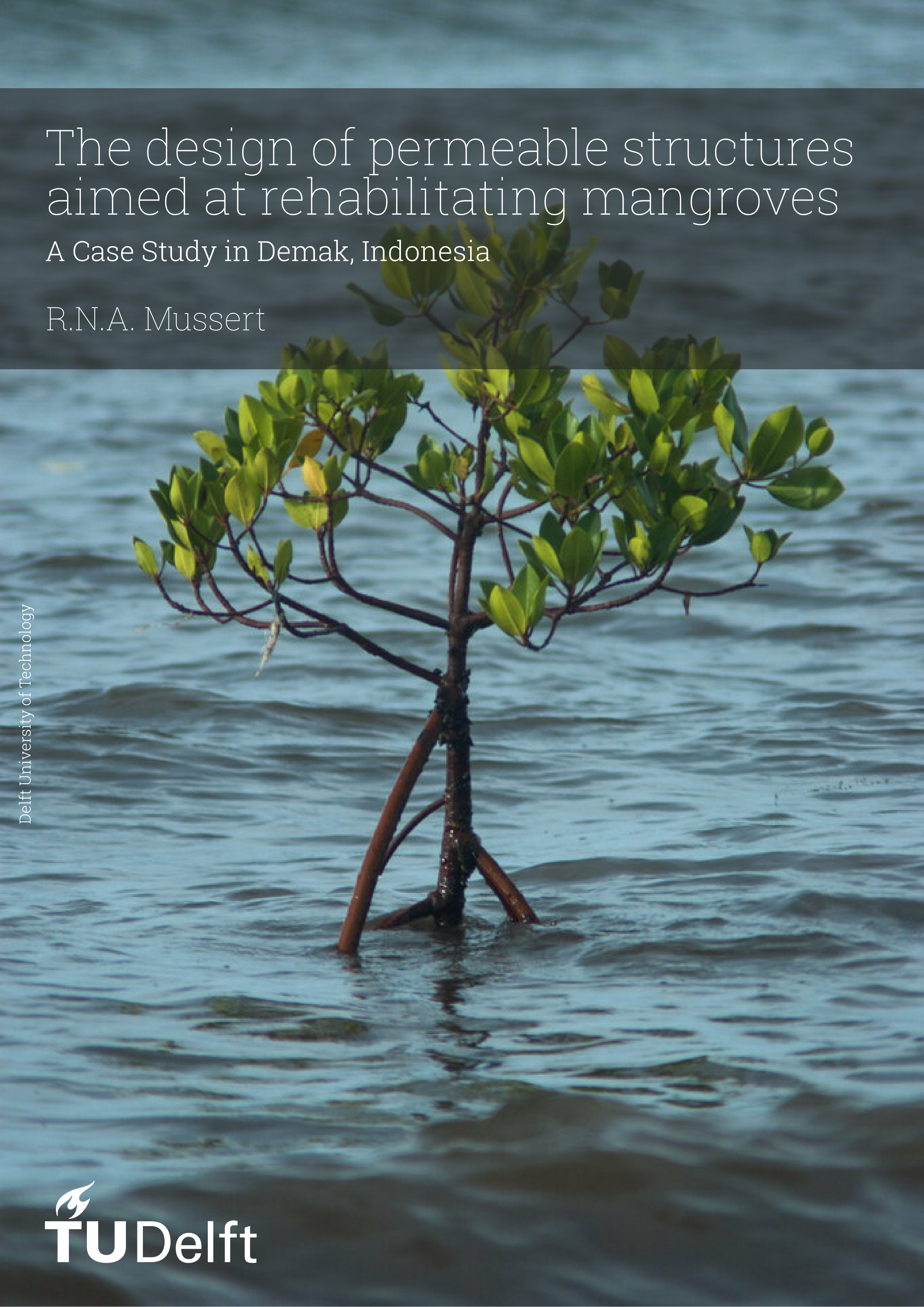
The design of permeable structures aimed at rehabilitating mangroves

A Case Study in Demak, Indonesia

R.N.A. Mussert



Delft University of Technology

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by

R.N.A. Mussert

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TU Delft

Van Oord
Marine ingenuity

Preface

Ever since participating in an international volunteering program in Malaysian Borneo after completing high school, I have aspired to empower society with sustainable solutions, enhancing the well-being of both people and planet. This eye-opening experience fueled my ambition to contribute to technological solutions and innovations within the field of hydraulic engineering, and more specifically, within the realm of Building with Nature. This ambition and motivation have led to this final thesis project, and the report that lies in front of you, on which I have worked for the past 8,5 months with great enthusiasm and pleasure to obtain my master's degree in Hydraulic Engineering at the TU Delft.

Throughout my seven-year journey as a student, I've undergone substantial growth, both professionally and personally. I'm grateful for the opportunities I've encountered and the exciting projects I've been able to participate in, as well as the various boards and committees I've been a part of alongside my studies. Moreover, I am deeply grateful for the many wonderful individuals I've had the pleasure of meeting along the way, and the lifelong friendships I've formed during my time as a student.

During this final thesis project, I have received extensive help and guidance from various people whom I would like to express my gratitude to. Firstly, my supervisor at Van Oord, Amrit Cado van der Lelij, who has been with me every step of the way, offering continuous support and positive feedback. Your cheerful attitude and enthusiasm in guiding me are deeply appreciated! Secondly, Alejandra Gijón Mancheño, who has always been so kind, supportive, and ready to assist at any time. Your passion for the topic, as well as the warmth with which you guided me and provided feedback, are truly admirable! Next, I would like to thank Stefan Aarninkhof and Ad Reniers, the professors at TU Delft who were part of my graduation committee as well. Thank you for your constructive feedback during our meetings, and for the assurance you provided, enabling me to proceed with confidence and successfully complete this graduation project. Furthermore, I am grateful to everyone involved in my project at Van Oord, particularly everyone of the Environmental Engineering department who showed their interest, and provided support. I felt warmly welcomed within the company and I have had a great time working besides you, for which I am thankful. Lastly, I would like to express my gratitude to Loukianos Panagopoulos, who has been immensely helpful, especially with the programming work that I had to undertake. Thank you so much for your time and assistance.

Besides, I want to express my heartfelt gratitude to my family and friends for their unwavering support, who have always shown genuine interest in me as well as in this project, and who spent their time with me to take my mind off graduation at night and on weekends. In particular, I would like to extend a huge thank you to my dear parents who have always stood by me, encouraging me with immense love. Thank you for providing such a warm nest, a safe haven, and your unconditional support, pride, and love!

I hope that my work can be both useful and inspiring to others, advocating for more sustainable and nature-inclusive solutions to address societal needs and to enhance the well-being of our planet. I believe that my journey toward empowering both society and our planet by promoting nature-based solutions does not end here; rather, this project marks the beginning of my career in contributing to sustainable technological solutions and innovations, and striving to make the world a greener and more harmonious place.

Rosalie Nine Annelotte Mussert
Delft, April 2024

Abstract

Mangrove forests are highly valuable environments that offer numerous ecosystem services, including carbon storage, serving as nurseries for fish and shrimp, and providing timber. Additionally, these ecosystems offer coastline protection against erosion and flooding by attenuating waves and trapping sediment. Despite the crucial role of mangrove ecosystems, global mangrove cover has significantly declined in recent decades, with deforestation and coastal erosion being one of the contributing factors, launching a variety of initiatives for mangrove rehabilitation. To rehabilitate mangroves along eroding coastlines, permeable structures are designed as a solution. These structures dissipate incoming waves and reduce current strength, creating low-energy areas behind them that are conducive to sediment deposition. However, these structures frequently prove ineffective in the rehabilitation of mangroves, possibly due to the absence of clear design guidelines, and a lack of understanding regarding the influence of design parameters on the performance of these structures.

This study, therefore, aimed to develop an integrated design guideline for permeable structures aimed at rehabilitating mangrove habitat along eroding coastlines by combining scientific knowledge with insights gleaned from pilot projects conducted globally. Furthermore, the research aimed to deepen understanding of the influence of design parameters on the performance of these permeable structures by conducting simulations of various structure configurations in a numerical, process-based model, and evaluating the performance of each configuration in reducing bed shear stress across the sheltered areas behind them. A nested model was employed in Delft3D-4, configuring the flow and wave modules to be coupled in order to incorporate the interaction between waves and currents.

A conceptual framework was developed illustrating the ecological and engineering variables important in the design of permeable structures aimed at rehabilitating mangrove habitat, serving as a guiding reference throughout the design process of these structures. In addition, within the framework of a Building with Nature design approach, a design guideline outlining the fundamental steps in the design process of permeable structures was developed. However, significant knowledge gaps impeded the development of quantitative content within the guideline. Currently, the design guideline offers insights into the essential aspects of the design process and outlines the sequence for approaching the design of permeable structures, thereby serving as an initial framework for designing these structures.

The Delft3D modelling research led to the identification of correlations between various design variables and the performance of permeable structures in reducing bed shear stress across the sheltered areas behind them. Increased structure length enhances the effectiveness of permeable structures, as the structures' influence on incoming waves and currents extends over a larger area. The degree to which it enhances structure performance, however, varies spatially, depending on local hydrodynamic conditions as well as the positioning of structures relative to the coastline/mangrove fringe. An increase in structure length of 66 meters is associated with an increased reduction in average bed shear stress of approximately 5% and an expanded spatial extent ranging from 3% to 7%. To some degree, placing structures at greater distances from a mangrove fringe enhances the effectiveness of permeable structures. An increase in distance of placement of 33 meters is associated with an additional 3% reduction in average bed shear stress. For extensive distances, however, currents can penetrate the sheltered areas behind the structures, resulting in an optimal distance of placement of structures from a mangrove fringe, which, in the case of the study area, is at a distance of 165 meters. While the distance of placement of structures from a mangrove fringe should be as large as possible to maximize the spatial extent of the effect of the structures, and, consequently, to maximize seaward expansion of the mangroves, structures should still be placed close enough to ensure its effect in reducing bed shear stresses below the threshold reaches the boundary of the mangrove fringe to facilitate seaward expansion. The gap width between structures does not significantly affect the performance of permeable structures. In fact, a wider gap width may slightly decrease the effectiveness of structures in reducing bed shear stress behind them, as waves are not effectively attenuated across the width of the gap. An increase in gap

width of 66 meters could decrease the reduction in bed shear stress across the sheltered areas by 2%. Placing multiple rows of structures behind each other significantly enhances the effectiveness of permeable structures in reducing bed shear stress across the sheltered areas behind them, as in the case of multiple rows of structures a significantly larger amount of wave energy is dissipated. This enhancement ranges from 3% to 16% in terms of increased reduction in average bed shear stress and from 4% to 20% in terms of expanded spatial extent of the reduction, compared to a single row. Besides this spatial variation, the influence of the distance in between multiple rows on structure performance varies slightly, depending on the location of structures and local hydrodynamics. As a result, depending on the location of structures within a coastal system and the local hydrodynamics, adding another row at the same distance improves the effectiveness of structures in reducing bed shear stresses more than increasing the spacing between the number of rows.

The conceptual framework, design guideline, and identified correlations between design parameters and structure performance in this study contribute to enhancing the design process of permeable structures aimed at rehabilitating mangrove habitat. It provides preliminary insights, highlights significant knowledge gaps and provides recommendations for further research, thereby opening up opportunities to expand knowledge surrounding the design of permeable structures aimed at morphodynamic restoration of mangrove habitat.

Contents

1 Introduction

1.1. Context

Mangrove ecosystems are widely recognized as highly valuable environments that offer numerous ecosystem services, including carbon storage, serving as nurseries for fish and shrimp, and providing timber (Barbier et al., 2011). These ecosystems also act as both suppliers and recipients of nutrients and sediments for nearby marine ecosystems like seagrass beds and coral reefs (Duke et al., 2007). Moreover, they offer coastline protection against erosion by attenuating waves and trapping sediment, as well as protection from flooding caused by storm surges and tsunamis (Alongi, 2008). Per square kilometer, mangroves contribute an annual estimated economic value ranging from 200,000 to 900,000 USD, through the products and ecosystem services they provide (Wells et al., 2006). The role of mangrove ecosystems becomes even more significant in the context of climate change, as they contribute to both the mitigation of its causes and the alleviation of its consequences. Mangroves sequester carbon dioxide (CO_2) from the atmosphere, and store it within their roots, trunks and leaves (Murdiyarso et al., 2015). They are among the world's most carbon rich forests, boasting an average carbon stock of approximately 1,000 tonnes per hectare (Donato et al., 2011). Besides that, mangroves have the capability to reduce the impact of waves and currents, causing sediment particles carried by the flow to settle. The deposition and subsequent accretion of sediment and organic matter raises the bed level elevation, which can offset the effects of rising sea levels (Woodroffe et al., 2016).

Despite the crucial role of mangrove ecosystems, a worldwide loss of approximately 7% of mangrove habitat, equivalent to a total area of 9.736 square kilometers, has been recorded between 1996 and 2016 (Worthington & Spalding, 2018). The region of South-East Asia, known for its historically extensive and diverse mangrove forests, has experienced the most substantial loss of mangroves (Polidoro et al., 2010). Around 50% of the initial mangrove area within this region was lost as a result of conversion to alternative land uses, such as urban expansion, rice cultivation, and oil palm plantations (Thomas et al., 2017). Mangrove degradation primarily arises from the transformation of these forests into economic land use, including aquaculture, agriculture, wood harvesting and the development of infrastructure and urbanization (Friess et al., 2019). Furthermore, coastal erosion resulting from factors such as sea level rise and subsidence, for instance caused by groundwater extraction, is projected to impact extensive mangrove regions in the coming century (Lovelock et al., 2015).

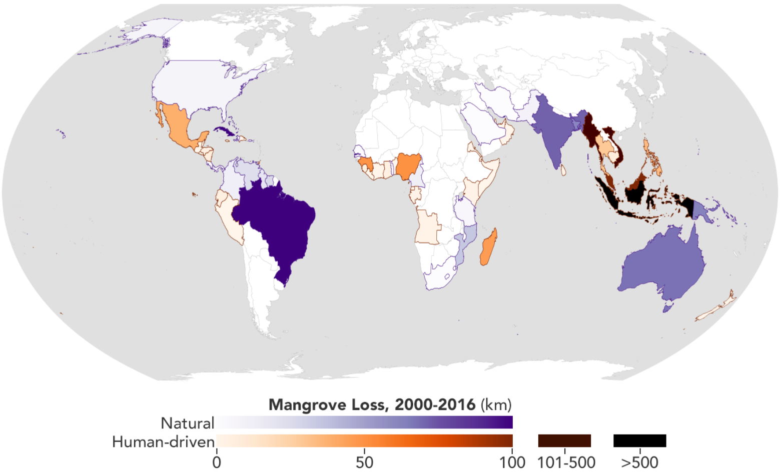


Figure 1.1: Global distribution of mangrove loss, recorded between 2000 and 2016 (Observatory, n.d.)

The loss and subsequent absence of mangroves along coastlines results in the loss of a natural buffer that mitigates wave impact between the land and the sea. Consequently, shoreline stability is compromised due to reduced wave attenuation, leading to increased wave forces on the land and subsequently coastal erosion (Winterwerp et al., 2013). The risk of flooding and extensive erosion along the already deteriorated mangrove-mud coasts is further exacerbated by rising sea levels, amplified storm frequency, and intensified storms caused by climate change. This not only threatens the loss of cultivable land but also endangers densely populated areas like villages and cities, given that deltas and coastlines are among the world's most densely inhabited regions (McGranahan et al., 2007). Therefore, globally, the accompanied loss of the ecosystem values provided by mangroves, especially in terms of flood protection, entails significant consequences for coastal communities (Winterwerp et al., 2020). It exposes millions of people worldwide to coastal hazards and the effects of sea level rise (Gijón Mancheño, 2022), since the removal of mangroves from low-lying areas increases the vulnerability of the resulting landscape to erosion (Van Bijsterveldt, 2023).

During the past decade, a multitude of initiatives for mangrove rehabilitation have been launched worldwide to stop or reverse mangrove depletion and to mitigate the ongoing coastal erosion. Nevertheless, the success rate has been low, mainly due to the fact that the biophysical and/or socio-economic circumstances were unfavorable for mangrove rehabilitation (Winterwerp et al., 2020). For instance, in an extensive rehabilitation project covering 44,000 hectares in the Philippines, the survival rate of newly planted mangroves was merely 5-10% (Primavera & Esteban, 2008). Planting efforts, however, can assist in rehabilitating areas with limited seedling availability, but their success hinges on the ongoing suitability of the coastal environment for mangroves (Lewis, 2005). Mangroves thrive in intertidal regions characterized by fine sediment deposition, the presence of freshwater inflow, and a mild wave climate (Ellison, 1999). If these conditions are altered, leading to a disruption of the natural habitat of these ecosystems, habitat restoration should be prioritized to facilitate mangrove rehabilitation and enhance their long-term survival (Lewis, 2005). Regarding the latter, the disruption of the fine sediment balance within such an ecosystem is a significant yet frequently overlooked process contributing to the limited success of rehabilitation endeavors along eroding coastlines (Winterwerp et al., 2020). Since mangroves rely on a stable sedimentary environment, halting coastal erosion is an essential prerequisite for the rehabilitation of mangroves (Winterwerp et al., 2013; Gijón Mancheño, 2022).

1.2. Problem statement

As a means to enhance the rehabilitation of mangroves in degraded coastal areas suffering from erosion, permeable structures constructed from bamboo and brushwood are designed as a solution and implemented in front of coastlines. These structures are constructed parallel to the coastline with the purpose of reducing wave energy, which promotes the accumulation of sediment behind them and subsequently restores the bed level elevation required for the establishment of vegetation (Winterwerp et al., 2013). In recent years, our scientific understanding of mangrove-mud coast dynamics along eroding coastlines and the role of permeable structures in their rehabilitation has significantly increased. Numerous insights and valuable empirical knowledge on the construction, operation and maintenance of these structures have been acquired from pilot projects, leading to the establishment of success criteria (Winterwerp et al., 2020). Additionally, efforts to quantify the effects of these permeable structures on waves, currents, and morphodynamics, using physical models and field observations, have contributed to establishing criteria for optimal arrangement and usage of structural elements (Gijón Mancheño, 2022). Nevertheless, these structures frequently prove ineffective in the rehabilitation of mangroves, possibly due to the absence of clear design guidelines (Gijón Mancheño, 2022) and a lack of understanding of the influence of design parameters, such as structure length and size of openings in between structures, on the performance of these permeable structures. To enhance the future designs and performance of these permeable structures to ensure successful mangrove rehabilitation, it is, first of all, essential to increase understanding of the influence of design parameters on the performance of these structures, and to establish design tools and guidelines. Secondly, the design process of these structures should encompass not just the physical aspects but also take into account mangrove ecology (Winterwerp et al., 2020). Thirdly, following the Building with Nature approach, studying the natural system of a specific coastal area can provide valuable insights for structure design (De Vries et al., 2021) and should be thoroughly explored during the design process of any project (Gijón Mancheño, 2022).

1.3. Research objective

As acknowledged in the work of Gijón Mancheño (2022), there is a demand for well-defined design guidelines for the successful establishment of mangrove habitat rehabilitation through permeable structures. These design guidelines should encompass both physical and ecological aspects, and, following the Building with Nature approach, should commence with a comprehensive examination of the natural system (De Vries et al., 2021). Additionally, there is a need to integrate the currently existing scientific knowledge with the lessons learned from pilot projects, as well as to increase understanding of the influence of design parameters on the performance of permeable structures. The primary goal of this research, therefore, is to develop an integrated design approach (design guidelines), which merges scientific knowledge with the lessons learned from pilot projects, for permeable structures aimed at rehabilitating mangrove habitat along eroding coastlines. Additionally, the research aims to enhance understanding of the influence of design parameters on the performance of these permeable structures. To fulfill these research objectives, the following research questions have been formulated:

1. *What are the relevant ecological and engineering variables that must be considered when designing permeable structures aimed at rehabilitating mangroves, and how do these relate to each other, within the context of a conceptual framework that can function as a design tool?*

2. *Within the framework of a Building with Nature design approach, what are the fundamental steps in the design process that, when combined, constitute a design guideline for permeable structures aimed at rehabilitating mangroves?*

3. *What is the influence of various design parameters on the effectiveness of permeable structures in reducing bed shear stress across the sheltered areas behind them?*

1.4. Research approach

To address the research questions and achieve the objectives of this thesis, the research was divided into two main parts. The first part entails an extensive literature review aimed at addressing the first two research questions. The second part comprises a numerical modelling research aimed at addressing the third research question.

Literature study

The first part of the research, the literature study, served a threefold purpose:

- To obtain a comprehensive understanding of the relevant theories essential for the remainder of the research, serving as its foundational basis;

- To facilitate answering the first research question, which involves identifying the relevant ecological and engineering variables, and their interacting processes, in designing permeable structures aimed at rehabilitating mangroves, as well as developing a conceptual framework within this context;

- To facilitate answering the second research question, which involves outlining the fundamental steps within the framework of a Building with Nature design approach for permeable structures aimed at rehabilitating mangroves.

The Building with Nature (BwN) five step design approach, as formulated by van Eekelen and Bouw (2020) and illustrated in Figure 1.2, was used as the foundational framework for developing the design guideline. The Building with Nature five-step design approach is an innovative design approach aimed at developing nature-based solutions to address societal needs for water-related infrastructure, such as flood protection, sustainable port development and ecosystem restoration. It aims to use the power of nature to benefit society, economy and the environment (EcoShape, 2021). However, due to constraints on time and the scope of this study, this study primarily focused on elaborating on the first two steps of this approach concerning the development of the design guideline.

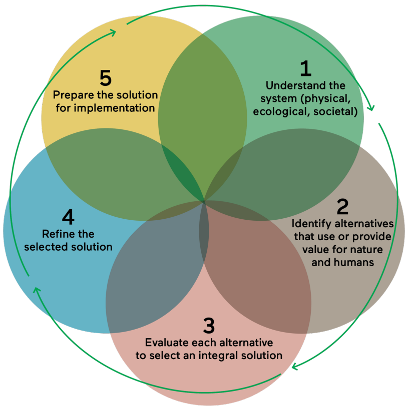


Figure 1.2: Building with Nature five step design approach (EcoShape, 2021)

Modelling research

To facilitate answering the third research question, a numerical, process-based model was employed within the context of a specific case study. The study area for this case study encompasses the coastal system of Demak, Indonesia. Previously, Bisschop (2023) established a morphostatic model in Delft3D-4 to examine relevant processes within the Demak coastal region. Building upon this groundwork, Thillaigovindarasu (2023) configured a nested model within the existing framework to investigate the influence of coastal structures on waves and currents in the area. The present study utilized and expanded upon the nested model framework initially developed by Thillaigovindarasu (2023) to investigate the influence of various design parameters on the performance of permeable structures by simulating various scenarios in the Delft3D model. Due to the absence of sufficient data regarding the sediment budget within the coastal system of Demak, and the utilization of a morphostatic model, this study predominantly focuses on assessing the effectiveness of permeable structures in terms of mitigating bed shear stress. This is assumed to provide a reasonable representation of the performance of permeable structures, considering that bed shear stress serves as an indicator of erosion and provides insight into the likelihood of sedimentation.

This modelling research considers four design parameters related to the design of permeable structures and their performance in mitigating bed shear stress. These parameters include structure length, gap width in between sets of structures, the number of rows of structures placed behind each other, and the distance of placement of structures from the coastline, which, within the context of the case study, relates to a mangrove fringe. A schematic representation of these design parameters is depicted in Figure 1.3.

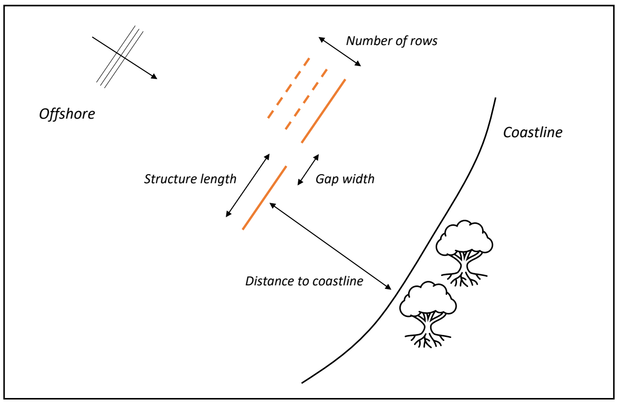


Figure 1.3: Schematic representation of the various design parameters considered in this study (not to scale)

1.5. Thesis outline

This Chapter introduced the research topic, stated the problem, introduced the research objective and questions, and elaborated on the approach used to address these questions as well as to achieve the research objective. Chapter 2 provides relevant literature on the topic of this research, covering the fields of mangrove ecology, mangrove-mud coast dynamics, mangrove rehabilitation, and permeable structures. Chapter 3 describes the study area used for the case study, which is the coastal system of Demak, Indonesia. It elaborates on its characteristics regarding its geographical location, meteorology, hydrodynamics, and morphodynamics. Chapter 4 offers detailed information about the numerical, process-based model employed in this study, including an explanation of the model type, the model set-up, descriptions of the various scenarios simulated within the model, and how the model outputs are analyzed. Chapter 5 expands upon the findings derived from both research components, encompassing both the extensive literature review and the Delft3D modelling research. In Chapter 6, a discussion on the methodology, findings, and some limitations of the research is presented. Finally, in Chapter 7, answers to the research questions are addressed, the research objective is concluded upon, and recommendations for future research are provided.

2 Literature

This chapter encompasses the findings from the extensive literature review covering various fields including mangrove ecology, mangrove-mud coast dynamics, mangrove rehabilitation, and permeable structures.

2.1. Mangrove ecology

Mangrove forests grow along coastlines in tropical and subtropical regions between 32° North and 38° South (Saenger et al., 2019). These ecosystems flourish in low-energy coastal areas within the intertidal zone, which is defined as the region between the high and low tide lines (Moore, 2009; Giri et al., 2010). Furthermore, they can be located along river banks, within deltas, in lagoons, and around tidal inlets (Winterwerp et al., 2016). Mangroves grow in challenging environmental conditions characterized by high salinity and temperature, severe tidal fluctuations, substantial sedimentation rates and muddy anaerobic soils (Giri et al., 2010). Conversely, the presence of freshwater inflow, a stable sedimentary environment and a gentle wave climate are essential requirements for mangrove habitat (Balke et al., 2011). A resilient mangrove ecosystem consists of a wide variety of mangrove species, demonstrating a significant change in the types of species present at a certain location within the ecosystem. This mangrove zonation, which refers to the relative distribution of species across the cross-shore coastal profile, depends on variations in factors influencing the viability of mangroves like salinity, inundation time and sediment availability (Woodroffe, 2003; Spalding, 2010), and varies from one geographic location to another. For instance in Demak, Indonesia, *Avicennia*, usually located closer to the shoreline, serves as pioneer species (first species to colonize bare flats or disturbed habitats), while *Rhizophora*, flourishing higher up on the mud flats, represents climax vegetation (mature and stable vegetation) (Winterwerp et al., 2016).

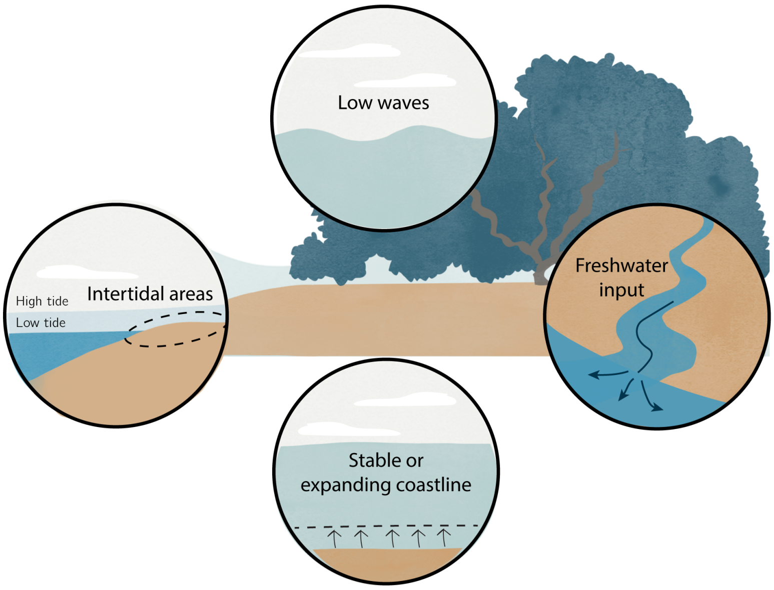


Figure 2.1: Schematic representation of mangrove habitat requirements (Gijón Mancheño, 2022)

Approximately 70 species of mangrove forests exist worldwide. *Avicennia* is the most commonly encountered genus of mangrove pioneer trees (see Osborne and Berjak 1997 for *A. marina* in Africa; Lee et al. 1996, Panapitukkul et al. 1998 for *A. alba* in SE Asia; Marchand et al. 2004, Proisy et al. 2009 for *A. germinans* in South America; Clarke 1993 for *A. marina* in Australia). Its seedlings are characterized by its rapid anchorage, allowing them to withstand hydrodynamic forces from waves and currents within a few days, and grow into young trees (Balke et al., 2011). These mangrove species are often the first to colonize bare tidal flats of tropical regions around the world, making them one of the most successful mangrove colonizers.

The colonization of a new site or mangrove habitat expansion begins with the dispersal and establishment of mangrove seedlings. Mangrove seedlings are commonly referred to as ”propagules”, since they germinate while still being attached to the tree. These propagules are subsequently transported by the movement of water and tides to different areas, where they can establish themselves and form new mangrove trees. This dispersal phenomenon facilitates the expansion of mangrove ecosystems and the colonization of other coastal areas (Moore, 2009). Balke et al. (2011) examined the specific requirements for mangrove seedling establishment and deduced that mangrove habitat expansion in seaward direction only takes place when a series of favourable conditions, associated with these requirements, follow each other, offering a window of opportunity for seedling establishment (Figure 2.2). According to Balke et al. (2011), certain thresholds have to be passed until a mangrove propagule is successfully established and able to grow into a young, reproductive mangrove tree. The initial threshold involves propagule availability (Figure 2.2, panel 0) (Lewis, 2005). Aquatic connectivity to a propagule-rich site is an essential prerequisite for the dispersal and subsequent establishment of propagules. The three consecutive thresholds are: 1) stranded propagules require an inundation-free period to develop long enough roots that can withstand displacement caused by flooding, 2) the roots need to further elongate to endure the forces of waves and currents, preventing the seedlings from being dislodged, and 3) even longer roots are required to survive higher energy events that potentially cause sheet erosion and dislodge the seedlings (Figure 2.2, panel 1-3) (Balke et al., 2011). The fourth threshold involves the challenges of growth that saplings (young trees) need to overcome to grow into mature trees, including predation, disease or other forms of stress that can hinder their growth and development (Van Bijsterveldt et al., 2022).

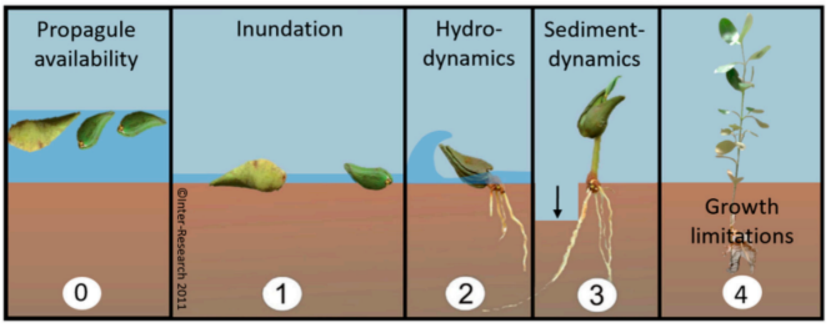


Figure 2.2: Windows of opportunity that propagules must encounter (or thresholds of establishment that propagules should overcome) before they are able to establish themselves at a site (Lewis, 2005; Balke et al., 2011; Van Bijsterveldt et al., 2022)

Each mangrove species, however, has distinct preferences concerning acceptable inundation height and duration (Van Loon et al., 2016), as well as unique threshold values for the other requirements related to successful seedling establishment. These threshold values may also vary under specific circumstances and abiotic conditions. For example, the rate at which a mangrove seedling extends its roots may vary depending on local conditions such as salinity and temperature (Krauss et al., 2008). Moreover, the minimum root length required to resist buoyancy, and subsequently, to withstand hydrodynamic drag forces will vary based on factors such as sediment composition and the local wave conditions. For instance, cohesive muddy sediments can offer greater support to the roots compared to loose sand, in which case shorter roots provide enough stability (Balke et al., 2011). In the context of mangrove rehabilitation, it’s essential to take into account these unique preferences and thresholds of establishment of different mangrove species. This consideration is crucial for ensuring long-term success of rehabilitation efforts (Balke et al., 2011).

2.2. Mangrove-mud coast dynamics

Mangrove-mud coasts are characterized by dynamic processes and naturally experience erosion and accretion. These erosion and accretion processes are caused by tides and waves (Winterwerp et al., 2016), as illustrated in Figure 2.3. The deposition of sediments in a mangrove-mudflat system is mainly controlled by tidal processes, the entrapment of sediment by mangrove roots, and the compaction of recently accumulated sediments. On the other hand, erosion is primarily governed by wave action. Even the smallest, capillary waves have the potential to disturb and erode fine sediments from in between the mangrove roots; and the larger the wave, the larger the amount of sediment that can be eroded. However, larger waves also stir up fines from the foreshore, which are subsequently transported towards the mangrove-mud coast during rising tides, resulting in an onshore sediment flux. Consequently, large waves contribute to both erosion and accretion processes (Winterwerp et al., 2013).

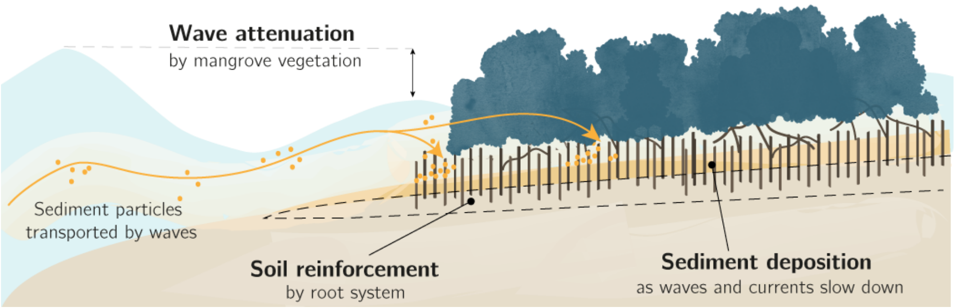


Figure 2.3: Schematic representation of the sedimentation process within a mangrove ecosystem (Gijón Mancheño et al., 2021)

Muddy coastlines often feature cheniers, which are essentially shallow sand ridges appearing on top of the predominantly muddy seabed. Over time, these features can evolve into terrestrial sand ridges within the coastal landscape. The formation and dynamic behavior of cheniers, including their migration, remain widely unexplored. Tas et al. (2020) observed that cheniers can display substantial dynamic variations, even when the hydrodynamic conditions are relatively calm, and are often temporarily present. Cheniers contribute significantly to the stability of mangrove-mud coastlines, primarily because of their distinctive, steeper features, which enable the to effectively absorb substantial amounts of wave energy (Winterwerp et al., 2020). They offer protection to the mangroves located behind them by reducing the incoming wave energy and modifying the local wave conditions. Cheniers are even able to create some windows of opportunity for mangroves by facilitating the accumulation of fine sediments on their landward side and providing protection to young seedlings from wave impacts (Van Bijsterveldt, 2023). Hence, cheniers have a positive impact on mangrove-mud coastlines and may contribute to the expansion of mangrove ecosystems in seaward direction.

Another dynamic feature commonly observed on mud coasts is the presence of migrating mud banks, which consist of thicker or thinner layers of soft, fluid mud. As an example, the Guiana coast in northern South America is characterized by the presence of fluid mud as a fundamental element of its coastal system, while in Indonesia, soft, fluid mud is frequently created in specific areas due to the redistribution and accumulation of eroded coastal sediments. Mud banks are recognized for their capacity to effectively reduce wave energy through viscous dissipation. In the direction of wave attenuation, forces, known as radiation stresses, push the soft, fluid mud in the same direction as the wave propagation. This phenomenon is referred to as ”mud streaming”, and in some coastal areas it stands as one of the primary mechanisms responsible for the transport of fine sediment toward the shore on the lee side of the mud banks (Winterwerp et al., 2020).

The variation in (mean) location of a mangrove-mud coastline cl can be conceptually described with the following formula (Winterwerp et al., 2005):

$$\frac{\mathrm{d}cl}{\mathrm{d}t} = \text{sedimentation rate} - \text{erosion rate} \tag{2.1}$$

Actual coastal accretion or erosion on the long term is thus determined by the net difference between deposition and erosion rates, which is much smaller than the gross deposition or erosion rates. This suggests that even a small difference in gross rates can have a significant effect on the coastal morphology and could turn a mangrove-mud coast into an erosive state (Winterwerp et al., 2016). Various processes responsible for alterations in gross rates leading to extensive coastal retreat in mangrove-mud coastlines have been identified in recent years. The following processes constitute the main causes of extensive coastal retreat of mangrove-mud coasts (Winterwerp et al., 2016):

1. Extensive cutting of mangroves, on a large scale, for purposes such as timber and charcoal production;
2. Infrastructure development like the construction of roads and ports, as well as urban development, frequently have an impact on the hydrology of and/or sediment supply to the coastal system;
3. Subsidence, either natural or caused by groundwater extraction;
4. Transformation into economic land use, such as extensive conversion of mangrove forests into agricultural land or aquaculture ponds.

The amount of sediment available in a coastal system, as well as the dispersion of this sediment, is an essential factor influencing coastal morphology and mangrove ecosystems. For instance if the sediment supply within a coastal system is inadequate to offset the local subsidence rates, the coastline will erode and retreat (Gijón Mancheño, 2022). Various sources of sediment in a coastal system can be distinguished (Winterwerp et al., 2020), including remnants resulting from geological and biological processes, riverine input (local or remote), longshore sediment transport resulting from coastal erosion or riverine input and mobilized fine sediments resulting from coastal erosion. Most of the sediment has originally been brought to coasts by rivers, though their influence at the time scales of coastal erosion is typically limited, as coastal erosion involves process at various time and spatial scales. Changes in the worldwide climate, like increasing storm activity and precipitation, can also affect how sediment is dispersed along the coastline by waves and ocean currents (Alongi, 2008), and largely influences mangrove-mud coast dynamics.

The perseverance of mangrove ecosystems over thousands of decades implies the capability to keep up with relatively high rates of relative sea-level rise resulting from climate change. Mangroves can adapt to rising sea levels by gradually building up sediment levels (vertical accretion), preventing them from becoming submerged and ensuring that the soil remains at an elevation conducive to plant growth (Woodroffe et al., 2016). Changes in the coastal morphology of mangrove-mud coasts thus also depend on the occurrence of relative sea level rise. However, the time scales associated with sea-level rise far exceed the response time of mangrove forests to human-induced interventions that form the main causes of extensive coastal retreat of mangrove-mud coasts.

The erosion of mangrove-mud coastlines caused by an inadequate sediment budget in the system, and subsequent loss of mangrove forests, deepens the coastline and initiates a feedback loop. This feedback loop arises as a result of the unfavorable interplay between sedimentation caused by tides and erosion driven by waves (Winterwerp et al., 2013). Greater water depths allow larger waves to propagate towards the shoreline, leading to further erosion of the bed as larger waves have the ability to erode larger amounts of sediment (Gijón Mancheño, 2022). Gradually, the initially stable, convex-up cross sectional profiles of mud flats then transform into unstable, concave-up profiles (Figure 2.4) (Winterwerp et al., 2013). The same feedback loop holds for the conversion of mangroves into economic land use or for the development of infrastructure (Winterwerp et al., 2013), as illustrated in Figure 2.5.

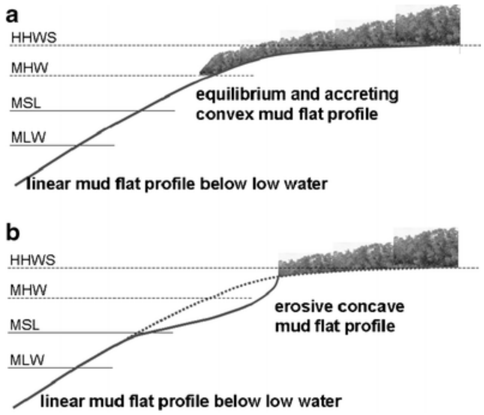


Figure 2.4: Illustration of a stable, accreting convex-up mudflat profile (panel a) and an unstable, eroding concave-up mudflat profile (panel b). The eroding profile results in larger waves closer to the mangrove fringe (Winterwerp et al., 2013)

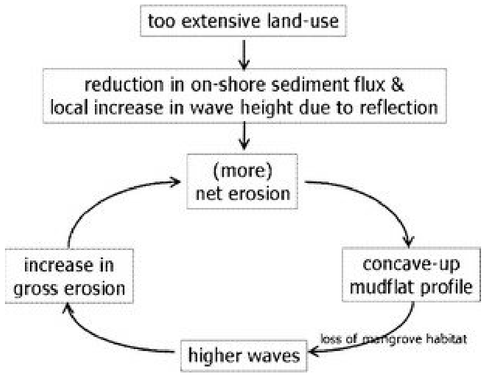


Figure 2.5: Positive feedback loop of coastal erosion of mangrove-mud coasts caused by the conversion of mangroves into economic land use (Winterwerp et al., 2013)

To break this positive feedback loop, it is essential to counteract coastal erosion and mitigate deforestation of mangrove forests, as these forests play a vital role in the retention of sediment and the prevention of erosion along mangrove-mud coastlines (Winterwerp et al., 2013).

2.3. Mangrove rehabilitation

Various types of mangrove rehabilitation methods have been developed and implemented in recent years, such as mangrove restoration by planting, integration into solid structures, and ecological mangrove rehabilitation (EMR). Planting can be effective in revitalizing areas with low seedling availability, but its success depends on the coastal area maintaining the appropriate conditions for mangroves to thrive and regenerate. In general, mangrove rehabilitation initiatives only succeed if the area remains a suitable habitat for mangroves (Lewis, 2005). This involves the ability of the area to provide the favourable conditions, resulting in windows of opportunity (Figure 2.2), that allow mangrove seedlings to establish themselves. Therefore, among the various rehabilitation methods, EMR stands out as the most effective method in establishing productive mangrove ecosystems (López-Portillo et al., 2017). EMR focuses on reducing the establishment thresholds that hinder natural propagule settlement and survival by restoring the favourable conditions necessary for a suitable mangrove habitat, ultimately aiding the natural regeneration of mangroves (Van Bijsterveldt et al., 2022). Building on lessons from rehabilitation attempts worldwide, six ecological principles, along with associated considerations and practical recommendations, have been outlined as essential components to be taken into account during EMR (López-Portillo et al., 2017). These principles are as follows:

1. Understand the autoecology of each mangrove species located at the site, like the patterns of reproduction, propagule dispersal, and successful seedling establishment;

2. Understand the hydrological factors (depth, duration and frequency of tidal inundation) governing the distribution, successful establishment and development of the mangrove species located at the site;
3. Assess the historical context of the area and the underlying cause of coastal erosion and/or mangrove degradation. Examine the modifications of the original mangrove environment that currently hinder natural reestablishment and regeneration;
4. Select suitable mangrove restoration sites through application of steps 1-3. These steps increase the probability of successful rehabilitation by thoroughly investigating the natural system of the site. This step also involves addressing land ownership/use issues crucial for ensuring long-term access to and conservation of the site, and incorporating socio-economic aspects and monitoring requirements;
5. Design the restoration program at the appropriate sites selected in step 4. Restore the hydrology and other environmental conditions, such as the fine sediment balance, to encourage natural recruitment of mangrove propagules and successful plant establishment;
6. If, after following the implementation of steps 1-5, it becomes evident that natural recruitment alone will not meet the objectives of the restoration project, such as achieving the required quantity of successfully established seedlings, stabilization rate, or sapling growth rate, consider the manual planting of propagules or cultivated seedlings.

As highlighted by Lewis (2005) and the EMR principles stated above, the effectiveness of rehabilitation efforts depends on the suitability of a specific site for mangrove regeneration and colonization processes. A site is considered suitable only if it can provide windows of opportunity for successful seedling establishment. This means that a site is only suitable if 1) the inundation frequency is within the acceptable physiological range for the mangrove species located in the area or the target mangrove species to be rehabilitated (Lewis, 2005), 2) the phase of the tidal cycle regularly facilitates propagule settlement and anchorage, and 3) the sediment is compact enough to minimize mixing and prevent heavy sheet erosion (Balke et al., 2011). If one of these conditions is altered, leading to a disruption of the natural habitat of mangrove ecosystems, habitat restoration should be prioritized to facilitate mangrove rehabilitation and enhance its long-term survival (Lewis, 2005). This often entails restoring the hydrological patterns and the sediment balance to maintain the appropriate soil elevation and propagule availability required for successful seedling establishment (Winterwerp et al., 2016). Identifying the cause(s) behind mangrove loss is thus the initial step in the rehabilitation process (Lewis, 2005; López-Portillo et al., 2017). Subsequently, the most suitable technique for mangrove habitat restoration at a site can be identified and implemented. Figure 2.6 provides an overview of potential techniques for ecologically restoring mangrove habitat to successfully rehabilitate mangroves at a certain site, depending on the underlying cause of mangrove loss.

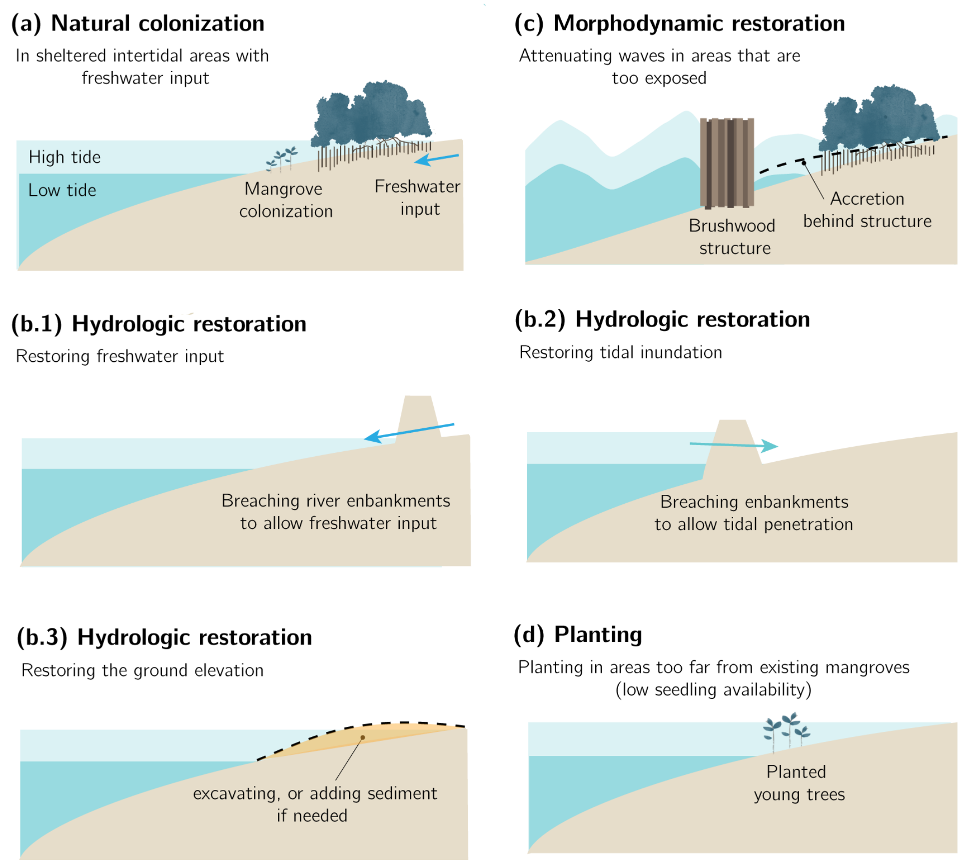


Figure 2.6: Schematic representation of various mangrove habitat restoration techniques (Gijón Mancheño et al., 2021)

The required restoration technique at a certain site thus depends on the underlying cause of mangrove degradation or absence, as illustrated in Figure 2.6 (Gijón Mancheño et al., 2021). This research addresses the rehabilitation of mangroves in degraded coastal areas suffering from erosion, and subsequent mangrove degradation, that require morphodynamic restoration. These areas lack the required bed level elevation to provide windows of opportunity for successful seedling establishment, and thus lack the favourable conditions for natural mangrove regeneration. This cause of mangrove degradation asks for morphodynamic restoration as the sediment balance in the system must be restored to halt coastal erosion and promote coastal accretion. This restoration technique involves modifying the sediment balance by placing permeable structures parallel to the coastline to dampen incoming waves, and to facilitate sediment deposition behind these structures. Consequently, this raises the bed level elevation and restores the bed level elevation required for mangrove seedling establishment. Winterwerp et al. (2013) proposed a strategy for rehabilitating mangrove habitat along eroding mangrove-mud coasts that is based on creating the right biophysical conditions required for successful mangrove rehabilitation and focuses on morphodynamic restoration. This strategy contains the following aspects:

- Restore the onshore fine sediment flux by recovering the intertidal zone. If human interventions have transformed a site into a subtidal area, take measures to restore the conditions and return the area to an intertidal zone;
- Enhance trapping of fine sediments on the mudflat in a natural way, for instance by constructing permeable structures (made of locally available materials such as brushwood, bamboo poles and/or flexible twigs) in the intertidal zone, and digging ditches to improve drainage and enhance seedling establishment;
- Reduce the incoming wave heights;
- If disturbed, restore the hydrological conditions, for instance by rehabilitating creeks to ensure sufficient freshwater flow towards the mangroves;

- In areas where natural propagule availability and supply is limited, plant the appropriate mangrove species at suitable locations (above MHW) and during the appropriate time period, i.e. within ”the windows of opportunity”.

2.4. Permeable structures

The purpose of permeable structures is thus to stop coastal erosion, stabilize the coastline, and to create the required conditions for mangrove regeneration and recolonization (Wilms et al., 2021). However, the effectiveness of constructing permeable structures along a specific eroding coastline depends on the underlying cause of coastal erosion in that particular area. For instance, if subsidence rates exceed the maximum sedimentation rate that can be facilitated given the available sediment in the system, the presence of permeable structures will not be able to stop coastline retreat and restore mangrove habitat on the long term. permeable structures cannot address structural sediment losses, but are designed to redistribute the sediment in the system, thereby modifying the local sediment balance between erosive and accretive processes. Sediment availability in the system thus also largely affects the effectiveness of permeable structures, and the presence of a sufficient suspended sediment budget is a prerequisite for the successful functioning of permeable structures. Assessing the performance of a certain design to promote coastal accretion and restore mangrove habitat thus involves evaluating the impact of the structure on the local sediment balance and thus on the changes in the landscape profile. This entails assessing various morphodynamic processes and simulating the morphodynamic response of a coastline to the constructed permeable structures using a morphodynamic model, which is emphasized as a vital stage in the design process of permeable structures by Gijón Mancheño (2022).

2.4.1. Function

permeable structures are designed to create sheltered areas with reduced flow velocities, turbidity and wave impact, thereby facilitating the deposition of suspended sediments, as illustrated in Figure 2.7. Inside these sheltered areas, during high tide, fine sediments can settle and deposit and are not resuspended by waves as the permeable structures mitigate the incoming wave energy. This prevents the sediment from being transported seawards during the next tidal cycle, resulting in a net onshore sediment flux (Wilms et al., 2021). Once the sedimentation rate exceeds the erosion rate, the bed level rises and can be restored to the level that ensures an inundation-free period, meeting one of the thresholds for successful mangrove seedling establishment (Figure 2.2, panel 1). In addition, the sheltered areas formed behind the permeable structures further promote mangrove regeneration as they are characterized by reduced wave and current forces, preventing the mangrove saplings from being dislodged. This process meets another threshold of establishment (Figure 2.2, panel 2). In this way, permeable structures aid in restoring the conditions required to provide windows of opportunity for mangrove seedling establishment (Wilms et al., 2021).

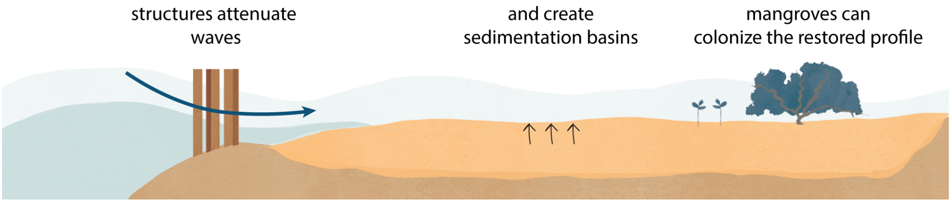


Figure 2.7: Schematic representation of the functioning of permeable structures (Gijón Mancheño, 2022)

Permeable structures generate resistance (drag) forces that hinder incoming currents (Nepf, 1999), causing them to deflect towards areas that experience less resistance. With respect to waves, permeable structures cause incoming waves to reflect at the front of the structures, and dissipate wave energy as they propagate through them (Winterwerp et al., 2013). The amount of wave dissipation caused by permeable structures is determined by the drag forces acting on the structures, which are often expressed using an empirical bulk drag coefficient. The value of this coefficient varies with the structure's geometric characteristics (surface roughness, cross-sectional shape, height relative to water depth), and with the type of flow, typically classified as either viscous or turbulent (Gijón Mancheño, 2022). The performance of permeable structures is thus predominantly controlled by the range of adjustable factors within a given design (design variables), that collectively result in a specific level of wave dissipation and the creation of sheltered areas characterized by reduced flow velocity and turbulence.

2.4.2. Design

Various structural designs of permeable structures have been implemented in pilot projects around the world, usually constructed from bamboo and brushwood (Winterwerp et al., 2013). Typically the structures are composed of two or more rows of bamboo poles perpendicular to the direction of wave propagation, frequently accompanied by horizontal poles or filled with brushwood (Gijón Mancheño et al., 2021). The employment of permeable structures may be considered low-tech, but it does require a sophisticated design founded on a comprehensive understanding of biophysical processes and mangrove ecology. It also requires continuous monitoring and an adaptive management and maintenance strategy (learning by doing) (Wilms et al., 2021).

Designing permeable structures as a solution for a specific location requires addressing a spatial design, a structural design of the permeable structures at an individual level, and considerations of socio-economic aspects, such as stakeholder mapping and continuous engagement. To ensure the effectiveness of designing and deploying permeable structures, they should be integrated into a comprehensive coastal zone management plan, and must be supported by policy and planning authorities. The active involvement of local governance entities is pivotal in guaranteeing successful implementation. Moreover, community engagement is imperative across the entire project cycle, encompassing training, preparation, planning, procurement, construction, monitoring, and maintenance (Wilms et al., 2021).

At both landscape level (spatial design) and individual level (structural design), the design of permeable structures needs to fulfil several functional requirements as well as structural requirements regarding stability. Functional requirements are primarily linked to the specific target mangrove species and target coastline, which, in turn, are related to the purpose for which mangroves need to be rehabilitated. Structural requirements are more closely associated with the timescale at which mangroves need to be rehabilitated and the intended lifespan of the structures. These, in turn, are also related to the purpose for which mangrove habitat needs to be restored.

Spatial design

At a landscape level, permeable structures should restore the natural sediment balance by creating conditions that promote sedimentation, and ensure that more sediment is deposited on the coast than is eroded. When designing permeable structures at a landscape level, factors such as the offshore bathymetry, morphodynamics, hydrology and long-time development of the coastline should be taken into account and mapped out, as they influence the positioning of the structures relative to the coastline and their spatial configuration.

Generally, permeable structures should be oriented perpendicular to the direction of the incoming wave propagation. The distance from the shoreline where the permeable structures should be constructed is determined by the desired location of the mangrove-mud coastline, also referred to as the target coastline, and depends on the local bathymetry, morphodynamics and hydrology, with the tidal range being the most influential. When multiple adjacent structures are required, the width of the gap between two structures is dependent on the tidal prism and the prevailing wave conditions. The gap's dimensions should be able to facilitate unrestricted tidal flow behind the permeable structure, while simultaneously preventing waves from entering and stirring up the sediment behind it. Constructing multiple consecutive rows of permeable structures at once is discouraged due to sediment source limitations within the coastal zone. The sediment may quickly settle behind the initial structure, leading to potential waterlogging and preventing sediment transport to the rear structures, and subsequently towards the coastline (Wilms et al., 2021).

Structural design

At an individual level, the following functional and structural requirements must be considered (Wilms et al., 2021):

- The structures should effectively dissipate wave energy so that the significant wave height decreases as waves pass through them, and create sheltered areas behind them with reduced orbital velocities and turbulence;
- The permeability of the structures should be sufficient to allow suspended sediments to flow through, thereby increasing the amount of sediment entering the sheltered area, promoting sediment settlement, accumulation and consolidation;
- The wave reflection caused by the structures should be limited so that erosion at the base of the structure (scour) is avoided and structural collapse is prevented;
- The structures should be robust enough to stay in place for a period at least as long as the sum of the estimated sediment accretion rate (2 to 5 years) and the rate of mangrove recovery (3 to 5 years), to allow sufficient time for the mangroves to regenerate and recover.

The core of the structural design process lies in determining the structural configuration, and in determining the materials and dimensions for each individual component within that specific configuration. The primary components of permeable structures comprise vertical poles, fill material, horizontal beams, and wires and/or nets (Wilms et al., 2021). A common practice consists of a combination of vertical bamboo poles and a filling of brushwood. These structures, however, require replacement of their brushwood filling once or twice per year, due to its rapid degradation under wave action. Permeable structures constructed solely from bamboo poles (solely vertical poles or in combination with horizontal beams) represent alternative designs that demand lower maintenance efforts (Gijón Mancheño, 2022).

Stability

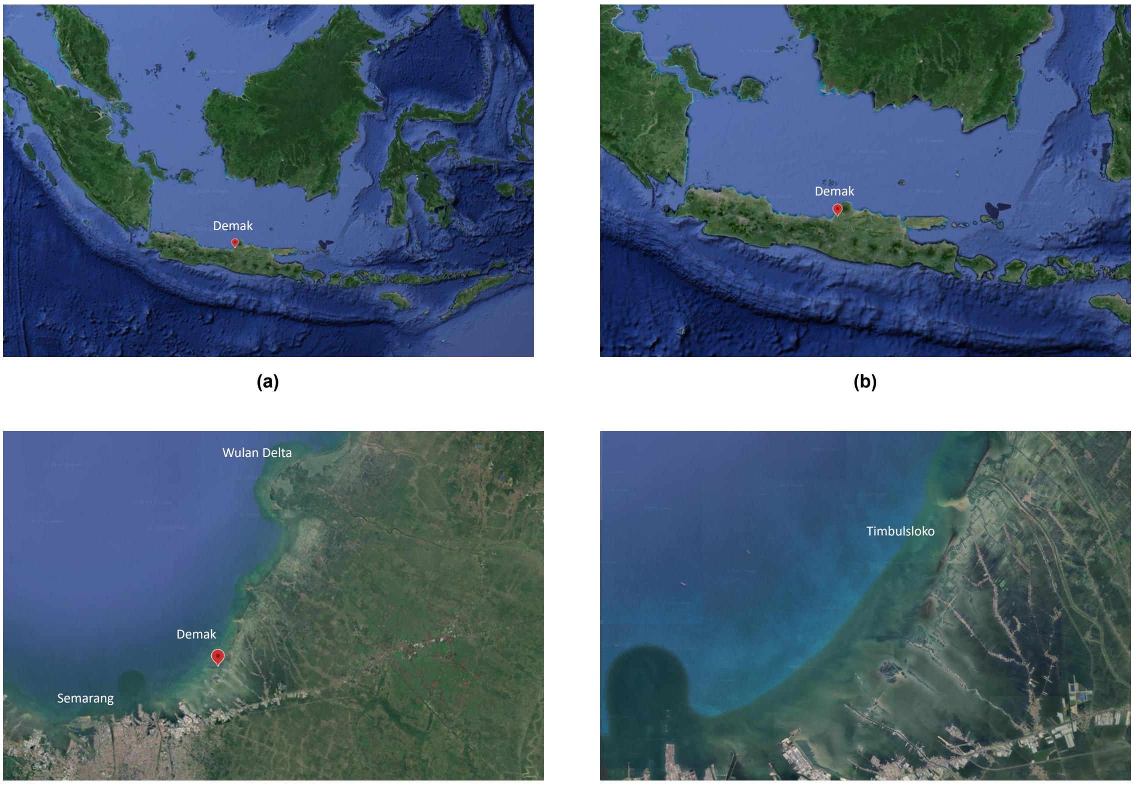
The design of permeable structures, thus, involves considering various factors to ensure their stability as well. These factors include structural stability, susceptibility to scouring, the risk of tipping over, and the potential threat of shipworm, which can weaken submerged materials over time (Winterwerp et al., 2020). Structures built in deeper waters are particularly vulnerable to shipworm damage, highlighting the importance of addressing this issue in design considerations (Winterwerp et al., 2020). Measures such as wrapping natural poles with protective materials and regularly refilling brushwood structures could provide solutions to mitigate degradation and maintain effectiveness (Wilms et al., 2021). Moreover, as submerged structures may face decay over time, an effective monitoring and adaptive maintenance strategy is required in order to ensure the long-term functionality and resilience of these permeable structures. Adaptive management involves conducting field measurements, modeling, data analyses, evaluation, and, subsequently, design optimization (Winterwerp et al., 2020). Overall, integrating considerations concerning structural stability into the design process is crucial for ensuring the long-term functionality and resilience of these permeable structures.

3 Study area

This chapter describes the characteristics of the area of the case study: the Demak coastal system in Indonesia. It provides details about its geographical location, site characteristics such as meteorology, hydrodynamics, and morphodynamics. Additionally, it delves into the severe coastal erosion that the region is experiencing.

3.1. Geographical location

The study area of this research is the Demak coastal system, as depicted in Figure 3.1, where previous research and a pilot project on the application of temporary permeable structures to rehabilitate mangroves have been conducted (see Ecoshape, 2015; Gijón Mancheño, 2022; Tas, 2022; Van Bijsterveldt, 2023). Demak, located in Central Java, Indonesia, lies along the northwest coast of the Java Sea, bordered by Semarang to the southwest and the Wulan Delta to the northeast. The coastal region of Demak forms part of the Java Sea, enclosed by Kalimantan to the north and Sumatra to the west, resulting in a shallow, protected basin. With its equatorial position, the area experiences a tropical monsoon climate (Tas et al., 2020). Additionally, the region experiences significant land subsidence and mangrove depletion, which has resulted in coastal erosion rates of up to 215 meters per year (Luijendijk et al., 2018).



(a) (b)

(c) (d)

Figure 3.1: Geographical location of the study area at various spatial scales: a) the Indonesian archipelago, b) the island of Java, c) the coastal system of Demak, and d) the intertidal basins of Timbulsloko

3.2. Site characteristics

This section provides detailed information on the meteorological, hydrodynamic, and morphodynamic characteristics of the Demak coastal area.

3.2.1. Meteorology

The study area, situated within the tropics, experiences a seasonally reversing monsoon climate. Within this climate two distinct seasons can be identified: the northwest monsoon (NW), which occurs from December to March, and the southeast monsoon (SE), which spans from April to October. The northwest monsoon prevails from October to April, bringing strong westerly winds and increased rainfall over the Java Sea, marking the wet season, with peak intensity typically observed from December to February. In April, the equatorial trough moves upwards, bringing southerly winds and marking the start of the dry season. By July and August, the southeast monsoon is fully formed, characterized by calm weather (Tas, 2022). These prevailing wind directions are shown in Figure 3.2.

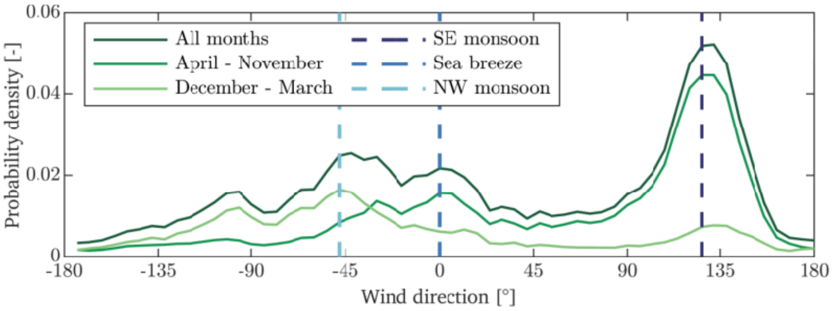


Figure 3.2: Probability density function of wind direction throughout the year (dark green), and the two monsoon seasons (NW and SE) individually (lighter green lines). Blue dashed lines indicate the primary directions of the two monsoon seasons (NW and SE) and the direction of the sea breeze peak (Tas, 2022)

3.2.2. Hydrodynamics

Waves

The coastal wave climate near Demak is characterized by seasonal changes, largely influenced by the monsoons. During the SE monsoon, gentle waves prevail due to offshore winds, whereas the NW monsoon brings stronger waves from the NW direction, often reaching heights of up to 2.5 meters with a period of approximately 5.5 seconds (Smits, 2016). Near the Demak coastline, average wave heights of 0.5 meters have been recorded (Deltares, 2020).

River discharge

The primary source of freshwater discharge in the study area originates from the Wulan River. Seasonal rainfall patterns in the region serve as a key indicator for the Wulan River's discharge distribution. Records from the Klambu Station, located 48.63 km south of the river mouth, indicate a maximum discharge of 350 m^3/s into the Wulan River. During the wet season (October to May), the average discharge from Klambu Station is 138.18 m^3/s, whereas it reduces to 31.6 m^3/s during the dry season (Fadlillah et al., 2019). However, due to its distance from the river mouth, Klambu Station does not accurately provide the distribution of discharge along the coastline. A measurement station closer to the coast, recorded an average discharge of 132.95 m^3/s during the wet season and 63.14 m^3/s during the dry season in 2016. The discharge from the Wulan River also carries sediment, making a significant contribution to the sedimentation of the local coastline. However, reports from local communities suggest a decline in sediment supply from the river due to agricultural and urban development upstream, contributing to a reduction in sediment budget and shoreline retreat in the area (Bisschop, 2023).

Tide

The tidal regime at Demak is characterized by a prominent diurnal component along with a smaller semi-diurnal component. Measurements from a tidal station in Semarang City indicate that under normal conditions, tidal ranges range from 0.4 to 0.6 meters, but during spring tide, this range can extend up to 1 meter. According to the form factor of 1.72, as identified by Tas (2022), the tide demonstrates a mixed diurnal pattern, resulting in an irregular periodicity (Smits, 2016) and classifying it as micro-tidal. Near the coastline, the tidal currents near the coastline predominantly flow perpendicular to the shore due to shallow water depths (Tas, 2022). Water levels measured at the Semarang IHO station throughout 2010 are depicted in Figure 3.3.

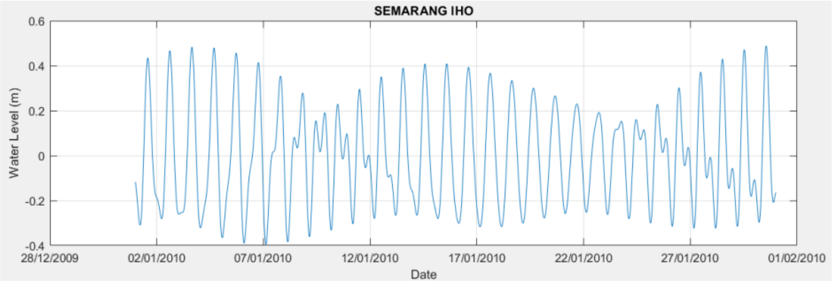


Figure 3.3: Water levels recorded at the Semarang IHO station, retrieved from Delft DashBoard (Bisschop, 2023)

Currents

The broader oceanic circulation near Demak is largely influenced by large-scale wind patterns and undergoes seasonal variations driven by the monsoon (Smits, 2016). During the NW monsoon and transitional months (October to April), currents are directed eastward along the coast, accompanied by significant freshwater discharge from rainfall, inducing gravitational circulation that retains fine sediments near the shore. Conversely, the SE monsoon drives residual currents westward, resulting in minimal sediment transport near the coast (Bisschop, 2023). Nearshore currents flow primarily from northeast to southwest but have minimal impact on sediment transport due to their limited strength. Wave-induced currents are negligible due to the mild foreshore slopes leading to low wave energy (Smits, 2016).

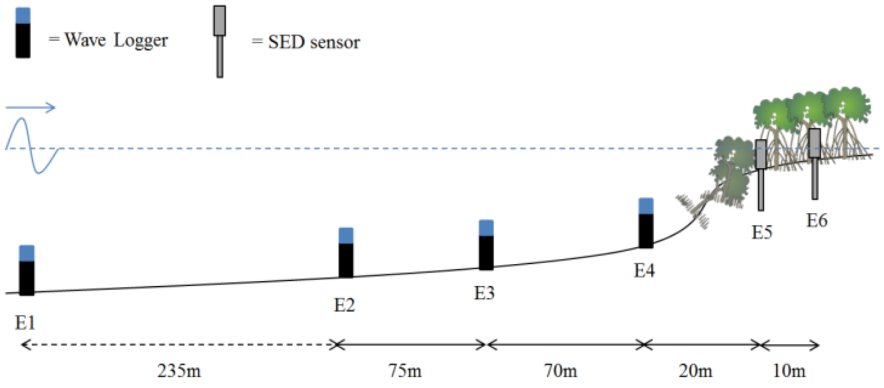
3.2.3. Morphodynamics

Bathymetry

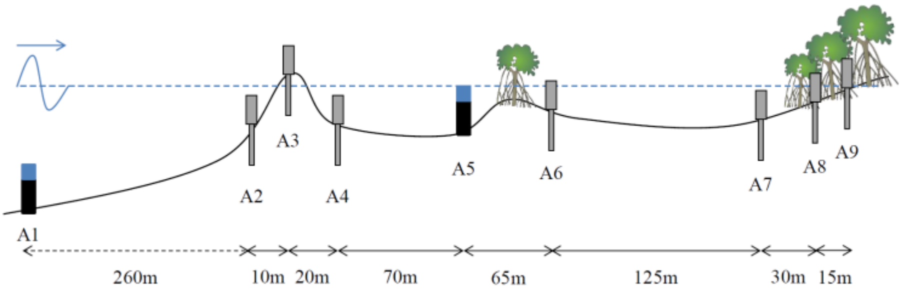
The Demak coastal zone exhibits very shallow characteristics, with slopes of about 1:1000 extending for about 1 km (Smits, 2016), typical for mud-mangrove coasts (Winterwerp et al., 2020). Beyond this point, the slope increases to around 1:500 (Smits, 2016). At locations experiencing erosion, steeper concave-shaped foreshores with slopes of approximately 1:600 have been observed (Deltares, 2020). Sediment deposition at the mouth of the Wulan River can result in the formation of cheniers, which are narrow sand lenses, under wave action (Tas et al., 2020). These cheniers may influence wave breaking patterns, potentially leading to sedimentation and stabilization of eroding coastlines (Tas, 2022).

Sediment characteristics

The sediment composition in the area is mainly muddy (80%) with some sandy (20%) content, exhibiting spatial variations (BioManCo, 2018). A research conducted by Van Domburg (2018) provided an analysis of sediment grain sizes along two distinct transects in the Demak coastal region, one experiencing accretion and the other undergoing erosion, which is illustrated in Figure 3.4. The accreting transect is marked by the presence of a chenier and vegetation between the chenier and coastline. Grain size data for both transects are presented in Table 3.1. The analysis reveals that the eroding transect contains coarser sediment (D_{50} of 24 μm) compared to the finer sediment (D_{50} of 12 μm) in the accreting transect, except for location A3 at the chenier. Smaller grain sizes are observed near the shoreline in both transects, transitioning to a muddier composition.



(a) Eroding transect



(b) Accreting transect

Figure 3.4: Schematic representation of experimental set-up (Van Domburg, 2018)

Location	D_{50} [μm]	Location	D_{50} [μm]
A1	13.94	E1	24.54
A2	12.47	E2	32.95
A3	145.22	E3	57.61
A5	10.68	E4	9.95
A6	27.05	E5	7.00
A7	7.35	E6	9.59
A8	7.28		
A9	6.42		

Table 3.1: Grain size data along both transects

According to the analysis of Van Domburg (2018), the chenier in the accreting transect primarily consists of sandy sediment (D_{50} of 145 μm), while on the other hand Tas (2022) suggests that the bed mainly comprises mud with a minor fraction of sand, featuring a D_{50} of 235 μm at the cheniers. Furthermore, at the locations in the coastal region where permeable structures have been deployed as part of the pilot project, positioned approximately 100 to 200 meters from the mangrove fringe, sediment sizes of around D_{50} 57.61 μm are detected. Furthermore, laboratory experiments conducted by BioManCo (2018) showed that muddy sediments in the area exhibit a dry bulk density of 585 kg/m^3, indicative of light sandy mud. This type of sediment has a critical bed shear stress for erosion ranging from 0.15 to 0.25 N/m^2. Conversely, a sand sample collected from the same area displays a dry bulk density of 1080 kg/m^3, resulting in a critical bed shear stress falling between 0.4 and 1.5 N/m^2 (Mitchener & Torfs, 1996).

3.2.4. Mangroves

Five mangrove species are identified in the Demak area, with *Avicennia marina* (grey or white mangroves) and *Rhizophora mucronata* (red mangroves) dominating the mangrove population (Ecoshape, 2015). *Avicennia marina* pioneers intertidal regions above MSL, while *Rhizophora mucronata* is primarily found along river banks (Verschure, 2012). (BioManCo, 2018) found that *Avicennia marina* primarily establishes during the southeast monsoon period, between April and August, while the pioneer mangrove species, *Avicennia alba*, predominantly establishes during the northwest monsoon period. Furthermore, a research conducted by Van Bijsterveldt et al. (2022) discovered that *Rhizophora mucronata* exhibits higher survival rates (67%) but slower growth, whereas *Avicennia marina* shows lower survival (21%) but significantly faster growth.

3.3. Coastal erosion

The Demak coastal region, including Semarang City, is experiencing substantial coastal erosion. Prasetyo et al. (2019) reported increasing absolute sea levels, contributing to significant coastline retreat in recent years. However, primary contributors to this coastal erosion are local land subsidence resulting from groundwater extraction, natural consolidation, and construction activities. Over the years, various regions have experienced subsidence at annual rates ranging from 20 to 200 cm (Marfai & King, 2007). In addition, human interventions, such as mangrove forest removal for shrimp ponds, have led to a disruption of the sediment budget within the coastal system, exacerbating this coastal erosion (Ecoshape, 2015; Winterwerp et al., 2014).

Figure 3.5: Coastal erosion at Demak measured from 2003 to 2013 (Winterwerp et al., 2014)

Coastal erosion and the increased flooding risks in the region have displaced thousands of people, causing significant economic losses (Winterwerp et al., 2016). Mitigation efforts, including dikes and sea walls, have been implemented but have proven ineffective and, in some cases, worsened erosion by blocking sediment transport (Marfai, 2011; Winterwerp et al., 2013). Mangrove planting initiatives in the area, aimed at halting erosion, have also been unsuccessful due to inadequate sediment conditions (Marfai, 2011). Despite these efforts, erosion remains a significant issue, which is exacerbated during the wet season when strong winds and high waves further degrade the coastline (Ecoshape, 2015).

4 Modelling

This chapter provides detailed information about the numerical, process-based model employed in this study. It includes an explanation of the model type employed, the model set-up, and descriptions of the various scenarios simulated within the model. Furthermore, it expands on the method of analyzing the model outputs.

4.1. Delft3D

Delft3D serves as a 2DH or 3D computer software for simulating flows, sediment transports, waves, water quality, morphological developments and ecology in river, estuarine, or coastal environments. It accommodates simulations across various timescales, from short-term storm impacts to long-term system dynamics (Deltares, 2023). Different versions of the Delft3D software suite are available, including Delft3D-4 and Delft3D-FM. Delft3D-4 employs a structured grid for numerical simulation of system processes. A structured grid is characterized by orderly grid cells arranged in a three-dimensional array, facilitating easy identification and labeling of individual elements. In contrast, an unstructured grid allows grid cells to be connected in various configurations, which is the case in the Delft3D-FM suite. In this study the Delft3D-4 suite is utilized.

Comprising multiple modules interconnected via a mutual interface, Delft3D's core components include the FLOW and WAVE modules, which simulate flow and wave generation and propagation, respectively. The WAVE module employs the SWAN (Simulating Waves Nearshore) model to replicate the development of irregular, short-crested waves generated by wind (Deltares, 2023). The FLOW module is a multi-dimensional (2DH or 3D) hydrodynamic and transport simulation tool, calculating non-steady flow and transport phenomena driven by tidal and meteorological forces. This module is also capable of simulating flows driven by variations in salinity and temperature, integrating factors such as river discharges and heat flux models. Additionally, it can compute sediment transportation and consequent changes in morphology. Both waves and currents can be incorporated as driving forces within this module (Online Delft3D-WAVE coupling) and the module offers a selection of various transport formulae (Deltares, 2023). The dynamic feedback between the WAVE and FLOW modules is crucial as it enables the flows and waves to adapt to the local bathymetry. Nonetheless, this study excludes morphological alterations to maintain computational efficiency, resulting in fixed bed levels over time. Thus, a morphostatic model within the Delft3D-4 suite is utilized.

4.2. Model set-up

The nested model, as set up by Thillaigovindarasu (2023), conducted simulations in uncoupled mode, wherein the FLOW and WAVE modules are not coupled, and thus, the influence of waves on the flow and vice versa is not considered. However, by incorporating the interaction between waves and flow, a more accurate representation of the hydrodynamic behavior of a coastal system can be achieved. Therefore, a coupled version of the model is configured to account for the interaction between waves and currents. The following sections provide additional information about the model set-up.

4.2.1. Domain

The domain of the model consists of two grids: one covering a larger-scale area across the Demak coastal system with lower resolution, and another smaller grid with higher resolution nested within the larger model, focusing on a region closer to the coast where permeable structures have been implemented to rehabilitate mangroves. The larger model domain, outlined by Bisschop (2023), spans from the Wulan Delta in the north to Semarang City in the south, covering an area of 50 by 23 kilometers at approximately -6.9 degrees latitude. Grid cells within this model are set at dimensions of 333 meters by 333 meters. Vertically, the model employs a σ-grid with 14 layers, each layer progressively thicker towards the surface and bottom, ranging from 2% thickness at both ends. This configuration results in layer thicknesses of [2, 3, 4, 6, 8, 11, 16, 16, 11, 8, 6, 4, 3, 2]% respectively. This variation in layer thickness is designed to accurately capture the logarithmic velocity profile across the horizontal plane and accommodate wind effects, which is the significant driving force of flow. The nested model domain, outlined by Thillaigovindarasu (2023), encompasses the intertidal region adjacent to Timbulsko, covering an area of 10 by 10 kilometers. The grid cells within this model exhibit variable sizes, with cells initially set at 100 by 100 meters around the periphery, gradually refining to 33 by 33 meters within the area of interest - around the vicinity of the permeable structures - to provide enhanced resolution of local processes. Similar to the larger model, the nested model utilizes a vertical σ-grid comprising 14 layers.

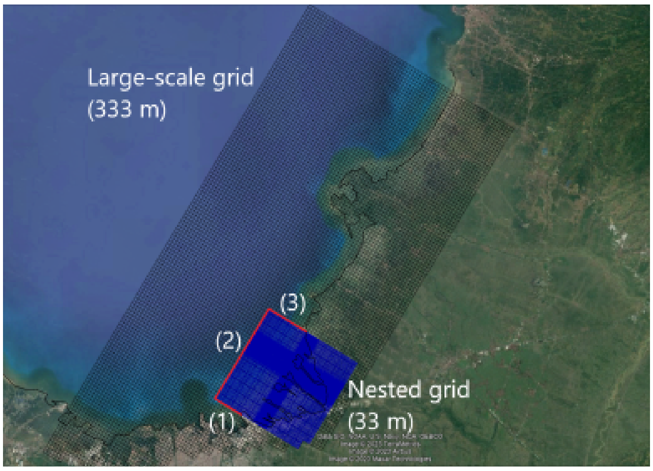


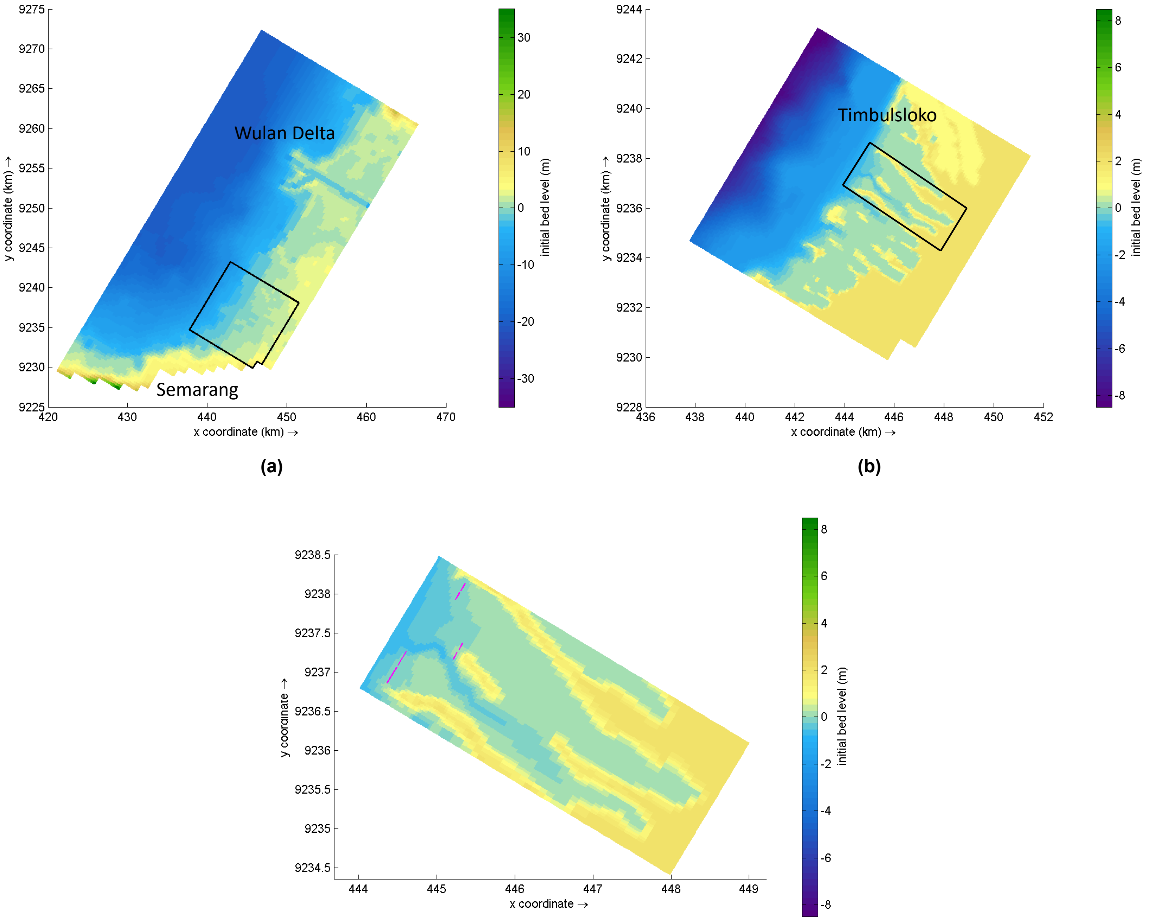
Figure 4.1: Domains of the larger-scale model as well as the nested model grid, with the boundaries of the nested model 1) the South boundary, 2) the offshore boundary, and 3) the North boundary (Thillaigovindarasu, 2023)

4.2.2. Time frame

Permeable structures are designed to facilitate sedimentation and elevate the bed level to the required elevation for mangrove rehabilitation. Even under extreme conditions, these structures must be able to maintain bed shear stresses below the threshold value for erosion to prevent sediment from being stirred up and potentially being transported. This study, therefore, focuses on the performance of permeable structures under extreme conditions. Furthermore, coupling the WAVE and FLOW modules within the updated configuration of the model increases computational load. Thus, to maintain reasonable computational times, careful selection of the time frame to simulate over is essential. Given that the coastal system of Demak exhibits an episodic morphodynamic response, and considering the study's focus on evaluating the performance of permeable structures under extreme conditions, the simulation period is selected to encompass a single representative tidal cycle during the stormy season. The chosen representative tidal cycle falls within the month of January, coinciding with the dominance of the NW monsoon (wet season) (Tas, 2022). This monsoon period is marked by onshore winds and increased wave activity, leading to increased bed shear stresses. A timestep of 1.5 minutes is selected for the overall model, while a finer timestep of 0.5 minutes is used for the nested model due to the Courant limitation.

4.2.3. Bathymetry

The underwater topography for the larger grid model was initially sourced from Bisschop (2023), based on the General Bathymetric Chart of the Oceans (GEBCO'08) dataset obtained from the Delft dashboard. Corrections and extensions were made as necessary, incorporating additional control contours and sounding point data provided by (Thillaigovindarasu, 2023). For the nested model, the bathymetry was constructed using a combination of the GEBCO dataset for offshore areas and field measurements conducted by Deltares (2020) in the intertidal region. To ensure seamless integration of the datasets, QUICKIN was utilized to smooth any abrupt transitions resulting from their combination (Thillaigovindarasu, 2023). The bathymetry of the larger grid model is shown in Figure 4.2a, and that of the nested model is shown in Figure 4.2b. The bathymetry in the vicinity of the implemented structures is depicted in Figure 4.2c.



(a)

(b)

(c)

Figure 4.2: Bathymetry of a) the larger-scale model, b) the nested model, and c) the area surrounding the permeable structures

4.2.4. River discharge

The Wulan river experiences discharge fluctuations throughout the year, which are significantly between the wet season and dry season. In 2016, near the river mouth, the mean discharge during the wet season was recorded at 132.96 m^3/s (Bisschop, 2023). This value is utilized as a boundary condition for the river and is incorporated into the model, as the simulation period encompasses a tidal cycle within the month of January.

4.2.5. Tide

The tidal regime in the study area exhibits a mixed nature, primarily diurnal with a minor semi-diurnal component, influenced by spring-neap variations (Tas, 2022). The tidal signal is imposed as the open boundary condition in the overall model, incorporating astronomic components. These components are sourced from a global tidal model and divided into smaller sections to address tidal phase lag (Bisschop, 2023). In the nested model, tidal boundary conditions are applied as a time-series of water levels derived from the overall model's results (Thillaigovindarasu, 2023).

4.2.6. Currents

The nested model utilizes currents from each of the 14 vertical layers of the overall model as its boundary conditions. This approach allows for increased control over the magnitude and direction of currents near the boundaries (Thillaigovindarasu, 2023).

4.2.7. Wind

In the Demak region, winds vary in direction and strength depending on the prevailing seasons. During the NW monsoon season, winds typically blow offshore from the WNW, while during the SE monsoon season, they tend to blow onshore from the ESE (Tas, 2022). To simplify the model, a constant wind speed of 4.4 m/s originating from 292.5 degrees is applied witin the model, representing the wet season conditions (Smits, 2016).

4.2.8. Waves

Waves are assumed to approach the shoreline from the NW direction, with a spreading angle of 15 degrees and a significant height of 0.7 meters, corresponding to the conditions of the wet season (Smits, 2016). The model accounts for depth-induced breaking and bottom friction, incorporating wind growth and white-capping processes. As the FLOW and WAVE modules are coupled, waves and currents update each other within the simulations.

4.2.9. Physical parameters

In both the larger-scale and nested models, a uniform bottom roughness coefficient, calculated using the Manning formula, is applied, set at a value of 0.012 $s/m^{1/3}$. Near the open boundaries offshore, the horizontal eddy viscosity and diffusivity exhibit higher values, reaching 10 and 7 m^2/s respectively, compared to the rest of the domain in the larger-scale model. This adjustment is made to prevent undesired circulatory currents near the boundaries. The initial viscosity for the nested model matches that of the overall model, set at 1 m^2/s (Thillaigovindarasu, 2023).

4.2.10. Permeable structures

The positions of the structures implemented in the model are shown in Figure 4.2c relative to the bathymetry of the nested model and are schematically represented in Figure 4.3. Within the FLOW module of the model, permeable structures are represented by porous plates. These plates are essentially partially permeable barriers inserted into the flow, oriented along one of the grid axes and extending across specific or all layers vertically (Deltares, 2023). The porosity of the plate is controlled by a resistance coefficient. The resistance coefficient values (ranging from 10 to 20, depending on the location of the structure) were determined to effectively reduce current velocities passing through them. This reduction pushes the flow to preferentially navigate between the structures rather than through them (Thillaigovindarasu, 2023). Specific resistance coefficient values assigned to different porous plates can be found in Table 4.1. Additional characteristics related to the structural configurations of the various structures implemented in the model are provided in Table 4.2.

Porous plate	1	2	3	4	5	6
Resistance coefficient [-]	15	10	20	10	10	10

Table 4.1: Resistance coefficient values of the various porous plates implemented in the Delft3D model

Within the WAVE module, permeable structures, implemented at the same locations as within the FLOW module, were simulated using sheet-type obstacles characterized by a reflection coefficient of zero and a constant transmission coefficient. The specific value for the transmission coefficient was derived from the work of Gijón Mancheño (2022), which modelled wave transformation through permeable structures using data from the study area. For storm waves, it was assumed that approximately 60% of the wave energy would transmit through the structures. With an incoming wave height of 0.13 meters, a height of about 0.08 meters was observed behind a permeable structure, leading to a transmission coefficient of 0.6 (Thillaigovindarasu, 2023).

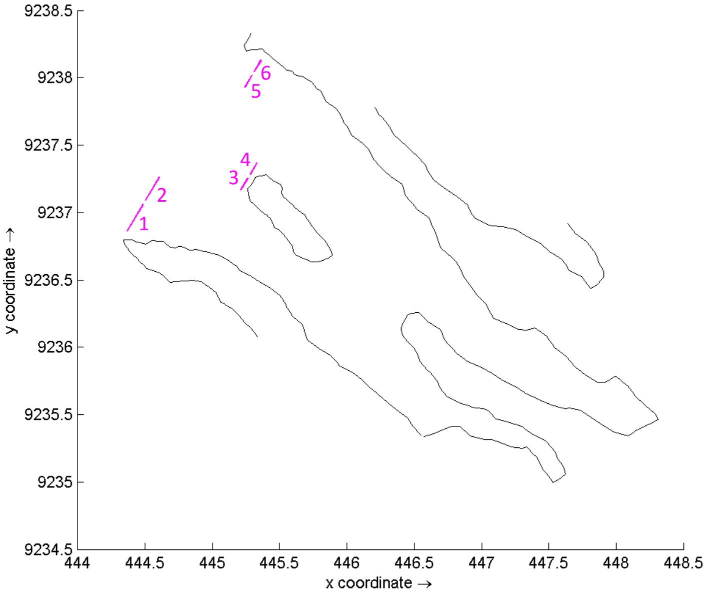


Figure 4.3: Location of the three sets of structures as implemented in the Delft3D model

	Structure length	Gap width	Water depth	Distance to mangrove fringe	Number of rows
1&2	231 m & 198 m	33 m	0.25 m MSL	-	1 row
3&4	99 m & 99 m	33 m	-0.07 m MSL	33 m	1 row
5&6	99 m & 99 m	33 m	0.19 m MSL	-	1 row

Table 4.2: Structural configurations of the structures sets as implemented in the baseline scenario with structures

4.3. Modelling scenarios

To analyze the influence of various design variables on the effectiveness of permeable structures in reducing bed shear stress behind them, multiple scenarios with different structural configurations are simulated in the Delft3D model. As mentioned in the previous section, three sets of permeable structures were implemented at different locations within the model set up by Thillaigovindarasu (2023), as depicted in Figure 4.3. These structural configurations are taken as the baseline scenario with structures within this research. Moreover, a baseline scenario without the presence of structures is employed to compare each scenario with a certain structural configuration to the situation without the presence of structures. To account for potential dependence on structure location within the coastal system, the influence of the various design variables on the performance of each set of permeable structures is analyzed separately. Thus, to analyze the impact of each design variable on the performance of each set of structures independently, within each scenario, only one design variable within the structural configuration - either structure length, distance of placement from the mangrove fringe, gap width in between the structures, or the number of rows of structures placed behind each other - is altered for only one set of structures, so either for structure set 1&2, or 3&4, or 5&6. The other sets of structures then have the same structural configuration as the baseline scenario, as established by Thillaigovindarasu (2023). For each design variable, multiple values are tested, resulting in multiple scenarios per design variable for each set of structures being simulated. Analysis of the influence of the distance of placement from the mangrove fringe on the performance of structures is, however, conducted solely for structures 3&4, as these are the only structures clearly positioned in front of a mangrove fringe. The values tested for each design variable are stated in Table 4.3 to 4.6, for each set of structures.

Structure length [m]				
1&2	231 & 198	297 & 264	165 & 132	99 & 66
3&4	99 & 99	165 & 165	132 & 132	99 & 99
5&6	99 & 99	165 & 165	132 & 132	99 & 99

Table 4.3: Values of structure length for each set of structures that are tested

Gap width [m]			
1&2	33	66	99
3&4	33	66	99
5&6	33	66	99

Table 4.4: Values of gap width in between each set of structures that are tested

Distance of placement [m]							
1&2	-	-	-	-	-	-	-
3&4	33; -0.07	66; -0.05	99;-0.01	132; 0.04	165; 0.23	198; 0.21	231; 0.27
5&6	-	-	-	-	-	-	-

Table 4.5: Values of distance of placement of structures to the mangrove fringe, including the associated water depth at that location in meters relative to MSL, that are tested

Number of rows [-]					
1&2	1 row	2 rows, 33 m	2 rows, 66 m	3 rows, 33 m	3 rows, 66 m
3&4	1 row	2 rows, 33 m	2 rows, 66 m	3 rows, 33 m	3 rows, 66 m
5&6	1 row	2 rows, 33 m	2 rows, 66 m	3 rows, 33 m	3 rows, 66 m

Table 4.6: Values of number of rows of structures placed behind each other, including varying distances in between the rows of structures, for each set of structures that are tested

4.4. Model output analysis

First, a detailed analysis is conducted on the model outputs of both the baseline scenarios - with and without structures - to investigate the influence of permeable structures at a broader scale, focusing on wave dissipation and current deflection induced by these structures, followed by an examination of their impact on bed shear stresses. The model outputs related to the bed shear stresses include the maximum bed shear stresses, as it is crucial that the maximum bed shear stresses are reduced by the permeable structures to below the critical threshold value for erosion to prevent erosion and allow for potential sedimentation to occur - as permeable structures are intended to facilitate sedimentation and an increase in bed level to the required bed level elevation for mangrove rehabilitation.

The influence of the various design variables on the performance of permeable structures in reducing the bed shear stresses behind them is, subsequently, analyzed by comparing the maximum bed shear stresses of each scenario, representing the different structural configurations, to the maximum bed shear stresses of the baseline scenario with structures. In this analysis, the impact of a design variable on the performance of structures in reducing bed shear stress is expressed through two parameters: 1) the magnitude of the decrease in bed shear stress across the area behind the structures, and 2) the spatial extent of the effect of permeable structures in reducing bed shear stresses. The magnitude of the decrease in bed shear stress is defined as the spatially averaged maximum bed shear stress over the area behind the structures where bed shear stresses are reduced, compared to the baseline scenario without structures. The spatial extent of the effect is defined as the size of the area where the maximum bed shear stresses are below the threshold value of erosion. In the vicinity of the structures, sediment sizes of around D_{50} 57.61 μm are detected, indicating light sandy mud (Van Domburg, 2018). An associated critical bed shear stress for erosion of 0.25 N/m^2 is assumed in this context (Mitchener & Torfs, 1996).

5 Results

This chapter expands upon the findings derived from both the extensive literature review and the Delft3D modeling research. Section 5.1 delves into the conceptual framework, illustrating the ecological and engineering variables pertinent to the design of permeable structures aimed at rehabilitating mangrove habitat. Following this, section 5.2 outlines the essential steps in the design process of these permeable structures, constituting a design guideline. Lastly, section 5.3 highlights the primary results obtained from the Delft3D modeling research.

5.1. Conceptual framework

This section presents a conceptual framework illustrating the ecological and engineering variables important in the design of permeable structures aimed at rehabilitating mangroves along eroding coastlines through morphodynamic restoration. This conceptual framework arises from the extensive literature review in the fields of mangrove ecology, mangrove-mud coast dynamics, mangrove rehabilitation, and permeable structures. The conclusions drawn from the literature review resulted in a set of variables that are categorized into biological, hydrodynamic, morphodynamic, and design variables, as indicated by the colored circles in Figure 5.1. These variables are further elaborated upon in sections 5.1.1 to 5.1.4, respectively. Section 5.1.5 provides an elaboration of the interplay among the various variables and enlightens the relevant processes that arise from these interactions that should be considered within the design process of permeable structures.

5.1.1. Biological variables

Two biological variables stand out as crucial factors in the design of permeable structures aimed at rehabilitating mangrove habitat: the mangrove species to be rehabilitated and the availability of propagules. The colonization of mangroves at a particular location or the seaward expansion of mangrove habitat only takes place when a sequence of favourable conditions follow each other, offering windows of opportunity for mangrove seedlings to establish and to grow into young, reproductive trees (Balke et al., 2011), as illustrated in Figure 2.2. Each mangrove species, however, has distinct preferences regarding these favourable conditions, in other words specific threshold values, depending on its species characteristics as well as on the biophysical conditions of their habitat (Van Loon et al., 2016). The desired inundation-free period of a specific mangrove species, for instance, is determined by the root extension rate of that specific mangrove species. This rate, consequently, dictates the required increase in bed level elevation that should be facilitated by permeable structures to restore the required habitat conditions for the mangrove species to be rehabilitated. Understanding the ecology of the mangrove species to be rehabilitated, which includes factors such as reproductive patterns and propagule dispersal, along with its distinct threshold values concerning the windows of opportunity, is therefore essential for the development of an effective design of permeable structures. As propagule availability is the initial threshold for seedling establishment (Lewis, 2005) (Figure 2.2, panel 0), evaluating propagule availability is another critical aspect within the design process to ensure successful mangrove rehabilitation.

5.1.2. Hydrodynamic variables

Waves, tides and currents are the primary hydrodynamic factors that must be considered within the process of designing permeable structures, as these factors interact to shape the functional criteria for the structures. Waves stir up fine sediments from the foreshore which are subsequently transported onshore during rising tides (Winterwerp et al., 2013). As permeable structures are intended to facilitate sedimentation in the sheltered areas behind them, and a subsequent increase in bed level elevation, their design should dissipate the incoming wave energy to create sheltered areas that are able to facilitate sediment settlement, while allowing for sediment to pass through, which can settle, accumulate, and lead to an elevation increase in the bed level elevation. In addition, since freshwater inflow is a prerequisite for the growth and survival of mangroves (Giri et al., 2010), evaluating and mapping the freshwater sources within the restoration zone is vital to prevent potential obstruction by the structures. Furthermore, it is essential to take into account a site's susceptibility to relative sea level rise, such as subsidence, during the initial design phase. In areas with relatively high local sea level rise and limited sediment availability, the construction of permeable structures for morphodynamic mangrove habitat restoration may not be feasible, as some rates of relative sea level rise could exceed the potential for compensation through local sediment accretion (Gijón Mancheño, 2022). Examining local subsidence rates before initiating the design process of permeable structures, therefore, is crucial to assess the potential of permeable structures as a solution for the morphodynamic restoration of mangrove habitat at a specific location, and thus to ensure the effective performance of these structures.

5.1.3. Morphodynamic variables

In the context of morphodynamics, factors such as bathymetry, bed sediment characteristics, suspended sediment budget, and dynamic sediment processes like cheniers and mud streaming are crucial considerations for designing permeable structures. Bathymetry plays a pivotal role as it influences the interaction between sedimentation driven by tides and erosion induced by waves, thereby shaping the morphodynamic response of mangrove-mud coastlines to restoration efforts (Winterwerp et al., 2013). Furthermore, bed sediment characteristics such as grain size distribution and cohesion determine the critical shear stress of the bed material and, as a result, they predominantly govern the bed material's ability to withstand hydrodynamic forces, with regards to erosion. These characteristics, along with the prevailing hydrodynamic conditions at the restoration site, determine the functional requirements of permeable structures. Specifically, they dictate the required degree of wave dissipation to create conditions conducive to sedimentation within the sheltered areas behind the structures. As permeable structures are intended to facilitate an increase in bed level elevation, a sufficient suspended sediment budget is a crucial prerequisite for the effective operation of these permeable structures. Assessing the magnitude and properties of the suspended sediment budget is therefore crucial in evaluating the potential effectiveness of permeable structures as a solution, particularly concerning potential relative sea level rise. Moreover, the presence of dynamic sediment features such as cheniers and mud streaming must be assessed and mapped. Cheniers positively impact mangrove-mud coastlines by dissipating incoming wave energy on their seaward side while simultaneously facilitating the accumulation of fine sediments on their landward side (Tas, 2022). In coastal areas featuring (migrating) mud banks, mud streaming stands as one of the primary driving mechanisms responsible for the transport of fine sediment towards the shore (Winterwerp et al., 2020). Like cheniers, mud streaming affects the dynamics of mangrove-mud coasts and has the potential to contribute to coastal accretion. Consequently, these features could contribute to the morphodynamic restoration of mangrove habitat. However, the presence of permeable structures could potentially interfere with or disrupt these dynamic features, reducing their positive impact on the morphodynamic restoration of mangrove habitat. Therefore, considering such features in the spatial design of permeable structures is essential.

5.1.4. Design variables

Permeable structures must be designed to meet both their functional requirements, such as effectively dissipating the required amount of wave energy, and their requirements regarding structural stability to ensure the structure doesn't fail within its intended lifespan. The degree of variation in potential designs, design alternatives, capable of meeting these requirements to achieve the defined rehabilitation objective relies on the quantity of design variables that can be modified. With respect to the spatial design of permeable, design variables include the location and orientation of placement of structures with respect to the coastline, and the spatial configuration of these structures, including the width of the opening in between multiple structures and the distance between multiple rows of structures. Concerning the structural design, design variables encompass the choice of material for each individual component and their respective dimensions, as well as the dimensions of the overall structural configuration, including parameters such as structure length and permeability. The selection of dimensions and materials is primarily driven by the functional requirements that the permeable structures must meet while also ensuring structural stability. Ideally, materials should be locally sourced, durable, and cost-effective (Wilms et al., 2021).

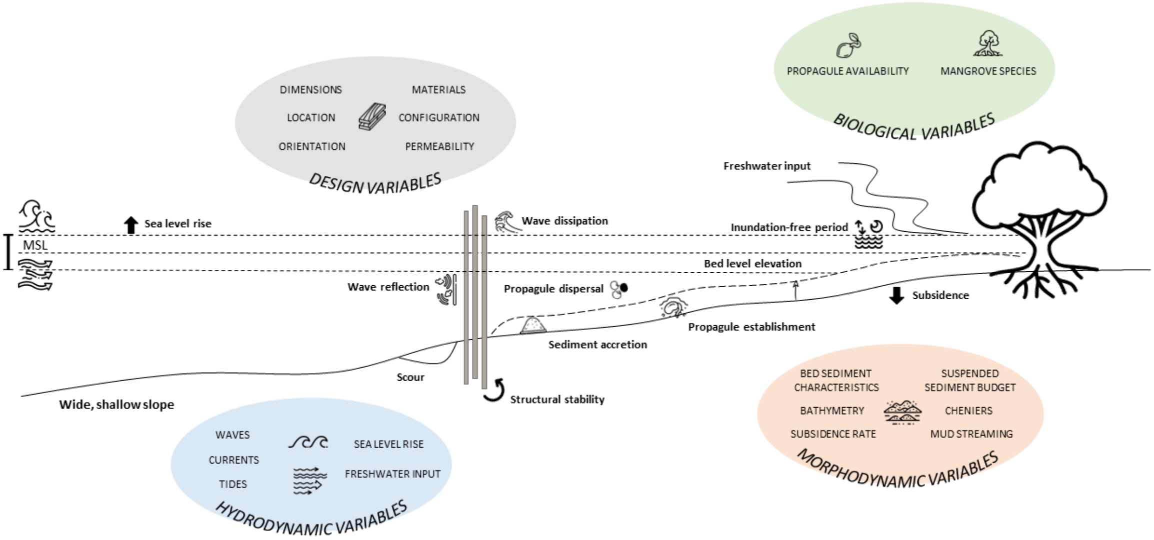


Figure 5.1: A conceptual framework illustrating the critical ecological and engineering variables, along with their interacting processes, important in the design of permeable structures aimed rehabilitating mangroves through morphodynamic habitat restoration

5.1.5. Interaction

The variables discussed in the preceding sections interact with each other, leading to specific processes that must be considered during the design of permeable structures at a particular site. This section provides an overview of these interactions and these specific processes, as indicated by the black icons in Figure 5.1.

Permeable structures are designed and implemented to contribute to the morphodynamic restoration of mangrove habitat by restoring the bed level elevation to the level that ensures the inundation-free period required by mangrove seedlings, meeting one of the thresholds for successful mangrove seedling establishment. These threshold values, associated with the windows of opportunity, are contingent upon the mangrove species type and the biophysical conditions of their habitat, making them highly site-specific. The necessary increase in bed level elevation facilitated by permeable structures at a specific site depends on these distinct threshold values, which, in turn, are influenced by the mangrove species targeted for rehabilitation and the biophysical conditions of the site's natural system. Permeable structures can facilitate this rise in bed level elevation by dissipating wave energy and deflecting currents, which results in sheltered areas with reduced flow velocities, turbidity, and decreased wave impact. These conditions are conducive to the deposition of suspended sediments. The deposition of suspended sediments within these areas, however, depends on the suspended sediment budget within the natural system of the site. A prerequisite for the successful performance of permeable structures is, therefore, a sufficient sediment budget. Specifically, the suspended sediment budget must be adequate to support sediment accretion rates that can outpace the rates of relative sea level rise, if present in the rehabilitation area. Another prerequisite for the successful performance of permeable structures in restoring mangrove habitat is the availability of a sufficient number of propagules in the natural system, either through an existing mangrove fringe that enables propagule dispersal or via aquatic connectivity to a nearby mangrove fringe. Besides these environmental factors, the performance of permeable structures in elevating the bed level largely depends on its design meeting the specific functional and structural requirements. Functional requirements primarily stem from the required restoration of bed level elevation, but also largely depend on the ecological, hydrodynamic and morphodynamic characteristics specific to the natural system of the rehabilitation site. Together, these factors determine the amount of wave dissipation that a specific permeable structure design should facilitate, the required permeability that a certain structural configuration must have to allow for sufficient sediments to pass through, and the spatial configuration of the permeable structures within the coastal system to be optimally placed and to avoid interference with other ecosystem values. The placement of permeable structures along the coastline should, for instance, consider existing creeks, as creeks play a crucial role in the local ecosystem, serving as freshwater input, drainage channels, and pathways for suspended sediments and mangrove seedlings. Hence, structures should not impede their natural flow. Moreover, the spatial design of permeable structures should take into account the presence of cheniers and (migrating) mud banks, as these features affect the dynamics of mangrove-mud coasts and have the potential to contribute to coastal accretion, and consequently, to contribute to morphodynamic restoration of mangrove habitat. In terms of spatial configuration, the width in between multiple structures is determined by the tidal range and the prevailing wave conditions of a site. It must ensure uninterrupted tidal flow in the sheltered area to promote sediment import, while preventing high waves from stirring up sediments. Structural requirements are closely associated with the intended lifespan of the structures. The structures must be robust enough to withstand the hydrodynamic forces exerted by waves and currents, and should possess the resilience to endure throughout their intended lifespan, which includes the ability to withstand various storms and high-energy events. Additionally, functional and structural requirements interact, as an optimal design should minimize wave reflection to prevent scour, while facilitating the required dissipation of wave energy to create the hydrodynamic conditions necessary for sedimentation in the sheltered areas behind them.

5.2. Design guideline

This section presents a design guideline outlining the fundamental steps in the design process of permeable structures aimed at rehabilitating mangrove habitat at a certain location. This design guideline is the result of the extensive literature review, incorporates the six ecological principles for ecological mangrove restoration outlined by López-Portillo et al. (2017), and utilizes the Building with Nature five step design approach as its foundational framework. As outlined in section 1.4, the steps within the design guideline emerged from elaboration of the initial two steps of the BwN design approach, as indicated by the black dashed square in Figure 5.2. These steps have been scrutinized in more detail, leading to 1) a broader strategy for mangrove rehabilitation through habitat restoration and 2) a specific design approach for permeable structures aimed at rehabilitating mangroves through morphodynamic habitat restoration. The steps constituting the entire design guideline are outlined in Figure 5.3. Subsequent sections first discuss the steps constituting the broader general strategy for rehabilitating mangroves through habitat restoration, followed by the steps that focus more specifically on the design of permeable structures aimed at morphodynamic restoration of mangrove habitat, as depicted by the black dashed square in Figure 5.3.

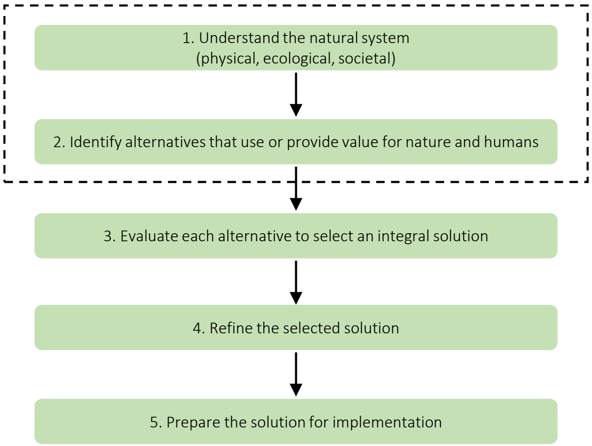


Figure 5.2: The five steps of the Building with Nature five step design approach: a design methodology aimed at developing nature-based solutions that address societal needs in a manner that benefits both people and nature. The black dashed square indicates the focus of this study concerning the development of a design guideline for permeable structures aimed at rehabilitating mangroves.

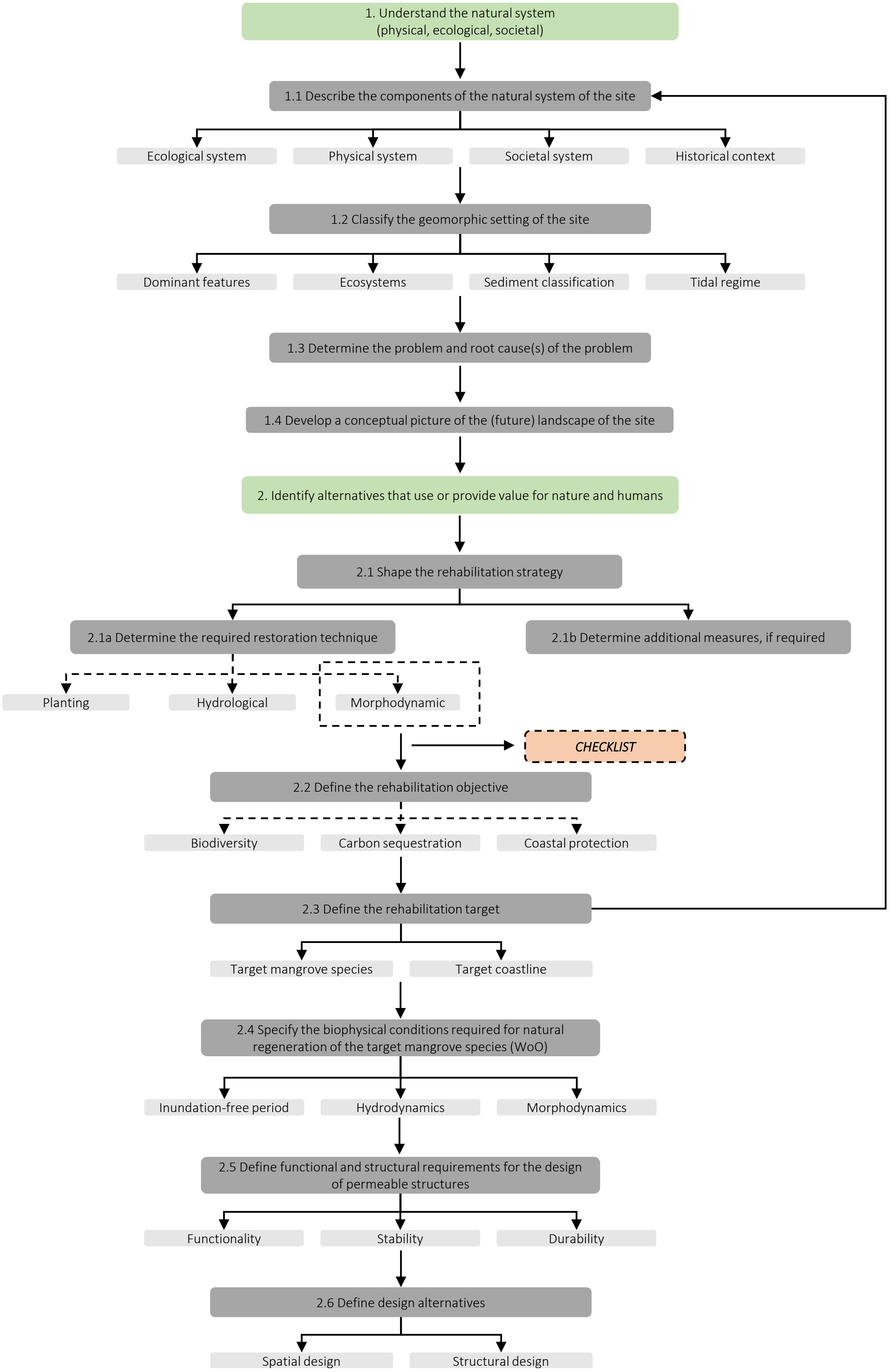


Figure 5.3: Design guideline for permeable structures aimed at rehabilitating mangroves through morphodynamic habitat restoration. Steps 1.1 to 2.1 encompass the broader strategy for mangrove rehabilitation through habitat restoration, while steps 2.2 to 2.6 constitute the specific design approach for permeable structures aimed at rehabilitating mangroves through morphodynamic habitat restoration.

Step 1. Understand the natural system (physical, ecological, societal)

Step 1.1 Describe the components of the natural system of the site

Goal: To assist in thoroughly understanding the natural system of the site in order to devise appropriate interventions and/or solutions to the problems of the site within the context of a mangrove rehabilitation strategy.

Elaboration: As prescribed by the Building with Nature design approach, the first step in developing a mangrove rehabilitation strategy is to assess the natural system of the site in question. This natural system comprises various components, including physical, ecological, and societal systems, all of which need to be thoroughly mapped out (EcoShape, 2021). The physical characteristics of the site encompass hydrology, morphology, and sediment transport processes. Based on available data and a general understanding of coastal dynamics, a description of local sediment dynamics must be developed. Particularly concerning the deployment of permeable structures, as a sufficient suspended sediment budget is a crucial prerequisite for the effective operation of these structures (Gijón Mancheño, 2022). Moreover, parameters such as tidal ranges, direction and magnitude of currents, wave characteristics, coastal geometry, bathymetry, and sediment properties are essential within this assessment (Winterwerp et al., 2020). The ecological system comprises biodiversity, habitats such as mangroves, coral reefs and seagrass meadows, and ecological processes within the area. An integrated ecosystem-based management is required within each mangrove rehabilitation initiative, like the deployment of permeable structures, to ensure interventions do not interfere with or harm adjacent ecosystems (Ferreira et al., 2022). This involves identifying keystone species, sensitive habitats, and ecosystem services provided by these natural environment. Assessing the societal system involves understanding the interactions between the environment and human activities, as well as the social, cultural, and economic dimensions of the site. This includes identifying stakeholders like governments, local communities, NGOs, and businesses, and considering their interests, concerns, and values related to the project. Understanding stakeholders' roles and capacities in project planning ensures that the design is socially inclusive, responsive to local needs, and aligned with broader development goals, enhancing its sustainability and effectiveness (De Vriend and Van Koningsveld, 2012; EcoShape, 2021).

Additionally, following the ecological principles of mangrove restoration outlined by (López-Portillo et al., 2017), the historical context of the area must be evaluated. This includes assessing any alterations to the original coastline, catchment, and mangrove environment that may impede natural reestablishment and regeneration of mangroves. Analyzing the historical changes in coastline position provides insights into the site's characteristics in terms of morphodynamic timescales and helps understand its morphodynamic response to environmental changes, including climate change and relative sea level rise, as well as (anthropogenic) interventions, such as coastal infrastructure like permeable structures. Furthermore, it could offer insights into historical mangrove colonizations that were once prevalent in the area but have since degraded or even disappeared entirely, shedding light on the potential causes of this degradation or disappearance that need to be addressed through habitat restoration.

Supportive resources:

- Building with Nature. Thinking, acting and interacting differently. De Vriend, H.J. and Van Koningsveld, M. 2012
- Mangrove Forest Restoration and Rehabilitation. López-Portillo, J. et al. 2017
- Managing erosion of mangrove-mud coasts with permeable dams - lessons learned. Winterwerp, J.C. et al. 2020

Step 1.2 Classify the geomorphic setting of the site

Goal: To assist in identifying the required ecological mangrove restoration technique, and thus in shaping the rehabilitation strategy.

Elaboration: The geomorphic characteristics of mangrove ecosystems exhibit considerable variation across tropical regions, influenced by factors such as suspended sediment availability and tidal amplitude. Enhancing the integration of geomorphic knowledge into site planning and design is expected to boost the success rates of restoration efforts (Balke & Friess, 2015). According to Balke and Friess (2015), the global distribution of mangroves can be categorized into three main types based on their geomorphic characteristics: 1) minerogenic with high tidal ranges, 2) minerogenic with low tidal ranges, and 3) organogenic with low tidal ranges. It is important to comprehend and categorize the geomorphic context in which a specific restoration initiative is being implemented, considering the significant impact of short- and long-term physical processes on the success of mangrove restoration efforts. Given the suitability of different restoration approaches for each type of mangrove ecosystem, classifying the natural system's environment of the site assists in identifying the most appropriate restoration technique, and thus in shaping the rehabilitation strategy.

Supportive resources:

- Geomorphic knowledge for mangrove restoration: a pan-tropical categorization. Balke, T. and Friess, D.A. 2015

Step 1.3 Determine the problem and root cause(s) of the problem

Goal: To identify the factors, considering both the biophysical and societal systems of the site, that need to be addressed in order to restore the conditions required for mangrove habitat.

Elaboration: Identifying the problem, in this case mangrove degradation or loss, and subsequently the root cause(s) of this problem, is a crucial step in the rehabilitation process (Lewis, 2005; López-Portillo et al., 2017). If the root cause(s) of mangrove degradation and/or entire loss is not properly addressed, any rehabilitation effort will be destined to fail. Within the process of identifying the problem, it is of utmost importance to consider both the biophysical system and the societal system of the site in question, as root causes may stem from both systems. As emphasized by Lewis (2005) and the EMR principles developed by López-Portillo et al. (2017), the success of rehabilitation efforts relies on the site's suitability for mangrove regeneration and colonization processes. A site is considered suitable mangrove habitat only if it can provide the windows of opportunity for successful seedling establishment, as illustrated in Figure 2.2. This means that a site is only suitable if 1) the inundation frequency is within the acceptable physiological range for the mangrove species located in the area or the target mangrove species to be rehabilitated (Lewis, 2005), 2) the phase of the tidal cycle regularly facilitates propagule settlement and anchorage, and 3) the sediment is compact enough to minimize mixing and prevent heavy sheet erosion (Balke et al., 2011). If any condition is altered, for instance due to coastal erosion or the damming of a river, disrupting the natural habitat of mangrove ecosystems and impeding the required windows of opportunity, restoration of this condition is necessary to facilitate successful seedling establishment and subsequent natural mangrove regeneration. However, mangrove degradation or loss could also result from the conversion of these forests by local communities into economic land uses, such as aquaculture or wood harvesting, or a combination of both. For instance, mangroves could be lost due to wood harvesting of these forests by local communities, which consequently results in the loss of a natural buffer mitigating wave impact between the sea and land, leading to coastal erosion. Coastal erosion could result in an inappropriate bed level elevation near the coastline, which is not able to provide the inundation-free period that propagules need to successfully establish and grow into young mangrove trees. If then, only the biophysical conditions of the site, in this case, the bed level elevation, are restored, and no attention is paid to the fact that wood harvesting serves as a major income to local communities inhabiting the area of the site in question, the rehabilitation effort will fail on the long-term as these communities will continue wood harvesting again. Identifying the root cause(s) of mangrove absence or degradation thus ensures that all factors that need to be addressed in order to restore the conditions required for mangrove habitat at a site are considered, within the context of both the biophysical system and the societal system. Furthermore, since the restoration of various biophysical conditions demands different techniques, as illustrated in Figure 2.6 (Gijón Mancheño et al., 2021), identifying the root cause of the problem facilitates the selection of the appropriate restoration technique to address the disturbed condition. This, in turn, assists in designing an effective and successful mangrove rehabilitation strategy on the long-term. By using the information gathered from steps 1.1 and 1.2, thus by describing the components, outlining the historical development of the natural system, and classifying the geomorphic setting of the site, the underlying cause(s) for the absence or degradation of mangroves can be identified.

Supportive resources:

- Ecological engineering for successful management and restoration of mangrove forests. Lewis, R.R. 2005
- Mangrove Forest Restoration and Rehabilitation. López-Portillo, J. et al. 2017

Step 1.4 Develop a conceptual picture of the (future) landscape of the site

Goal: To assist in identifying and mapping opportunities with regards to shaping the rehabilitation strategy, including the selection of the appropriate restoration technique and the development of potentially required additional measures.

Elaboration: Once the components and geomorphic setting of the site's natural system have been described, and the root cause(s) of the problem have been uncovered, developing a conceptual picture of the landscape of the site, with respect to its problems as well as its potential, helps identify and map opportunities that are mutually beneficial to both people and nature within the site's natural system (van Eekelen & Bouw, 2020). Through a comprehensive system analysis, a conceptual picture can be developed to illustrate both the social and ecological benefits provided by the natural system, highlighting its intrinsic values, potential, and opportunities for development. Additionally, mapping resource flows within the natural system of the site can contribute to the development of sustainable solutions. In this manner, landscape design can reveal opportunities for the future landscape of the site stemming from the various services offered by the natural system, with respect to its deficiencies and/or problems. Consequently, interventions can be devised to utilize the system's ecosystem services, leading to integrated nature-based solutions (van Eekelen & Bouw, 2020). Figure 5.4 illustrates an example of a conceptual picture of a landscape. It showcases the components of the natural system, along with their intrinsic values and potential, maps out all the stakeholders involved along with their interests, and highlights opportunities for interventions to meet societal demands while enhancing ecosystem resilience. Developing such a conceptual picture in the initial stages of a mangrove rehabilitation initiative aids in identifying and designing appropriate solutions to address the problems of the site, utilizing the ecosystem values of the site's natural system while considering the various stakeholders and habitats within the system. This ensures the (long-term) effectiveness of a rehabilitation effort.

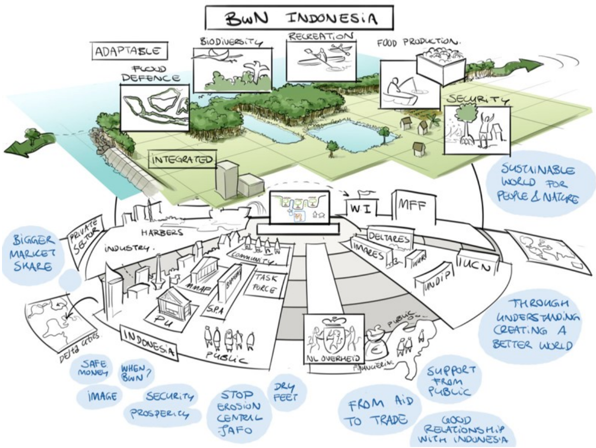


Figure 5.4: Example of a conceptual picture illustrating the landscape of a site, along with its values and potential (van Eekelen & Bouw, 2020)

Supportive resources:

- Design with Nature. McHarg, I.L. 1995
- Building with Nature. Thinking, acting and interacting differently. De Vriend, H.J. and Van Koningsveld, M. 2012

- Building with Nature - Creating, implementing and upscaling Nature-based Solutions. Van Eekelen, E. and Bouw, M. 2020

Step 2. Identify alternatives that use or provide value for nature and humans

Step 2.1 Shape the rehabilitation strategy

Through a conceptual picture of the (future) landscape of the site in question, potential solutions to the problems and opportunities for sustainable development that provide value for both nature and humans can be identified. In the context of mangrove rehabilitation through habitat restoration, identifying alternatives involves determining the required restoration technique to address the biophysical condition that has affected mangrove habitat, as well as identifying any additional measures that may be necessary. In others words, identifying alternatives involves shaping the rehabilitation strategy.

Step 2.1a Determine the required restoration technique

Goal: To ascertain the required ecological mangrove restoration technique to ensure the right biophysical condition is addressed that has affected mangrove habitat.

Elaboration: The restoration of various biophysical conditions demands different techniques, as illustrated in Figure 2.6 (Gijón Mancheño et al., 2021). To ensure the success of a rehabilitation initiative, the right ecological mangrove restoration technique must be selected to address the right biophysical condition that has affected mangrove habitat and that needs to be restored. In coastal areas where coastal erosion, caused by high wave exposure, has led to coastline retreat, or where the bed level elevation is too low to support mangrove habitat, restoration of the morphodynamic conditions using permeable structures is required, as illustrated in Figure 2.6c - on which the subsequent steps within the design guideline are elaborated as indicated by the black dashed square in Figure 5.3. Other root causes that have affected mangrove habitat require different techniques, as illustrated in Figure 2.6b.1, 2.6b.2, and 2.6b.3.

Supportive resources:

- Geomorphic knowledge for mangrove restoration: a pan-tropical categorization. Balke, T. and Friess, D.A. 2015
- Mangrove Forest Restoration and Rehabilitation. López-Portillo, J. et al. 2017
- Mangrove Restoration: the key elements to be considered in any restoration project. Technical Guide. Pôle-relais zones humides tropicales. 2018

Step 2.1b Determine additional measures, if required

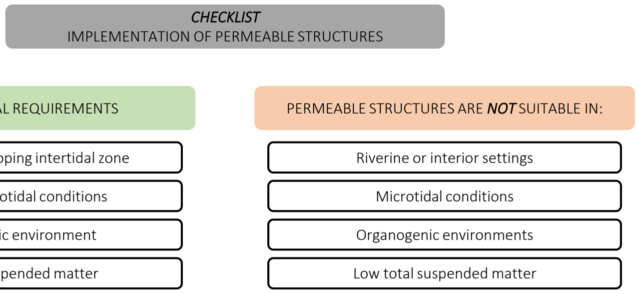
Goal: To ascertain any potentially required additional measures to ensure the long-term success of the rehabilitation initiative.

Elaboration: Since the success of a rehabilitation initiative also depends on various external factors besides the selection of the right ecological mangrove restoration technique, additional measures might be necessary. Seedling availability within the area is one of these external factors. If the seedling availability is low at one site, planting of propagules or cultivated seedlings could be an additional measure that can aid in facilitating natural recruitment (Figure 2.6d). Moreover, in a mangrove-based economy, mangrove greenbelts not only provide coastal safety but also resilience for communities to thrive. In such areas, mangrove forests are often utilized by communities for economic activities such as wood harvesting. Therefore, alongside mangrove habitat restoration efforts, there might be a need to raise awareness within these communities about their importance. Proper management strategies must be developed and deployed, and sustainable land use practices must be advocated within local communities, such as sustainable aquaculture and integrated mangrove-aquaculture projects, fisheries, eco-tourism, and the harvesting of non-timber forest products. Within this process, it is of utmost importance to engage and collaborate with these communities, and to integrate their interests in shaping the rehabilitation strategy throughout the entire project cycle. Furthermore, integrating land ownership and usage rights for conservation as well as protection measures into local, district, provincial, and national policies form additional measures to ensure the long-term effectiveness of restoration techniques (Winterwerp et al., 2020).

Supportive resources:

- Manual on community-based mangrove rehabilitation. Primavera, J.H. et al. 2012
- Best practice guidelines for mangrove restoration. Beeston, M. et al. 2023

Before proceeding to the next step and elaborating on shaping a morphodynamic habitat restoration technique, which involves the design of permeable structures, it is crucial to thoroughly assess whether a specific site is suitable for the deployment of these permeable structures, and thus whether permeable structures as a solution could be feasible, as their applicability is constrained to particular settings (Balke & Friess, 2015). Hence, a checklist outlining the environmental prerequisites for deploying permeable structures, as outlined by Balke and Friess (2015), is formulated, as depicted in Figure 5.5. These requirements are established with consideration for the diverse geomorphic settings of mangroves worldwide. These settings are influenced by abiotic factors like suspended sediment supply and tidal range, which impact mangrove ecosystem dynamics and are thus related to the long-term success of a restoration technique. Following the classification of a site as determined in step 1b, the suitability of the site for the deployment of permeable structures can be reassessed using this checklist.



CHECKLIST
IMPLEMENTATION OF PERMEABLE STRUCTURES

ENVIRONMENTAL REQUIREMENTS	PERMEABLE STRUCTURES ARE ***NOT*** SUITABLE IN:
A wide, shallow sloping intertidal zone	Riverine or interior settings
Meso- to macrotidal conditions	Microtidal conditions
A minerogenic environment	Organogenic environments
High total suspended matter	Low total suspended matter

Figure 5.5: Checklist for the implementation of permeable structures

Furthermore, it is imperative to thoroughly evaluate the sediment budget relative to the rates of relative sea-level rise, whether driven by absolute sea-level rise or subsidence, before embarking on the design process of permeable structures. The deployment of permeable structures as a solution may not be viable at sites characterized by low sediment availability compared to high local sea-level rise. In such cases, certain rates of relative sea-level rise may exceed the capacity for local accretion. Additionally, geological evidence indicates that mangrove forests can only expand seaward at rates of up to 6–7 mm/year of sea-level rise, constraining mangrove colonization and rehabilitation efforts through permeable structures in areas with significant subsidence (Gijón Mancheño, 2022).

Step 2.2 Define the rehabilitation objective

Goal: To assist in determining the rehabilitation target in terms of mangrove species to be rehabilitated and the spatial extent of the area to be restored in order to shape the restoration technique.

Elaboration: The initial stage in the specific design guideline of permeable structures involves defining a rehabilitation objective. Setting a clear goal provides direction and helps determine the strategies and actions required to achieve that goal, which, in the context of shaping a morphodynamic habitat restoration technique, includes determining the design for permeable structures. Moreover, it is essential to clarify the purpose of mangrove rehabilitation at a particular site, as this greatly influences the target mangrove species to be restored (Ferreira et al., 2022) and the spatial extent of the rehabilitation area, which together, subsequently, result in the formulation of functional requirements of the design of permeable structures. A rehabilitation objective could, for instance, be linked to one of the ecosystem value(s) for which mangrove habitat restoration is desired, tailored to the site's characteristics and future landscape. Possible objectives within this context include enhancing biodiversity, carbon sequestration, or aiding in coastal protection. For example, if the goal is to enhance carbon sequestration, it is crucial to focus on rehabilitating mangrove species known for their superior carbon dioxide sequestration capabilities. In the case of rehabilitating mangroves for enhancing flood protection, the target coastline may need to be positioned farther to create a broader mangrove green belt, effectively safeguarding the adjacent land against flooding.

Supportive resources:

- New contributions to mangrove rehabilitation/restoration protocols and practices. Ferreira, A.C. 2022

Step 2.3 Define the rehabilitation target

Goal: To assist in specifying the conditions to which mangrove habitat must be restored in order to shape the requirements of the restoration technique.

Elaboration: Defining a rehabilitation objective leads to establishing a rehabilitation target in terms of the type of mangrove species to be restored and the spatial extent of the rehabilitation area, which includes defining a target coastline. In other words, the rehabilitation objective must be further specified and quantified in greater detail to effectively shape the requirements of the restoration technique and, consequently, to devise an appropriate design for permeable structures. During this process, it is crucial to verify whether the natural system of the site is able to accommodate these targets. For instance, the spatial extent of the rehabilitation area should not encroach upon other nearby ecosystems, such as coral reefs or seagrass meadows (Ferreira et al., 2022). Moreover, the biophysical conditions of the site must be conducive to the thriving of the desired mangrove species; otherwise, the rehabilitation effort will likely fail anyway. A feedback loop to the description of the components of the natural system of the site is therefore present within the design guideline. If the desired mangrove species aren't currently present in the area, or the entire mangrove colonization has been lost, the suitability of a site to a certain mangrove species can be assessed by examining historical records of the area to determine if the desired mangrove species have previously inhabited the site. Alternatively, comparing the site with a nearby reference site characterized by similar biophysical conditions and hosting mangrove colonies can help ascertain whether the desired species would be able to thrive in the natural system of the site in question (Lewis, 2005).

The choice of mangrove species for a restoration project primarily depends on the extent to which the species' characteristics align with the specific biophysical conditions of a given site, and secondarily on the objectives for rehabilitation (Primavera & Esteban, 2008). The type of mangrove species desired for a specific rehabilitation objective, such as enhancing flood protection or carbon sequestration, depends on both the species-specific characteristics and the biophysical conditions of the site. For example, the carbon sequestration capacity of a mangrove species is influenced by factors like biomass, which is in turn affected by nutrient availability and ecological productivity. These factors are, in part, determined by the biophysical conditions of the mangrove habitat, including salinity, temperature, and pH (Ewel et al., 1998). Generally, it is most effective to focus on restoring mangrove habitat for the pioneer species of the particular area. These species are the first to colonize and establish themselves in a newly forming or disturbed mangrove habitat. Pioneer species thrive in challenging conditions, such as areas with high salinity, shifting sediments, and periodic flooding, and are known for their rapid growth and high biomass (Ferreira et al., 2022). Although *Avicennia alba* is the most widespread genus of mangrove pioneer species (Balke et al., 2011), the specific type of pioneer species varies worldwide. Moreover, if a site has or previously had a high tree diversity of mangrove species, restoring the maximum number of native species present in the region leads to the most successful rehabilitation (Ferreira et al., 2022). Depending on the regional setting and characteristics, restoring multiple mangrove species increases the likelihood of a rapid and effective restoration of functional features and diversity to the ecosystem. In conclusion, the choice for the mangrove species to be rehabilitated is highly site-specific, as it depends on the biophysical conditions at a site. Moreover, the focus should be on restoring the pioneer species of the area for which the characteristics align with the biophysical conditions of the area.

With regards to determining the required spatial extent of the rehabilitation area to achieve a specific objective, such as enhancing flood protection or achieving a targeted level of carbon sequestration, there are currently various tools and formulas available to assist in quantification. A guideline for carbon sequestration, for instance, is that mangroves contain an average of 937 tC ha-1 (metric tons of carbon per hectare), facilitating the accumulation of fine particles and fostering rapid rates of sediment accretion (5 mm/year) and carbon burial (174 gC m-2/year) (Alongi, 2012). However, similar to other forest ecosystems, mangroves exhibit variations in size and age, resulting in differences in production rates and the balance between carbon production and respiration. Research on the specific carbon production of individual mangrove species is, however, lacking (Alongi, 2012). Regarding the required spatial extent to provide a certain amount of coastal protection, numerous studies suggest that mangrove forest widths exceeding 100 meters are sufficient to offer coastal protection against wind and swell waves, as well as extreme events such as tsunamis (Alongi, 2008; Ferreira et al., 2022; Van Bijsterveldt, 2023). Besides, some studies have established certain relations between forest dimensions and the attenuation of waves. Méndez and Losada (2004), for instance, has devised an empirical model for quantifying wave transformation over vegetation fields, incorporating wave damping and breaking over variable depths. This model establishes a relationship between mangrove forest dimensions and short-period waves. Additionally, Montgomery et al. (2019) has developed a simplified analytical solution to predict peak surge levels across mangrove forests given forest density and cross-shore extent. However, the exact functionality of mangroves during high-magnitude flood events is yet to be quantified (Gijsman et al., 2021). Moreover, the practical applicability of the existing correlations and formulas is not yet clear and requires further assessment before integration into design guidelines and practical usage can be considered feasible.

Supportive resources:
Coastal protection:

- An empirical model to estimate the propagation of random breaking and nonbreaking waves over vegetation fields. Mendez, F.J. and Losada, I.J. 2004
- Quantifying wave attenuation to inform coastal habitat conservation. Pinsky, M.L. 2013
- Non-linear wave attenuation quantification model improves the estimation of wave attenuation efficiency of mangroves. Zhang, Y. et al. 2020
- Attenuation of Tides and Storm Surges in Coastal Mangroves. Montgomery, J.M. 2021
- Solitary wave attenuation characteristics of mangroves and multi-parameter prediction model. Yin, Z. et al. 2023

Carbon sequestration:

- Carbon sequestration in mangrove forests. Alongi, D.M. 2012
- Mangrove Restoration Potential: A global map highlighting a critical opportunity. Worthington, T. and Spalding, M. 2018
- New contributions to mangrove rehabilitation/restoration protocols and practices. Ferreira, A.C. 2022

Step 2.4 Specify the biophysical conditions required for natural regeneration of the target mangrove species (Windows of Opportunity)

Goal: To assist in formulating functional requirements for the design of permeable structures.

Elaboration: As highlighted by Balke et al. (2011), successful mangrove seedling establishment, and subsequent colonization, depend on specific requirements to a suitable mangrove habitat. The colonization and seaward expansion of mangrove habitat only takes place when a series of favourable conditions, associated with these requirements, follow each other, offering windows of opportunity for seedling establishment, as illustrated in Figure 2.2. Each mangrove species, however, exhibits distinct preferences regarding these requirements, in other words specific threshold values, that may vary under particular biophysical conditions. There is a crucial need to consider these species-specific characteristics in mangrove restoration, particularly concerning the design of restoration interventions (Su et al., 2022). The first window of opportunity (Figure 2.2, panel 1), and thus the related threshold value for this requirement, holds utmost importance in morphodynamic habitat restoration, and thus in the design of permeable structures. It encompasses the inundation-free period required for propagules to develop into saplings and subsequently establish roots long enough to withstand displacement caused by tidal flooding. As previously mentioned, morphodynamic habitat restoration using permeable structures becomes necessary in areas where coastal erosion has led to inadequate bed level elevation, impeding the required inundation-free period. Therefore, after determining the target mangrove species for rehabilitation, specifying the required inundation-free period for successful seedling establishment of the target mangrove species, along with the other required biophysical conditions for natural regeneration, becomes crucial. However, except for the threshold values of *Avicennia alba* as determined by Balke et al. (2011), specific threshold values to these species-specific characteristics, particularly concerning the windows of opportunity, are currently lacking.

A way to gain insight into the specific threshold values of the target mangrove species to be restored, today, is to identify and utilize a reference site that shares similar conditions to the site in question and supports mangroves. This reference site can help assess the typical hydrology and biophysical conditions for mangroves in the target area. For instance, installing tide gauges at the reference site allows for measuring the tidal hydrology of a mangrove forest to determine the necessary flooding frequency and inundation-free period. Alternatively, surveying the elevation of the reference mangrove forest floor can serve as a proxy for hydrology, and subsequently as a proxy for the required bed level elevation (Lewis, 2005). However, this procedure is subject to considerable uncertainty.

Supportive resources:

- Ecological engineering for successful management and restoration of mangrove forests. Lewis, R.R. 2005
- Windows of opportunity: thresholds to mangrove seedling establishment on tidal flats. Balke, T. et al. 2011

Step 2.5 Define functional and structural requirements for the design of permeable structures

Goal: To facilitate the development of design alternatives.

Elaboration: As permeable structures are intended to facilitate sedimentation and the required increase in bed level elevation, their design must meet certain functional requirements to ensure the successful performance of the structures in restoring the requisite biophysical conditions for successful mangrove seedling establishment. Designing permeable structures involves addressing both spatial and structural design aspects. This includes determining the placement of structures relative to the coastline and specifying parameters such as structure length and permeability. Functional and structural requirements need to be defined at both scales to ensure an effective design. Functional requirements primarily focus on restoring the biophysical conditions necessary for successful mangrove seedling establishment and subsequent natural regeneration of the target mangrove species toward the target coastline. Structural requirements are more closely associated with the timescale for mangrove rehabilitation and the intended lifespan of the structures.

The structures should effectively dissipate wave energy so that the significant wave height decreases as waves pass through them, and create sheltered areas behind them with reduced orbital velocities and turbulence, so that sediment can deposit. In addition, the permeability of the structures should be sufficient to allow suspended sediments to flow through, thereby increasing the amount of sediment entering the sheltered area, promoting sediment settlement, accumulation and consolidation. Besides, permeable structures must be capable of withstanding the hydrodynamic forces exerted by waves and currents, and should possess the resilience to endure throughout their intended lifespan, which includes the ability to withstand various storms and high-energy events. Moreover, seasonal or annual variations in certain physical factors, such as the wave climate and sediment input from rivers, should be considered with regards to the functionality and structural stability of the permeable structures (Gijón Mancheño, 2022). According to Wilms et al. (2021), the structures should be robust enough to stay in place for a period at least as long as the sum of the estimated sediment accretion rate (2 to 5 years) and the rate of mangrove recovery (3 to 5 years), to allow sufficient time for the mangroves to regenerate and recover. Moreover, wave reflection caused by the structures should be limited so that erosion at the base of the structure (scour) is avoided and structural collapse is prevented. An optimal design should, therefore, minimize wave reflection while facilitating the required dissipation of wave energy to create the hydrodynamic conditions required for sedimentation in the sheltered areas behind them. Furthermore, designs should consider the threat of shipworm, which can also pose a risk to structural stability, and the potential decay of materials submerged for extended periods of time (Winterwerp et al., 2020).

This step thus involves translating the required biophysical conditions for successful mangrove seedling establishment and subsequent natural regeneration of the target mangrove species into clearly defined and measurable functional and structural requirements. Subsequently, design alternatives that meet these requirements can be identified.

Supportive resources:

- Managing erosion of mangrove-mud coasts with permeable dams - lessons learned. Winterwerp, J.C. et al. 2020
- Permeable Structures: Building with Nature to restore eroding tropical muddy coasts (tech. rep.). Wilms, T. et al. 2021

Step 2.6 Define design alternatives

Goal: To foster innovation and optimization in order to discover the most effective design that meets the specified requirements.

Elaboration: This step involves translating functional and structural requirements into design alternatives that satisfy these criteria, both at landscape level (spatial design) and individual level (structural design). Defining alternatives at landscape level involves considering parameters such as the placement and orientation of the structures relative to the coastline, as well as factors that are part of the spatial configuration. permeable structures are generally constructed perpendicular to the direction of the incoming waves. The specific placement of the structures with respect to the coastline is determined based on factors such as bathymetry, morphodynamics, hydrology, and the target coastline (Wilms et al., 2021). The placement of the structures should also take into account existing creeks and the possibility of future creek development. Creeks are vital within the natural system of the area, serving as important sources of water, drainage, and for transporting suspended sediments and mangrove seedlings. Structures should, therefore, not obstruct the natural flow of existing creeks. Regarding the spatial configuration, the width of the opening in between multiple structures relies on both the tidal prism and the wave conditions. The minimum width of the opening between structures is dictated by the tidal prism and must allow uninterrupted tidal flow into the sheltered area behind the permeable structure. Conversely, the maximum width is influenced by the wave conditions and should be narrow enough to prevent high waves from entering the area behind the structure and stirring up sediment (Wilms et al., 2021).

The core of the structural design process (individual level) lies in defining the structural configuration that meets the functional and structural requirements, and subsequently selecting the materials and dimensions for each component within that specific configuration. These requirements involve achieving the required level of wave energy dissipation, facilitating the passage of an adequate volume of suspended sediments, and minimizing wave reflection that may lead to scour in front of the structure, potentially affecting its structural stability (Wilms et al., 2021). Parameters within a structural configuration encompass the dimensions of specific components, such as vertical poles, as well as those of the overall structure, including factors like structure length and permeability. Several analytical frameworks exist that describe the relationship between a specific structural configuration and the extent of wave dissipation and reflection it induces, as well as the extent of currents deflection. Gijón Mancheño (2022) introduced a theoretical analytical framework for predicting wave reflection and dissipation within arrangements of cylinders. This framework considers sheltering and blockage processes that result in a particular drag coefficient generated by the structures, thereby leading to a certain amount of wave dissipation. Such frameworks can aid in translating a required level of wave energy dissipation into a specific structural configuration capable of achieving that desired amount of wave energy dissipation. However, it's important to note that these frameworks primarily focus on the permeability of a given structural configuration. Frameworks that describe the relationship between design parameters, such as structure length, width of openings in between structures, and the distance of structure placement from the coastline, are currently lacking. The impact of design parameters like these on structure performance is largely unknown, which currently still hinders the development of potential design alternatives, and consequently, the development of optimal structure configurations.

Supportive resources:

- Permeable Structures: Building with Nature to restore eroding tropical muddy coasts (tech. rep.). Wilms, T. et al. 2021

5.3. Delft3D modelling

This section elaborates on the results of the Delft3D modelling research. First, in section 5.3.1, the impact of permeable structures on bed shear stresses is examined at a broader scale, focusing on wave dissipation and current reflection induced by these structures. Subsequently, in section 5.3.2, attention is narrowed to the vicinity of the permeable structures, where the effects of the various design variables on the effectiveness of permeable structures in reducing bed shear stress behind them are examined.

5.3.1. Large-scale influence of the presence of permeable structures

The change in maximum bed shear stress resulting from the presence of permeable structures at the time of maximum bed shear stresses within the representative tidal cycle is illustrated in Figure 5.6. In the close proximity behind the permeable structures, maximum bed shear stresses are reduced, whereas around the tips of the structures and in the area between the sets of structures, maximum bed shear stresses are increased due to the presence of structures. The reduction in bed shear stress arises from the dissipation of wave energy by the permeable structures, causing a reduction in orbital velocity near the bottom directly behind the structures, as indicated by Figure 5.7a and 5.7b, and a slight decrease in current velocities caused by the resistance of the permeable structures as currents pass through. The effect of permeable structures on incoming waves is larger than the effect of the structures on incoming currents, as elaborated on in Appendix A. The increase in bed shear stress around the tips of the structures and in the area between the sets of structures results from the deflection of currents caused by the resistance of the structures as they pass through them, as illustrated in Figure 5.8. Currents are deflected towards areas of lower resistance, thus towards the sides of the structures, thereby causing a compression of flow around the tips of the structures. This compression of flow results in an increased depth-averaged velocity of the flow and consequently, an increase in bed shear stress around the tips of the structures.

In addition, Figure 5.6 shows that the reduction in bed shear stresses behind structures 1&2 reaches over increased spatial extent than behind structures 3&4 and 5&6. This can be attributed to the increased structure length of structures 1&2, measuring 231 and 198 meters respectively, compared to the other sets of structures which are 99 meters long. Besides, behind structures 3&4, a mangrove fringe is located which acts as a barrier, limiting the extent of the structures' effect in reducing bed shear stress behind them. Moreover, spatial variations in the magnitude to which bed shear stresses are reduced across the sheltered areas behind the structures are identified. These spatial variations could be attributed to very localized variations in hydrodynamic conditions. Appendix B elaborates on the differences in hydrodynamic conditions across the various structure locations that potentially contribute to the spatial variations in structure performance in reducing bed shear stresses.

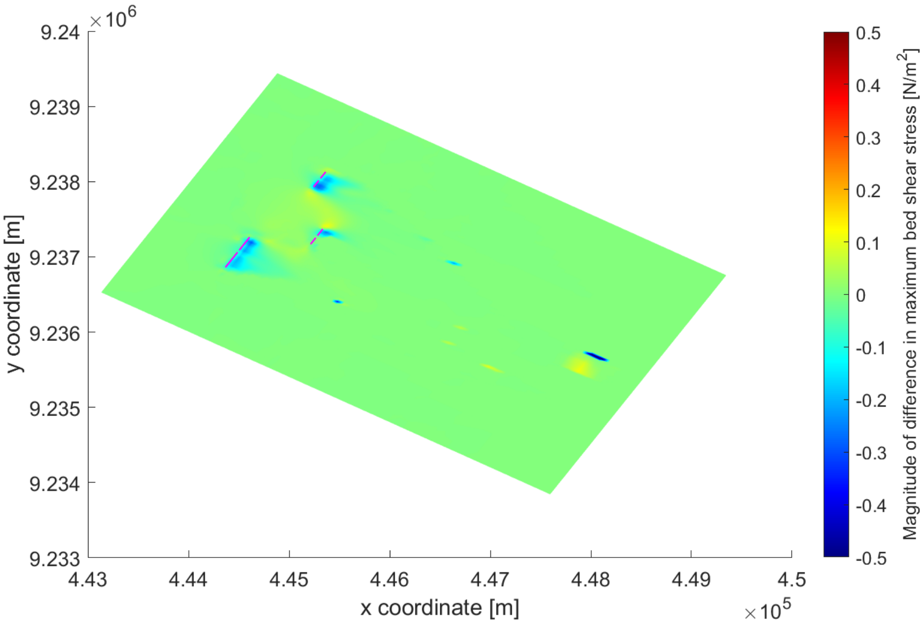
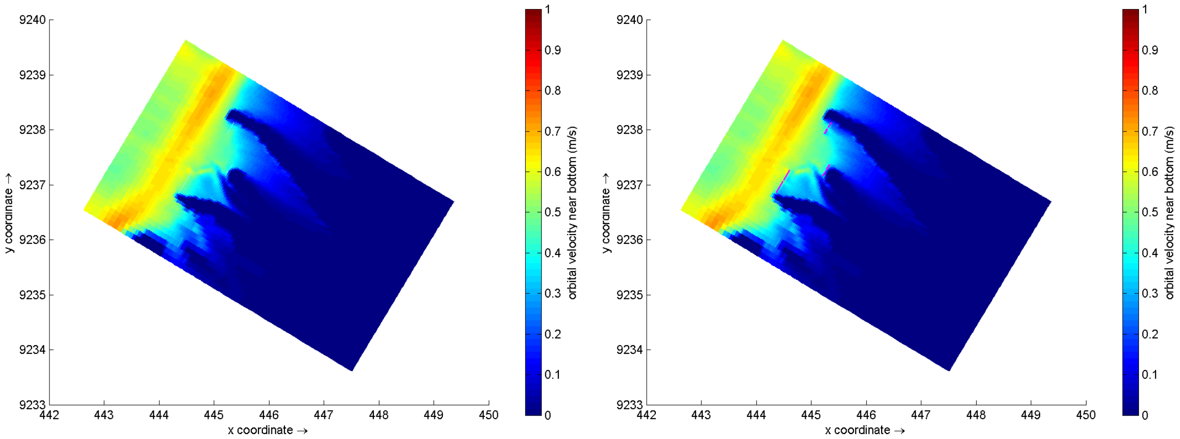


Figure 5.6: Difference in maximum bed shear stress between scenarios with and without the presence of structures



(a) (b)

Figure 5.7: Orbital velocity near the bottom in a) absence of permeable structures, and b) in the presence of permeable structures

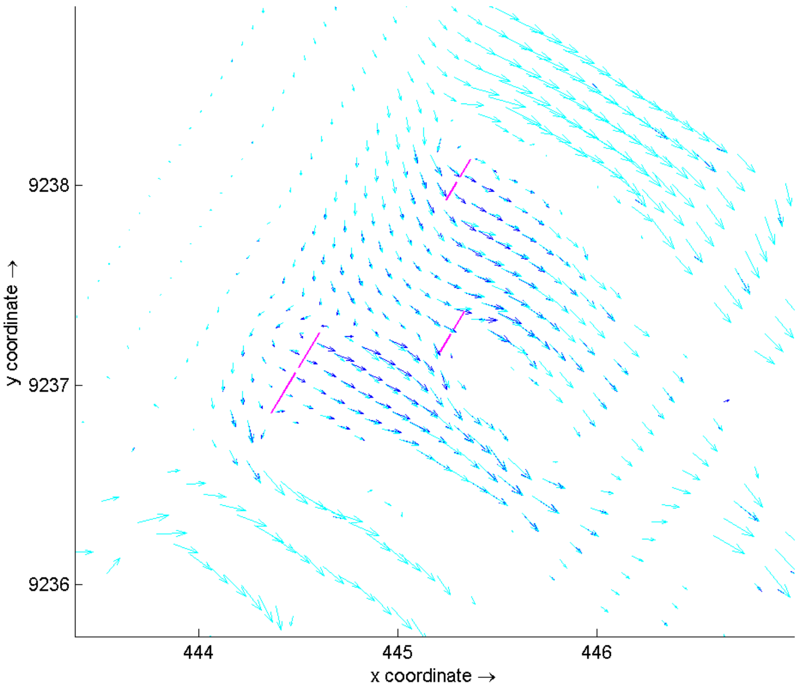


Figure 5.8: Difference in depth-averaged velocity between scenarios without the presence of permeable structures (dark blue) and with the presence of permeable structures (light blue)

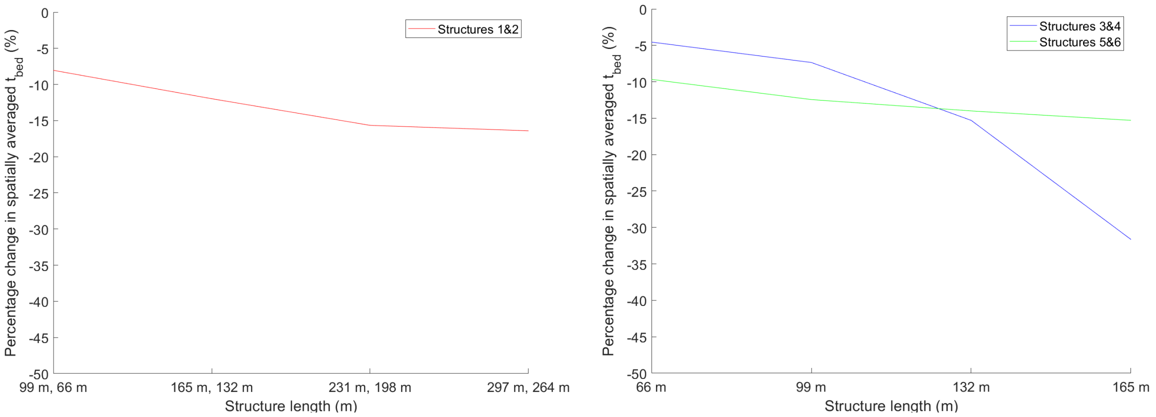
Furthermore, Figure 5.6 shows that in a specific area at the end of one of the channels behind the permeable structures near the coastline, a very localized decrease as well as increase in maximum bed shear stresses occurs. This phenomenon could be attributed to the combined impact of a change in water depth due to the presence of permeable structures and variations in the local bathymetry of that particular area. However, due to the highly dynamic and alongshore nonuniform coastline of Demak, and considering that this study aims to gain general insights on the influence of various design parameters on the performance of permeable structures, with a focus on the reduction in bed shear stress across the area directly behind the structures, no further attention is given to this aspect.

5.3.2. Influence of design variables on structure performance

To analyze the influence of various design variables on the performance of permeable structures in reducing bed shear stress behind them, particular attention is given to the area directly behind each set of permeable structures, individually, to accommodate potential variations among the different structure locations. The results of the analysis on the influence of structure length, distance of placement of structures from the mangrove fringe, gap width in between a set of structures, and the number of rows of permeable structures placed behind each other on the performance of structures in reducing bed shear stress, are elaborated in the following sections, respectively. Appendix C demonstrates the diverse impact of the various design variables on the efficacy of permeable structures in reducing bed shear stress behind them, in terms of the magnitude of the decrease in spatially averaged maximum bed shear stress attributed to a specific structure configuration, across the area behind the structures where bed shear stresses are reduced due to the presence of structures, throughout the entire tidal cycle. Besides, Appendix D showcases the varying influence of these design variables on the efficacy of permeable structures in reducing bed shear stress, in terms of the spatial extent over which bed shear stresses fall below the threshold value for erosion, attributed to a specific structure configuration, throughout the entire tidal cycle. These graphs reveal that the influence of design variables is most prominent during the flood period of the tidal cycle, during which bed shear stresses are highest. Therefore, the subsequent sections focus on analyzing the influence of these various design variables on the efficacy of permeable structures in reducing bed shear stresses behind them during the flood period of the tidal cycle.

Structure length

Figures 5.9a and 5.9b illustrate that an increase in structure length results in a greater percentage decrease in the spatially averaged maximum bed shear stress across the area behind the structures with reduced bed shear stress compared to the scenario without structures. Increasing the length of structures 1 and 2 from 99 and 66 meters to 165 and 132 meters, respectively, leads to a greater reduction in bed shear stresses of approximately 4%. Similarly, increasing the length of structures 3 and 4 from 99 meters to 165 meters results in a more significant reduction in bed shear stresses, approximately 25%. For structures 5 and 6, this reduction is approximately 3%. Furthermore, increased structure length results in a higher percentage increase in the area behind the structures where the maximum bed shear stresses fall below the threshold value of erosion, as demonstrated in Figures 5.10a and 5.10b. The corresponding expansion in spatial extent, where bed shear stresses fall below the critical erosion threshold due to the increased length of structures 1 and 2 from 99 and 66 meters to 165 and 132 meters, respectively, is approximately 7%. Similarly, for structures 3 and 4, extending structure length from 99 meters to 165 meters results in a larger spatial extent where bed shear stresses fall below the critical erosion threshold, approximately 3%. For structures 5 and 6, such an increase in structure length is associated with an expanded spatial extent of around 2%. The extent of the greater reduction in bed shear stress behind structures, attributed to increased structure length, including both the magnitude of the effect and the spatial range over which the effect operates, thus, varies spatially. Hence, the degree to which structure length affects the effectiveness of permeable structures in reducing bed shear stress behind them varies depending on the location of structures. The area behind structures 3 and 4 exhibit a significantly larger percentage reduction in average bed shear stresses for increased structure length, 25%, than the areas behind structures 1 and 2 and 5 and 6, which exhibit reductions of 4% and 3%, respectively. This can be attributed to the placement of structures 3 and 4 relative to the mangrove fringe behind them. Increasing the length of these structures from 99 meters to 165 meters significantly expands the affected area where the structures reduce bed shear stress behind them, as the structures' effect is less blocked by the presence of the mangrove fringe, as shown in Figure E.2. Moreover, the spatial disparity in the impact of increased structure length on reducing bed shear stresses is ascribed to the diversity in local hydrodynamic conditions near the different sets of structures. Ahead of the extended length of structure 4, the approaching hydrodynamic conditions exhibit greater magnitude compared to those in front of structure sets 1&2 and 5&6, as deduced from the depicted depth-averaged velocity in Figure 5.8.



(a) **(b)**

Figure 5.9: Percentage change in the spatially averaged maximum bed shear stress, computed over the area behind the structures where bed shear stresses are reduced compared to the scenario without structures, determined at the point within the tidal cycle where the reduction in average bed shear stress is at its maximum, for a) structures 1&2 with varying structure lengths, and b) structures 3&4 and 5&6 with varying structure lengths

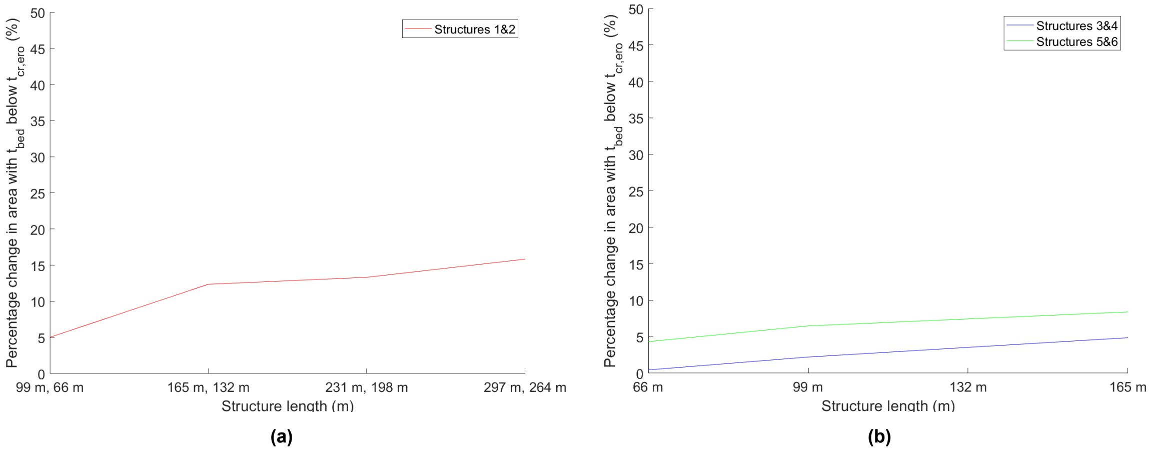
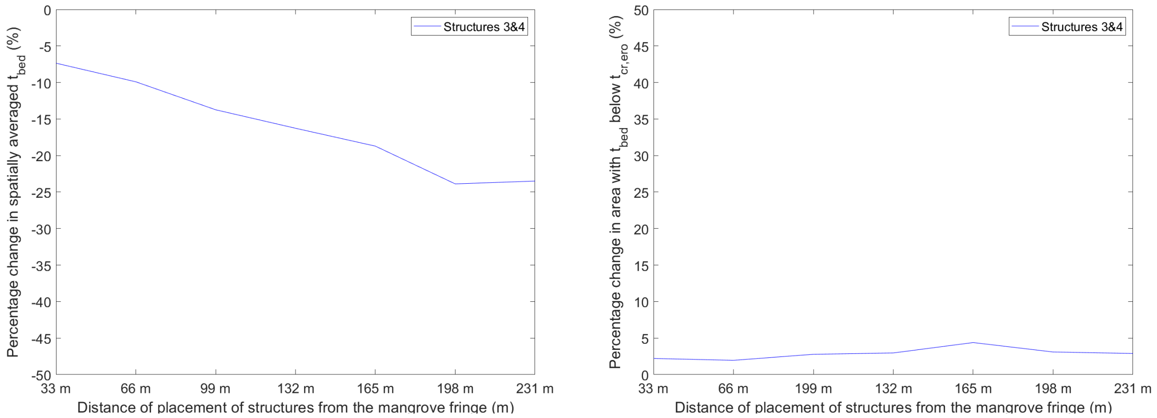


Figure 5.10: Percentage change in the area behind structures where the maximum bed shear stresses are below the threshold value of erosion, determined at the point within the tidal cycle where the area exhibiting bed shear stresses below the threshold value is at its minimum size, for a) structures 1&2 with varying structure lengths, and b) structures 3&4 and 5&6 with varying structure lengths

The spatially varying impact of increased structure length on the effectiveness of permeable structures in reducing bed shear stress behind them, is also depicted in Figures E.1, E.2, and E.3 for each set of structures. At certain structure locations, while there's an overall increase in bed shear stress reduction across an area behind the structures due to longer structures, other regions experience an increased increase in bed shear stresses because of the extended structure length. Figure E.2a distinctly illustrates a greater increase in bed shear stresses around the tips of structures for an increased length of structures 3 and 4. The same phenomenon applies to structures 5 and 6, as depicted in Figure E.3a. This is a consequence of the wider area over which resistance is applied to incoming currents, which is associated with increased structure length. This leads to greater deflection of flow towards regions of lower resistance, thus, towards the sides of the structures, and subsequently, to a greater compression of flow around the tips of the structures. However, the magnitude of this increase in bed shear stresses around the tips of the structures associated with increased structure length (approximately 0.15 N/m^2), is smaller compared to the increased reduction in bed shear stress behind the permeable structures associated with increased structure length (approximately 0.50 N/m^2), as permeable structures exert a more substantial impact on waves than on currents.

Distance of placement from the mangrove fringe

Increasing the distance of placement of structures from the mangrove fringe results in a greater percentage reduction in the spatially averaged maximum bed shear stress behind the structures, as can be concluded from Figure 5.11a. Increasing the distance of placement of the structures to the mangrove fringe from 33 meters, associated with a water depth of -0.0682 meters relative to MSL, by 33 meters incrementally results in a greater reduction of approximately 3% each time. Extending the distance of placement of the structures even further, from 165 meters (water depth of 0.2250 m relative to MSL) to 198 meters (water depth of 0.2061 m relative to MSL), results in a 5% greater reduction. Consequently, by extending the distance from 33 meters, associated with a water depth of -0.0682 meters relative to MSL, to 198 meters, associated with a water depth of 0.2061 meters relative to MSL, an overall increased reduction in average bed shear stresses across the sheltered area behind structures 3 and 4 of 17% is attained. Additionally, increased distance from the mangrove fringe leads to a (slightly) larger spatial extent behind the structures where the bed shear stress falls below the threshold value of erosion, as depicted in Figure 5.11b. Increasing the distance of placement from 33 meters to 165 meters results in a 2% larger spatial extent behind the structures where the bed shear stress falls below the threshold value of erosion.



(a) **(b)**

Figure 5.11: Percentage change in a) the spatially averaged maximum bed shear stress, computed over the area behind the structures where bed shear stresses are reduced compared to the scenario without structures, determined at the point within the tidal cycle where the reduction in average bed shear stress is at its maximum, and b) the area behind structures where the maximum bed shear stresses are below the threshold value of erosion, determined at the point within the tidal cycle where the area exhibiting bed shear stresses below the threshold value is at its minimum size, for various distances of placement of structures 3&4 from the mangrove fringe

However, there seems to be a limit to the impact of the distance of placement of structures from the mangrove fringe on the efficacy of permeable structures in reducing bed shear stress. The percentage reduction in spatially averaged bed shear stress behind the structures remains consistent for structures positioned at both 198 meters (water depth of 0.2061 m relative to MSL) and 231 meters (water depth of 0.2686 m relative to MSL) from the mangrove fringe, at 24%. Besides, the percentage change in spatial extent of bed shear stresses below the threshold value reaches a peak value for structures situated 165 meters from the mangrove fringe, at 4%, after which it slightly reduces for structures located at 198 meters and 231 meters from the mangrove fringe. This could be attributed to the fact that for extensive distances from the mangrove fringe, currents, depending on their incoming direction, could penetrate from the sides across the area directly behind the structures and influence the area again, which can be derived from Figure 5.12. It can be observed that for the extensive distance of placement of structures 3 and 4 at 231 meters from the mangrove fringe (Figure 5.12a), the direction of depth-averaged velocities is oriented towards the sheltered areas behind these structures, which is not the case for the structures placed at 132 meters from the mangrove fringe (Figure 5.12b). This suggests that currents are capable of penetrating from the sides across the sheltered areas behind structures, in the case of extensive distances of placement of structures from a mangrove fringe and when currents are directed in this manner.

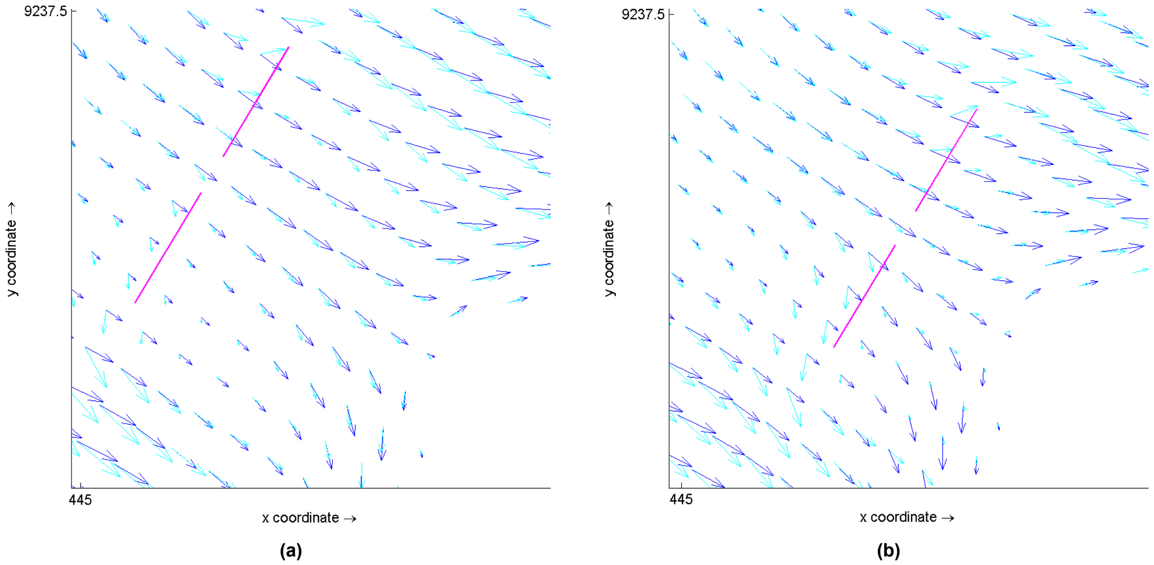


Figure 5.12: Differences in depth-averaged velocities for a structures 3&4 placed at a distance from the mangrove fringe of a) 231 meters (light blue), and b) 132 meters (light blue), compared to the baseline scenario without structures (dark blue)

Besides a reduction in bed shear stress related to increased distance of placement of structures from the mangrove fringe, Figures E.4e, E.4f and E.4g illustrate that for extensive distances, the areas in between the various sets of structures exhibit a slight increase in bed shear stress. This can be attributed to the fact that for extensive distances of placement of structures from the mangrove fringe, the flow between the sets of structures 3&4 and 5&6 gets more compressed, due to the closer proximity of structures 3 and 4 to structures 5 and 6 in that case. The magnitude of this increase in bed shear stress is however smaller compared to the increased reduction in bed shear stress behind the permeable structures.

Gap width in between a set of structures

Figure 5.13a shows that a larger gap width in between structures 1 and 2 and structures 5 and 6 results in a slightly smaller percentage reduction, with 1% and 2%, respectively, in the spatially averaged maximum bed shear stress across the sheltered areas behind the structures, compared to a narrower gap width. Moreover, Figure 5.13b illustrates that a larger gap width in between these sets of structures result in a smaller area behind the structures where the bed shear stresses fall below the threshold value of erosion, with a difference of approximately 5% for both sets of structures, compared to a narrower gap width. These phenomena can be explained by the fact that across the width of the gap in between structures, waves are not attenuated, thus the effect of waves on the bed shear stresses across the width of the gap behind the structures is not reduced. Moreover, a wider gap width leads to currents being deflected towards the gap in between the two structures instead of solely around the tips of the structures at both ends, as is demonstrated in Figure 5.14b for a wider gap width of 99 meters in between structures 5 and 6. This results in a compression of flow through the wider gap, consequently increasing depth-averaged velocities and forces on the bed throughout the gap width. This is not the case for a smaller gap width of 33 meters, as is demonstrated in Figure 5.14a for a gap width of 33 meters in between structures 5 and 6. A larger gap width, therefore, results in a wider area where wave energy is not dissipated and where currents get deflected towards the gap, leading to larger depth-averaged velocities through the gap in between the structures and consequently, to an area behind structures where bed shear stresses are less reduced compared to a structure configuration with a smaller gap width.

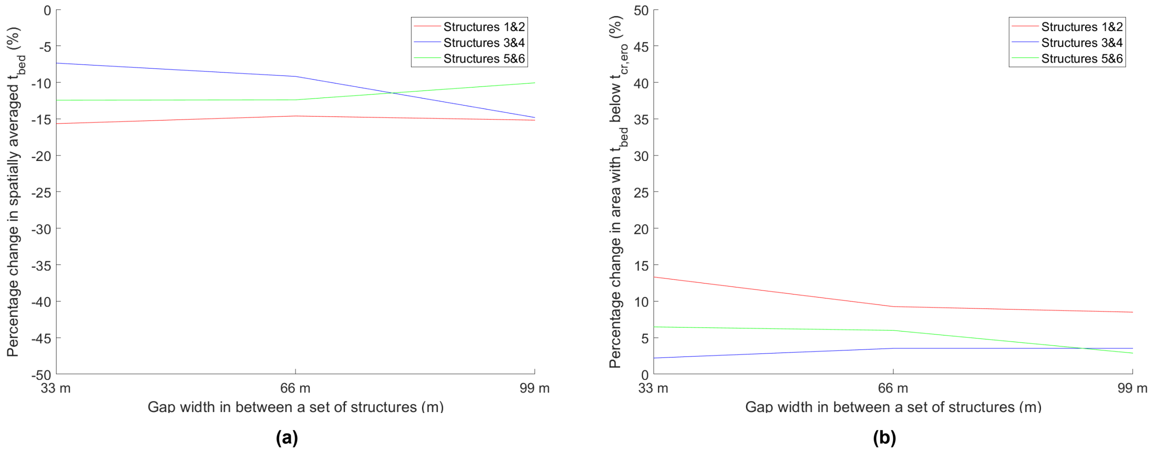


Figure 5.13: Percentage change in a) the spatially averaged maximum bed shear stress, computed over the area behind the structures where bed shear stresses are reduced compared to the scenario without structures, determined at the point within the tidal cycle where the reduction in average bed shear stress is at its maximum, and b) the area behind structures where the maximum bed shear stresses are below the threshold value of erosion, determined at the point within the tidal cycle where the area exhibiting bed shear stresses below the threshold value is at its minimum size, for varying gap widths in between structures

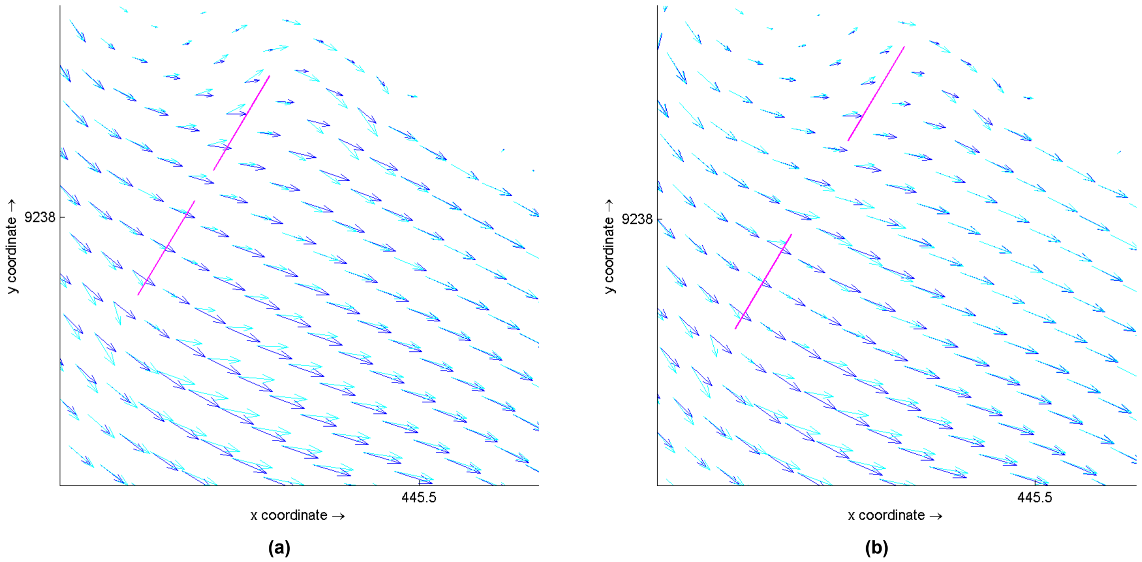
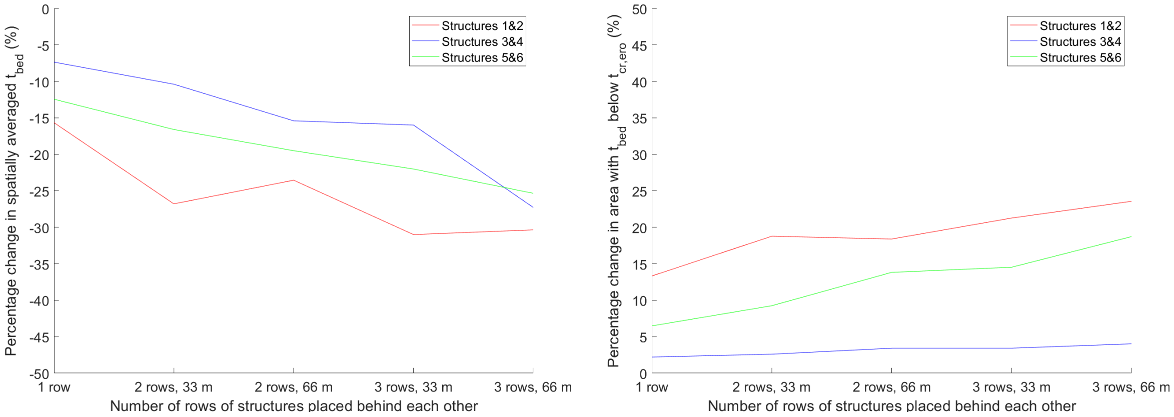


Figure 5.14: Difference in depth-averaged velocity between scenario a), featuring a structure configuration with a gap width in between structures 5&6 of 33 m (light blue), and scenario b), featuring a structure configuration with a gap width in between structures 5&6 of 99 m (light blue), compared to the baseline scenario without structures (dark blue)

The opposite, however, occurs for a larger gap width in between structures 3 and 4, as depicted by the blue lines in Figure 5.13a and 5.13b. For this set of structures, increasing the gap width to 99 meters leads to a 7% greater percentage reduction in the spatially averaged maximum bed shear stress behind the structures compared to a gap width of 33 meters. Additionally, it results in a slightly larger area behind the structures where the bed shear stresses are below the threshold value of erosion. This is attributed to the relative positioning of these structures to the mangrove fringe, which hinders the spatial extent of the structures' influence, as well as the increased effect of the structure 4 on the incoming hydrodynamics due to its increased length. A larger gap width in between structures 3 and 4 is associated with a slight displacement of structure 4 to the right relative to the mangrove fringe, allowing its influence to extend over a slightly larger area to the right of the mangrove fringe than for the structure configuration with a smaller gap width, as depicted in Figure E.6. This leads to a larger area behind structure 4 across which bed shear stresses are decreased for the structure configuration with a wider gap width compared to the structure configuration with a narrower gap width. This phenomenon potentially counteracts the lesser reduction in bed shear stress across the area directly behind the structures related to the wider gap width, contributing to the greater percentage reduction in spatially averaged bed shear stress and increased area where bed shear stresses fall below the threshold value for a wider gap width of structures 3 and 4.

Number of rows of structures placed behind each other

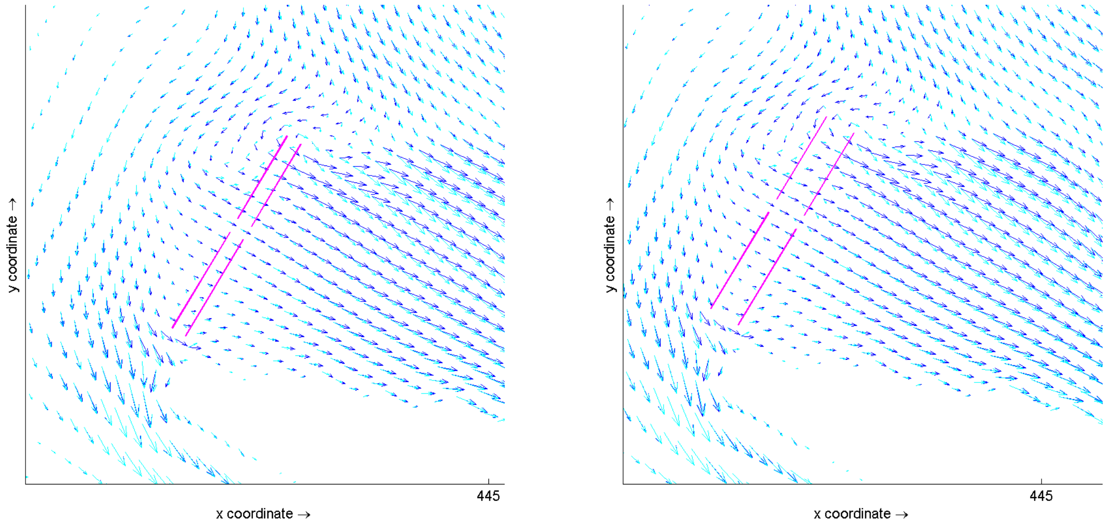
Multiple rows of structures placed behind each other result in a significantly greater percentage reduction in spatially averaged maximum bed shear stress compared to a single row, for all structure locations, as illustrated in Figure 5.15a. Adding an additional row at a distance of 33 meters for structure set 1&2 results in a 12% greater reduction in average bed shear stresses across the sheltered areas behind the structures. Adding two extra rows at intervals of 33 meters for structure set 1&2 results in an even greater reduction of 16%. As for structure set 3&4, this percentage increase in reduction in average bed shear stresses amounts to 3% and 9%, respectively. For structure set 5&6, adding an extra row at a distance of 33 meters yields a 4% greater percentage reduction in bed shear stresses, and adding two extra rows at intervals of 33 meters results in a 10% greater reduction. Moreover, multiple rows of structures placed behind each other result in an increased spatial extent across which the maximum bed shear stress falls below the threshold value of erosion for structure sets 1&2 and 5&6, as depicted in Figure 5.15b by the red and green line, respectively. Adding an extra row at a distance of 33 meters for structure sets 1&2 and 5&6 results in a 6% and 4% greater spatial extent, respectively. The effect of the number of rows on the spatial extent of structure set 3&4 is however of a much smaller magnitude. Adding an extra row at a distance of 33 meters for structures 3&4 results in a percentage increase in spatial extent of only about 1%. This is attributed to the presence of the mangrove fringe closely behind structures 3&4, which blocks the spatial extent of the structures' effect. Hence, the degree to which multiple rows of structures affect the effectiveness of permeable structures in reducing bed shear stress varies spatially.



(a) **(b)**

Figure 5.15: Percentage change in a) the spatially averaged maximum bed shear stress, computed over the area behind the structures where bed shear stresses are reduced compared to the scenario without structures, determined at the point within the tidal cycle where the reduction in average bed shear stress is at its maximum, and b) the area behind structures where the maximum bed shear stresses are below the threshold value of erosion, determined at the point within the tidal cycle where the area exhibiting bed shear stresses below the threshold value is at its minimum size, for varying number of rows of structures placed behind each other

Upon comparison of Figure 5.15a and 5.15b, it can also be deduced that the effect of the distance in between multiple rows of structures on the effectiveness of structures in reducing bed shear stresses behind the structures varies spatially. For structure set 1&2, the red lines, the effectiveness of structures in reducing the spatially averaged bed shear stress behind them decreases with 3% for an increased distance of 66 meters between the rows compared to a smaller distance of 33 meters between the rows. Conversely, structure sets 3&4 and 5&6 exhibit increased effectiveness in reducing the spatially averaged bed shear stress with a larger distance between multiple rows of structures. This contrast could be attributed to local variations in hydrodynamic conditions in the vicinity of the structures. On the right side of structure set 1&2, currents are directed towards the structures. When the spacing between the rows of these structures is increased, currents are able to penetrate across the area in between the rows of structures, as is demonstrated in Figure 5.16b, thereby increasing forces on the bed again. This is not the case for structure sets 3&4 and 5&6, as is demonstrated in Appendix F.



(a) **(b)**

Figure 5.16: Differences in depth-averaged velocities for a 2 rows of structure set 1&2 with a distance in between the rows of structures of a) 33 meters (light blue), and b) 66 meters (light blue), compared to the baseline scenario without structures (dark blue)

The varying impact of multiple number of rows of structures placed behind each other on the effectiveness of permeable structures in reducing bed shear stress behind them, is also depicted in Figures E.8, E.9 and E.10 for each set of structures. Upon examining these spatial graphs, it can be deduced that placing multiple rows of structures behind each other at the location of structure sets 3&4 and 5&6 results in a slight increase in bed shear stress around the tips of the structures and in between these sets of structures. This is attributed to the increased compression of flow in between these sets of structures in the case of structure configurations of these sets of structures featuring multiple rows. However, this increase in bed shear stresses is not of significant magnitude and is of much smaller magnitude than the decrease in bed shear stresses behind the structures.

5.3.3. Summary

The presence of permeable structures leads to a significant reduction in bed shear stress across areas directly behind the structures, attributed to the dissipation of wave energy and a slight decrease in current velocities caused by the resistance of the permeable structures as currents pass through them. Around the tips and in between sets of structures, a slight increase in bed shear stresses occurs due to deflection of currents and subsequent compression of flow. Nevertheless, this increase in bed shear stress is considerably smaller than the reduction observed behind the structures, as the influence of structures on incoming waves is larger than their effect on incoming currents.

Increased structure length is associated with a greater percentage reduction in the average maximum bed shear stress behind the structures. Furthermore, it leads to a larger spatial extent behind the structures in which the average maximum bed shear stresses fall below the critical threshold for erosion. The extent of the impact of structure length on the reduction of bed shear stresses varies spatially.

Increasing the distance of placement of structures from the mangrove fringe results in a greater percentage reduction in the average maximum bed shear stresses behind the structures. Additionally, this leads to a (slightly) larger spatial extent behind the structures where bed shear stresses fall below the erosion threshold. However, there appears to be a limit to the influence of the distance of placement of structures from the mangrove fringe on the performance of permeable structures in reducing bed shear stress. Beyond a distance of placement of 198 meters from the mangrove fringe, the effectiveness of the structures in reducing bed shear stress behind them, both in terms of magnitude and spatial extent, does not further increase, as from that distance onwards, currents are able to penetrate the areas behind the structures again.

A larger gap width between structures 1 and 2 and 5 and 6 results in a slightly smaller percentage reduction in bed shear stresses behind the structures. Moreover, it leads to a smaller area behind the structures where bed shear stresses fall below the erosion threshold. Conversely, a larger gap width between structures 3 and 4 results in a slightly larger percentage reduction in bed shear stresses and a slightly larger spatial extent where bed shear stresses fall below the threshold value. This is, however, attributed to the relative positioning of these structures to the mangrove fringe, affecting the spatial extent of the structures' influence.

Multiple rows of structures placed behind each other result in a significantly greater percentage reduction in averaged maximum bed shear stress behind the structures, as well as a larger area where the bed shear stress falls below the threshold value of erosion, compared to structure configurations consisting of a single row. However, the effect of the distance in between multiple rows of structures on the performance of permeable structures in reducing bed shear stress varies depending on the location of the structures. Besides, the magnitude of the effect of the number of rows on the spatial extent of the effect of structure set 3&4 is much smaller than for structure sets 1&2 and 5&6.

6 Discussion

This research aimed to develop an integrated design guideline for permeable structures aimed at rehabilitating mangrove habitat, merging scientific knowledge with the lessons learned from pilot projects. Moreover, it aimed to deepen understanding of the influence of design parameters on the performance of these permeable structures. This chapter presents a discussion on the methodology, findings, and some limitations of the research.

6.1. Conceptual framework

Through the extensive literature review, the ecological and engineering factors crucial in designing permeable structures for mangrove rehabilitation along eroding coastlines were identified and categorized into biological, hydrodynamic, morphodynamic, and design variables. These factors were subsequently presented by means of a conceptual framework representing a visualization of these important and interrelated variables, along with their interacting processes. It is important to acknowledge that these interrelations are intricate, given that mangrove habitat restoration through permeable structures is an interdisciplinary endeavor spanning engineering and ecological domains. Moreover, the dynamics and interactions between permeable structures and mangrove-mud coastlines are highly site-specific. To effectively address the objectives and challenges of individual rehabilitation projects, and to devise an adequate design for permeable structures, careful consideration of all relevant variables is imperative.

The conceptual framework thus visually represents the essential variables and interactive processes relevant to designing permeable structures with the goal of rehabilitating mangroves on eroding coastlines through morphodynamic habitat restoration. It functions as a design tool for practical applications, fulfilling the following objectives:

1. Identifying the biophysical variables that influence the specific environmental requirements of mangrove seedling establishment;
2. Identifying the design variables that influence the performance of permeable structures in restoring mangrove habitat;
3. Identifying the interactions between biophysical and design variables that influence the performance of a specific permeable structure design in the restoration of mangrove habitat.

This framework serves as a foundation for initial assessments and acts as a guiding reference during the design process of permeable structures, and is in this way supportive to the design guideline developed in this study. By identifying, comprehending, and conducting in-depth analyses on the various variables and their interactive processes, the conceptual framework can offer valuable insights into the complex dynamics of morphodynamic mangrove habitat restoration through permeable structures, assisting in the design process of such structures.

6.2. Design guideline

The extensive literature review of the research has also resulted in the formulation of a design guideline for permeable structures aimed at rehabilitating mangroves. As the complete story of morphodynamic mangrove habitat restoration through permeable structures requires an interdisciplinary approach, incorporating the domains of both ecology and engineering within the design of permeable structures is extremely important with regards to the long-term success of such a rehabilitation initiative. Moreover, since mangrove characteristics are highly site-specific, the design process involves a complex interplay among the ecological and engineering variables, as illustrated within the conceptual framework. There is no singular, universally applicable optimal design or one-size-fits-all solution to every location. Therefore, it is of utmost importance to approach each project or case as unique and to carefully consider its distinctive characteristics when reviewing the design guideline. However, with the design guidelines developed in this study, it is not yet possible to generate a detailed design for permeable structures. There are significant knowledge gaps in certain areas crucial for developing a sound and effective design, particularly concerning the specific threshold values of distinct mangrove species and the precise influence of certain design parameters on the performance of permeable structures. Therefore, the limitations of the design guideline, along with the associated knowledge gaps identified in this study, are listed and elaborated upon in section 6.2.1. Furthermore, in section 6.2.2, the degree of applicability of this design guideline is discussed.

6.2.1. Limitations

Concerning the determination of the spatial extent of the area to be rehabilitated to meet a certain rehabilitation objective, while existing literature provides some estimates and relations, there is insufficient detailed information and established methodologies for quantifying this. For instance, concerning coastal protection as a rehabilitation objective, numerous studies suggest that mangrove forest widths exceeding 100 meters are sufficient to offer coastal protection against wind and swell waves, as well as extreme events (Alongi, 2008; Ferreira et al., 2022; Van Bijsterveldt, 2023). However, the level of coastal protection provided by a mangrove forest depends on the local geomorphic setting and the magnitude of the event being mitigated (Balke & Friess, 2015). Furthermore, Méndez and Losada (2004) has established a correlation between mangrove forest dimensions and wave attenuation, and Montgomery et al. (2019) offers a predictive model for estimating peak surge levels within mangrove forests based on their dimensions. However, the practical feasibility of applying these formulas has not been fully clarified and requires more thorough assessment before they can be practically implemented. While predicting the extent of ecosystem values, like coastal protection and carbon sequestration, offered by a specific mangrove forest, is challenging due to its dependency on various mangrove characteristics such as tree density, height, and canopy width, which in turn are influenced by local biophysical conditions as well, further research aimed at developing practical tools akin to the formulations proposed by Méndez and Losada (2004) and Montgomery et al. (2019) could enhance the effectiveness of design guidelines. Such formulations, like those of Méndez and Losada (2004) and Montgomery et al. (2019), need to be developed from a practical standpoint, ensuring their applicability within design guidelines.

Regarding the specification of the biophysical conditions required for the natural regeneration of the mangrove species targeted for rehabilitation, a significant knowledge gap exists regarding species-specific threshold values associated with the windows of opportunity. Although much of the literature emphasizes the critical importance of considering species-specific characteristics in mangrove restoration planning (Lewis, 2005; Balke et al., 2011; Cannon et al., 2020; Su et al., 2022), fewer studies have quantified these species-specific characteristics or threshold values. Without information on these species-specific threshold values, it remains challenging to specify precise design requirements for permeable structures. For instance, if no specific threshold values are known regarding the inundation-free period required by seedlings of the target mangrove species, it becomes impossible to determine the required increase in bed level elevation that permeable structures must facilitate. This lack of information consequently impedes the determination of the required amount of wave dissipation to be facilitated by a certain structural configuration, thereby hindering the formulation of clear functional and structural requirements, and thus design alternatives. Increasing knowledge on species-specific threshold values associated with the windows of opportunity is thus highly valuable in improving the design of permeable structures, and subsequently, in enhancing the effectiveness and successful performance of these structures in restoring mangrove habitat.

As emphasized earlier in section 1.2, there is a lack of understanding regarding the influence of certain design parameters, such as structure length and size of openings between structures, on the performance of permeable structures. Within the design process, this hinders the translation of functional and structural requirements into design alternatives, as the relationship between certain design parameters, related to both spatial and structural design of permeable structures, and the performance of permeable structures remains unclear. Even though this study aims to contribute to increasing this knowledge, much can be gained through further research. Recommendations for addressing this knowledge gap are elaborated upon in section 7.2.

Regarding the stability of permeable structures, a lack of knowledge is identified as well. Detailed information on the structural stability of these structures, such as how to assess forces on the structural components and quantify their strength, is currently missing. Although Wilms et al. (2021) provides some information and ways to increase the strength of structures to withstand hydrodynamic forces, practical tools to assess structural strength and stability are lacking. This knowledge gap impedes the formulation of clear structural requirements and, consequently, hinders the translation of these requirements into design alternatives that meet the necessary criteria for structural stability and strength.

Lastly, there is an overall lack of knowledge on the exact interaction between the overall configuration of permeable structures and morphodynamic processes, such as the performance of a certain configuration in promoting sedimentation and an increase in bed level elevation under various hydrodynamic conditions. As the performance in facilitating an increase in bed level elevation highly depends on local conditions, such as prevailing wave conditions and suspended sediment budget, and is thus highly site-specific, quantifying the expected associated morphodynamic changes will be difficult. Gijón Mancheño (2022) therefore recommends assessing and simulating the morphodynamic response of a certain coastal system to the implementation of a certain permeable structure configuration. However, this process is very time-consuming. For this reason, it would be useful to establish ”general relationships” or practical tools that could provide a rough estimate of the amount of sedimentation that could be facilitated by a certain design of permeable structures, given certain hydrodynamic conditions and morphodynamic characteristics of the coastal system.

6.2.2. Application

According to Beeston et al. (2023), guidelines for mangrove restoration extend beyond physical design and restoration activities. Drawing on a wealth of experience from best practices, they should encompass additional factors that can significantly impact the success of a restoration project. Beeston et al. (2023) have established a project cycle for mangrove restoration that includes additional factors beyond the design phase of a restoration project, as depicted in Figure 6.1. As explained in section 5.2, the specific design guideline for permeable structures developed in this study elaborates on the first two steps of the Building with Nature five step design approach, which falls within the ”Project Design” phase of the project cycle for mangrove restoration as outlined by Beeston et al. (2023). The BwN five-step design approach concludes with ”Preparing the solution for implementation”, marking the end of the ”Project Design” phase and leading into the next step of the project cycle (see Figure 6.1). The design guideline for permeable structures developed in this study thus pertains to the first two phases of this project cycle. It addresses the phase of ”Setting goals and assessing feasibility” and partially covers the ”Project Design” phase.

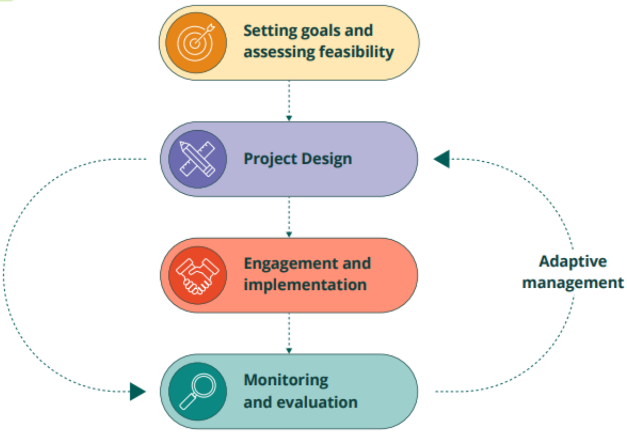


Figure 6.1: Project cycle for mangrove restoration (Beeston et al., 2023)

As highlighted by Beeston et al. (2023) and numerous others (Ellison, 1999; López-Portillo et al., 2017; Winterwerp et al., 2020; Wilms et al., 2021; Ferreira et al., 2022), it is crucial to acknowledge that the success of a mangrove restoration project isn't solely contingent on an adequate physical design but also hinges on various additional factors. For permeable structures to be effective, they must be part of an integrated coastal zone management strategy and must be supported by policy and planning authorities. Local governance structures play a crucial role and must be engaged to ensure successful implementation. Additionally, community engagement is essential throughout all stages of the project cycle, including training, preparation, planning, procurement, construction, monitoring, and maintenance (Wilms et al., 2021). Stakeholder mapping and continuous engagement throughout the entire project cycle, including throughout the implementation of the specific design guideline for permeable structures, are thus crucial aspects. Additionally, establishing a monitoring and adaptive management strategy is an indispensable aspect in the project cycle of a restoration project, and thus within the design process of permeable structures. Adaptive management, which involves conducting field measurements, modeling, data analyses, evaluation, and subsequent design optimization, helps ensure the long-term effectiveness of permeable structures in restoring mangrove habitat.

Regarding the current practical application of the developed design guideline in this study, it is important to recognize that it presents an initial framework rather than a quantitative step-by-step plan. As outlined in section 6.2.1, there are currently significant knowledge gaps that hinder the development of quantitative content within certain steps, including practical tools and formulas that depict relationships between interacting variables. Therefore, it was not possible to elaborate the complete content of the steps comprising the design guideline in detail. Consequently, it is not yet possible to directly apply this design guideline in practice and to achieve a fully refined design for permeable structures aimed at morphodynamic habitat restoration of mangroves through this design guideline. However, it can already serve as a set of guidelines to, for instance, coastal engineers, to understand the design process for such permeable structures aimed at rehabilitating mangroves, and to gain insight into both the pertinent engineering as well as ecological variables involved in the design process of these nature-based solutions.

6.3. Delft3D modelling

To enhance understanding of the influence of design parameters on the performance of permeable structures aimed at mangrove rehabilitation, a numerical modeling study using a process-based Delft3D model was conducted. This section outlines the constraints associated with the Delft3D model and the challenges in interpreting its results, as well as discusses the application of the findings of this modeling research. Section 6.3.1 elaborates on certain limitations associated with the Delft3D model, followed by section 6.3.2, which expands upon the interpretation of the model results. Section 6.3.3 delves into the application of the findings derived from this modelling research.

6.3.1. Delft3D model limitations

Configuring a coupled version of the Delft3D-4 model improved the accuracy of hydrodynamic coastal processes within the model outputs compared to the model initially set up by Bisschop (2023) and subsequently elaborated on by Thillaigovindarasu (2023), as it accounts for the interaction between waves and currents. As this study focuses on the performance of structures in reducing bed shear stress, obtaining the most accurate representation of bed shear stress is highly valuable. This is achieved by coupling the FLOW and WAVE modules, which considers the interaction of waves and currents in determining the bed shear stress across the model domain. However, to maintain reasonable computational efficiency, and because modelling over one storm is expected to provide reasonable outputs given the episodic morphodynamic nature of the Demak coastal system, the model is configured to simulate one tidal cycle. The performance of permeable structures, aimed at facilitating sedimentation and increasing bed level elevation, on the contrary, unfold over longer timescales as an increase in bed level is associated with the morphodynamic response of a natural system to an intervention, on the long-term. Therefore, while investigating the influence of the various design variables on structure performance over a single tidal cycle provide insights, a more accurate assessment of their impact on the performance of permeable structures could be achieved by extending simulation duration over longer periods of time. This way multiple storms and variations in hydrodynamic forcing can be considered.

In addition, to maintain computational efficiency and given that this study aims to offer preliminary insights into the influence of design variables on structure performance, a morphostatic approach is employed in the model, resulting in fixed bed levels. However, without updating bed levels, factors such as bed shear stress, water depths, and currents remain static, diverging from real-world variability. Consequently, the model does not consider potential variations in bathymetry associated with the presence of permeable structures. Since permeable structures aim to facilitate sedimentation and an increase in bed level elevation, adopting a morphodynamic approach could lead to more realistic model outputs and provide a better representation of the performance of permeable structures. A morphodynamic approach could enhance understanding on the influence of design parameters on the performance of permeable structures in restoring the bed level elevation instead of only considering the obtained reduction in bed shear stress.

To avoid over-complicating the nested model, the effects of the mangrove fringe located within the intertidal region behind structures 3 and 4 is not modelled in this study (Thillaigovindarasu, 2023). The model does consider the bathymetry of the mangrove fringe, but it does not account for the effects of vegetation on currents and waves. Mangrove stands, however, have the ability to dampen waves and slow down water flow as tides and waves pass through them. Consequently, they play a significant role in shaping hydrodynamics and, consequently, bed shear stresses in their vicinity. Moreover, the model does not account for the presence of cheniers, which are present in the Demak coastal system as identified by Van Bijsterveldt (2023). Cheniers can dissipate incoming wave energy and subsequently, influence hydrodynamics as well as morphodynamics in the vicinity of the structures. These influences are, on the other hand, not anticipated to significantly alter the correlations between design variables and the performance of structures in reducing bed shear stresses, as the model analysis of this study focuses on the relative differences in the performance of structures associated with a varying design variable. However, the absolute magnitude of the effect of a design variable on structure performance may slightly differ when considering factors such as cheniers and the mangrove fringe.

6.3.2. Interpretation of model results

An important aspect to consider when interpreting the model results is the lack of validation for the effect of permeable structures on current reduction due to a lack of field data. Without validation against field data, the model's ability to accurately represent the effect of permeable structures on currents is compromised, potentially resulting in less precise and reliable simulation outcomes. This limits the accuracy and reliability of predictions regarding the impact of these structures on currents, leading to slight uncertainty surrounding the correlations between design parameters and structure performance as identified in this study. On the other hand, this is not expected to significantly influence the correlations identified in this study, as the research focuses on relative differences rather than absolute values.

Another important point to note is that the analysis of the model results primarily focuses on the performance of structures in reducing bed shear stress behind them. It is, however, equally important to assess the potential increase in bed shear stresses across certain areas concerning scour, as this can lead to instability or even failure of the structures. Ensuring long-term effectiveness and structural integrity of permeable structures requires a comprehensive understanding of the influence of design parameters on both the reduction as well as potential increase in bed shear stresses, with regards to structural stability. This study qualitatively assesses the areas of increased bed shear stress associated with certain structure configurations, and thus associated with certain design variables, but doesn't provide quantitative expressions for them.

In terms of the robustness of the findings in this study, it is important to note that only a limited number of values for each design variable were tested, as only a restricted number of scenarios in the Delft3D model could be executed due to time constraints. This limitation impacts the ability to generalize the findings regarding the influences of the design variables on structure performance. Moreover, the constrained number of scenarios may compromise the accuracy of results and, consequently, the robustness of the conclusions drawn. To enhance the reliability and robustness of the conclusions, it is recommended to expand the scope of values tested for each design variable, which can lead to more robust and accurate findings.

Another aspect to consider regarding the analysis of the model results, particularly concerning the correlation between the distance of placement of structures from the mangrove fringe and structure performance, is the lack of assessment in this study regarding the influence of water depth with respect to these structure configurations. A change in the distance of placement of structures from the mangrove fringe is associated with a change in water depth. Therefore, it is possible that the alteration in water depth affects the performance of the structure in reducing bed shear stresses rather than the change in distance to the coastline. However, in this study, the relative influences of these two parameters on the performance of permeable structures could not be assessed thoroughly, as their influence is intertwined. Consequently, the influence of the water depth at which structures are placed on structure performance is not assessed in this study, but could potentially contribute to the correlation identified in this study between the distance of placement of structures and structure performance.

Furthermore, in analyzing the influence of a design variable on the effectiveness of structures in reducing bed shear stress in terms of the spatial extent in which the bed shear stress are reduced to below the critical value of erosion, it is imperative to note a critical aspect. The spatial extent of the effect associated with a certain structure configuration is defined as the size of the area where the maximum bed shear stresses are below the threshold value of erosion. A critical bed shear stress for erosion is assumed 0.25 N/m^2 in the context of the study area. However, the critical shear stress that is required for incipient motion largely depends on the sediment properties. As the sediment composition in the area displays spatial variations (muddy (80%) with some sandy content (20%)) (BioManCo, 2018), there is some uncertainty surrounding the precise value of the critical bed shear stress of the area. Consequently, as the spatial extent is related to this threshold value, some uncertainty lays within this analysis as well. On the other hand, it is not expected that a different value of the critical bed shear stress significantly changes the correlations identified between design variables and the effectiveness of structures in reducing bed shear stresses across a certain spatial extent. This is because this study concentrates on the relative disparities in the spatial extent linked to a design variable, rather than the absolute values of this spatial extent. The absolute values associated with the spatial extent in which bed shear stress fall below the critical threshold value, nonetheless, will slightly differ for a different value for the critical bed shear stress.

Regarding the findings concerning the influence of placing multiple rows of structures behind each other on structure performance, it is crucial to point out an identified contrast regarding the associated structural effectiveness. The model outcomes indicate that placing multiple rows of structures behind each other leads to a significantly higher percentage reduction in average maximum bed shear stress behind the structures, as well as a larger area behind them where the bed shear stress falls below the erosion threshold, compared to a single row of structures. This suggests that placing multiple rows of structures behind each other enhances the performance of permeable structures significantly. However, as noted by Wilms et al. (2021), simultaneous construction of multiple consecutive rows of permeable structures is not advisable. This is due to the risk of sediment rapidly accumulating behind the initial structure, potentially resulting in waterlogging and hindering sediment transport toward the rear structures and eventually toward the coastline. It is, therefore, essential to recognize that the results of this study primarily focus on assessing structure performance in terms of reducing bed shear stresses, while morphodynamic factors also significantly influence structure performance, which are not addressed in this modeling investigation.

The contrast mentioned above sheds light on one other crucial aspect to consider regarding the interpretation of the model results of this study. While the influence of design variables on structure performance is assessed in terms of the reduction in bed shear stresses they induce, the intended function of permeable structures is to facilitate sedimentation in the sheltered areas behind them and an increase in bed level elevation. In other words, structure performance is intricately linked to the morphodynamic response of a coastal system. Besides dissipating wave energy and reducing bed shear stresses, the effectiveness of permeable structures also hinges on their ability to import and trap sediments. This capability is influenced by factors such as structure permeability and the sediment characteristics of the coastal system, including its suspended sediment budget. Therefore, evaluating the performance of permeable structures, and consequently assessing the impact of design variables on their performance, entails more complexity than simply measuring the reduction in bed shear stresses. Morphodynamic processes and the interactions between various design variables, such as the interplay between permeability and the distance of structure placement from the coastline, must be taken into account. However, time constraints and model simplifications in this study limited this possibility. To gain a better understanding of how design variables influence structure performance and their interactions, it is recommended to incorporate morphodynamic processes, to bridging the existing knowledge gap on the influence of design parameters on the performance of permeable structures more accurately.

6.3.3. Application

The highly dynamic and non-uniform nature of the Demak coastal zone, coupled with high subsidence rates (Prasetyo et al., 2019), makes this coastal system challenging to compare with others worldwide. However, the analysis conducted in this study is set up to mitigate the impact of these factors as much as possible, aiming for conclusions that are more generally applicable. The focus of this research analysis is, therefore, primarily on areas directly surrounding the permeable structures rather than those closer to the coastline, which exhibit long channels and significant alongshore non-uniformity. Additionally, the analysis emphasizes relative differences between distinct structure configurations rather than absolute values. Furthermore, each structure set is analyzed individually and independently, with an inter-comparison conducted between various locations to explore potential differences, and consequently, location dependence of correlations between design variables and structure performance.

Although the study aimed to establish generally applicable conclusions regarding the influence of various design parameters on the performance of permeable structures, further research is required to enable the application of the correlations between design variables and structure performance identified in this study to other coastal systems, and subsequently, to enable incorporation of these correlations into the design guideline, as developed in this study. Besides the highly dynamic and non-uniform nature of the Demak coastal zone, other limiting factors to the study's applicability range, are the facts this research only considers one combination of tidal and wave conditions, and that morphodynamic processes are not considered. The impact of permeable structures on waves and currents depends on the magnitude and incoming direction of these forces (Gijón Mancheño, 2022). Consequently, the question arises whether the correlations between design variables and structure performance, as identified in this study, alter under varying hydrodynamic conditions. In other words, it raises the question how hydrodynamic conditions influence the correlation between design variables and structure performance. Moreover, the question arises whether the correlations identified in this research remain unchanged when considering morphodynamic processes and employing a morphodynamic approach that updates bed level elevation.

7 Conclusion and recommendations

In this concluding chapter, answers to the research questions are addressed, aligning with the fulfillment of the research objective. Furthermore, recommendations for future research are provided.

The objective of this research was:

To develop an integrated design approach (design guidelines) for permeable structures aimed at rehabilitating mangrove habitat along eroding coastlines, merging scientific knowledge with the lessons learned from pilot projects, and to enhance understanding of the influence of design parameters on the performance of these permeable structures.

7.1. Conclusions

The answers to the research questions will be addressed sequentially, commencing with the initial research question:

> **RQ1:** What are the relevant ecological and engineering variables that must be considered when designing permeable structures aimed at rehabilitating mangroves, and how do these relate to each other, within the context of a conceptual framework that can function as a design tool?

A conceptual framework that visually represents the relevant ecological and engineering variables, as well as their interactive processes, relevant to designing permeable structures aimed at rehabilitating mangroves through morphodynamic habitat restoration is presented in Figure 7.1. The conceptual framework encompasses these variables through the categorizations of the variables into biological, hydrodynamic, morphodynamic and design variables, and displays their interactive processes.

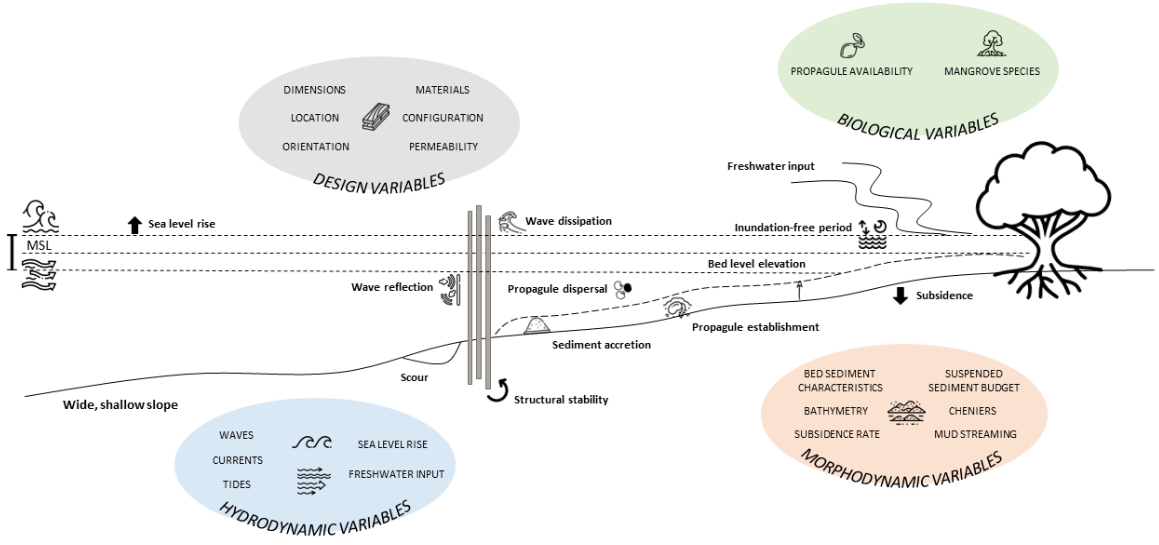


Figure 7.1: A conceptual framework illustrating the critical ecological and engineering variables, along with their interacting processes, important in the design of permeable structures aimed rehabilitating mangroves through morphodynamic habitat restoration

The relevant biological variables include the mangrove species targeted for rehabilitation and the availability of propagules. Mangrove colonization or seaward expansion only occurs when a series of favorable conditions align, providing windows of opportunity that allow seedlings to establish and grow into reproductive trees. Each mangrove species has specific preferences, associated with specific threshold values, regarding these favourable conditions, which are dependent upon its species characteristics as well as on the biophysical conditions of their habitat. Understanding the ecology of the mangrove species targeted for rehabilitation, along with their threshold values, is essential for effective structure design. Additionally, assessing propagule availability, as the initial threshold for seedling establishment, is critical to ensure successful mangrove rehabilitation.

Waves, tides, and currents are the key hydrodynamic factors in designing permeable structures, and, among other, shape their functional criteria. Waves mobilize sediments from the foreshore that are subsequently transported onshore by currents during rising tides. Since permeable structures are intended to facilitate sedimentation in the sheltered areas behind them, and a subsequent increase in bed level elevation, their design should effectively dissipate the incoming wave energy to create sheltered areas conducive to sediment settlement, while permitting sediment to pass through. Moreover, as a freshwater source is a prerequisite to mangrove habitat, evaluating and mapping freshwater sources are crucial within the design process of permeable structures, to prevent obstruction caused by presence of the structures. Considering a site's susceptibility to relative sea level rise, such as subsidence, is vital during the initial design phase as well. In areas with high local sea level rise and limited sediment availability, permeable dam construction may be unfeasible. Examining subsidence rates beforehand, therefore, is essential in assessing a site's suitability to permeable structures as a solution to restore mangrove habitat, and ensures the potential effectiveness of permeable structures for morphodynamic mangrove habitat restoration.

In the realm of morphodynamics, various factors including bathymetry, bed sediment characteristics, suspended sediment budget, and dynamic sediment processes such as cheniers and mud streaming are pivotal in the design of permeable structures. Sedimentation and erosion processes are influenced by the bathymetry of a coastal system, shaping the response of mangrove-mud coastlines to restoration efforts. Bed sediment properties, including grain size distribution and cohesion, determine the bed material's resistance to hydrodynamic forces. Alongside the prevailing hydrodynamic conditions at a restoration site, they dictate the degree of wave dissipation a permeable structure design must achieve to promote sedimentation within the sheltered areas behind them. Furthermore, before diving into the design process of permeable structures, it is essential to evaluate the suspended sediment budget within a natural system. This assessment is particularly crucial for determining the suitability of a site for permeable structures as a solution to restore mangrove habitat, especially considering a site's potential vulnerability to relative sea level rise. Lastly, dynamic sediment features like cheniers and mud streaming play significant roles in coastal accretion along mangrove-mud coastlines. Considering these features in the spatial design of permeable structures is essential to prevent interference or disruption by the presence of these structures, as this could diminish their positive impact on the morphodynamic restoration of mangrove habitat.

The design variables governing permeable structure design encompass both spatial and structural considerations. Spatial design variables involve placement of the structures with respect to the coastline and/or mangrove fringe, orientation relative to the coastline, and a spatial configuration, involving the gap width in between multiple structures and distances in between multiple rows of structures. Structural design factors include material selection, the dimensions of individual components, and overall structural configuration parameters like structure length and permeability.

This conceptual framework serves as a foundation for initial assessments and acts as a guiding reference during the design process of permeable structures. It visually represents the core elements of the ecological and engineering variables relevant in designing permeable structures aimed at rehabilitating mangrove habitat, and serves as a design tool supportive to design guidelines. It can be interpreted, tailored and implemented in various projects or initiatives involving the design of such permeable structures to rehabilitate mangroves. It's crucial to acknowledge the complexity of the interactive processes among the variables, as restoring mangrove habitat using permeable structures involves an interdisciplinary endeavor. Furthermore, the dynamics and correlations within mangrove-mud ecosystems are highly site-specific. To tackle the goals and complexities of such a restoration project effectively, it's essential to carefully assess all pertinent variables with respect to the site in question.

> **RQ2:** Within the framework of a Building with Nature design approach, what are the fundamental steps in the design process that, when combined, constitute a design guideline for permeable structures aimed at rehabilitating mangroves?

The fundamental steps in the design process of permeable structures aimed at rehabilitating mangrove habitat, constituting a design guideline, are illustrated in Figure 7.2. This design guideline elaborates on the first two steps of the Building with Nature five step design approach, which is part of a broader project cycle. Guidelines for mangrove restoration efforts extend beyond physical design and restoration activities. For permeable structures to be effective, they must align with an integrated coastal zone management strategy, supported by policy and planning authorities. Successful restoration initiatives involve community empowerment, engagement with local government, and alignment of local initiatives with overarching policies and planning throughout the entire design, implementation and management phase. Additionally, establishing a monitoring and adaptive management strategy is crucial within the project cycle of a restoration project, and thus, during the design process of permeable structures. The design process of permeable structures thus involves further steps after following the steps of the design guideline developed in this study.

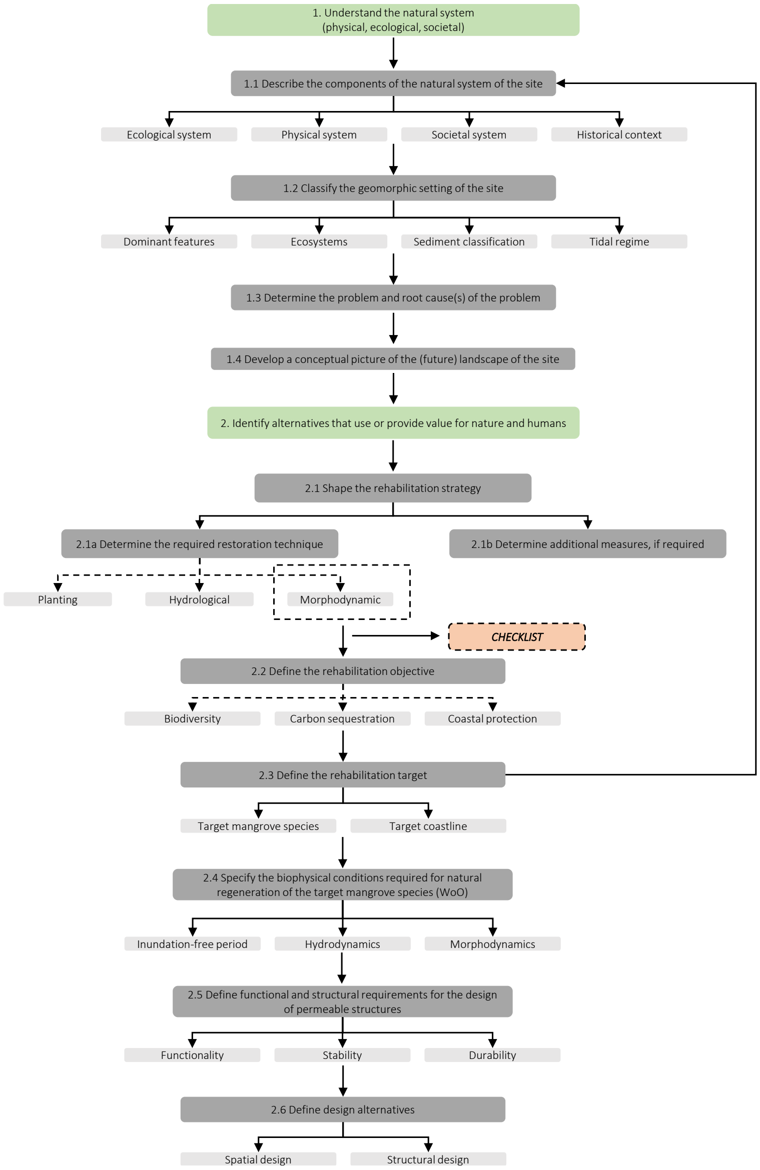


Figure 7.2: Design guideline for permeable structures aimed at rehabilitating mangroves through morphodynamic habitat restoration

Significant knowledge gaps identified throughout the development of these design guidelines hindered the development of quantitative content within the guideline. As a result, it is not yet possible to apply this guideline in practice and obtain a fully refined design for permeable structures aimed at morphodynamic habitat restoration. At present, the design guideline could only serve as an initial framework to provide understanding of the design process for such permeable structures aimed at rehabilitating mangroves through morphodynamic habitat restoration. It provides insights into both the relevant engineering and ecological variables involved in the design process of these nature-based solutions, and illustrates the sequence in which the design of permeable structures should be approached.

> **RQ3:** What is the influence of various design parameters on the effectiveness of permeable structures in reducing bed shear stress across the sheltered areas behind them?

This research question is addressed by systematically assessing the influence of each design parameter on the effectiveness of permeable structures in reducing bed shear stresses, one by one. Consequently, subsequent sections elaborate on the influence of structure length, distance of placement from the mangrove fringe, gap width between sets of structures, and the number of rows of structures placed behind each other, respectively.

Structure length

A longer structure length enhances the effectiveness of permeable structures in reducing bed shear stress across the sheltered areas behind them. This is due to longer structures exert influence over a broader expanse of incoming waves and currents. Consequently, wave energy is dissipated over a broader expanse, and resistance is exerted on incoming currents across a broader expanse. Increasing the length of structures by 66 meters leads to an increased reduction in bed shear stresses across the sheltered areas behind the structures, of approximately 5%, and an expanded spatial extent where bed shear stresses fall below the threshold value of erosion by 3% to 7%. The degree to which longer structures enhance the performance of permeable structures in reducing bed shear stress across the sheltered areas behind them thus varies spatially, which is attributed by local variations in hydrodynamic conditions and the positioning of structures relative to the coastline, particularly in relation to a detached mangrove fringe within the coastal system. When structures are placed relatively close to a (detached) mangrove fringe, at a distance of 33 meters, the fringe acts as a blockage and obstructs the spatial extent of the effect of permeable structures in reducing bed shear stresses behind them, thereby influencing the degree to which longer structures influence the performance of permeable structures in reducing bed shear stresses.

Distance of placement of structures from the mangrove fringe

Greater distances of placement of structures from a mangrove fringe enhance the effectiveness of permeable structures in reducing bed shear stress across the sheltered areas behind them, albeit to a certain extent, as the extent of the structures' effect is less obstructed by the presence of the mangrove fringe for increased distances. By increasing the distance of placement from the mangrove fringe by 33 meters, an additional 3% reduction in bed shear stress across the sheltered areas behind structures is achieved. In addition, it accompanies a slightly expanded area behind the structures where bed shear stresses fall below the threshold value of erosion. For extensive distances of placement of structures from the mangrove fringe, however, for distances of 198 and 231 meters from the fringe, the effectiveness of the structures in reducing the bed shear stress behind them does not increase anymore. This can be attributed to the fact that for extensive distances from a mangrove fringe, currents, depending on their incoming direction, may penetrate from the sides across the area directly behind the structures, leading to increased forces on the bed once again. To facilitate seaward expansion of a mangrove fringe, however, it is crucial that the extent of the structures' effect to reduce bed shear stresses below the threshold value of erosion reaches the boundary of a mangrove fringe without interruption. Altogether, this suggests that there is a limit to the positive influence of greater distances of placement of structures from a mangrove fringe. There appears to be an optimal distance for placing structures from a mangrove fringe, which, in the case of the study area, is at a distance of 165 meters from the mangrove fringe. Thus, while the distance of placement of structures from a mangrove fringe should be as large as possible to maximize the spatial extent of the effect of the permeable structures, and to maximize seaward expansion of the mangroves, structures should still be placed close enough to ensure its effect in reducing bed shear stresses below the threshold reaches the boundary of the mangrove fringe to facilitate seaward expansion.

Gap width in between a set of structures

The gap width in between a set of structures does not significantly influence the performance of permeable structures in reducing bed shear stresses behind them. In fact, a wider gap width could potentially slightly decrease the effectiveness of structures in reducing bed shear stress. Increasing the gap width in between a set of structures by 66 meters could decrease the amount of reduction in bed shear stresses by 2% and reduces the spatial extent behind structures where bed shear stresses are reduced by a similar percentage. This is because waves are not attenuated across the width of the gap in between structures, resulting in orbital velocities near the bottom and bed shear stresses not being reduced. Consequently, a larger gap width creates a wider area where wave energy is not dissipated, leading to a greater expanse over which orbital velocities near the bottom are not reduced. As a result, behind structures with a larger gap width, bed shear stresses are less reduced compared to a structure configuration with a smaller gap width.

Number of rows of structures placed behind each other

Placing multiple rows of structures behind each other enhances the effectiveness of permeable structures in reducing bed shear stress across the sheltered areas behind them compared to a single row of structures. This is due to the fact multiple rows of structures placed behind each other dissipate a significantly larger amount of wave energy compared to a single row of structures. Adding an additional row of structures at a distance of 33 meters behind the initial set results in a further reduction in bed shear stress ranging from 3% to 12% and an expanded spatial extent in which the bed shear stresses are below the threshold value of erosion of 4% to 6% compared to a single row of structures. Adding two extra rows of structures at a distance of 33 meters behind the initial set even results in a further reduction in bed shear stress ranging from 9% to 16% and an expanded spatial extent of 12% to 20% compared to a single row of structures. The degree to which placing multiple rows of structures behind each other enhances the performance of permeable structures in reducing bed shear stress across the sheltered areas behind them thus varies spatially. Moreover, the influence of the distance between multiple rows of structures on structure performance in reducing bed shear stress varies spatially. Increasing the distance in between multiple rows of structures either decreases or increases the reduction in bed shear stress. These spatial variations may arise from very localized differences in hydrodynamic conditions, such as currents approaching from different directions. Depending on the direction of incoming currents, increasing the distance between multiple rows of structures could lead to currents penetrating from the sides, thereby affecting bed shear stresses between the rows of structures once again. Hence, depending on the location of the structures within a coastal system and the local hydrodynamics, adding another row at the same distance enhances the effectiveness of structures in reducing bed shear stresses more than increasing the spacing between multiple rows.

By answering the research questions, the research objective:

To develop an integrated design approach (design guidelines) for permeable structures aimed at rehabilitating mangrove habitat along eroding coastlines, merging scientific knowledge with the lessons learned from pilot projects, and to enhance understanding of the influence of design parameters on the performance of these permeable structures.

is now accomplished. A design guideline for permeable structures aimed at rehabilitating mangroves along eroding coastlines through morphodynamic habitat restoration, merging scientific knowledge with the lessons learned from pilot projects, has been developed, thereby fulfilling the first objective. In addition, correlations between various design parameters and the performance of permeable structures in reducing bed shear stress across the sheltered areas behind them are identified, thereby fulfilling the second objective. Thus, while this study identified several knowledge gaps during the development of the design guideline, it has also contributed to bridging one of these knowledge gaps by fulfilling the second objective of this study.

7.2. Recommendations

Design guideline

Throughout the development of the design guideline for permeable structures in this study, several significant knowledge gaps have been identified, as was elaborated upon in section 6.2.1. This hindered the development of quantitative content within certain steps, including the inclusion of practical tools and formulas that depict relationships between interacting variables, which could aid in the design of permeable structures. Further research on these knowledge gaps is therefore highly recommended. This involves further research into the development of practical tools to determine and quantify the required dimensions of a mangrove forest to meet a specific rehabilitation objective, such as a certain amount of coastal protection or carbon sequestration. The suitability of the formulas proposed by Méndez and Losada (2004) and Montgomery et al. (2019) within a practical context could be explored to determine if these models can be utilized to determine forest dimensions based on the hydrodynamic conditions at a specific site and a desired level of coastal protection to be attained. Additionally, further research involves expanding our understanding of species-specific threshold values related to their favorable conditions, like species-specific values to the required inundation-free period that its propagules need. This entails determining species-specific threshold values to their windows of opportunity, similar to the study conducted by Balke et al. (2011) on threshold values of the species *Avicennia alba*. Lastly, while this study aims to increase understanding of the influence of design parameters on the performance of structures, further research is required to enhance this understanding, as will be elaborated on in the following section.

Furthermore, as more quantitative content becomes available for the design guideline, it would be valuable to apply the guideline to a case study. This would allow for an assessment of whether the sequence of steps outlined in this study could effectively lead to an adequate design of permeable structures. Through such a case study, practical insights could be gained regarding the application of the guideline into practice, providing valuable feedback for further refinement and improvement of the design process of permeable structures aimed at rehabilitating mangrove habitat.

Delft3D modelling

Due to time constraints, only a limited number of values for each design variable were tested in this study. To enhance the reliability and robustness of the correlations between design parameters and structure performance identified, it is recommended to expand the scope of values tested for each design variable. Moreover, it would be interesting to assess various combinations of values of design variables within a structure configuration to observe how they are interrelated and interact, ultimately influencing structure performance. As a permeable structure design must achieve a required degree of wave dissipation while allowing sediments to pass through, design variables must be aligned to satisfy both requirements. Moreover, enhancing comprehension of the interactions between design variables could aid in identifying optimal structural configurations. Conducting research on the interrelations between design variables in the context of a certain structure's performance is therefore recommended.

Furthermore, since this study lacks an assessment of the influence of water depth on structure performance, it is recommended to further research this aspect. Simulating various water depths in combination with different distances of placement of structures from the coastline could identify their respective contributions to structure performance.

Simulating scenarios under various hydrodynamic forcing is also highly recommended, as this study has only assessed the influence of various design parameters under one tidal and wave forcing. Since the impact of permeable structures on waves and currents depends on the magnitude and incoming direction of these forces, it is important to assess whether the correlations identified in this study alter under varying hydrodynamic conditions. This enhances understanding of the influence of design parameters on structure performance and increases the reliability and robustness of correlations. Such research allows for drawing more generalized conclusions and could enhance the applicability to other coastal systems. Additionally, it could enable the incorporation of these correlations into the design guidelines developed in this study.

As this study has focused on analyzing the influence of design parameters on the performance of structures in reducing bed shear stresses and lacks an assessment of the influence of these parameters on structural stability, it is highly recommended to investigate and map the stability of structures in relation to these design variables. Ensuring the long-term effectiveness and structural integrity of permeable structures requires a comprehensive understanding of the influence of design parameters on structural stability as well.

Lastly, since permeable structures aim to facilitate sedimentation and an increase in bed level elevation over time, adopting a morphodynamic modeling approach could lead to more realistic and robust model outputs and provide a better representation of the performance of permeable structures in terms of morphodynamics. A morphodynamic approach could enhance understanding of the influence of design parameters on the performance of permeable structures, as structure performance is intricately linked to the morphodynamic response of a coastal system over time. Therefore, it is recommended to simulate over extended periods of time, and to deploy a morphodynamic model to analyze the influence of design parameters on the performance of permeable structures in more detail.

Overall, while this study aims to contribute to improving the design process of permeable structures and, subsequently, enhancing the success of these structures in morphodynamic restoration of mangrove habitat by developing design guidelines and deepening understanding of the influence of design parameters on structure performance, there is still much knowledge to be gained in this field. This research marks a starting point in the development of proper design guidelines and initiates progress in enhancing understanding of the interaction between design parameters and structure performance. It provides preliminary insights, highlights significant knowledge gaps and provides recommendations for further research, thereby opening up possibilities to expand knowledge surrounding the design of permeable structures aimed at morphodynamic restoration of mangrove habitat.

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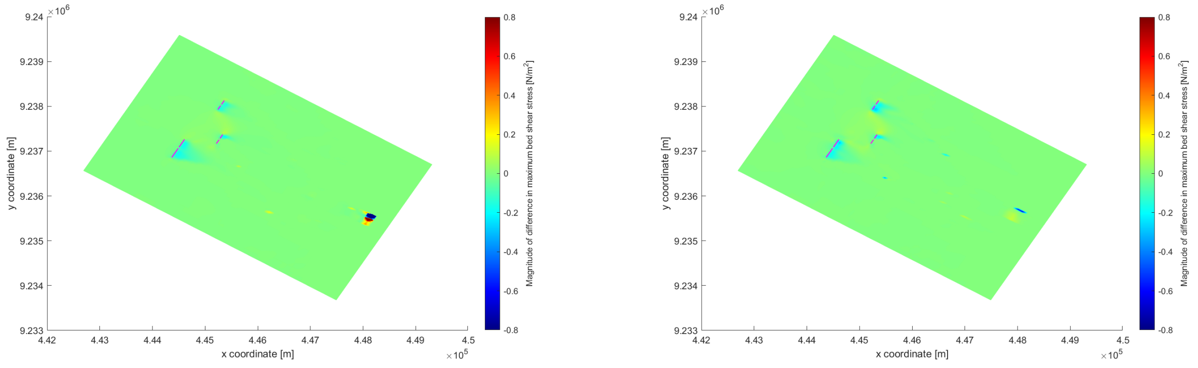
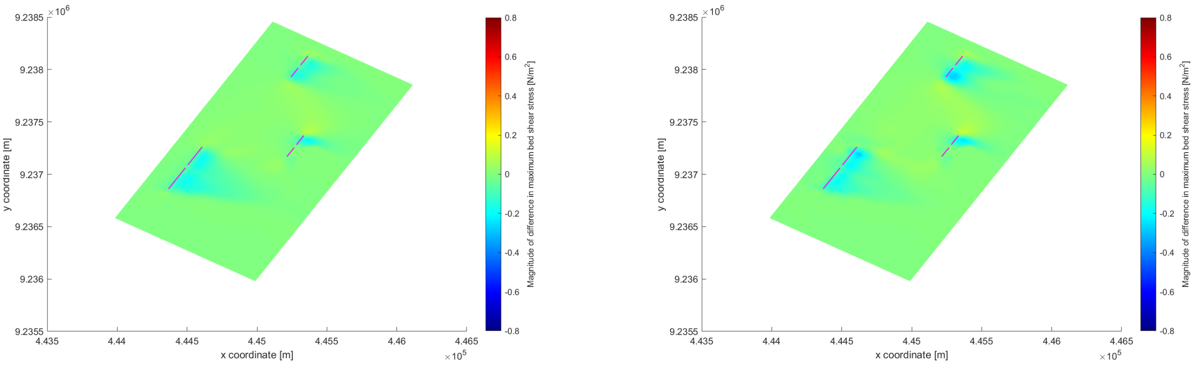
A Influence of permeable structures on waves and currents

To determine whether the reduction in bed shear stress behind the permeable structures primarily arises from wave dissipation or from the resistance of the structures to currents, two extra scenarios are simulated using the Delft3D model. These scenarios - one without the presence of structures, and the other with the presence of structures - feature currents only, as the significant wave height for these scenarios is set at 0.009 meters, instead of 0.7 meters. The discrepancy in bed shear stresses between these scenarios is subsequently compared with the difference observed in scenarios where both currents and waves (significant wave height of 0.7 meters) are present. Upon comparing Figure A.1a to Figure A.1b, it becomes apparent that the influence of structures on incoming waves is larger than their effect on incoming currents. This contrast is further emphasized in Figures A.2a and A.2b. The reduction in bed shear stresses behind the structures is considerably more pronounced under conditions with both currents and waves than under conditions with currents alone. This phenomenon can be attributed by the fact that nearshore currents in the coastal region of Demak have a limited strength (Bisschop, 2023).



(a) **(b)**

Figure A.1: Difference in maximum bed shear stress between scenarios with and without the presence of structures for the conditions a) with currents only, and b) with currents and waves



(a) **(b)**

Figure A.2: Difference in maximum bed shear stress between scenarios with and without the presence of structures for the conditions a) with currents only, and b) with currents and waves, across the area in the vicinity of the structures

B Spatial variations in the influence of permeable structures

Figure B.1 highlights the spatial variations in the magnitude to which bed shear stresses are reduced across the sheltered areas behind the structures are identified. This can be attributed to variations in hydrodynamic forcing across the coastal area as from Figure B.2, it is evident that the magnitude of depth-averaged velocities varies across the area, particularly in the vicinity of the different sets of structures. Notably, the area near structures 1&2 shows significantly smaller depth-averaged velocities compared to structures 3&4 and 5&6. This variation could potentially be attributed to waves diffracting around the prominent headland situated to the right of structures 5&6. As waves diffract around obstacles, wave energy is transferred along the wave crests as it bends around the edges of the obstacle, causing changes in wave direction and the distribution of wave energy beyond it (Bosboom & Stive, 2015). Consequently, around the prominent headland, waves are diffracted, leading to the compression of wave energy and increased depth-averaged velocities in front of structures 5&6. This is primarily the case in front of structure 5, where bed shear stress is clearly reduced to a greater extent than behind structure 6.

These variations in local hydrodynamic forcing, resulting in variations in depth-averaged velocities and consequently in variations in bed shear stress, could thus be the reason behind the spatial variation in structure performance in reducing bed shear stress behind them. It seems that increased hydrodynamic forcing, associated with increased depth-averaged velocities, leads to increased performance of structures in reducing bed shear stress.

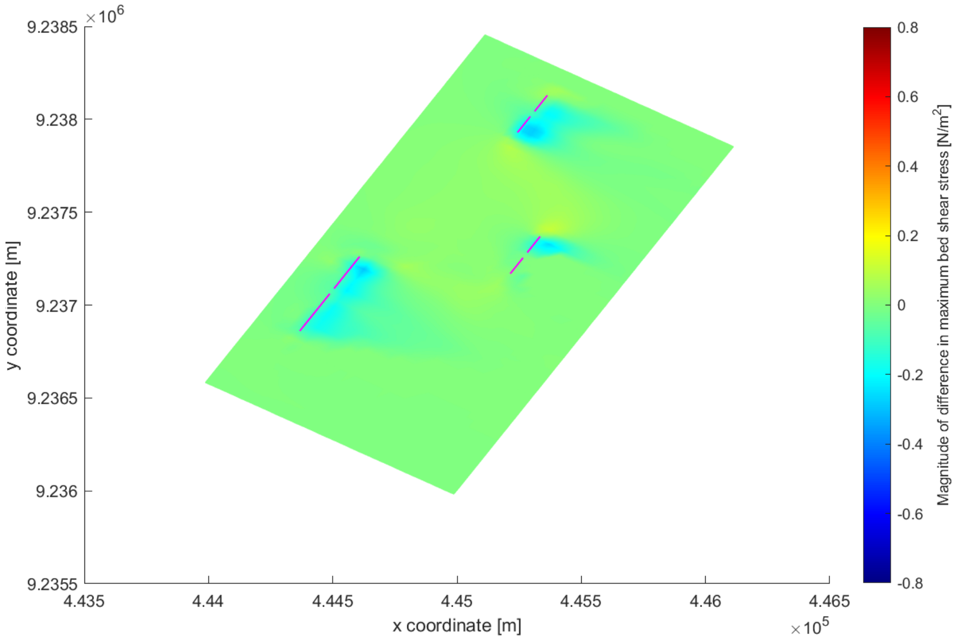


Figure B.1: Difference in maximum bed shear stress between scenarios with and without the presence of structures

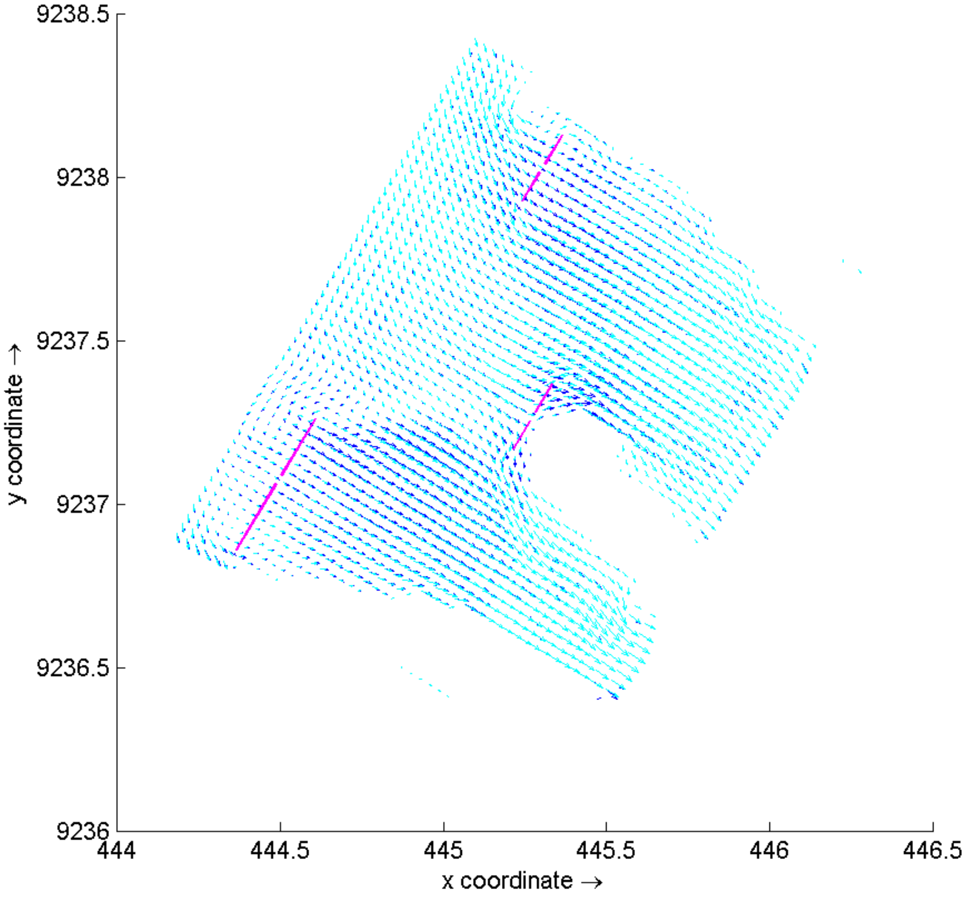
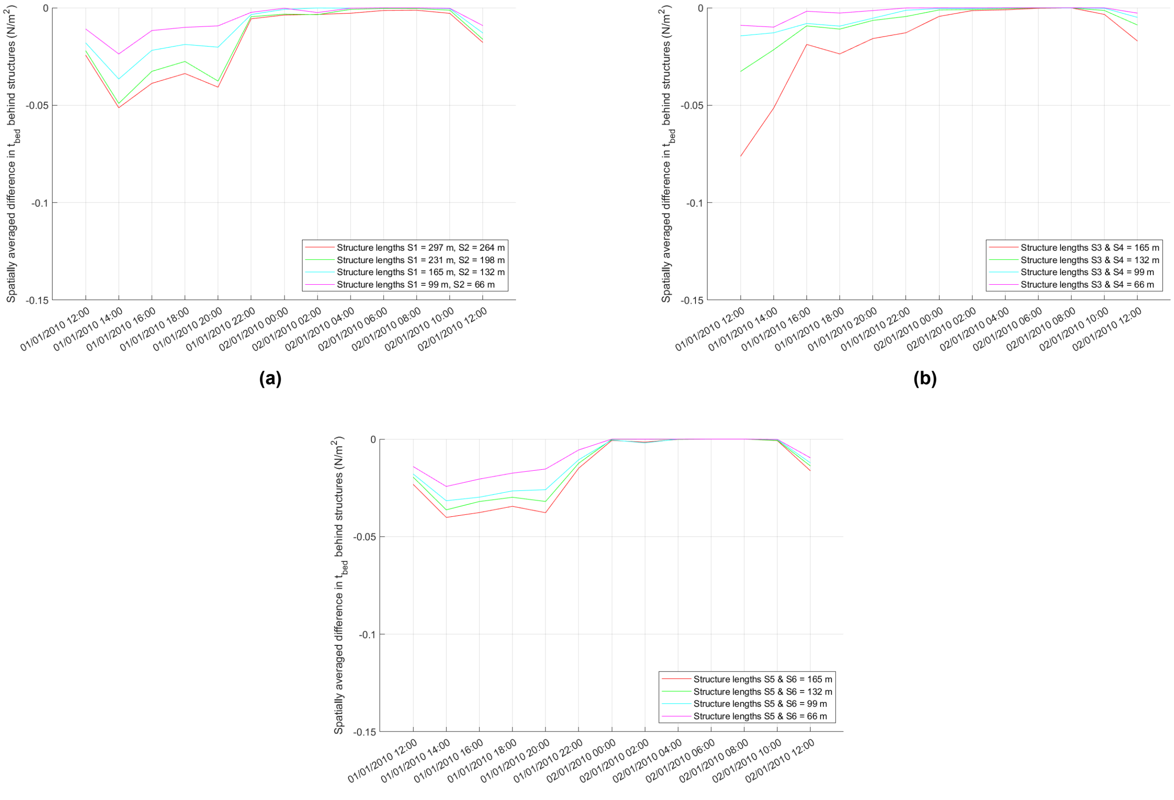


Figure B.2: Spatial variations in depth-averaged velocities for the scenario without the presence of structures (dark blue), and with the presence of permeable structures (light blue)

C Spatially averaged bed shear stress throughout tidal cycle



(a) (b)

(c)

Figure C.1: Spatially averaged difference in maximum bed shear stress across the area behind structures, where bed shear stresses are reduced due to the presence of structures, throughout the tidal cycle, for a) structure lengths 1&2, b) structure lengths 3&4, and c) structure lengths 5&6

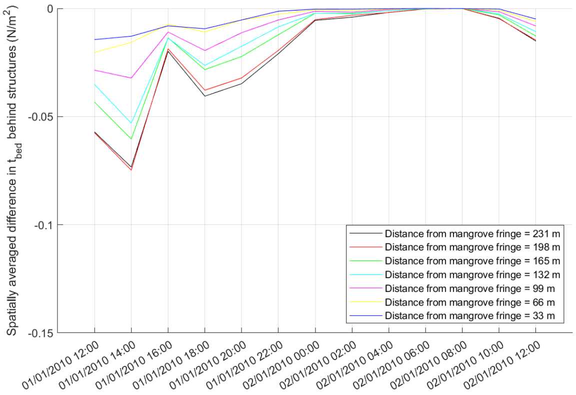
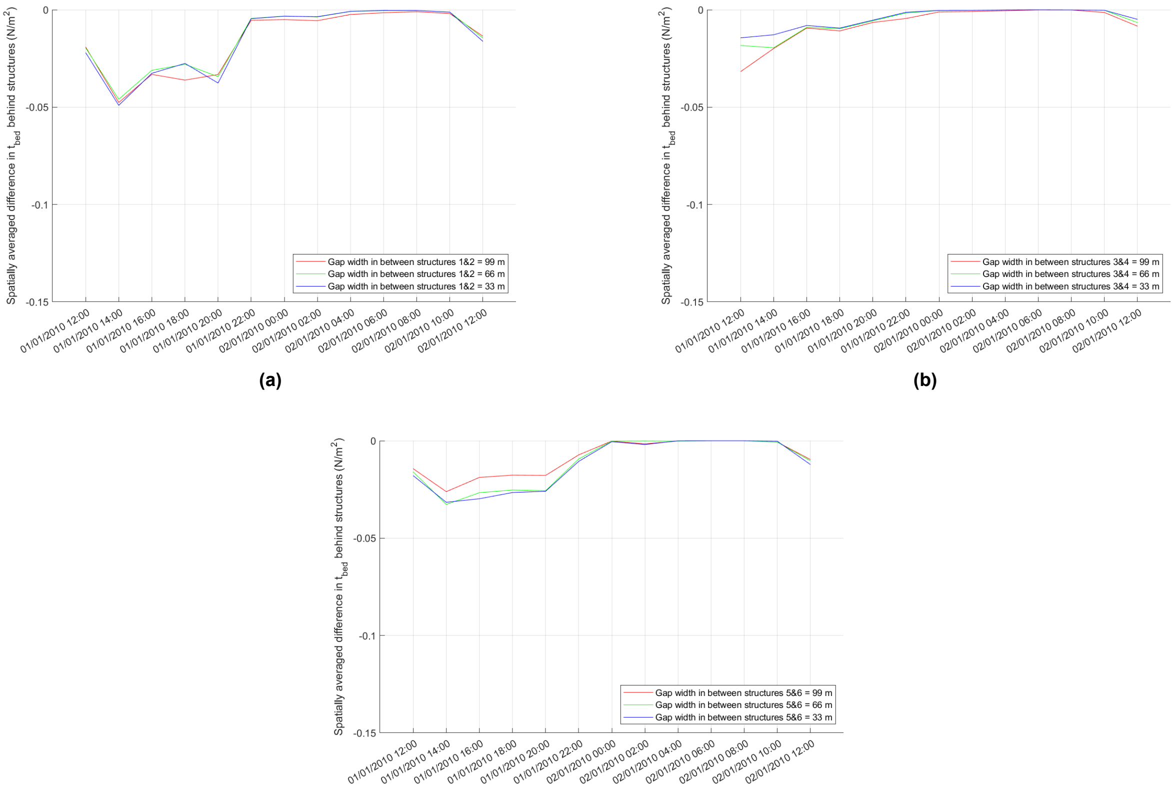


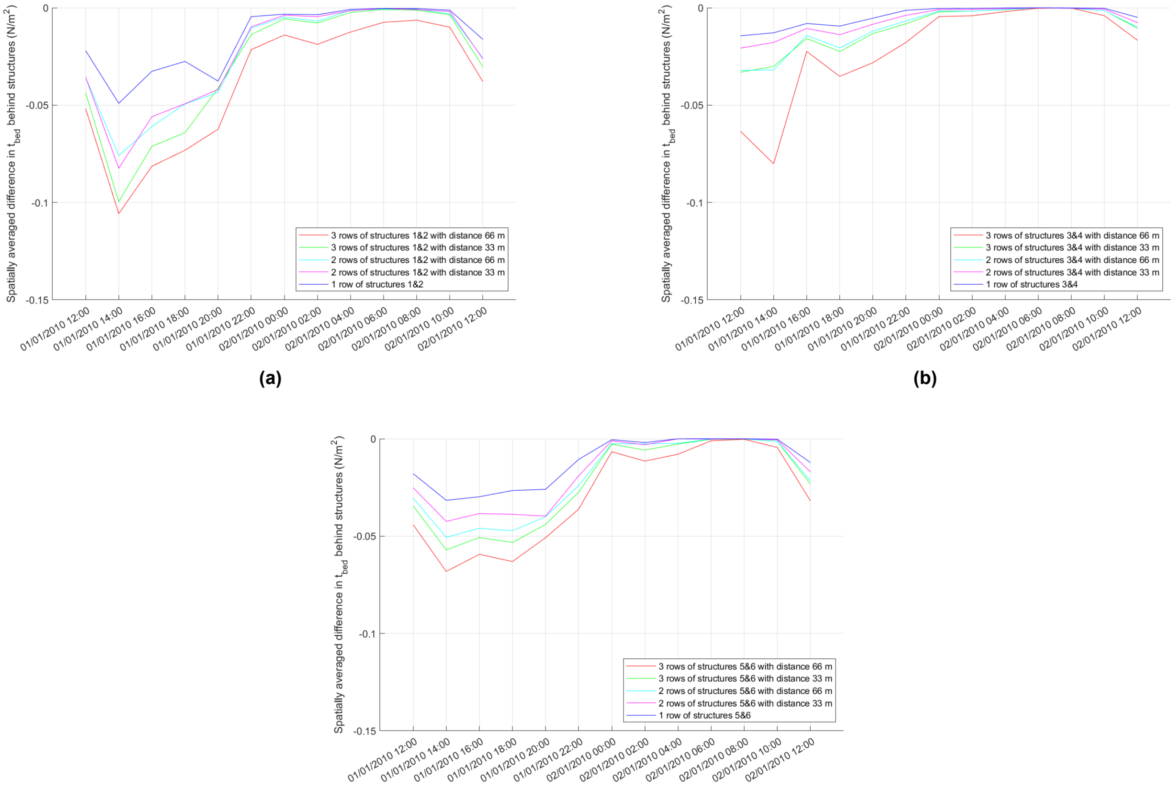
Figure C.2: Spatially averaged difference in maximum bed shear stress across the area behind structures, where bed shear stresses are reduced due to the presence of structures, throughout the tidal cycle, for various distances of placement of structures 3&4 from the mangrove fringe



(a) **(b)**

(c)

Figure C.3: Spatially averaged difference in maximum bed shear stress across the area behind structures, where bed shear stresses are reduced due to the presence of structures, throughout the tidal cycle, for varying gap width in between structures a) 1&2, b) 3&4, and c) 5&6



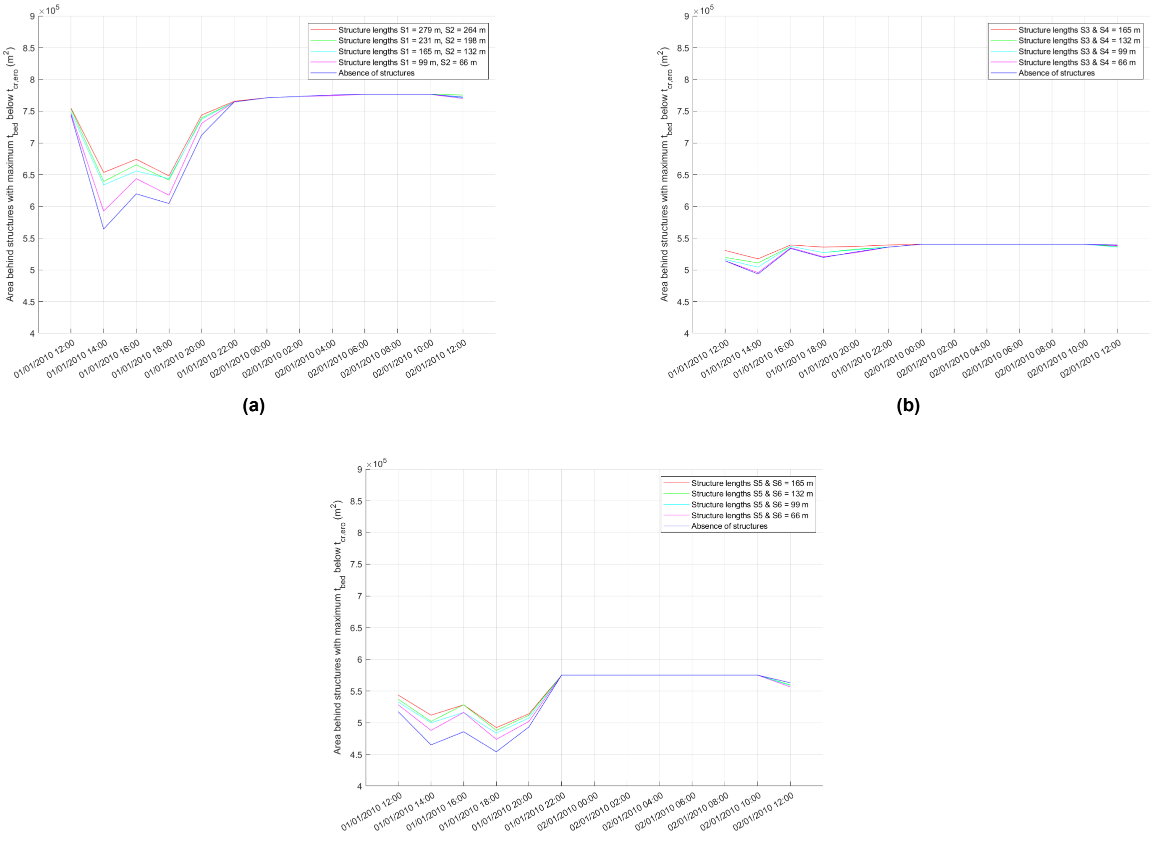
(a)

(b)

(c)

Figure C.4: Spatially averaged difference in maximum bed shear stress across the area behind structures, where bed shear stresses are reduced due to the presence of structures, throughout the tidal cycle, for varying number of rows of structures placed behind each other for structures a) 1&2, b) 3&4, and c) 5&6

D Spatial extent of bed shear stress below threshold throughout tidal cycle



(a)

(b)

(c)

Figure D.1: Spatial extent of maximum bed shear stress below the threshold value of erosion behind structures, throughout the tidal cycle, for a) structure lengths 1&2, b) structure lengths 3&4, and c) structure lengths 5&6

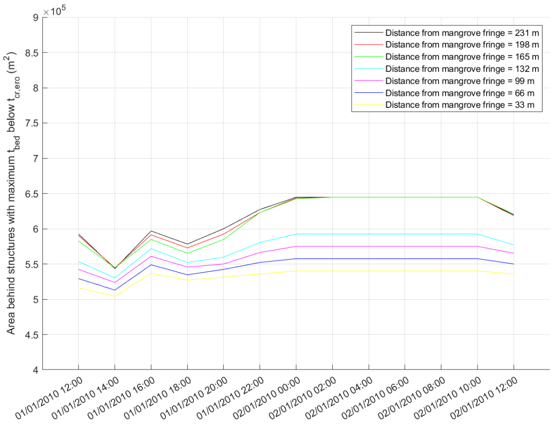
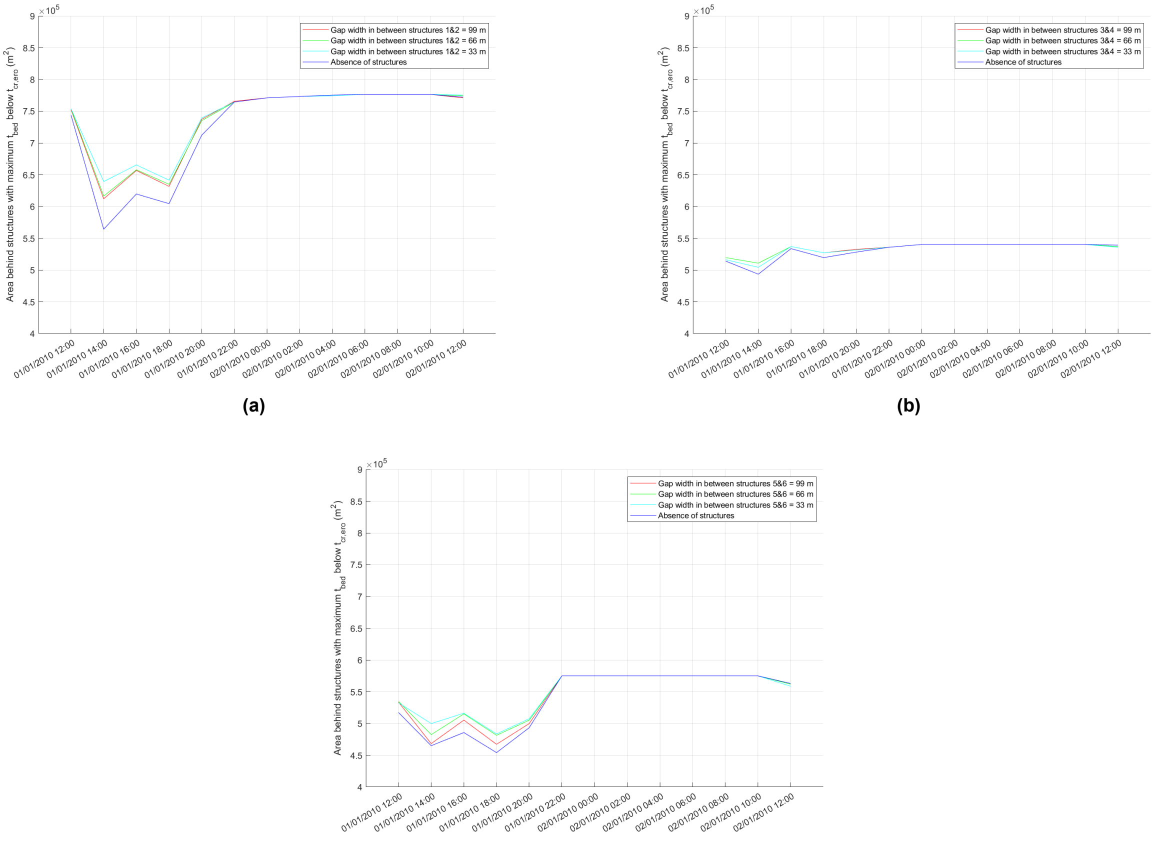


Figure D.2: Spatial extent of maximum bed shear stress below the threshold value of erosion behind structures, throughout the tidal cycle, for various distances of placement of structures 3&4 from the mangrove fringe

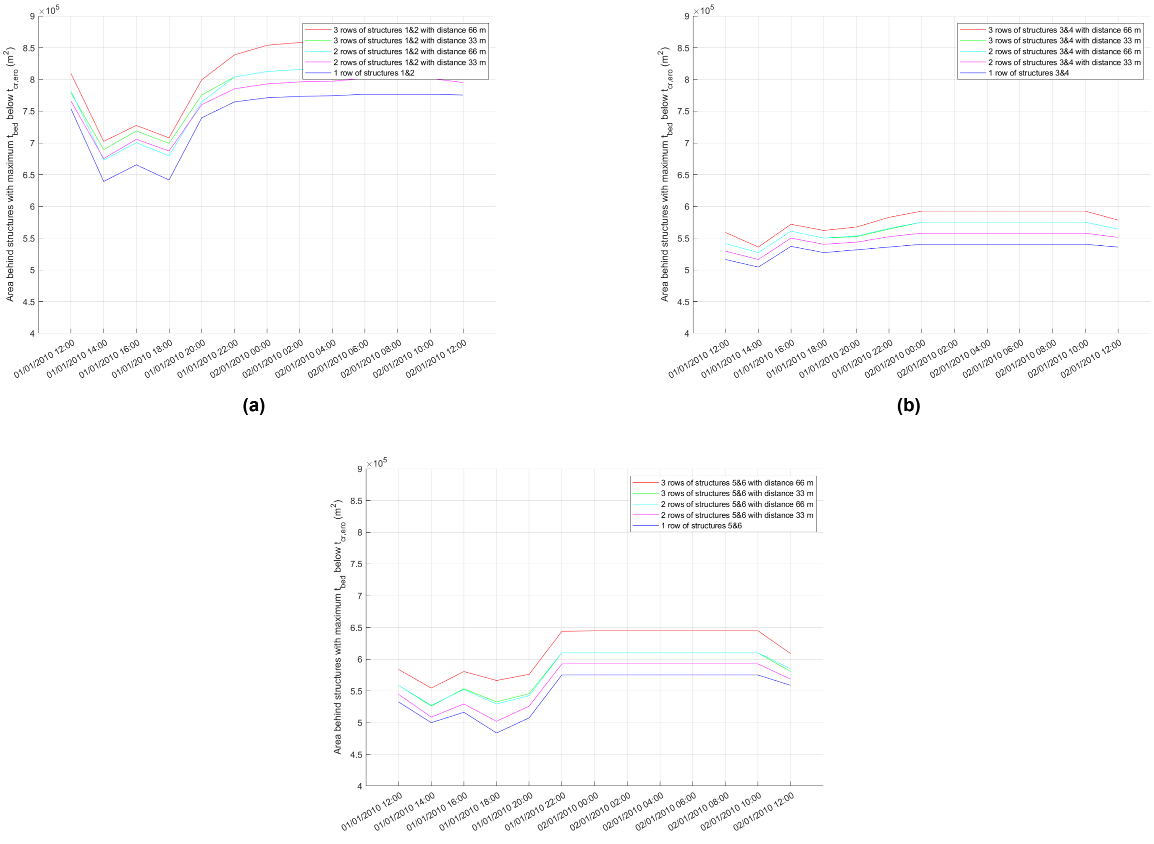


(a)

(b)

(c)

Figure D.3: Spatial extent of maximum bed shear stress below the threshold value of erosion behind structures, throughout the tidal cycle, for varying gap width in between structures a) 1&2, b) 3&4, and c) 5&6



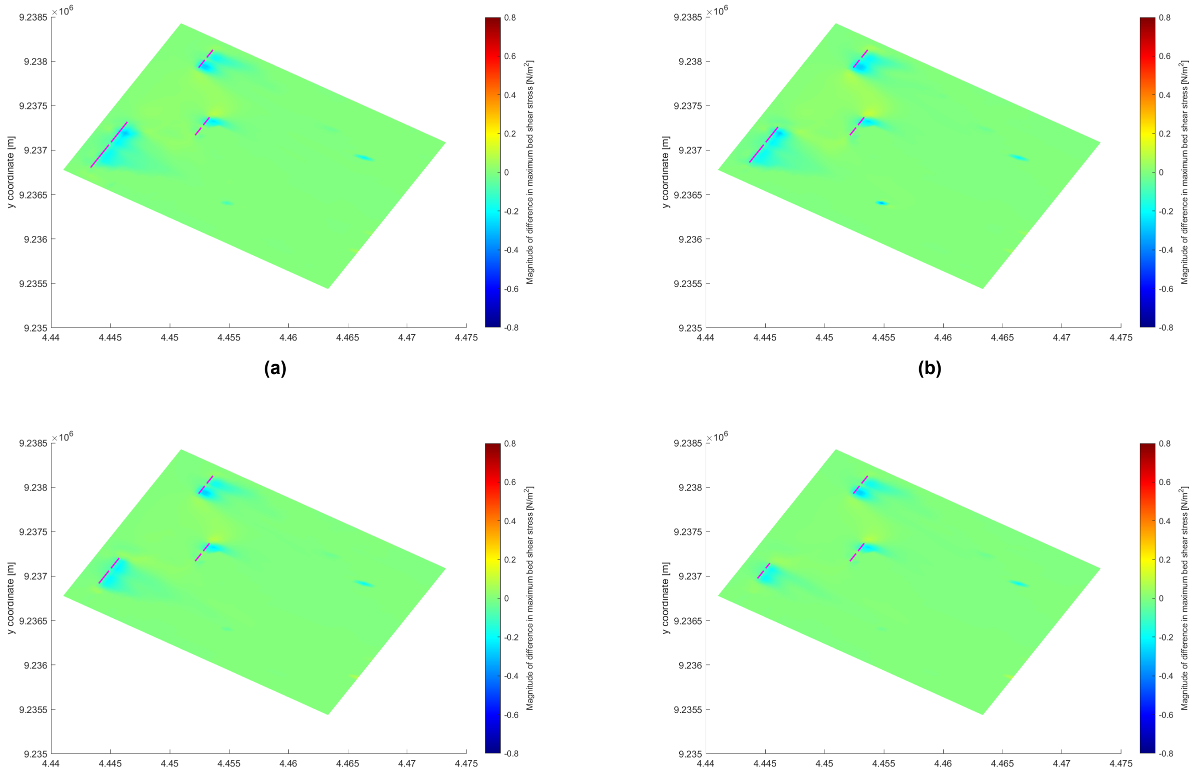
(a)

(b)

(c)

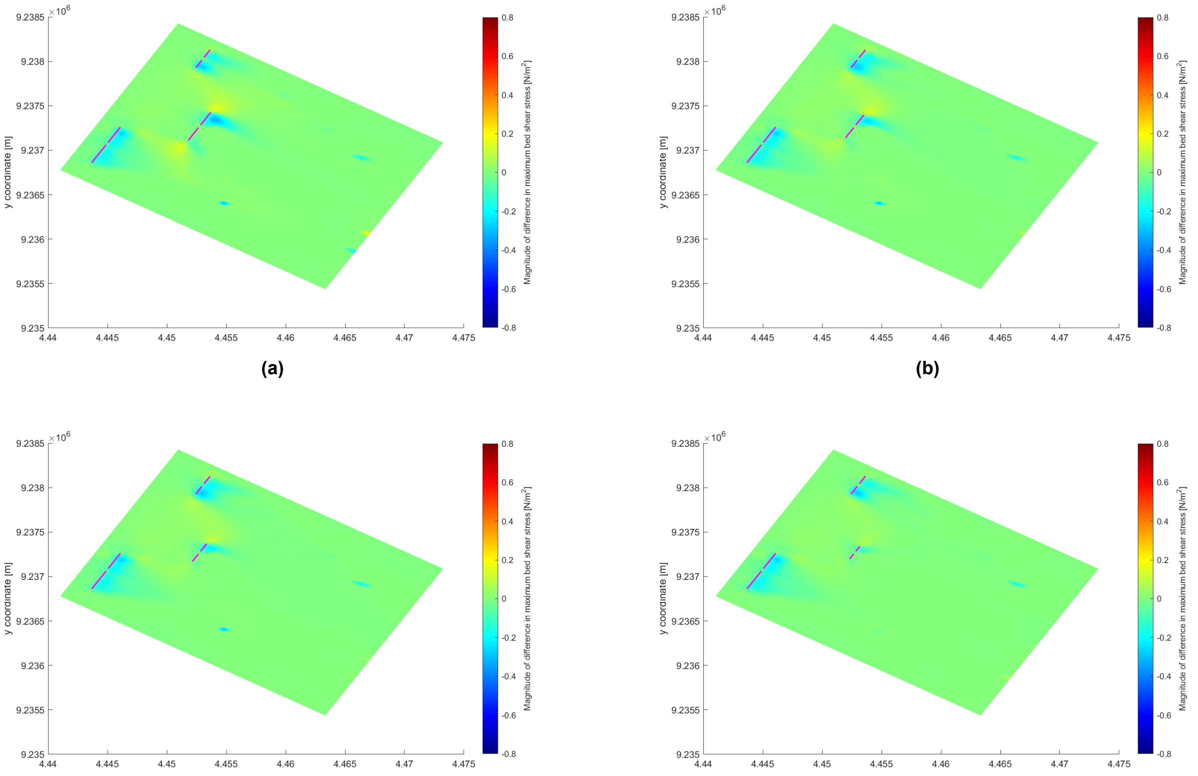
Figure D.4: Spatial extent of maximum bed shear stress below the threshold value of erosion behind structures, throughout the tidal cycle, for varying number of rows of structures placed behind each other for structures a) 1&2, b) 3&4, and c) 5&6

E Spatial graphs depicting the magnitude of differences in bed shear stress



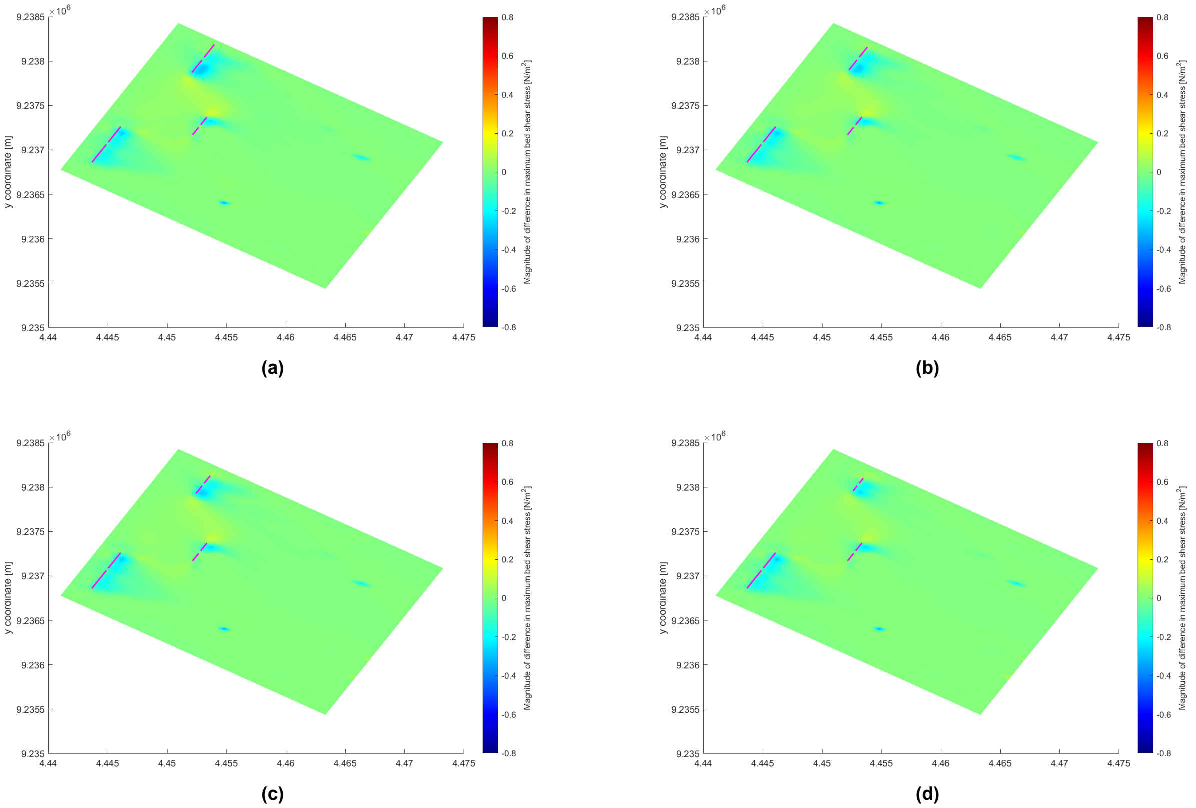
(a) (b) (c) (d)

Figure E.1: Difference in maximum bed shear stress between the scenario without the presence of structures and the scenarios featuring a structure configuration of structures 1&2 of a) lengths S1 = 297 m, S2 = 264 m, b) lengths S1 = 231 m, S2 = 198 m, c) lengths S1 = 165 m, S2 = 132 m, d) lengths S1 = 99 m, S2 = 66 m



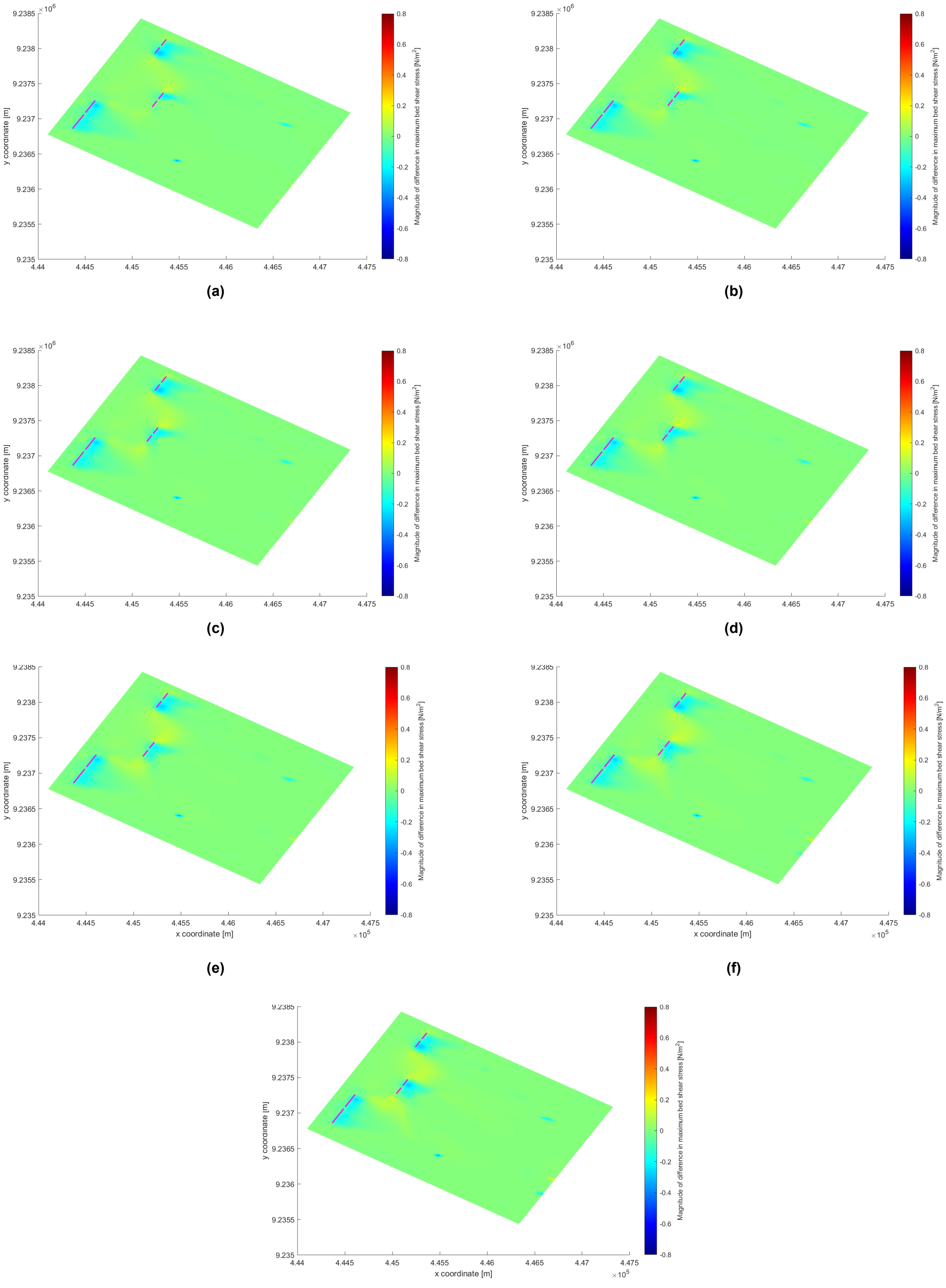
(a) **(b)** **(c)** **(d)**

Figure E.2: Difference in maximum bed shear stress between the scenario without the presence of structures and the scenarios featuring a structure configuration of structures 3&4 of a) lengths 165 m, b) lengths 132 m, c) lengths 99 m, d) lengths 66 m



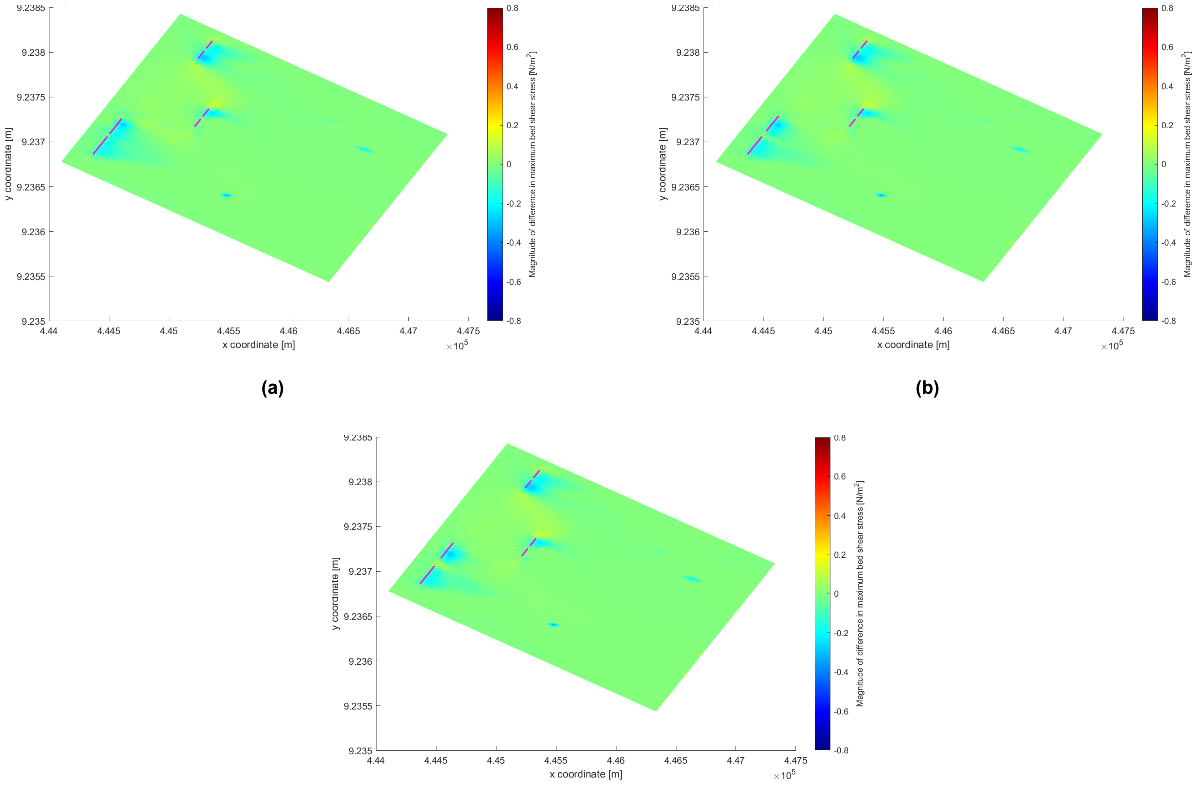
(a) (b) (c) (d)

Figure E.3: Difference in maximum bed shear stress between the scenario without the presence of structures and the scenarios featuring a structure configuration of structures 5&6 of a) lengths 165 m, b) lengths 132 m, c) lengths 99 m, d) lengths 66 m



(a) (b) (c) (d) (e) (f) (g)

Figure E.4: Difference in maximum bed shear stress between the scenario without the presence of structures and the scenarios featuring structures 3&4 at varying distances from the mangrove fringe: a) 33 m, b) 66 m, c) 99 m, d) 132 m, e) 165 m, f) 198 m, and g) 231 m

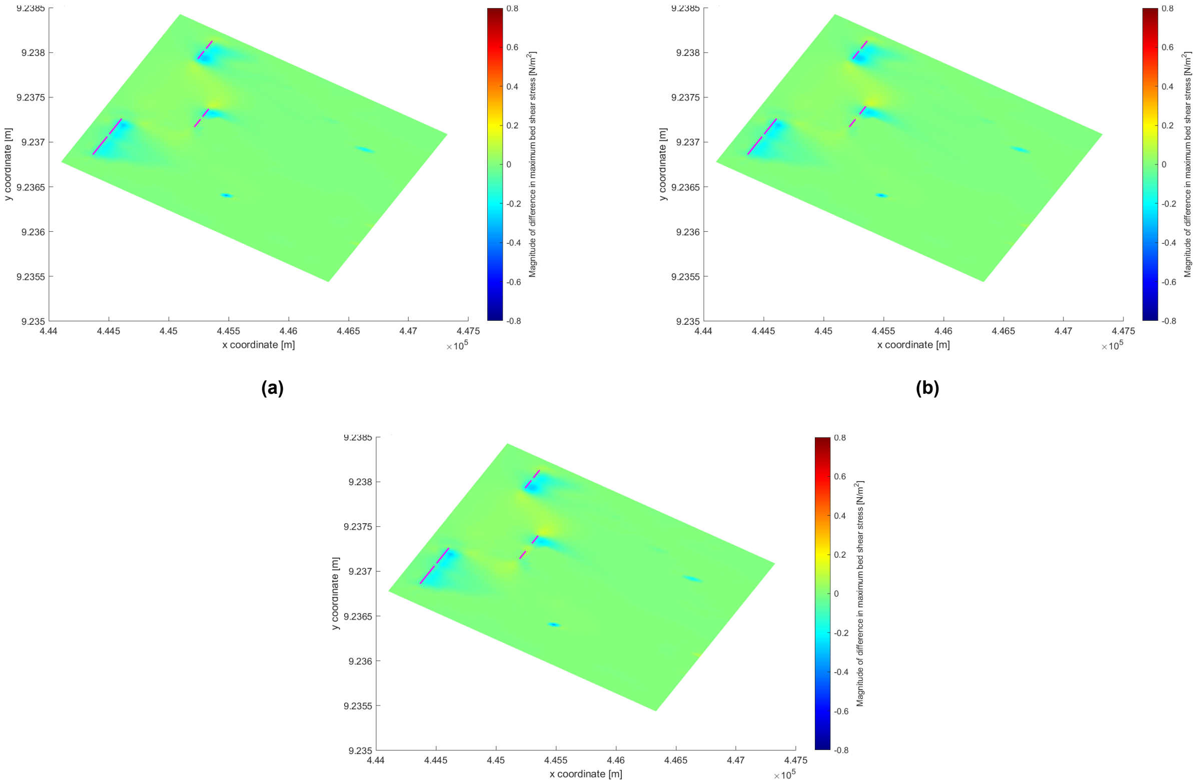


(a)

(b)

(c)

Figure E.5: Difference in maximum bed shear stress between the scenario without the presence of structures and the scenarios featuring a structure configuration of structures 1&2 with varying gap widths in between the set of structures: a) 33 m, b) 66 m, and c) 99 m

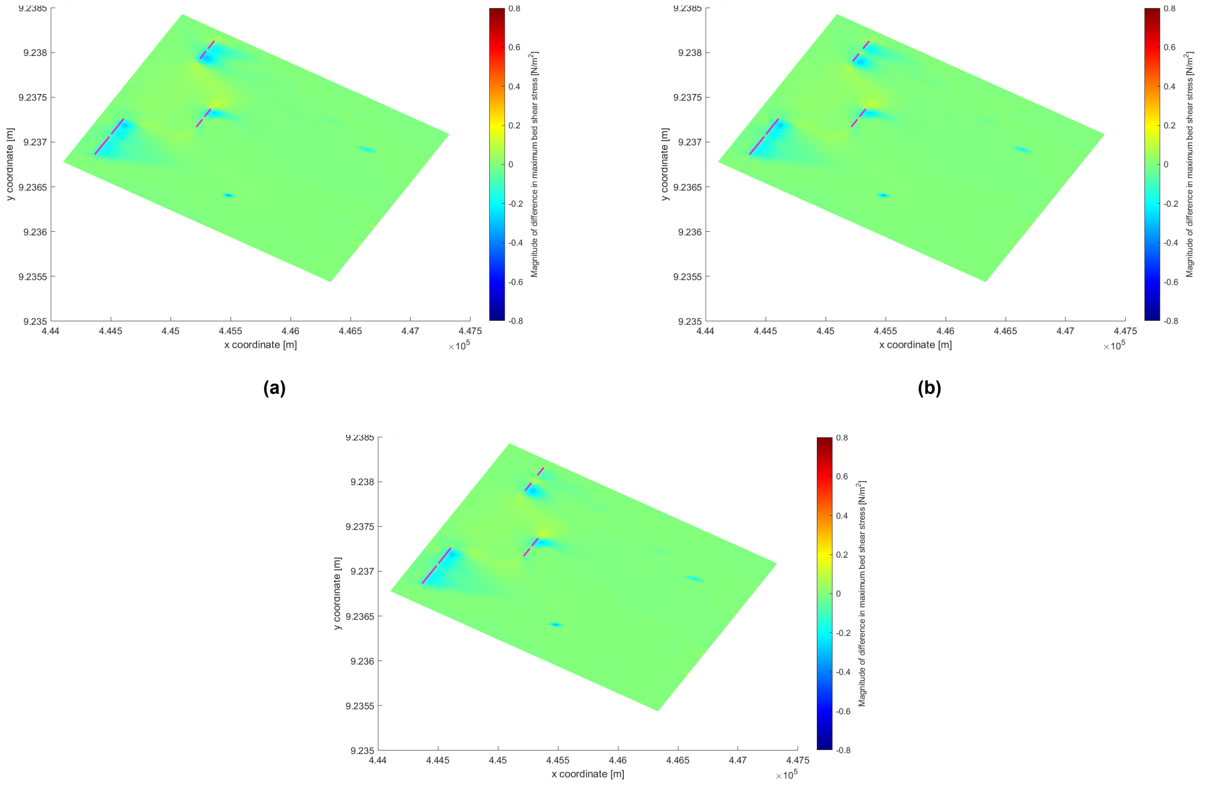


(a)

(b)

(c)

Figure E.6: Difference in maximum bed shear stress between the scenario without the presence of structures and the scenarios featuring a structure configuration of structures 3&4 with varying gap widths in between the set of structures: a) 33 m, b) 66 m, and c) 99 m

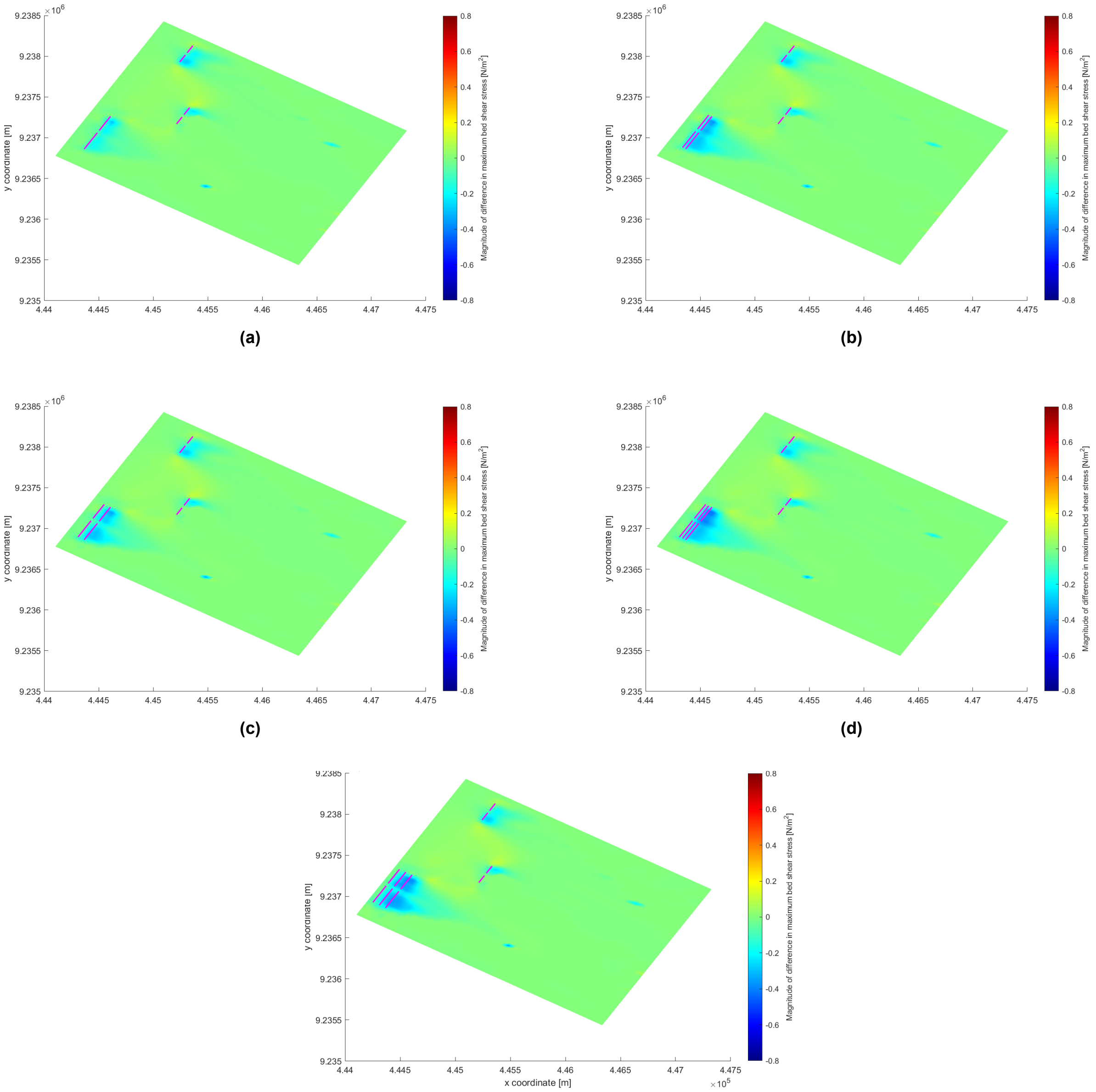


(a)

(b)

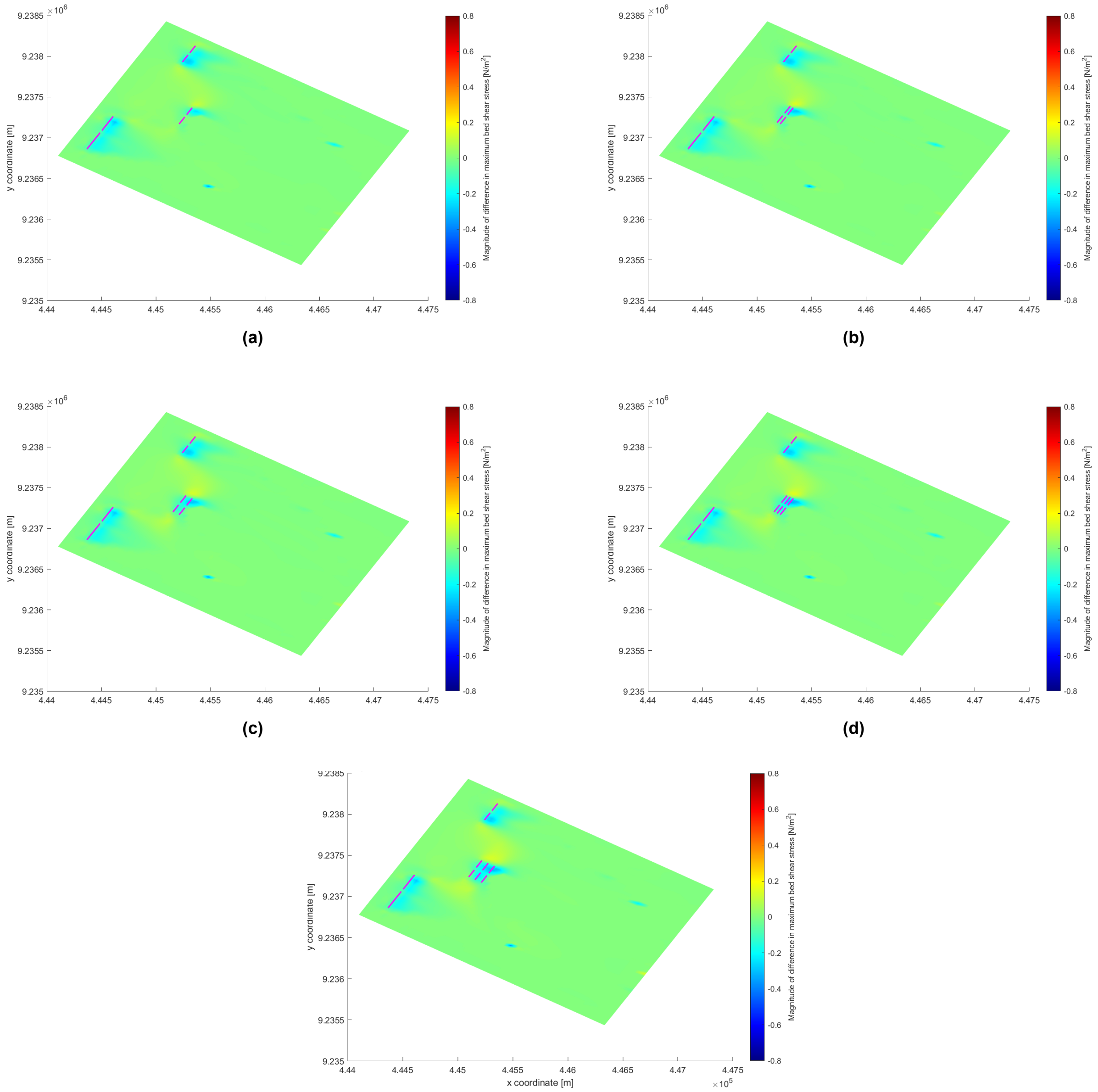
(c)

Figure E.7: Difference in maximum bed shear stress between the scenario without the presence of structures and the scenarios featuring a structure configuration of structures 5&6 with varying gap widths in between the set of structures: a) 33 m, b) 66 m, and c) 99 m



(a) (b) (c) (d) (e)

Figure E.8: Difference in maximum bed shear stress between the scenario without the presence of structures and the scenarios featuring a structure configuration of structures 1&2 with varying number of rows of structures placed behind each other: a) 1 row, b) 2 rows with a distance of 33 m in between, c) 2 rows with a distance of 66 m in between, d) 3 rows with a distance of 33 m in between, and e) 3 rows with a distance of 66 m in between



(a)

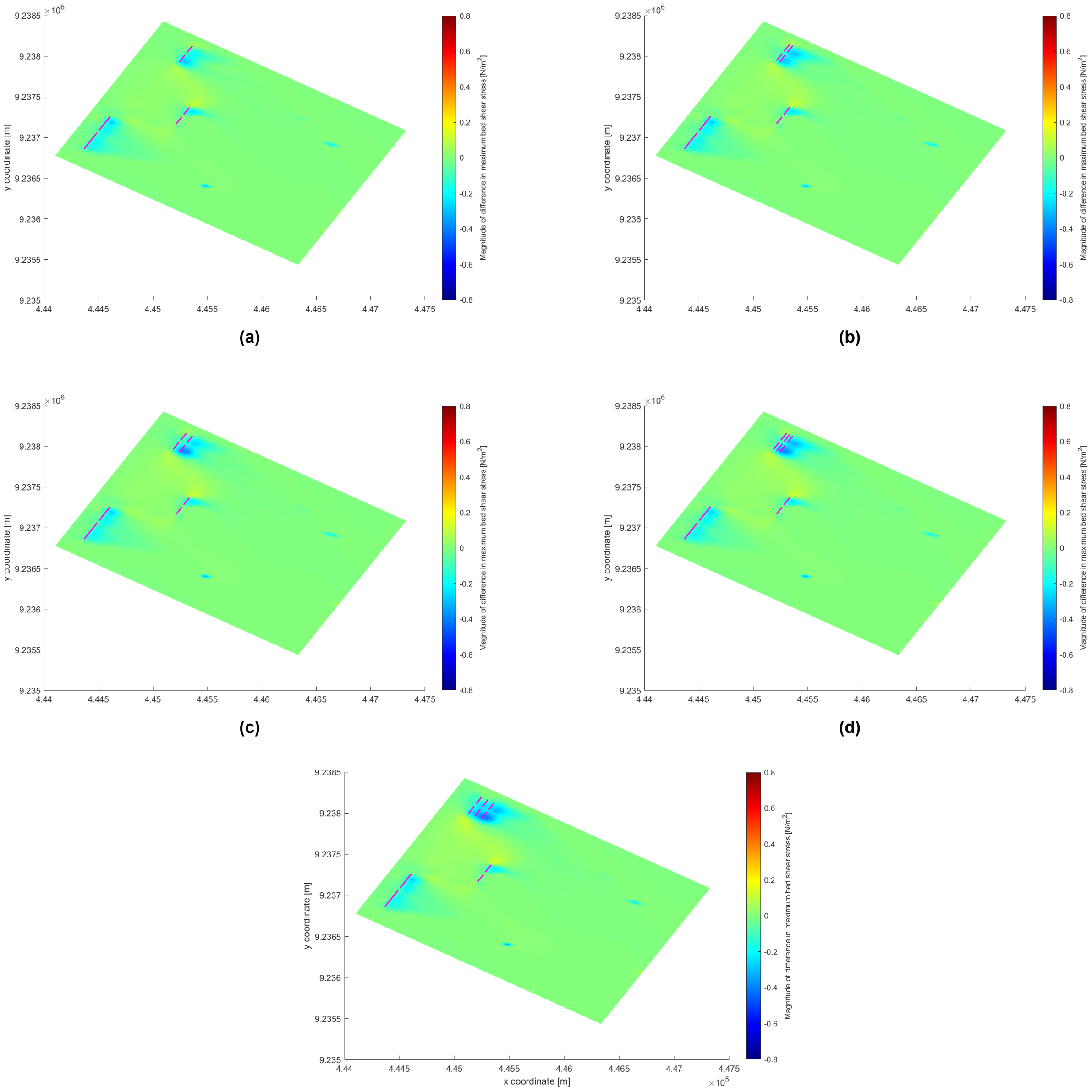
(b)

(c)

(d)

(e)

Figure E.9: Difference in maximum bed shear stress between the scenario without the presence of structures and the scenarios featuring a structure configuration of structures 3&4 with varying number of rows of structures placed behind each other: a) 1 row, b) 2 rows with a distance of 33 m in between, c) 2 rows with a distance of 66 m in between, d) 3 rows with a distance of 33 m in between, and e) 3 rows with a distance of 66 m in between



(a)

(b)

(c)

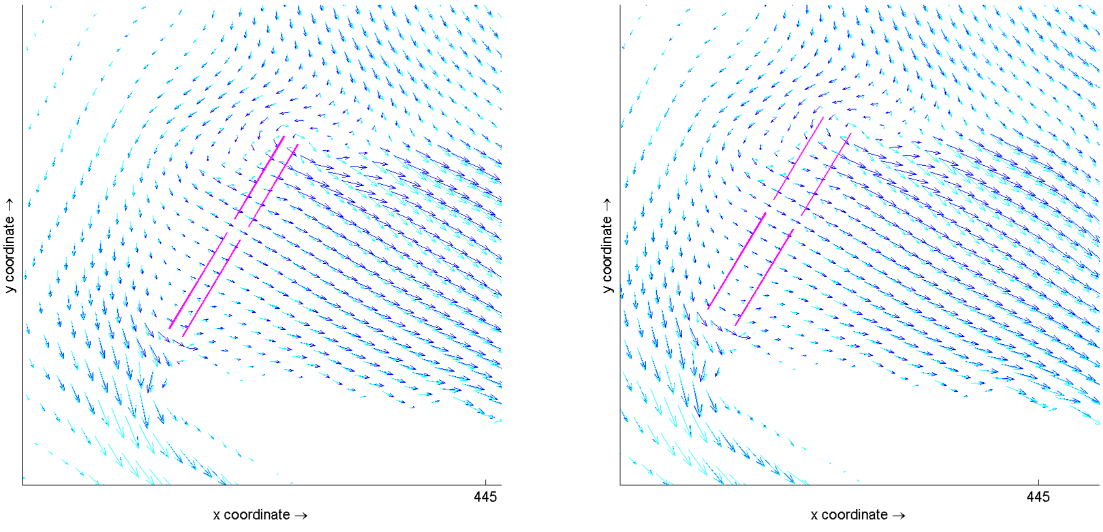
(d)

(e)

Figure E.10: Difference in maximum bed shear stress between the scenario without the presence of structures and the scenarios featuring a structure configuration of structures 5&6 with varying number of rows of structures placed behind each other: a) 1 row, b) 2 rows with a distance of 33 m in between, c) 2 rows with a distance of 66 m in between, d) 3 rows with a distance of 33 m in between, and e) 3 rows with a distance of 66 m in between

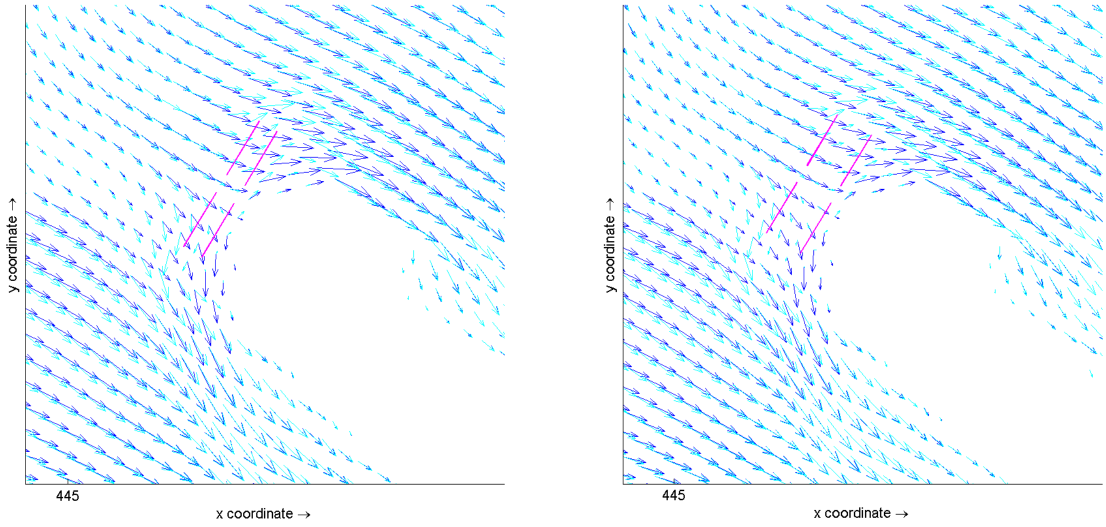
F Influence of distance in between multiple rows of structures

Figures F.1, F.2, and F.3 depict the depth-averaged velocities for structure configurations featuring two rows of structures positioned behind each other for structures 1&2, 3&4, and 5&6, respectively. Upon comparing Figures F.1a and F.1b, it is evident that for increased distance between the two rows, on the right of structure 2, the direction of depth-averaged velocity is towards the gap between the multiple rows, suggesting that currents can penetrate slightly between these rows of structures as the currents surrounding structure 2 are directed towards the structures. However, Figures F.2 and F.3 show that this is not the case with increased distance between the two rows of structures for structures 3&4, and 5&6, as currents are not directed in that manner around these structures. Depending on the direction of incoming currents, increasing the distance between multiple rows of structures could lead to currents penetrating from the sides, thereby affecting bed shear stresses between the rows of structures once again.



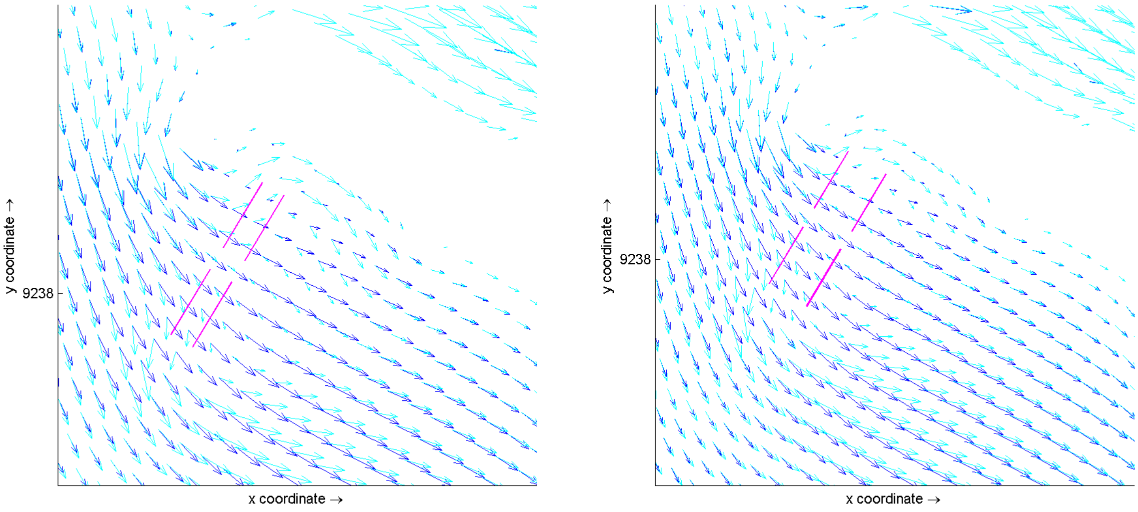
(a) (b)

Figure F.1: Differences in depth-averaged velocities for a 2 rows of structures 1&2 with a distance in between the rows of structures of a) 33 meters (light blue), and b) 66 meters (light blue), compared to the baseline scenario without structures (dark blue)



(a) (b)

Figure F.2: Differences in depth-averaged velocities for a 2 rows of structures 3&4 with a distance in between the rows of structures of a) 33 meters (light blue), and b) 66 meters (light blue), compared to the baseline scenario without structures (dark blue)



(a) (b)

Figure F.3: Differences in depth-averaged velocities for a 2 rows of structures 5&6 with a distance in between the rows of structures of a) 33 meters (light blue), and b) 66 meters (light blue), compared to the baseline scenario without structures (dark blue)