unfortunately..
6. Sea-level rise. On longer time scales, absolute sea-level rise may also endanger mangrove forests, in particular when sediment becomes scarce. However, the time scales of sea-level rise are still

much larger than the response time of mangrove forests to anthropogenic interventions, be it favorable or unfavorable.

7. Sediment availability. Sufficient fine sediment should be available to fill in the sedimentation basins up to or above mean sea-level and/or to compensate for subsidence and sea-level rise. Hydrodynamic transport processes should be able to bring these fines to the targeted locations, without disturbing the fine sediment dynamics at other locations too much – one does not want to enhance erosion at other locations.
8. Sediment type. The lessons-learned in this article are based on experience with fine, muddy sediment. Sandy sediment behaves very different, and the current results are not applicable in sandy coastal waters.
9. Tidal range. In conjunction with the slope of the foreshore, the tidal range determines the area between low water, mean sea-level and high water, hence the potential area for mangrove habitat. The local sediment transport capacity scales with tidal velocities, thus with tidal range. The tidal range therefore affects time scales for erosion and sedimentation. The tidal range also governs water depths at which waves can penetrate a mangrove forest and/or attack the coast/hinterland. Hence, coastal protection from mangroves requires wider green belts for larger tidal ranges.
10. Wave climate. Wave attack causes coastal erosion, and mild wave conditions seem favorable for mangrove recovery. However, mangroves are found along most coasts across the tropics, also where exposed to ocean waves (possibly covered with different species that withstand such waves). We therefore anticipate that only a fraction of incoming wave energy has to be dissipated by permeable dams for mangrove recolonization. Most likely the rate of dissipation required is a function of the state of degradation of the coastal system. We stress however, that a loss in coastal resilience is the root cause of coastal erosion, and waves are “only” the final executer of the erosion process.
11. Wave stirring. It is essential to appreciate that waves also mobilize fines from the seabed necessary for the coastal rehabilitation, thus contributing to the sediment availability. Coast parallel breakwaters therefore work contra-productive; these can only catch sediment mobilized elsewhere.
12. Tide/wave. As a rule of the thumb it seems safe to assume that tide and wave conditions are suitable for mangrove habitat rehabilitation if mangroves have flourished earlier under these conditions.
13. Rate of erosion. The philosophy behind the sequential installation of sedimentation basins is to slowly build out into the sea, but not further than up to the original coastline. If erosion rates are larger than rates of habitat reformation, this method fails. However, erosion rates themselves are retarded by the construction of permeable dams. In case of cyclical erosion/accretion processes, as along the north coast of South America, the erosion cycle may be weakened, resulting in net accretion over longer times.
14. Land-use. Many coastal erosion problems have commenced with converting mangrove forests in favor of aquaculture, industrialization, infrastructure and urbanization along with associated ground water extraction that induces subsidence. These developments will have to be controlled to be successful on the long term.
15. Wave reflection: Green belt restoration in front of seawalls/dykes may suffer from wave reflection against these hard structures, attacking the mangroves from the back. This sets constraints on the green belt width, while reflection-damping structures on the seawalls/dykes may enhance chances of success.
16. Fresh water. Juvenile mangroves need (some) fresh water. In drier regions, precipitations may not be sufficient and fresh water has to be supplied from the hinterland. If blocked, this may seriously affect the development of (young) mangroves.
17. Waste products. Waste, especially plastics will hinder the development of the mangroves and should be managed when/where possible.
18. Debris. When breaking down, parts of the brushwood and bamboo become debris, which may endanger the mangrove forest and/or block drainage channels. Debris management should therefore be included in the maintenance plans Smith (2012).

Two final comment concern the ecological/natural value of mangrove-mud coasts Leong et al. (2018). It is important to appreciate that the mudflats in front of healthy coasts have considerable ecological value, and we strongly discourage land reclamation with permeable dams at the cost of these mudflats, though this was of course the original aim of the salt march works in NW-Europe. Next, as far as known to the authors, no detailed studies have been carried out on the ecological value of restored mangrove green belts. However, it seems likely that biodiversity, thus a variety of mangrove species as occur in nature is an important aspect.

Concluding, permeable dams can successfully support mangrove recovery in eroding settings thus contributing to coastal safety as part of Integrated Coastal Zone Management. They can be considered a low cost and no-regret measure that creates multiple benefits compared to traditional engineering solutions. But implementation requires adaptive management and learning by doing.

Author contribution

This research was done in the context of Building with Nature Indonesia, which is a programme by Ecoshape, Wetlands International, the Indonesian Ministry of Marine Affairs and Fisheries (MMAF), and the Indonesian Ministry of Public Works and Housing (PU), in partnership with Witteveen+Bos, Deltares, Wageningen University & Research, UNESCO-IHE, TU Delft, Blue Forests, Von Lieberman and Kota Kita, with support from the Diponegoro University (UNDIP), and local communities. Building with Nature Indonesia is supported by the Dutch Sustainable Water Fund and the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) as part of the International Climate Initiative (IKI). Field work in Indonesia was carried out and supported by members of UNDIP-Corem, Semarang.

All authors have contributed either to the BwN experiments and their analyses or the writing of this manuscript, or both.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Data requirements

This appendix presents suggestion on data sources for the generally data-poor mangrove-mud coastal environments, while local capacity to analyze these data is often undeveloped as well. It is contra productive to try and get mangroves on coasts where they never have been growing. A most useful step in assessing whether or not it is possible to rehabilitate an eroding mangrove green belt, is inspection of historical satellite images, such as from Google's Earth Engine. This gives information on the historical presence of mangroves, of erosion rates and erosion events, and a first idea on the availability of fine sediment to restore the sediment balance. In Demak, Indonesia, for instance, satellite images show that spontaneous mangrove recovery may occur along the otherwise eroding coast, suggesting a pool of mobile mud that may accumulate in quiet places. Note that this pool likely originates from previous coastal erosion events. A more stable supply of mud is found in the coastal zone of the Guyana's, South America, where eroding mud banks bring large quantities of Amazon borne sediment toe the coast.

A first step in the conceptual design of permeable dams consists of a geographical analysis of the site, which includes:

- assessment of pre-erosion coastal features, presence of mangroves, rivers, creeks, etc.,
- assessment of land use, such as aquacultures, housing, infrastructure, industry, etc.
- rates of subsidence,
- availability of fine sediments, such as a stock in the foreshore and/or ingress by local rivers,
- width and depth of foreshore,
- assessment of historic coastline evolution, i.e. the rate of erosion and possible spontaneous mangrove recolonization.
- assessments of causes of erosion, such as subsidence, land-use, wood production, infrastructure, etc., event-driven or more gradual,
- assessment of critical places, where breaching would have far reaching consequences,
- assessment of vulnerable places, think of housing, infrastructure, etc.
- presence and dynamics of cheniers,
- indications for mud streaming (see section **).

The majority of this information can be obtained from satellite images, such as Google Earth and the Google Earth Engine, and interviews with local stakeholders, e.g. fishermen. Of course, open literature is to be consulted as well, bearing in mind that these sites are generally not well studied. This step provides the information for a go/no-go decision: is there a fair chance that the eroding coast can be restored with Building with Nature techniques. Next, hydro-sedimentological data are analyzed, as summarized in Section 2, assessing seasonal variations in hydrodynamic forcing, such as monsoonal variations in wind speed and direction, in wave height, period and direction, currents, rainfall, etc. The permeable dams should be effective during the most dynamic conditions, when most of the coastal erosion is to be expected. When the tidal currents are more or less perpendicular to the coast, as in the case of tidal filling, the configuration of Fig. 3a is advocated. These sedimentation basins contain openings of about 5 m wide to allow the sediment-laden flow to enter. In case longshore currents prevail, the stilling basins may consists of coast parallel dams as well, as in Fig. 3b, to prevent blockage of the sediment-laden flow.

Mangrove habitat is found between high-high water spring (HHWS) and mean sea-level (MSL) or mean high water (MHW), the lower level depending on the hydrodynamic forcing (Balke et al., 2011). Hence, a fair idea on the coastal bathymetry has to be obtained, which includes slopes and width of the foreshore. When depths are too large, it is unlikely that sufficient sediment can be caught to restore the sediment balance, and attain mud flats of sufficient height for mangroves to colonize. Note that sediment may also be supplied from local rivers, in particular at places with large terrestic erosion due to e.g. deforestation.

Along many eroding and stable mangrove-mud coast cheniers are found, relatively small lenses of sand on top of an otherwise muddy seabed. As waves break on these cheniers, they modify the wave climate locally, and provide shelter for the mangroves behind (Anthony et al., 2019; Van Bijsterveldt et al., 2020a). These cheniers may be very dynamic (Tas et al., 2020), thus difficult to monitor. Yet their presence has to be accounted for, and inspection via the Earth Engine is advised.

Balke et al. (2011) found a "window of opportunity" within which mangrove propagules may root and anchor to withstand hydrodynamic forces emerging from (tidal) currents and waves. Hence, information on currents and waves is important, and their variation over the season (monsoon, …). As explained by Winterwerp et al. (2005, 2013), waves do not only erode the coast, but also mobilize fine sediments which can restore the coast. These sediments are advected by the tidal currents, hence also direction of these currents has to be known. Information on tide and waves may be obtained from a global tide model (e.g. Topex Poseidon global ocean tide model: Egbert and Erofeeva, 2002) or wave model (e.g. Wavewatch III by NOAA, Environmental Modeling Center)

We appreciate that only qualitative information may be available, and information from locals, such as fishermen, can be very useful, even if only anecdotal. In summary, the following data have to be collected and analyzed as basis to inform system understanding.

Table A.1
Data requirements

Parameter		Possible sources
Coastline geometry		
	Historic evolution	Satellite images
	Land use	Satellite images
	Presence of mangroves	Satellite images
Bathymetry		
	Historic evolution	Satellite images
	Depth and bed slope	Satellite images, measurements, fishermen
	Cheniers	Satellite images
Availability of sediment		
	Stock on foreshore	Satellite images, open literature

(continued on next page)

Table A.1 (*continued*)

Parameter		Possible sources
	Input by rivers	Satellite images, open literature
	Sediment composition	Local inspection, open literature
Tide		Global tide model (Topex Poseidon)
	Tidal range	Literature
	Spring-neap yearly variations	Local tidal stations
Tidal and residual currents		Global tidal model
	Magnitude	Literature
	Direction and circulations	Literature
Waves		Global wave model (Wave Watch III)
	Height	Ship-borne data, local measurements
	Period (local/swell) and direction	Global wave model
	Seasonality	Global wave model
Winds		Local meteo stations
	Speed & direction	Local meteo stations
	Seasonality	Local meteo stations

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