The physical solution space for mangrove restoration and conservation for coastal flood protection in the Mekong River Delta

MSc thesis
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Preface

I want to hereby thank everyone that helped me along this journey. Hans and Marjolijn, for their new ideas, guidance and for their patience, but also Maaike, my parents, brother, sister and roommates, who kept believing I would finish it.

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Summary

The Mekong River Delta (MRD) in Vietnam is currently under severe threat of coastal flooding due to rapid growth and industrialisation of the delta population and climate change. Mangrove restoration and conservation (MRaC) is known to protect against coastal flooding, among other valuable ecosystem services and is thus a promising nature based solution to this problem in the MRD. However, uncertainty exist about the long-term effectiveness of mangroves to protect against coastal flooding under large SLR, subsidence and low sediment input conditions that are present in the MRD and that may drown the mangrove population.

Defining "solution space" can help decision makers tackle future uncertainty of adaptation measures (Haasnoot et al. 2020). The solution space represents the boundaries of what is economically, politically, socially, and technically possible ("room to manoeuvre"). It consists of the different possible ways of action regarding climate adaptation and their estimated costs, risks, difficulties and benefits in the long-term future, and is constantly changing its form due to new insights, views and opportunities.

This study's goal is to identify and describe the "physical" solution space for MRaC in the MRD until 2100. Physical is defined here as the climatic and environmental conditions that will allow effective protection from mangroves against flooding. The results could support decision makers to (1) work towards (a) the total solution space of MRaC in the MRD and (b) the solution space of climate adaptation measures in the MRD as a whole. Finally, a better understanding of the physical solution space will support decision makers in the MRD with legislation for mangrove protection and restauration.

To this end I made a spreadsheet model that calculates, along 1D profiles, where and if mangroves survive and can protect against flooding in the future: the Dynamic Mangroves Model (DMM). The model is based on the 6 most influential physical factors for MRaC identified in this study: 1) current elevation of the MRD coastal profile (geomorphology), (2) SLR, (3) subsidence (natural and human-induced), (4) tidal range, (5) human-induced mangrove barriers, (6) sedimentation within mangroves that is dependent on suspended sediment input (SSC), and organic matter accumulation. Nine selected profiles along the southeastern (SE) MRD coast were modelled according to 3 linked scenarios for SLR, land subsidence, sediment supply and placement of embankments: (S1) sustainable: SSP1-2.6 with an embankment retreat of 5 km, a gradual sediment supply increase to +50% in 2100 and no more groundwater extraction, (S2) middle of the road: SSP2-4.5 with an embankment retreat of 2.5 km, a stable sediment supply and without increasing groundwater extraction, (S3) fossil fuel development: SSP5-8.5 with no embankment retreat, a gradual sediment supply decrease to -50% in 2100 and an increasing groundwater extraction (3% per year increase).

The average flooding date of the simulated MRD profiles ranged from the year ~2065 in S3 to ~2095 in S2 to ~2110+ in S1 (2110 being maximum in the simulation). However, even in the sustainable best case scenario and using all adaptation measures considered in this research, RSLR will still occur at the SE MRD coast. Eventually, without extra mitigation measures the SE MRD will drown (and with it the rest of the MRD). The most important physical factors that impede MRaC in the MRD are 1) SLR, 2) decreased sediment input, 3) human-induced subsidence, and 4) limited space for mangroves to retreat. Because of sedimentation feedback effects, combining multiple mitigation measures will have a greater total positive influence on MRaC solution space than the sum of the effect of each individual measure. It is thus recommended to implement MRaC in conjunction with other mitigation strategies. If combined with other mitigation measures, the results indicate that MRaC will extend the lifetime of the MRD coastline at a relatively low effort, buying the delta crucial time to adapt.

1. Introduction

The Mekong River Delta (MRD) in Vietnam is currently under severe threat of coastal flooding due to a combination of 1) damming and land-use changes in the drainage basin that impede sediment supply to the delta mouth, 2) a rapidly growing and industrializing delta population with an increasing demand for fresh water, space, and raw materials, which causes among others extraction induced subsidence, salt intrusion and the destruction of mangrove forests, 3) an uncertain climate future with possible heavier rainfall, longer droughts, and increased cyclone frequency, and 4) increasing rates of sea level rise (Allison et al. 2017). Because the Delta is home to a) 20 million people, b) Vietnams most productive rice fields and fisheries, c) profitable and popular tourist locations, and d) rich ecosystems, there is a large demand for possible measures to tackle these problems (Schmitt, Rubin & Kondolf 2017).

A large amount of research has focused on so called "Nature-based Solutions" (NbS, Narayan et al. 2016; Pontee et al. 2016; Sudmeier-Rieux et al. 2021) "soft measures" or Sedimentation Enhancing Strategies (SES, Cox et al. 2021) to protect against coastal flooding. Opposed to "hard measures" that focus on man-made structures to prevent flooding, "soft" nature based solutions for coastal flooding try to harness the power of natural processes to raise the delta land or to protect the coastline. When implemented well, nature based solutions have the benefit of often being more sustainable, cheap, and eco-friendly than hard measures. NbS have already been succesfully used locally in a large number of cases (Seddon et al. 2020) also in the MRD (Van et al. 2022). However, scaling up NbS to a delta-wide scale has been problematic. Not only because of physical, but also due to socio-economical and governmental problems.

One of the more well-known soft, nature-based solutions to protect against coastal flooding is the restoration and conservation of mangroves. Due to their high vegetation density, mangroves have been shown to dissipate hydrodynamic energy. In this way mangroves enhance sedimentation processes and reduce erosion under the right climatic and geological conditions. Mangrove roots also stabilize the soil. Finally, organic matter production in mangrove forests significantly promotes vertical substrate elevation (Besset et al. 2019; Gijsman et al. 2021; Horstman et al. 2014; Furukawa and Wolanski 1996; Rogers and Saintilan 2005).

In addition to their coastal flooding protection potential, mangroves provide a number of other ecosystem services (Mitra 2020): (1) mangroves directly provide food and raw material for locals, (2) support a biodiverse rich ecosystem that (3) attract ecotourism and (4) increase aquaculture yields because mangroves act as fish nurseries, (5) mangroves also increase water quality, and (6) serve as a large carbon sink due to the efficient burying and sequestration of organic matter in mangrove sediments. It is even thought that 11% of all terrestrial carbon input into the ocean is produced in mangrove forests (Jennerjahn and Ittekkot 2002).

However, the effectiveness and feasibility of mangroves to protect against coastal flooding under changing conditions over a time scale of decades and on a delta wide scale is uncertain. It can be assumed that mangroves aid against flooding if mangroves can persist in a particular area, because there is scientific consensus that mangroves help promote sedimentation and protect against erosion (Besset et al. 2019; Furukawa and Wolanski 1996). However, mangroves cannot survive without sufficient sediment supply, neither under prevailing erosion and/or extremely fast inundation. A large and healthy mangrove fringe is thus not in all circumstances enough to stop shoreline erosion and flooding. Before making predictions of mangrove restoration and conservation success the whole delta system needs to be taken into account (Besset et al. 2019).

This uncertainty is hampering the ability of decision makers to take immediate action to reduce mangrove destruction (Woodroffe et al. 2016). Consequently, the existing mangrove population in the

MRD is still declining due to severe anthropogenic pressure (Veettil et al. 2019). A comprehensive guide of the different possible ways of action regarding mangrove restoration and conservation (MRaC) and the estimated costs, risks, difficulties and benefits in the long-term (coming decades) future is needed to tackle this problem in the MRD. In fact, the uncertainty about risks, costs and benefits, of climate adaptation measures in general in the long-term future, is one of the reasons why current plans for the MRD primarily aim at economically developing areas, instead of climate adaptation (Ha et al. 2012).

A new method that supports a better understanding of the consequences of actions in an uncertain climate and social future is: *defining solution space* (Haasnoot et al. 2020). Defining solution space gives researchers a comprehensive way of presenting the different possible ways of action regarding climate adaptation and their estimated costs, risks, difficulties and benefits in the long-term future. Haasnoot et al. (2020) define the solution space as "the space within which opportunities and constraints determine why, how, when, and who adapts to climate risks. The solution space is shaped by biophysical, cultural, socio-economic, and political-institutional dimensions at a given moment in time. Within these dimensions, there are 'hard' (unsurpassable) limits and 'soft' (surpassable) limits". The solution space thus represents the boundaries of what is economically, politically, socially, and technically possible, and is constantly changing its form due to new insights, views and opportunities (Figure 1). Change in the solution space is possible in two ways: First, due to exogenous changes beyond the direct influence of the actors. Second, solution space can be intentionally changed by planned actions for adaptation, unless hard limits occur. This method can also be applied to MRaC. If it is known for example how mangroves in the MRD react to a range of probable climate and social scenarios, it is possible to deduct how the solution space of this measure would be shaped. Future MRaC solution space may shrink due to rapid climate change that causes large SLR, but planned actions could increase space or "room to manoeuvre" by e.g. a sediment supply program that adds new sediment to the MRD coast.

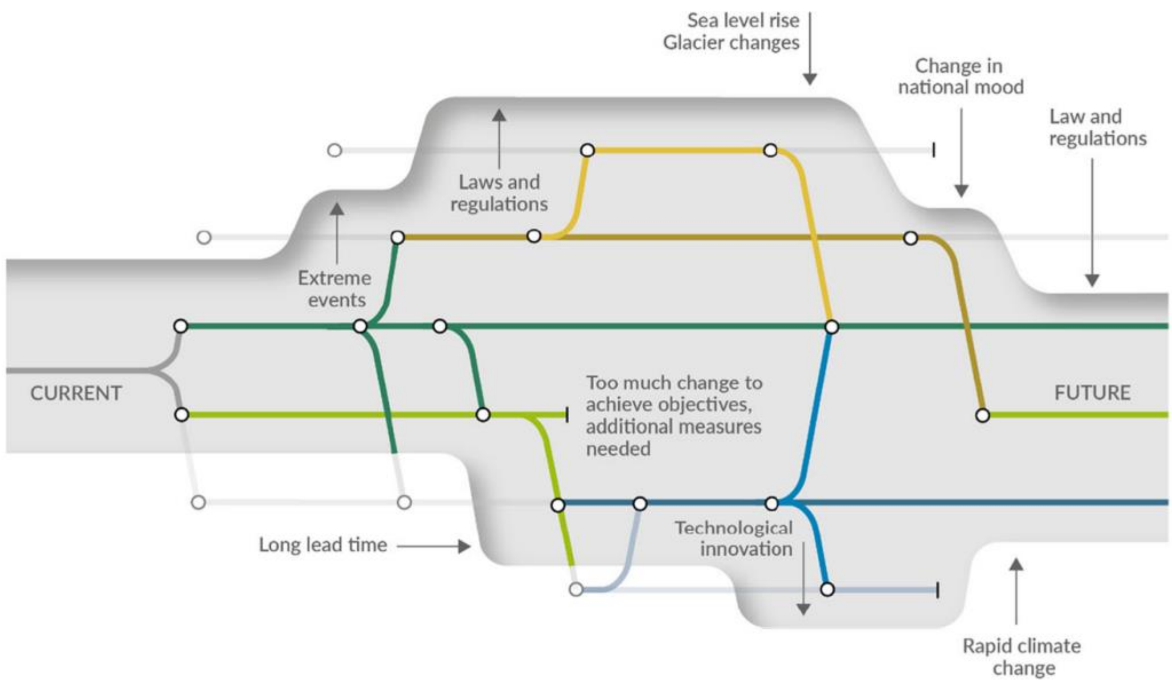

Figure 1: A schematic model of solution space (From Haasnoot et al. 2020).

Defining the MRaC solution space in the MRD may give decision makers a much needed insight into the longer-term (i.e. beyond the current 5-10 year planning horizon) consequences of their decisions on, and limitations of, land use and climate adaptation through mangrove restoration and conservation, within a probable range of future climate and social scenarios. In this manner, it may tremendously support the decision process on choosing a sustainable strategy for mangroves in the MRD and in doing so may prevent future coastal flooding in the MRD (Besset et al. 2019; Woodroffe et al. 2016).

The question is how to define the solution space for mangrove restoration and conservation in the MRD. How do you determine the boundaries, controlling and limiting factors, and opportunities for growth of this space if a problem is so complex with so many interconnected factors that could influence its future? Considering the potential complexity of setting up a multi-dimensional (physical, social, economic, legal dimensions) solution space it was decided for this study to first focus on starting to map out the "physical" part of the solution space. First, the physical mangrove system in the MRD and its main driving factors should be fully understood to be able to determine what will be the response of a particular change in the future. What determines physically, at a long-term delta wide scale in the MRD, if mangrove forests can persist or not? And what areas in the MRD have the most or least potential for MRaC and why? Secondly, the mangrove response should be modelled according to these conditions to be able to predict long-term future solution space of MRaC in the MRD. How will these physical factors change in the future and influence this "physical" solution space? This will be the focus of this research.

1.1 Objectives and Research Questions

The overall objective of this study was to identify and describe the "physical" solution space for mangrove restoration and conservation (MRaC) in the Mekong River Delta (MRD) as a nature based solution (NbS) to protect against coastal flooding until 2100. Physical is defined here as the climatic and environmental conditions that will allow effective protection from mangroves against flooding. Physical conditions are often influenced by human activities, which will be considered using scenarios for sea level rise, ground subsidence, sediment supply, and embankment placement: (S1) sustainable: SSP1-2.6, (S2) middle of the road: SSP2-4.5, (S3) fossil fuel development: SSP5-8.5.

First the critical physical factors that determine mangrove sustainability in the MRD were determined. Second, it was calculated how these factors would influence mangroves in nine locations along the southeastern MRD coastline until 2100. Finally, that data was used to shape and quantify the physical MRaC solution space. This supports (1) a more complete understanding of (a) the total solution space of MRaC in the MRD and (b) the solution space of climate adaptation measures in the MRD as a whole, and (2) supports decision makers in the MRD with the implementation of mangrove protection legislation. Essentially, using defining solution space as an approach, this research tries to answer the following question:

What is the effectivity, from a physical perspective, of mangrove restoration and conservation as a long-term measure against coastal flooding in the Mekong River Delta?

To help answering the main research question, 3 sub-questions were formulated:

1. *What physical factors on a long-term (10-80 years) delta wide scale determine whether mangroves can persist in the MRD?*
2. *How do these factors shape the solution space for mangrove restoration and conservation as measure for sediment accumulation and flood protection in the MRD throughout the coming decades?*
3. *What are possible additional adaptation measures to support mangrove persistence and increase MRaC solution space in the MRD?*

1.2 General approach and thesis outline

To tackle the problem of determining the feasibility of mangrove restoration and conservation (MRaC) as a measure against coastal flooding in the Mekong River Delta (MRD), this research followed a six-step approach:

Step 1: Literature review to identify the physical factors that determine mangrove growth in the MRD

To determine the most important physical factors that influence mangrove persistence on a long-term (10-80 years) basis in the MRD, and to understand how these factors would influence the effectiveness of MRaC in the MRD, a literature review was done from which a mangrove knowledge-base was constructed. This knowledge-base formed the basis from which the future response of mangroves in the MRD to changing environmental factors was predicted/modelled. The knowledge-base is described in chapter 2. This chapter also forms the basis that answers sub-question 1.

Step 2: Literature review on mangrove models and their suitability for this study

A background on the modelling of mangroves, and the reason to make a new model is given in chapter 3.

Step 3: Creating the Dynamic Mangrove Model

Using input from the mangrove knowledge-base (chapter 2), a simple spreadsheet-type numerical model, called the Dynamic Mangrove Model (DMM), was created to calculate, a) how long mangroves can persist in the MRD under changing physical conditions dictated by the three chosen scenarios, b) how the most important factors that influence MRaC shape the physical part of the solution space of MRaC in the future, and c) to see how possible adaptation measures can support mangrove persistence in the MRD and increase the future solution space of MRaC. The methodology of the creation and usage of the model is given in chapter 4.

Step 4: Obtaining the results using the Dynamic Mangrove Model

The results from the modelling of the DMM are presented in chapter 5. This chapters provides the data basis to answer sub-questions 2 and 3.

Step 5: Determine the solution space of mangrove restauration and conservation

With the results of the DMM (chapter 5), the shape MRaC solution space is determined in chapter 6. This answers sub-question 2 and 3.

Step 6: Discuss the implications of the findings

Finally, the implications of the results of the study are discussed in chapter 7. Here, first the reliability of the results is discussed. Afterwards the results are compared to the literature. The study is concluded by a discussion of the relevance of this research for decision makers in the MRD and gives recommendations. This chapter answers the main research question.

2. Critical physical factors for long-term Mangrove persistence in the Mekong River Delta

Mangroves are associations of trees and shrubs that are salt tolerant and that prefer upper intertidal habitats just above mean sea level. They are most diverse and extensive in the humid tropics, but do also occur in the warm temperate climatic zones and are adapted to a wide range of coastal environments (Perry and Berkeley 2009). What areas are suitable for mangrove occupation is mostly controlled by climate, coastline sedimentology and geomorphology (mangroves generally prefer intertidal mudflats), and the input of fresh water (fluvial or annual rainfall), but their extent can most convincingly be correlated to a local sea-surface temperature of at least 15 ºC (Woodroffe and Grindrod 1991). At present these factors can be simplified to a general range for mangroves that is between 30ºN and 30ºS latitude.

Mangroves provide a wide range of valuable ecosystem services. However, they are of particular interest to this study because of their ability to protect against erosion and support sedimentation. Due to their high vegetation density, mangroves have been shown to dissipate hydrodynamic energy. Mangrove roots also stabilize the soil. Finally, Organic matter production in mangrove forests, especially underground root growth, significantly promotes vertical substrate elevation (Besset et al. 2019; Gijsman et al. 2021; Horstman et al. 2014; Furukawa and Wolanski 1996; Rogers and Saintilan 2005). However, mangroves cannot survive without sufficient sediment supply, neither under prevailing erosion and/or extremely fast inundation. A large and healthy mangrove fringe is thus not in all circumstances enough to stop shoreline erosion and flooding (Besset et al. 2019).

To understand how mangroves will affect the MRD coast in different future scenarios, a knowledge-base is needed, on the basis of which the future response of mangroves in the MRD to environmental changes can be predicted. This chapter forms the "knowledge-base" of this study that was used to model future mangrove sustainability in the MRD.

2.1 Mangrove life cycle and critical physical boundaries

To fully understand the boundaries for mangrove sustainability, it is crucial to take into account the life cycle of a mangrove and the niche they fill in their ecosystem. There are three critical bottlenecks that apply to different life stages of mangroves and mostly determine if a mangrove forest will survive (Balke et al. 2011). These bottlenecks are (1) a period with salt/brackish water inundation to disperse seeds and during which competing species die off, followed by a period without inundation to allow the anchoring of seedlings (2) a period without too much disturbance (e.g. waves, currents, erosion, and sedimentation) to allow for seedling establishment, (3) a period without major storms (or other disrupting events) that severely damages the mangrove forest. The boundaries of these bottlenecks are not exactly defined, because they not only depend on a maximum or minimum physical state that is exceeded (severity of the event), but also on the frequency of such an event (Balke et al. 2013a, 2013b). Additionally, many local environmental factors influence the critical habitat requirements of a mangrove tree and different mangrove species have different tolerances for certain disturbances (Osland et al. 2017). Finally, if mangrove habitat requirements are not met, the damage done to a mangrove forest results most often not in a complete forest loss or a complete forest survival, but somewhere in between.

The closest we can get in determining a mangrove sustainability boundary is thus an estimation that consists of a certain frequency, duration and severity of these critical physical conditions. The frequency and duration of a boundary condition can be tied to the specific bottleneck for each life stage because of the typical length of the life stage of the mangrove tree. A seed needs about 5 days without inundation to anchor itself in the sediment, and a couple of flooding events a year to kill of competitive flora and be dispersed (bottleneck 1) (Proisy et al. 2009), a seedling needs about 2-3 months to grow and become less vulnerable to disturbance (bottleneck 2) (Proisy et al. 2009), and a forest needs multiple years to decades to recover from a large disturbance (bottleneck 3) (Nardin et al. 2016). The three bottlenecks and their associated mangrove sustainability boundaries are shown in Table 1. In Table 1 the following factors have been taken in consideration: maximum and minimum inundation time, erosion, sedimentation, temperature, salinity, and maximum wave heights, storm events, drought and RSLR.

Table 1: The physical boundaries and timeframes of reoccurrence of mangrove sustainability in the Mekong River Delta sorted by bottleneck stage.

Period/bottleneck	***boundary***
Bottleneck 1 → Preferably multiple 5 consecutive dry days and at least a couple of flooding events a year	- Mangroves generally only occur **between Mean Sea Level (MSL) and Mean Higher High Water (MHHW)** due to a couple of flooding events and multiple 5 consecutive dry days a year that are required (Lewis 2005; Lovelock et al. 2015; Proisy et al. 2009).
Bottleneck 2 → No fatal seedling disturbance for 2 to 3 consecutive months a year	- An event of about 1-3cm of **sedimentation or erosion** (Balke et al. 2013a, 2013b), 4+ cm sedimentation event (Terrados et al. 1997), 10-20mm/day erosion or sedimentation (Balke et al. 2013b). - **Wave heights** of about H50 = 4.2 ± 0.4cm and H80 = 8.0 ± 0.5cm. Low intertidal slopes were observed to enhance mangrove wave tolerance (So ≅ 0; H80 = 9 cm) while high slopes led to dramatic reductions in threshold wave heights (So ≅ 1; H80 = 4 cm) (Cannon et al. 2020). - **The maximum amount of inundation** (in the critical seedling stage) is 30% of the time (Lewis 2005).
Bottleneck 3 → no severe mangrove forest killing event for at least 5-15 years	- **Sedimentation/erosion**; an event of 10+ cm of erosion/sedimentation (Ellison 1999), an event of 16+ cm of sedimentation(Thampanya et al. 2002), 60 cm of sedimentation causes forest collapse (Nardin et al. 2021). - **Storm events** are hard to quantify, because of the large dependence on the severity of the event (Balke et al. 2013b) (see rest of the boundaries). - **Drought**, the range-limit-specific precipitation-based minimum thresholds for mangrove presence and species richness ranged from 0.32 to 1.34 m of rainfall per year (Osland et al. 2017). - **Salinity stress**, highly species dependent some mangroves can still survive long periods with double the amount of salt, doesn't seem to be a very important factor in the Mekong Delta (Alongi 2015; Biber 2006). - **Temperature**, mangroves generally like warm temperatures, they are present from about 15 degrees (Woodroffe and Grindrod 1991), although from about 33-35 degrees photosynthesis degrades (Alongi 2015). - If mangroves want to sustain the current shoreline **RSLR** needs to stay below 6.1mm/yr - 90% certainty, 7.6mm/yr - 95% certainty (under pre human conditions) (Saintilan et al. 2020). - With 20mm/yr **elevation deficit** (RSLR-accretion) all mangroves with tidal ranges less than 4m in the Indo Pacific will have drowned within 100 yrs. sites with low tidal range and low sediment supply, mangrove forests will be vulnerable at moderate SLR by 2080 (Lovelock et al. 2015).

2.2 Critical physical conditions that control long-term delta-wide mangrove forest sustainability in the Mekong River Delta

Whereas it is already hard to quantify critical mangrove sustainability boundaries for a specific location (2.1) this becomes even more complicated when one tries to upscale these factors to delta level as is required in this study.

It was found that, from a long-term delta-wide perspective in the MRD, the most crucial physical requirements for mangrove persistence is the availability mangrove habitat between mean sea level (MSL) and mean higher high water (MHHW) (Lewis 2005; Lovelock et al. 2015; Proisy et al. 2009) and the absence of direct mangrove destruction by humans (Veettil et al. 2019). Because all mangrove species occupy this habitat (Table 1), and it is severely threatened by relative sea level rise (RSLR) and human occupation. Therefore, the main factors that control mangrove sustainability, are (1) the amount and rate of relative sea level rise (RSLR), (2) the amount and elevation of space that is available for mangrove forests to retreat during (inevitable) coastal regression ('coastal squeeze') (Rogers 2021), and (3) the amount of direct human-induced mangrove forest destruction (Veettil et al. 2019). RSLR is in term controlled by the amount and speed of future SLR, sedimentation and erosion processes, and subsidence (natural- and human-induced through e.g. fresh water extraction) (Dunn and Minderhoud 2022). These factors are thus classified as having a large potential impact in Table 2. Furthermore, the potential mangrove habitat and the factors that influence it are schematically shown in Figure 2.

How much a mangrove system will be affected by the changing factors described above depends on the resilience of that particular mangrove system. Physical factors that have a large impact on mangrove resilience include the geomorphology and the tidal range (Lovelock et al. 2015; Osland et al. 2017; Rogers 2021; Woodroffe et al. 2016). Because mangroves grow between MSL and MHHW (Table 1, Figure 2), the tidal range determines the vertical elevation at the coast that mangroves can occupy and the amount of RSLR that is needed to drown the current mangrove population. The geomorphology mainly determines (together with the tidal range and human-induced mangrove barriers/ habitat borders) the amount of space that is naturally available for mangroves to grow and the potential for mangroves to retreat landwards during SLR. In the MRD this space is generally small, because of human-induced habitat borders and a flat morphology that does not allow for much RSLR before all land is flooded (Minderhoud et al. 2019; Woodroffe et al. 2016). This is also shown in the schematic model in Figure 2; the size of the potential mangrove habitat (green) is controlled by the difference between Mean Sea Level (MSL) and Mean Higher High Water (MHHW) (= 0.5 * tidal range) and the geomorphology (lower slope = a larger potential mangrove habitat). The movement of the potential mangrove habitat can be restricted due to habitat borders, which can consist of particular geomorphology, infrastructure or direct cutting of mangroves. Habitat borders can eventually reduce the potential mangrove habitat to 0 if the potential mangrove habitat keeps moving upwards. The space that is available for mangroves to move upwards until it reaches a habitat border is called the mangrove retreat space.

As seen in Figure 2 mangrove resilience and RSLR in the MRD are also significantly influenced by sedimentation and erosion processes; e.g. organic matter accumulation, a high sediment availability, lower coastal gradients, sheltering geomorphology and larger areas that are occupied by mangroves, aid sedimentation processes and/or wave attenuation, decrease erosion and increase coastal flood protection (Besset et al. 2019). Sedimentation thus can raise the ground underneath the mangrove forest, thereby decreasing RSLR and increasing the mangrove forest capability to adapt to SLR. Sedimentation and erosion processes also for a large part determine if a particular mangrove stretch will be eroded, and if local conditions are favourable for mangrove colonisation (Balke et al. 2013b). Some research even suggests that there is a critical minimum width for the mangrove forests strip below which the mangrove forest becomes unstable because it loses its ability to sustain and effectively regulate and promote sedimentation (Phan et al. 2015; Truong et al. 2017). Besset et al. (2019), however, contest this statement. They found that there was no significant relation between mangrove strip width and accretion/erosion. Instead of mangrove forest strip width, they argue a better indicator for accretion/erosion is the amount of sediment supply in an area, specifically SSC (Suspended Sediment Concentration) in a particular area. Mangroves mainly sequestrate finer sediments because, due to mangroves efficient dissipation of hydrodynamic energy, sand can generally not stay in suspension within the mangrove forest (Furukawa and Wolanski 1996). SSC values differ along the coastline due to local sedimentation mechanisms (most of the sedimentation and erosion processes on the MRD coast are a form of redistributing sediment (Figure 3) (Marchesiello et al. 2019)), but are still linked to the total sediment input at the MRD mouth (Li et al. 2017) (Figure 3). So, if MRD sediment input declines also on average SSC at the MRD coast declines.

Finally, (as can be seen linked to potential habitat in Figure 2), if mangroves actually do grow in the potential mangrove habitat is influenced by the rate at which mangroves can colonise a new potential growing area and thus the speed at which the potential mangrove area moves. Other Physical factors that may change in the future and negatively affect mangrove growth in the potential mangrove habitat in the MRD include increased temperature increase, salinity increase, water quality decrease (e.g. pollutants and nutrient increase), and a drought increase. Conversely, an expected increase in rainfall in the MRD may positively affect future mangrove sustainability in the MRD ("see environmental factors" Figure 2) (Alongi 2015; Biber 2006). However, different mangrove species are adapted to a wide range of these environmental conditions. Because (1) the MRD has one of the most species rich mangrove habitat in the world (Hong and San 1993), and (2) these conditions in the MRD are at present well within the boundaries for mangroves persistence in the MRD (Table 1), these factors are thought to not play a significant role for long-term mangrove sustainability in the MRD (Alongi 2015; Biber 2006). Similarly, the effect of increased CO_2 will be very minor and will probably benefit certain mangrove species and hinder others (Alongi 2015). Furthermore, storm frequency and intensity, and a decrease in biodiversity may negatively impact mangroves in the future. However, the impacts of these factors on mangroves are still very hard to quantify (Balke et al. 2013a). These factors are therefore also considered here as having a minor influence on mangrove sustainability in the future (Table 2).

The various factors that were identified in the literature have been sorted according to (1) their relative importance to long-term delta-wide mangrove sustainability in the MRD and (2) the causes of change of these factors in Table 1.

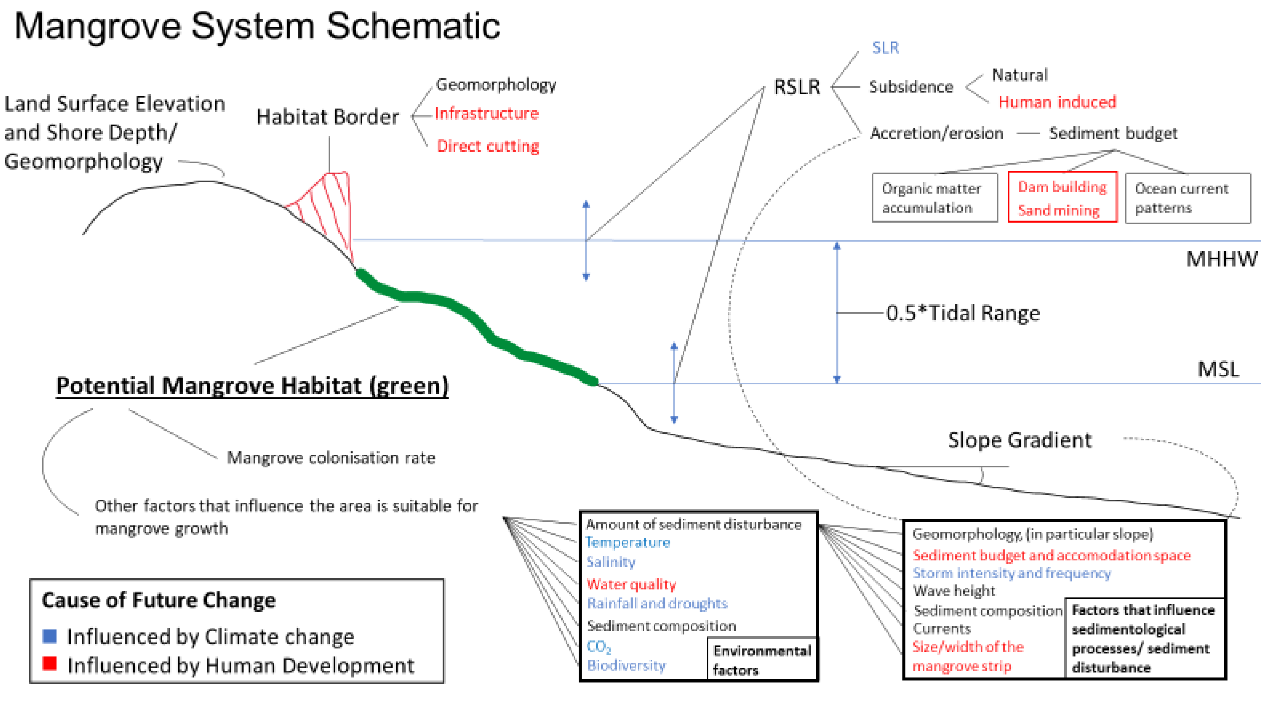

Figure 2: A schematic overview of a mangrove system. Factors are sorted by whether they will change due to direct human influence or climate change.

Table 2: physical factors affecting mangrove sustainability in the MRD. Red = this factor will probably increasingly limit mangrove sustainability. Green = this factor will probably increasingly benefit mangrove sustainability. Grey = this factor has a varying impact on mangrove sustainability. Black = this factor will not change in the future but has an impact on future mangrove sustainability. a = The effect of increased CO_2 will be very minor and will probably benefit certain mangrove species and hinder others (Alongi 2015). b=Direct mangrove harvesting has been decreasing and will probably decrease in the future however it will still hinder mangrove sustainability (Veettil et al. 2019).

	Large potential impact	*Small potential impact*
Climate change	- increasing SL - rate of SLR	-increasing temperature -increase in droughts -increase in salinity -increase in tropical storms (may also be important factor but hard to quantify) -decreasing biodiversity (may also be important factor but hard to quantify) -more rainfall -more CO_2 in the atmosphere [a]
Change under direct human control	-reducing sediment delivery to the Mekong Delta mouth due to dam building and sand mining -increasing rates of human-induced subsidence - increasing amount of Mekong Delta space occupied by human infrastructure (preventing mangrove retreat/settling) - direct mangrove harvesting/cutting[b] -geomorphology/coastal gradient	-water quality decrease
No change/natural	-natural subsidence -tidal range	

2.3 Mangroves in the Mekong River Delta: current state, recent changes and prospects

2.3.1 Current state mangroves in the MRD and recent shoreline change

Because mangroves grow in upper intertidal areas, preferably at a delta mouth that provides riverine input of fresh water, they are currently under severe pressure from humans, for whom this land is also greatly desirable, due to abundant natural resources, and aqua- and agricultural value. However, mangroves have not only suffered due to deforestation, and land-use change, but also climate-change-induced SLR. It is even argued that mangrove forests suffer one of the highest rates of decline of any natural environment. (Spalding, Blasco, and Field 1997). Because the main pressures on worldwide mangrove populations are only increasing (industrializing population and SLR increase), the decline is not expected to stop in the near future.

An estimated 400.000 ha of mangroves in Vietnam in 1943 were reduced by at least 100.000 ha (25%) from 1965-1970 (the war). Overexploitation and unsustainable shrimp farming with little to no oversight reduced the remaining mangrove area with 23% until 1995. From then on steps were taken to conserve the remaining mangrove area and since the decrease in mangrove area has slowed. However total mangrove area is still experiencing a decline to this day (Veettil et al. 2019). Using satellite imagery from 1997-1998 (Blasco et al. 2001) it has been suggested that in the MRD 210.000 ha was occupied by mangroves of which 80.000 ha was degraded and 130.000 ha replanted by the end of the 20th century. Almost all mangroves in the MRD are secondary because of widespread forest destruction in the Vietnam war and heavy exploitation post war (Veettil et al. 2019). The current largest reasons of mangrove decline in Vietnam are 1) unsustainable aquaculture 2) storms and natural disasters, 3) deforestation for natural resources, 4) pollutants from agriculture and urban areas, 5) lack of sufficient management and regulatory systems for the protection of mangrove areas (Veettil et al. 2019).

Mangroves have been protected under the centralized forest law, but since the 1990 protection of forest and mangroves has undergone a devolution from central to local management. Vietnam has been allocating pieces of mangrove forest to maintain to families since 1995. A problem however is that shrimp farming (even if it needs mangroves to be productive) is at present much more economically rewarding per area than mangrove forest protection and sustainable harvesting, because locals have only a small share in the rewards from forest protection/sustainable harvesting. At present local decisions are thus often focused on improving aquaculture yields instead of protecting mangroves (Ha et al. 2012).

Additionally, satellite measurements show that the MRD shows a significant decrease in progradation rate. Around 2005 the MRD is thought to have experienced a shift from expanding to shrinking and in 2017 66% of the MRD was eroding (Li et al. 2017) (Figure 3). This decline is thought to be mainly caused by declining sediment input from the Mekong River due to extensive damming and sandmining. Furthermore, the decline is expected to accelerate in the future due to the discussed threats of mainly subsidence, SLR and further sediment input decline. Different parts of the MRD coast currently experience different stressors to shoreline change; sedimentation in the west and at the delta mouth, erosion in the southwest, and subsidence between Bac Liêu and Cà Mau city and in the northwest (Figure 3) (Marchesiello et al. 2019). Although the current retrogradation of the MRD is mainly taking place outside of the estuarine coast, it is already putting mangrove sustainability under pressure.

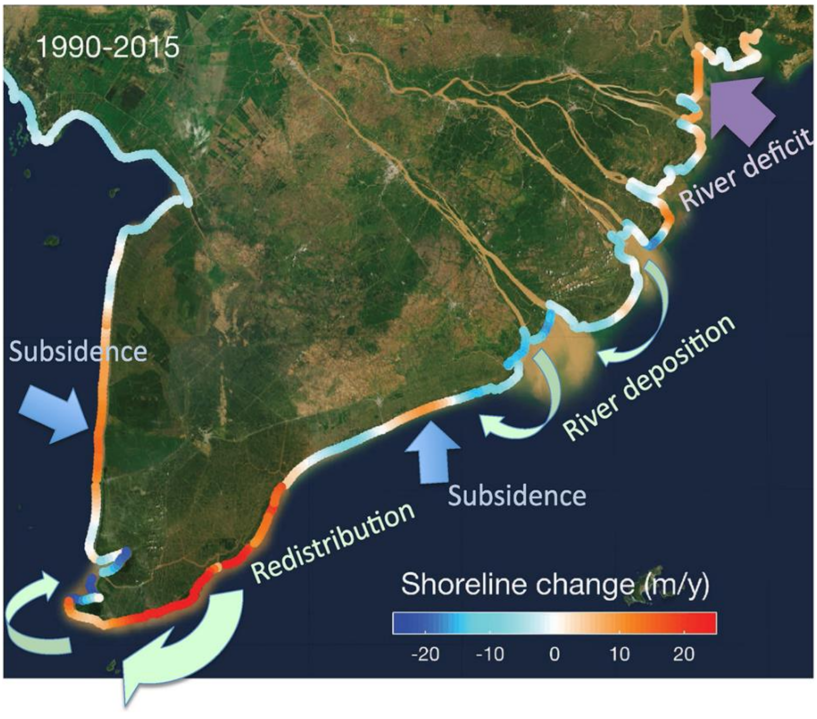

Figure 3: The shoreline change and their main causes in the MRD from 1990-2015. Currently the MRD is experiencing an overall shrinkage (From Marchesiello et al. 2019).

2.3.2 Current state and change in the future of factors that control long-term mangrove sustainability in the Mekong Delta

Land surface elevation / Geomorphology

This study used data from Minderhoud et al. (2019) who created a new elevation model for the MRD: the topo DEM59 (digital elevation model). This elevation model is based on nearly 20,000 topographical elevation points and gridded at 500m x 500m (Figure 4).

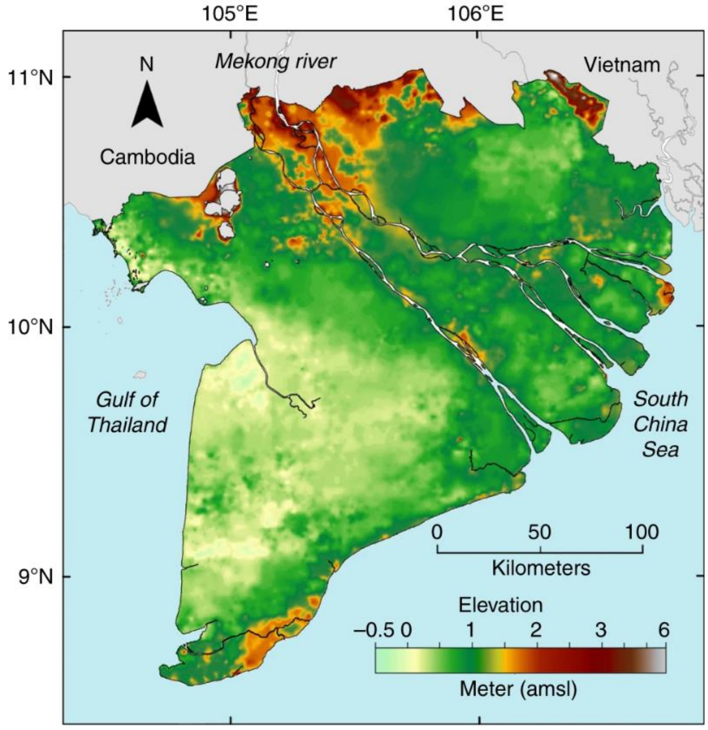

Figure 4: The digital elevation model used in this study: Topo DEM59 (From Minderhoud et al. 2019).

There is not much room for RSLR in the MRD (Figure 5). Topo DEM59 shows that the MRD is especially susceptible for flooding in the northwest of the delta. That is why it was decided to focus the research on the relatively highly elevated southeastern part of the MRD. Because of higher elevation, the chance of succesfully using MRaC is highest in this area.

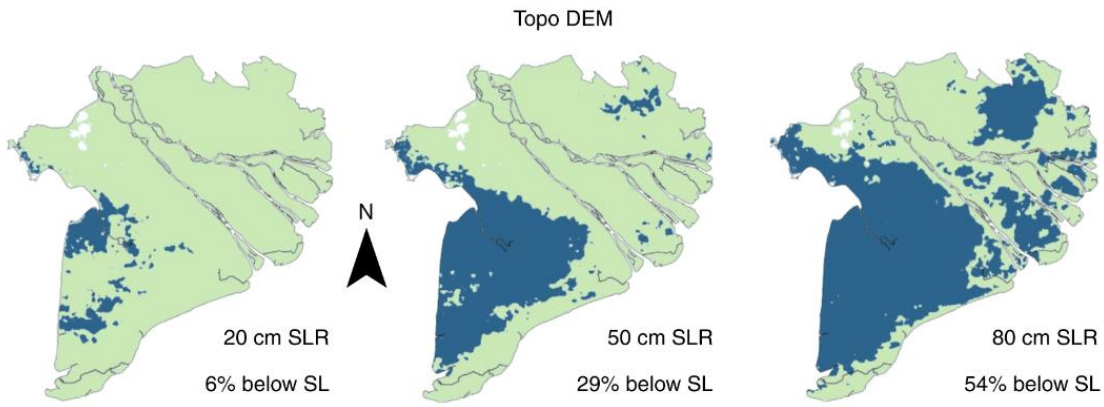

Figure 5: The Mekong delta according to Topo DEM59 when exposed to different hights of relative sea level rise (From Minderhoud et al. 2019).

Subsidence

Natural compaction of coastal Holocene sediments in the MRD is estimated at an average of 20 mm/yr by Zoccarato et al. (2018) and is not expected to change in the coming century.

The current human-induced subsidence data used in this research was obtained from Minderhoud et al. (2017) who used a modelling approach to determine ground water exploitation induced subsidence rates in the MRD. According to Minderhoud et al. (2017) over the last decades groundwater extraction increased dramatically and caused a ~18 cm average drop in delta elevation during this time. In 2015 subsidence rates due to groundwater extraction were on average 11 mm/yr and increasing (Figure 6). It is clear that human-induced subsidence plays a key role in this research as these rates exceed current SLR rates by almost an order of magnitude in certain areas.

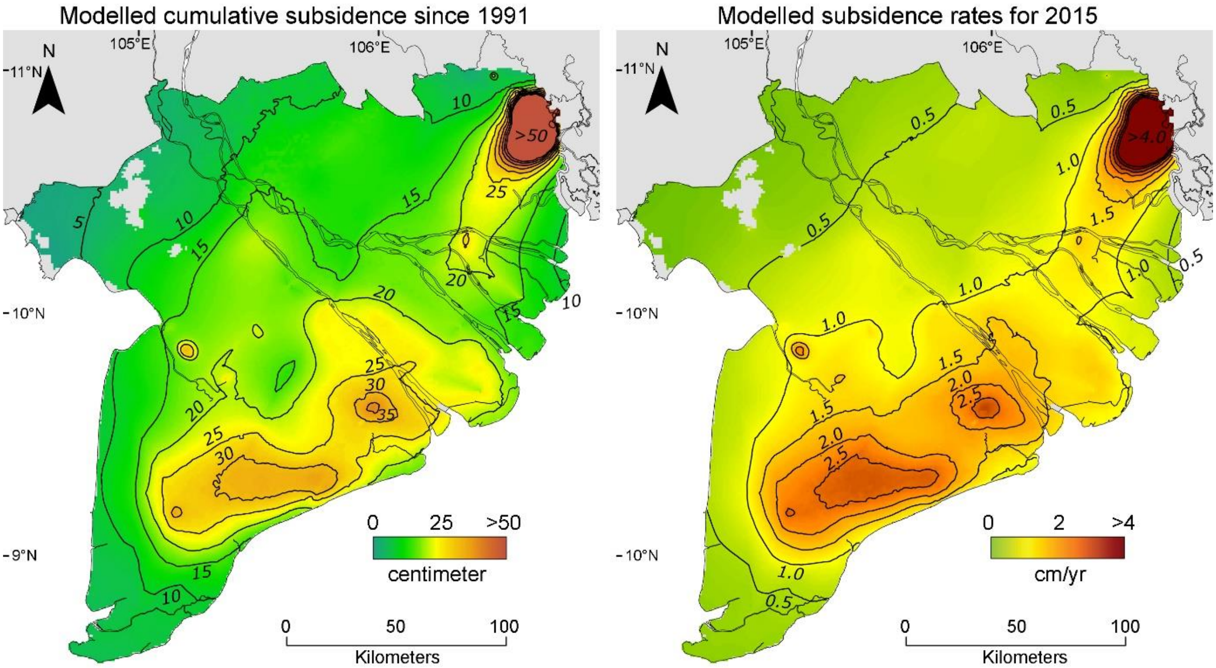

Figure 6: The modelled cumulative subsidence from 1991-2015 and the modelled subsidence rates in 2015 (From Minderhoud et al. 2017).

How human-induced subsidence will change in the coming century is dependent on the amount of groundwater extraction. Minderhoud et al. 2020 calculated the subsidence rate according to 4 mitigation (M1, M2, M3, M4) and two non-mitigation (B1, B2) scenarios (Figure 7).

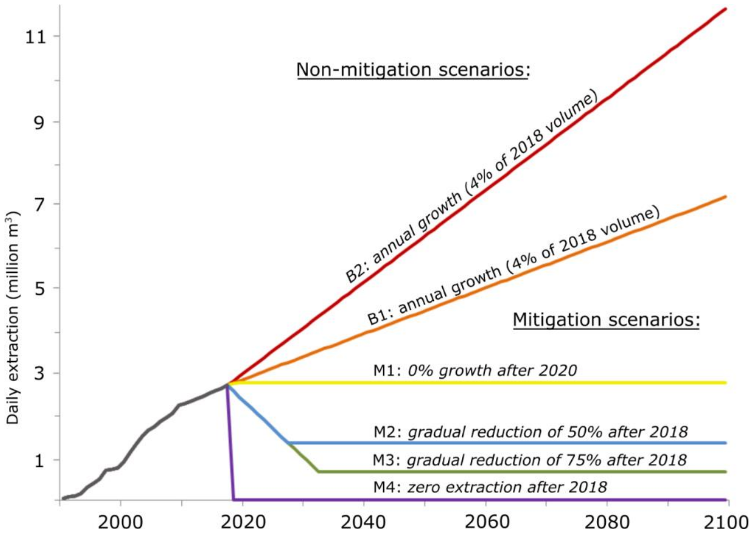

Figure 7: The six groundwater extraction scenarios considered in Minderhoud et al. 2020 (note: B1 = 2% annual growth extraction increase) (From Minderhoud et al. 2020).

For these 6 scenarios total human-induced subsidence was calculated by minderhoud et al. (2020) over the whole MRD until the year 2100 (Figure 8).

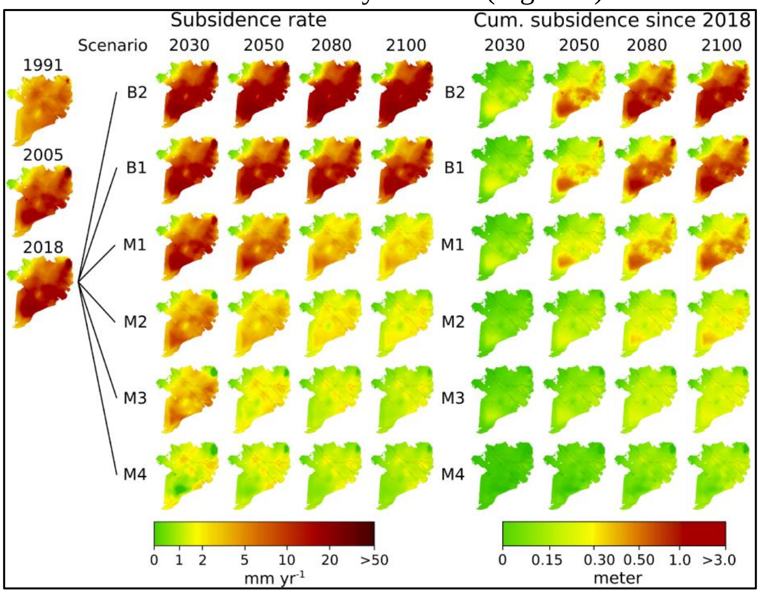

Figure 8: The modelled human-induced subsidence rate and total human-induced subsidence until 2100 (From Minderhoud et al. 2020).

Sea level rise

Current and time transient predictions sea level rise scenarios for the MRD were retrieved from the IPCC AR6 report (IPCC, 2022) using the sea level projection tool (https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool?psmsl_id=1495). Data was obtained for the location of Vũng Tàu which lies just north of the MRD and was the closest that could be used from this database. In this report the IPCC predicted a total SLR from 2020 to 2100 of 0.43m, 0.55m, and 0.76m for the scenarios: scenario 1 (SSP1-2.6), scenario 2 (SSP2-4.5), and scenario 3 (SSP5-8.5) respectively.

Tidal range

Tides In the South China Sea near the southeastern part of the MRD have a semidiurnal character with tidal ranges of 2 m at mean tide to 4 m at spring tide. Tidal ranges decrease towards Ca Mau Cape (the southwestern tip of the delta) and the tide shows more diurnal characteristics to that side, causing the tide to have a more diurnal than semidiurnal appearance at Ca Mau Cape (Phan et al. 2015). Tidal range is not expected to change significantly in the coming decades.

Habitat borders

Especially aquaculture has imposed a large amount of habitat borders to mangroves in the MRD (Veettil et al. 2019). By looking at satellite data, this study determined that only the far southwest part of the MRD has large area of relatively undisturbed mangrove habitat present. In other areas especially between Bac Liêu and Cà Mau city, or where the coast has been eroding, habitat borders are most often right at, or within a kilometre of the coastline. There are currently no significant plans to remove habitat borders and increase potential mangrove habitat (Ha et al. 2012).

Sedimentation input of the MRD coast

The sediment input of the MRD coast consist almost entirely of input from the Mekong River. At present, a) damming, b) land-use changes and c) unregulated sand mining in the drainage basin have significantly impeded sediment supply to the delta mouth (Allison et al. 2017). The total sediment input into the MRD coast has dropped drastically by about 75% since the period before major dam construction (pre-1992), from about 100Mt/yt to 25Mt/yr (160Mt/yr = pre-Anthropocene estimate) (Dunn and Minderhoud 2022). The decline is expected to slow but no plans for the removal of dams exist, so this value is not likely to increase in the coming decades (Dunn and Minderhoud 2022).

2.4 Discussion: requirements for the modelling

On the basis of the mangrove knowledge-base it was possible to identify (1) what processes will be the basis for modelling of the future MRD, (2) what thresholds, factors and processes have to be included in the future MRD modelling, (3) what boundary conditions will be changed under the SSP and RCP scenarios, (4) what additional flood protection measures can be modelled.

With this knowledge I was able to determine what would be the focus and approximate method of the modelling done in this research. Namely: this research will model how long, and where mangroves will be able to persist along the MRD coast during three different scenarios ((1) = SSP1-2.6, (2) = SSP2-4.5, and (3) = SSP5-8.5) until 2100. Mangroves in this model grow between MSL and MHHW and should be able to retreat landwards if there is retreat space available. Mangroves die if there is no suitable space available between MSL and MHHW (Figure 2). The southeastern (SE) part of the MRD possesses the highest elevation (Figure 4, Minderhoud et al. 2019) and consequently has the most natural protection against flooding and the highest elevated potential retreat space for mangroves. Mangroves will have the highest chance of survival in this area. Therefore, this area will be the focus of the modelling. During the modelling the research should take care to incorporate the entire length of the SE MRD, because of different stresses and sedimentation environments along different parts of the coast (Figure 3).

Additionally, the modelling has to include all the large potential impact factors (Table 2): (1) SLR, (2) detailed elevation of the MRD (geomorphology), (3) subsidence (natural and human-induced), (4) tidal range, (5) human-induced mangrove barriers, (6) sedimentation within mangroves. These factors should interact as seen in the simplified mangrove system (Figure 2).

Regarding sedimentation within the mangroves, it should consist of 1) an organic matter accumulation value that incorporates all surface elevation due to organic matter sequestration and subsurface root growth in an area, and 2) an inorganic sedimentation value that is linked to the SSC at that site, but also influenced by changing sediment input of the Mekong river (Besset et al. 2019; Furukawa and Wolanski 1996; Li et al. 2017; Marchesiello et al. 2019)

Finally, in the three scenarios modelled, the four important factors for mangrove persistence in the MRD that may change will vary through time until 2100: 1) SLR, 2) subsidence, 3) human-induced mangrove barriers and 4) sediment input of the MRD coast (Table 2). Direct mangrove destruction by humans will not be incorporated by research as this is determined to be outside of the main research focus, namely it is deemed to be mostly due to social and governmental conditions instead of the physical conditions in the MRD. Because decision makers in Vietnam can not feasibly influence future SLR. Potential extra measures that are modelled to support mangrove sustainability in the MRD will be linked to human-induced subsidence mitigation, increasing mangrove retreat space and increasing suspended sediment input.

3. Modelling mangroves: a review and potential application for this study

To calculate the physical solution space of mangrove conservation and restoration in the MRD, I chose to model climatic and environmental conditions of the future, to test when, if, and how the maximum thresholds for sustainable mangrove growth in the MRD would be reached. There are various complex process-based numerical models that calculate the presence of mangroves (or wetlands), taking into account a large number of boundary conditions and processes, and that are thus the most likely to generate an accurate projection. Examples of such models are presented by: Costanza et al. (1990), D'Alpaos et al. (2007), Kirwan and Murray (2007), and Roelvink and Van Banning (1995). However, their inherent complexity makes them often only applicable to a small geographical and temporal scale, because (1) they need exact/precise input that is often unavailable and/or uncertain for multiple decades into the future, and (2) they are computationally very intensive and thus often cannot be practically applied when used beyond the local scale and immediate timeframe such as is also the case in this study (Martin et al. 2000; Wu et al. 2015). Thus, to model the presence of mangroves in the whole SE MRD until 2100, as is the requirement for this study, a relatively simple model is preferred. Such a model will inevitably greatly simplify natural processes but might still prove reliable in predicting future mangrove presence in the MRD (Kirwan and Temmerman 2009; Wu et al. 2015).

In several studies, more simple models were applied to predict the presence of mangroves/wetlands during changing physical and climatic factors in the future (Dang et al. 2022; Doyle et al. 2003, 2010; Fagherazzi et al. 2012; Lovelock et al. 2015; Payo et al. 2016; Rogers et al. 2012; Schuerch et al. 2018; Strauss et al. 2012). Most of these models, except the models used in Lovelock et al. (2015) and Doyle et al. (2003), are not specifically designed for mangroves, but for wetlands in general. This poses a problem because (1) different kinds of wetland flora can occur between the MLLW and MHHW while mangroves persist only between MSL and MHHW and (2) mangroves are especially well suited to counter erosion with deep rooting systems and (3) mangroves are especially well suited to promote sedimentation due to abundant organic matter production and the possession of dense foliage that, compared to other wetland fauna, more efficiently dissipates hydrodynamic energy (Woodroffe et al. 2016).

Few models have focussed exclusively on mangroves. Most relevant is the model from Lovelock et al. (2015) which calculated the potential submergence of mangroves in Indo-Pacifc regions due to SLR in 2100. The model used the known ecophysiology of mangroves (their habitat lies between MSL and MHHW) to predict the potential for mangroves to persist in face of SLR based on tidal range, amount of SLR and suspended sediment concentration (SSC). However, Lovelock et al. (2015) simplifies the sedimentation of mangroves to one value across the full width of the mangrove forest strip that is empirically coupled to the amount of sediment availability at that site and considers no erosion. Additionally, mangroves cannot migrate upland and the model uses one global subsidence value that is constant through time. Sedimentation is not considered at all in the model from Doyle et al. (2003) which is designed to model influence of storms on mangroves. These models thus do not consider feedback loops between vegetation, sedimentation and erosion, and the ability for mangroves to adapt and migrate, which is the reason mangroves are considered as a partial solution to sea level rise and thus critical to this research.

I identified SLAMM (Sea Level Affecting Marshes Model) (Payo et al. 2016; Dang et al. 2022) and the model from Schuerch et al. (2018) as the main candidates to be potentially used in this research, because, although these models were not specifically designed for mangroves, they do have a more dynamic way of modelling wetlands that incorporates sedimentation and erosion feedbacks, and upland migration of wetlands which are critical in the MRD. The main drawbacks of these two models are summarized in Table 3. Both of these models calculate future landscape evolution that relies on RSLR in cells on a 2D grid. Especially the fact that cell-type changes are based upon RSL in these models is relevant. It was already determined that mangroves can generally only survive between MSL and MHHW (chapter 2), so this can easily be translated to this study. The model from Schuerch et al. (2018) focusses on the ability of the wetland to adapt or retreat. The ability of the wetland to retreat is directly linked to human occupation. This system is very much applicable in the MRD and can be easily tied to different SSPs in the future. Additionally, the accretion model in SLAMM has potential for this study because it is simple while being customizable for mangroves, as a function of a particular variable e.g. *SSC*. However, subsidence is not well represented in both models because it is taken as a constant through time. Also, the accretion calculations in the model from Schuerch et al. (2018) are too simple for the purpose of this study and not designed for mangroves. The accretion calculation in SLAMM has potential but cannot be tied to multiple factors (while it has been shown to be dependent on distance from the creek system and sediment concentration (Furukawa and Wolanski 1996)). More importantly, SLAMM considers mangrove growth to occur between MLLW and MHHW, while research has shown that between MSL and MHHW is more accurate (Woodroffe et al. 2016). (Payo et al. 2016) bypassed this problem in their research by setting the tidal range at 0m, however in this case that would severely influence model results because of the large impact tidal range has on mangrove resilience (Lovelock et al. 2015) (Figure 2).

Table 3: the main drawbacks from SLAMM and the model from Schuerch et al. 2018

model	*deficits*
SLAMM 6.7	• *mangroves grow from MLLW-MHHW instead of MSL-MHHW* • *accretion follows a polynomial equation instead of an exponential decline* • *accretion can not be tied to sediment availability while also being tied to distance from the creek system* • *subsidence is constant instead of variable through time* • *mangrove expansion is impossible with SLR*
Schuerch et al. 2018	• *accretion and erosion in the model is not dependent on the critical physical factors and not specifically designed for mangroves* • *subsidence is constant instead of variable through time* • *mangrove expansion is impossible with SLR*

In conclusion, although these models are helpful as a reference on particular parts that are modelled in this study, they did not effectively tackle the specific problems encountered in this study (Table 3). It was thus decided to create a new model using inspiration from SLAMM and the model from Schuerch et al. (2018): the Dynamic Mangrove Model (DMM).

4. The Dynamic Mangrove Model (DMM)

4.1 Introduction to the DMM, inundation model

Because the existing models did not effectively tackle the specific problems encountered in this study associated with the long-term modelling of mangrove growth in the MRD, this study opted to create a new model: the Dynamic mangroves Model (DMM). As discussed in chapter 3 the DMM should be relatively simple, therefore the DMM consists of a 1D profile in an Excel that is based on relatively simple calculations.

The DMM needed to simulate the change of mangrove shore elevation resulting from sediment deposition and determines the width and location of the mangrove zone that can persist under different future scenarios. The model needed to comprise the main controls of the existence of mangroves that were determined in chapter 2: shore profile geomorphology, subsidence, sea level rise, suspended sediment concentration in the coastal sea water, tidal range, and barriers/habitat borders for mangrove growth.

The DMM incorporates these factors in the following manner: from an initial elevation, MSL, barrier placement, and tidal range the model calculates the position of mangroves (between MSL and MHHW). Afterwards, mangroves retreat or advance due to RSLR = subsidence + SLR - sedimentation inside the mangroves in time-steps of 10 years. The amount of sediment deposited inside the mangrove area is dependent on SSC in the coastal waters and distance from the sea is accreted inside the mangrove area (potentially partly blocked by a barrier).

Four of the main controls discussed above were determined to be able to significantly be able to change in the future (chapter 2): (1) SLR, (2) human-induced subsidence (natural subsidence will stay more or less constant), (3) suspended sediment input and thus sedimentation, and (4) human-induced mangrove barriers. The potential change of those four factors was linked to three future scenarios: (S1) SSP1-2.6, (S2) SSP2-4.5, (S3) SSP5-8.5. S1 is an optimistic scenario, S2 is a "middle of the road"/most likely scenario, and S3 is a pessimistic scenario. How these scenarios will influence the factors is described in chapter 4.10.

An option was created to add an empirical vertical sedimentation value seaward of the mangroves and to include an erosion factor that is dependent on the slope of the profile in the DMM. These options were not used in the modelling for this study. Consequently, in the DMM used in this study the mangrove zone only displaces due to drowning and colonising landward areas under increased RSLR and the profiles cannot accrete seaward under SLR. The choice to leave out erosion, and sedimentation outside the mangroves was made because 1) with increasing SLR, significant subsidence and decreasing sediment input from the MR, inundation is the primary threat to mangroves in the MRD (Chapter 2, Woodroffe et al. 2016), 2) there was little data of offshore sedimentation in the MRD, and 3) it was difficult to correctly validate the method of erosion used in this simple model.

4.2 Model Area and profiles of the 1D model

It was decided to only study the southeastern part of the delta, because these are the areas of the Mekong delta that have the highest elevation according to topo DEM59 (chapter 2) (Minderhoud et al. 2019) (Figure 4) and thus highest chance of successfully accommodating mangroves in the future. Along the southeastern MRD coastline 10 profile locations were chosen (of which the first was not used in the final modelling due to insufficient data) which together represent this part of the MRD in this study (Figure 9). The profiles were chosen to encompass most different kinds of sedimentation regimes, elevation, and subsidence rates along the southeastern MRD coast (Figure 9, Table 4) according to the study of Marchesiello et al. (2019) discussed in chapter 2 (Figure 3). In this way the study attempts to encompass most of the coastal variation in this area, to on average best represent the entire southeastern MRD. Profiles are numbered 1-10.

Table 4: the profiles used in this study, their characteristics, and historical m/yr change (1990-2015) (Marchesiello et al. 2019, Anthony et al. 2015). Note that profile 1 is not used for the final modelling.

Profile	Characteristics	Shoreline approximate change horizontal m/yr from 1990-2015
1	Not used because of bad data	-
2	Low suspended sediment input, medium subsidence, medium elevation, low amount of erosion	-9
3	Low suspended sediment input, medium subsidence, high elevation, low amount of erosion	-5
4	Medium suspended sediment input, medium subsidence, medium elevation, large amount of erosion	-25
5	High suspended sediment input, medium subsidence, medium elevation, large amount of accretion	43
6	Medium suspended sediment input , medium subsidence, medium elevation, about stable	-1
7	Medium suspended sediment input, large amount of subsidence, low elevation, low amount of erosion	-11
8	Medium suspended sediment input, medium amount of subsidence, low elevation, low amount of accretion	8
9	Low suspended sediment input, low subsidence, high elevation, large amount of erosion	-25
10	High suspended sediment input, low subsidence, medium elevation, large amount of accretion	25

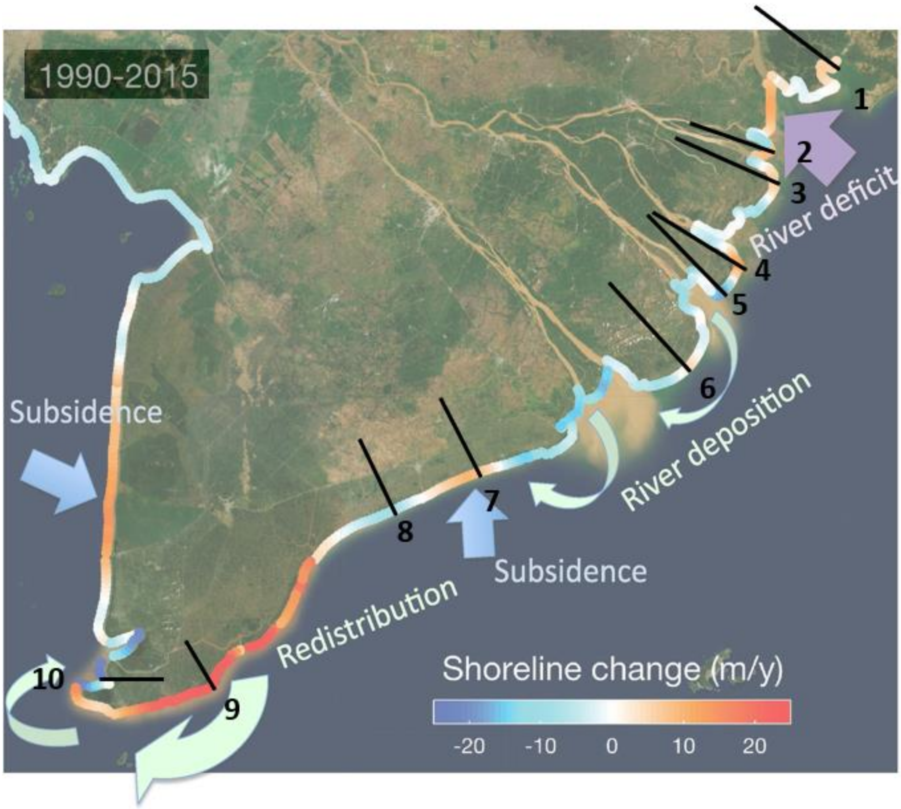

Figure 9: the MRD with the average shoreline change from 1990-2015 (m/yr) and the proposed causes of these changes. In black are added the profiles used for this study. Notice the placement of the profiles aligns with different sedimentation regimes (Marchesiello et al. 2019).

4.3 DMM layout and basic functioning

Each profile modelled in the DMM comprises of 100 cells that are 100m long and an elevation value is attributed to each side of the cell. Every 10 years a new elevation is calculated for each side of every cell to produce a new profile. To calculate a new elevation an input is needed that consist of a 1) subsidence value and 2) a sedimentation value for every cell (new elevation = old elevation - subsidence + sedimentation). In the model, mangroves exist in cells that have had an average elevation between MSL and MHHW for at least 2 timesteps, without mangrove barriers (Table 5). The zone where mangroves grow can expand or retreat along with the changing conditions along the profile. Mangroves colonise a new area with a time lag of 10 years, but drown instantly (chapter 2) according to how the profile hight compares to this suitable mangrove zone. Mangrove migration into a cell can however be stopped by habitat borders (hereafter referred to as dikes) that are manually added into the model. The presence of a dike makes that cell and the cells behind it unsuitable for mangrove growth. MSL and MHHW are adjusted for SLR every timestep.

A schematic explanation of the basic functioning of the DMM is given in Figure 10. In timestep 0 initial conditions are put into the model. This includes profile elevation for every cell, initial subsidence value and the initial MSL and tidal range (see 4.5, DMM input). From this information the initial mangrove area is calculated. Timestep 1 takes place 10 years after timestep 0. The profile height is adjusted to 10 years of subsidence, however, for this timestep the amount that is sequestrated inside the mangroves is added in the initial mangrove area. Afterwards the new potential mangrove is calculated using an adjusted MSL. Mangroves outside this zone are removed (eroded) from the model instantly. However, the new potential mangrove habitat is not colonized yet due to a colonisation lag implemented in the model of 10 years. In timestep 2 sedimentation is added in the timestep 1 mangrove area. After subsidence and MSL adjustments again mangroves outside the potential mangrove zone are eroded. The area that is not yet colonised but was suitable for mangroves in the last and the current timestep is colonised (however no sedimentation has taken place yet. In timestep 3 no suitable mangrove habitat is left due to a mangrove barrier. All mangroves die, and after this timestep no sedimentation will take place unless otherwise specified in base sedimentation.

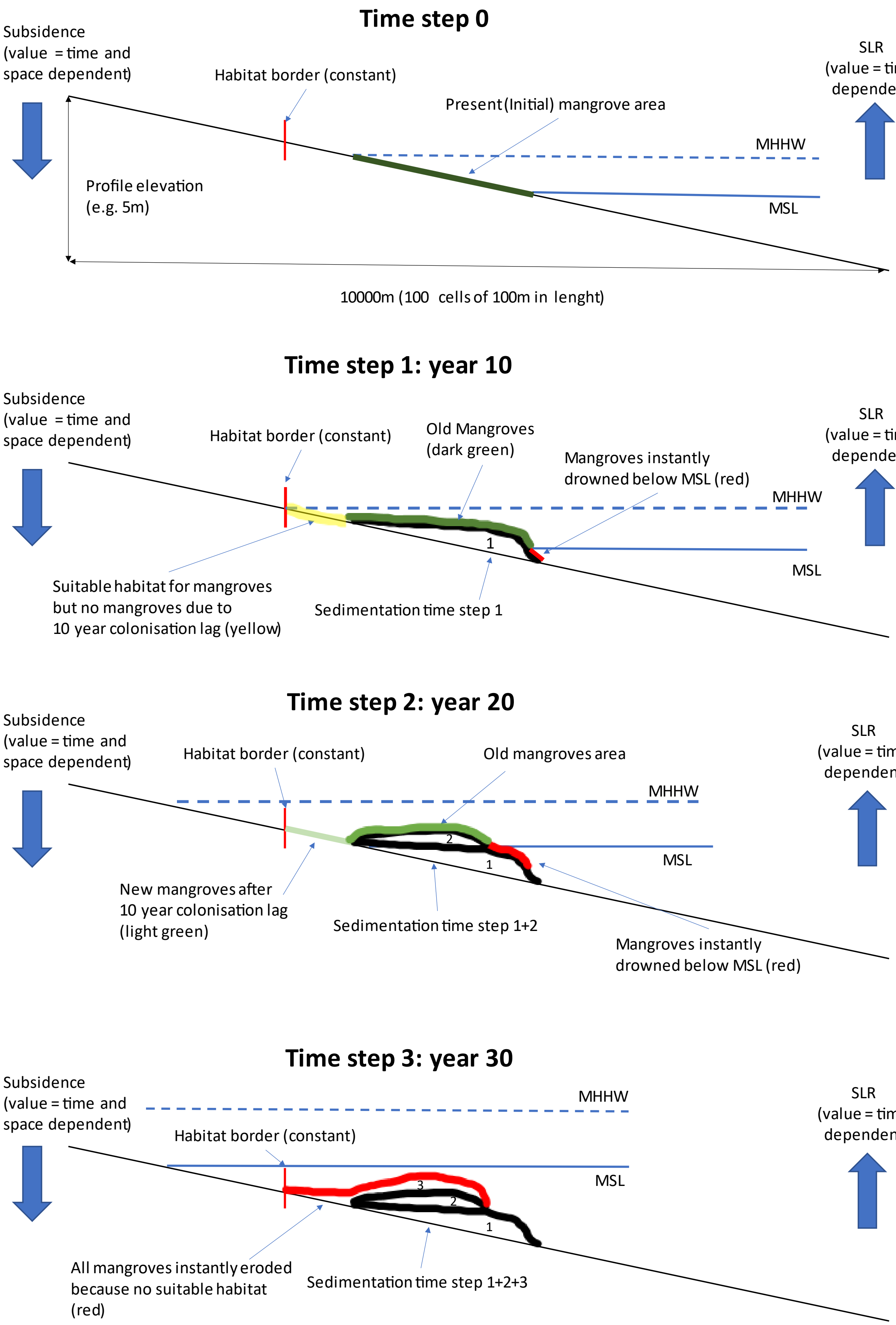

Figure 10: a schematic representation of the functioning of the DMM.

Sedimentation in the DMM is dependent on location and is divided into two categories:

1) base bio-accumulation inside the mangroves; this is sedimentation caused by organic matter accumulation (litter fall and root growth) and is taken as 1 value for the entire mangrove strip per time step and over the entire simulation period, and vertically accreted in each simulation time step in cells that house mangroves.

2) calculated sedimentation in the mangroves. This sedimentation is assumed to be mainly dependent on suspended sediment in the MRD (chapter 2) and is represented by an exponentially declining function based on SSC, particle settling velocity, water depth, inundation time, and mean water flow velocity. This represents the most important sedimentation input into the model. There is an option to take the water velocity as a constant in the model.

Additional optional features in the DMM that **were not used in this research** because of the inability to successfully validate these methods and because of insufficient data are:

a) base sedimentation (or erosion) in the unvegetated foreshore of the profile. This sedimentation is mainly dependent on sand in the MRD (chapter 2) and is and is taken as 1 value for the entire drowned part of the profile in front of the mangrove forest, unless blocked by a mangrove barrier. Without erosion implemented, this value does not impact the amount of time mangroves can persist in the profile, so long as the sedimentation in this part of the profile is not more than the highest amount of sedimentation in the mangroves. However, for mangrove expansion seaward this value has to be higher than RSLR.

b) wave erosion on the seaward side of mangroves is another optional feature in the DMM. It is represented by a maximum slope (determined by the user) before mangroves erode due to waves. The maximum slope is calculated from the hight of the cell to the hight of the start of the profile. Mangroves can only erode when there are no mangroves in front of their cell, as mangroves dissipate wave energy (chapter 2).

c) Finally, a minimum mangrove strip width (meaning a critical minimum forest width on the profile in which mangroves can still promote sedimentation) can be implemented into the model. After 10 years with a strip depth under this minimum all mangroves disappear. This assumption however is at the moment contested and not used in the results of this research (Besset et al. 2019).

Table 5: conditions needed for mangrove growth in the DMM

Need considered for mangroves	**Explanation/notes**	**source**
Between MSL and MHHW	Mangroves generally occur between MSL and MHHW	Lewis 2005; Lovelock et al. 2015; Proisy et al 2009
No human barrier	Mangroves can be cleared or displaced by people due to e.g. agri/aquaculture and deforestation. This may be simulated by a customizable barrier that can be placed in the model	Lovelock et al. 2015; Osland et al. 2017; Rogers 2021; Woodroffe et al. 2016
10 years of favourable conditions for colonisation	Mangroves need 10 years of favourable conditions to colonise that area	Nardin et al. 2016
Optional need for mangroves, not used in this research	**Explanation/notes**	**source**
Maximum slope	Mangroves mainly erode due to waves in the MRD. An option in the model is to add a customizable maximum slope. If the foreshore gets too steep (and thus, wave erosion is more prominent) the mangroves in the cell closest to the sea get eroded. The slope is calculated from the elevation of the cell with mangrove closest to the sea to the elevation of the most seaward cell in the model divided by the distance between them.	Besset et al. 2019
Minimum mangrove forest width	A critical minimum forest width on the profile in which mangroves can still promote sedimentation can be implemented into the model. After 10 years with a strip depth under this minimum all mangroves disappear.	Phan et al. 2015

4.4 DMM detailed Calculations

4.4.1 Calculation of subsidence

The amount of subsidence $Subtot_{i,t}$ of a cell i in a profile during time step t is calculated as:

$Subtot_{i,t} = Subnat + Subhum_{i\,t}$

Where: $Subnat$ = natural subsidence, which is a constant value for all time steps t and cells i; $Subhum_{i\,t}$ = human-induced subsidence, which varies along the transect with i, and t according to different groundwater extraction scenarios. The values for $Subhum_{i\,t}$ were determined by multiplying the total amount of subsidence until the year 2100 according to a particular scenario by the factor $fsubs_t$ (amount of subsidence of total) for the particular time step in a scenario (see 4.5, DMM input).

4.4.2 calculation of SLR

The mean sea level MSL_t of in a profile during time step t is calculated as:

$MSL_t = MSL_{t-1} + SLR_t$

Where: MSL_{t-1} = the MSL from the last timestep.

4.4.2 Calculation of sedimentation deposition

The amount of sediment deposition at a cell depends on whether there are mangroves present or not and whether the profile is inundated or not (behind a dike a cell is not able to be inundated). It is calculated as a vertical accretion of a cell (m/10yrs).

The increase in elevation $dEL_{i,t}$ (m) of cell i in a profile resulting from sediment deposition during each time step t of 10 years in the mangroves is calculated as:

- $dEL_{i,t} = I_{i,t} * (S_{i,t} / \text{RhoS}) * 365 * 10$

where: $I_{i,t}$ = *inundation time per day (s)*, $S_{i,t}$ = *sedimentation rate (kg/m²/s)*, *RhoS* = sediment density after deposition *(kg/m³)*, 365 is the number of days per year and 10 is the time step length of 10 years. Of which:

- $I_{i,t} = mh_{i,t} / (0.5*td_0) * 6 * 2 * 360$

Where $mh_{i,t}$ = maximum water depth of a cell, and td_0 = tidal range. $mh_{i,t} / (0.5*td_0)$ = the approximate factor of how much time during high tide the cell is under water. The SE MRD is best characterised with a semidiurnal tide (Phan et al. 2015) = two high tides a day of 6 hours = 2*6 (*360 for seconds)

The amount of sediment deposition inside mangroves (calculated sedimentation inside mangroves) is given by the following formula:

- $S_{i,t} = C_0 * w_0 * \exp((-w_0 * x_{i,t}) / (h_{i,t} * u_{i,t}))$

Where: $S_{i,t}$ = *Sedimentation rate inside mangroves (kg/m²/s)*, C_0 = SSC (suspended sediment concentration) (kg/m³), w_0 = settling velocity of sediment particles (m/s), $x_{i,t}$ = distance inside the mangroves(m), $h_{i,t}$ = average water depth in cell during flooding (m), and $u_{i,t}$ = average water velocity in cell during flooding (m/s).

Table 6: Formulas of the increase in elevation due to sedimentation, inundation time and sedimentation rate inside mangroves.

Variable	calculation	references
$dEL_{i,t}$ = increase in elevation due to sedimentation	$dh_{i,t} = I_{i,t} * (S_{i,t} / \text{RhoS}) * 365 * 10$	-
$I_{i,t}$ = Inundation time (seconds)	$I_{i,t} = mh_i / (0.5*td) * 6 * 2 * 360$	Phan et al. 2015
$S_{i,t}$ = Sedimentation rate inside mangroves (kg/m³/s)	$S_{i,t} = C_0 * w_0 * \exp((-w_0 * x_{i,t}) / (h_{i,t} * u_{i,t}))$	Furukawa and Wolanski 1996

The formula $S = C_0w_0\exp((-w_0x)/(hu))$ was taken from Furukawa and Wolanski (1996) (Figure 11) who analysed sediment transport into mangroves from a tidal creek and observed a fast exponential sedimentation decline deeper into the mangroves. However, in this study, the formula is amended to better fit long-term sedimentation on a larger scale. Instead of x = distance from the creek system, x = distance inside the mangroves from the shoreline in this study. Furthermore, instead of using constants for u and h like Furukawa and wolanski (1996), this study used calculated variables that approximate the average u and h for every cell while inundated (Table 7) (for reference: validation of the sedimentation formula):

- $h_{i,t} \approx 0.5 * MHHW_t - EL_i$

where $MHHW_t$ = the mean high higher water (m) of that timestep. $h_{i,t}$ is calculated assuming a perfectly sinusoidal tide where 0.5 * the maximum water depth is the average water depth during inundation.

- $u_{i,t} \approx xmw_i / I_i$,

where xmw_i = horizontal distance from cell to maximum horizontal water location at MHHW within the model (m), (if a dike is implemented in the model this will be the furthest reachable point for water). $u_{i,t}$ is calculated assuming that on average the water that crosses a cell still will travel half of the possible distance and back in a flood cycle (inundation time of that cell).

The study thus uses a sedimentation formula that is based on variables that are known to be critical (mainly SSC and distance into the mangrove forest) and bases the shape of the curve on empirical values (Table 8) a strategy like this has been effectively used to predict sedimentation in SLAMM 6.7 (SLAMM 6.7 technical documentation).

Table 7: calculations of the input variables and variables used to calculate the inundation time and sedimentation rate inside mangroves.

Input variable / variable	**calculation**	**notes**
$MHHW_t$	$MSL_t + 0.5 * td_0$	-
$mh_{i,t}$ = Maximum water depth of a cell (m)	$MHHW_t - EL_{i,t}$	-
C_0 = SSC (suspended sediment concentration) (kg/m^3)	No calculation = input variable	See input
w_0 = settling velocity of sediment particles (m/s)	No calculation = input variable	See input
$h_{i,t}$ = average water depth in cell during flooding (m)	$h_{i,t} \approx 0.5 * MHHW_t - EL_i$	$MHHW_t - EL_i$ = the maximum water depth in that cell. 0.5 * the maximum water depth is the average water depth during inundation assuming a perfectly sinusoidal tide
$x_{i,t}$ = distance inside the mangroves (m)	The number of cells between the shoreline and the target cell that support mangroves * 100	Every cell is 100 meters long
$u_{i,t}$ = water velocity (m/s)	$u_{i,t} \approx xmw_i / I_{i,t}$	Assumed is that most of the water from the specific cell travels about half the maximum possible distance and back within the inundation time

Validation of the sedimentation formula

Although The formula $S = C_0 w_0 \exp((-w_0 x)/(hu))$ (Furukawa and Wolanski 1996) contained the right input variables that were found to be crucial in this study (SSC, settle velocity, water depth, water velocity, and depth into the mangrove forest), the sedimentation resulting sedimentation curve using the input variables used in Furukawa and Wolanski (1996) is not the same as observed in studies that analysed mangrove sedimentation on a larger space and time scale (Kraus et al. 2014) (Table 8). This study analysed sedimentation on a larger scale, and instead of being based of the distance to the creek system this study based the amount of sedimentation on the distance to the shoreline. From here sea water enters the mangrove forest mainly through creek systems deeper into the forest, instead of going directly through dense mangrove forest (Horstman, Bryan and Mullarney 2021).

Additionally, on longer timescales erosion plays a larger role. Where there is wave action and/or sufficient water velocity during a storm or other extreme event, sediment will be eroded, and the total accretion will be lower on the longer timescale than is described in the function of Furukawa and Wolanski (1996) which describes only a single tide (Van Santen et al. 2007). This erosion is more prominent in the mangrove fringe than in the interior, because of the decreasing hydrodynamic energy towards the forest interior, due to friction (Kraus et al. 2014).

The knowledge that (1) with creek systems present sea water (and thus sediment) can more easily penetrate deeper into the mangrove forest, and that (2) a small amount of erosion (especially in the mangrove fringe) will be present, were combined into an adjusted sedimentation curve that was fitted on (a) the long-term empirical data collected (Table 8) but still based on (b) the variable relationship described in Furukawa and Wolanski (1996). A similar method has been successfully used in SLAMM 6.7 (SLAMM 6.7 technical documentation).

In general this means that instead of a convex exponentially declining sediment curve (Figure 11) this model uses more of a constant decline (Figure 12, 13). The way this model achieved this was to decrease the settling velocity used in Furukawa and Wolanski (1996) from 0.0005m/s to 0.00003m/s which is also more in line with the 0.00001-0.00008m/s that was found to be typical for in the MRD for a free settling regime of SSC<200mg/l (Gratiot et al. 2017) (Table 8). The validation of the settling velocity is further discussed in 4.9 (validation).

Additionally, in contrast to Furukawa and Wolanski (1996), this study used calculated variables that approximate the average u and h for every cell while inundated (Table 7) and uses the inundation time ($I_{i,t}$) to calculate sediment deposition *($dEL_{i,t}$)* (Table 6).

The sedimentation curves with and without calculated u and h are compared in Figure 12 and Figure 13 in sedimentation per year graphs. The sedimentation curve with constant u and h was calculated with typical mangrove forest input values that are the same as had been used in the original sedimentation rate graph from Furukawa and Wolanski (1996); $h_{constant}$ = 0.4m, and $u_{constant}$ = 0.1m/s. However, for the calculated $u_{i,t}$ and $h_{i,t}$ sedimentation curve a slope was created (h_{0m} = 0.4m, h_{1000m} = 0m). Both sedimentation curves used C_0 = 0.03kg/m^3 and an adjusted w_0 to better represent data from (Gratiot et al. 2017); w_0 = 0.00003m/s. Furthermore the calculated $I_{i,t}$ (inundation time) that is dependent on the slope added (Table 6), was used to determine the total sediment deposited in a year in both sedimentation curves. In Figure 13 a dike is added at 500 m that influences the $u_{i,t}$ of the calculated $u_{i,t}$ and $h_{i,t}$ sedimentation curve (Table 7) and prevents sedimentation behind 500m in the constant u and h sedimentation curve.

In general the sedimentation deeper in the mangrove forest is lower with the calculated $u_{i,t}$ and $h_{i,t}$, than with the constant u and h. In Table 8 the results of the two methods are compared with different settling velocities. Both formulas give relatively similar results in a no dike scenario, however in a scenario with dike (Figure 13) the results are more disparate. This is because the $u_{i,t}$ is influenced by the barrier while $u_{constant}$ is not. It was decided to use the calculated $u_{i,t}$ and $h_{i,t}$ in this research because a) a gradually declining water velocity deeper into the mangroves, and b) a declining water depth at higher elevation is more realistic than using constant values.

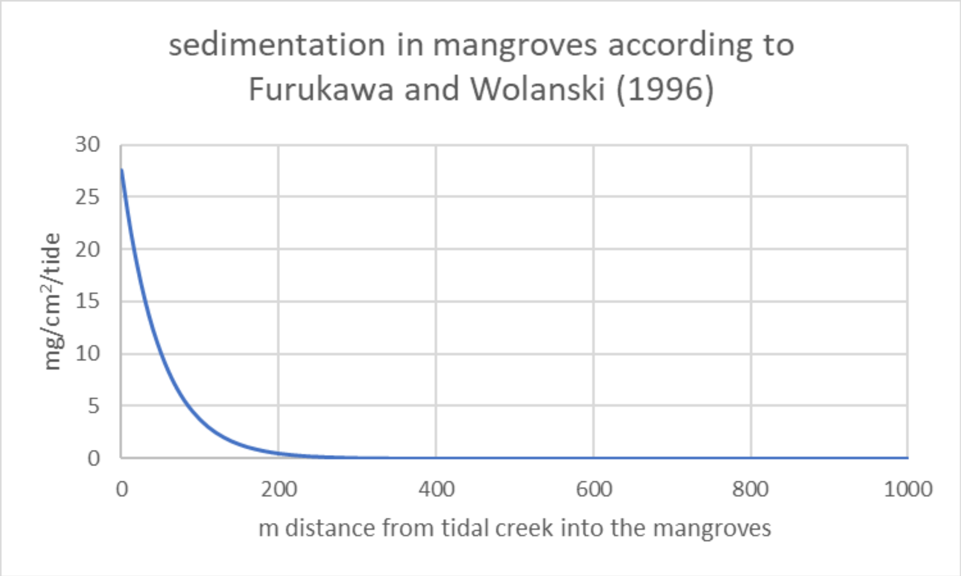

Figure 11: the sedimentation per tide calculated by Furukawa and Wolanski (1996) using h = 0.4m, u = 0.1m/s, SSC =0.03kg/m3, and w0=0.0005m/s.

Table 8: published ranges of vertical accretion in mangrove hydrogeomorphic settings adjusted for inundation time of a linear slope and a tide that reaches 1000 m inland. The table shows the results of 1) the direct equation of Furukawa and Wolanski (1996) h (0.4m) and u (0.1m/s) are constant, SSC = 0.03kg/m3 and sediment density 1200kg/m3. 2) Using the sedimentation model, h0 =0.4m h1000=0m constant decline, u = calculated, SSC = 0.03kg/m3 and sediment density 1200kg/m3.

author	**Vertical accretion fringe (mm/yr)**	**Vertical accretion basin/interior (mm/yr)**
Krauss et al. 2014, for a full list of references, see paper	+1.6 to (+8.6)	+0.7 to (+20.8)
Perez et al. 2018	+2.8 mm per year on average in a mangrove system	
1) Using the values and equation of Furukawa and Wolanski (1996) and a sediment density of 1200kg/m^3	(Average first 100m) w_0 = 0.00003 m/s = +10.9 w_0 = 0.0005 m/s = +124	(Average 100-1000m) w_0 = 0.00003 m/s = +4.1 w_0 = 0.0005 m/s = +6.8
2) Using the sedimentation model, and a sediment density of 1200kg/m^3	(Average first 100m) w_0 = 0.00003 m/s = +10.7 w_0 = 0.0005 m/s = +115	(Average 100-1000m) w_0 = 0.00003 m/s = +2.6 w_0 = 0.0005 m/s = +3.6

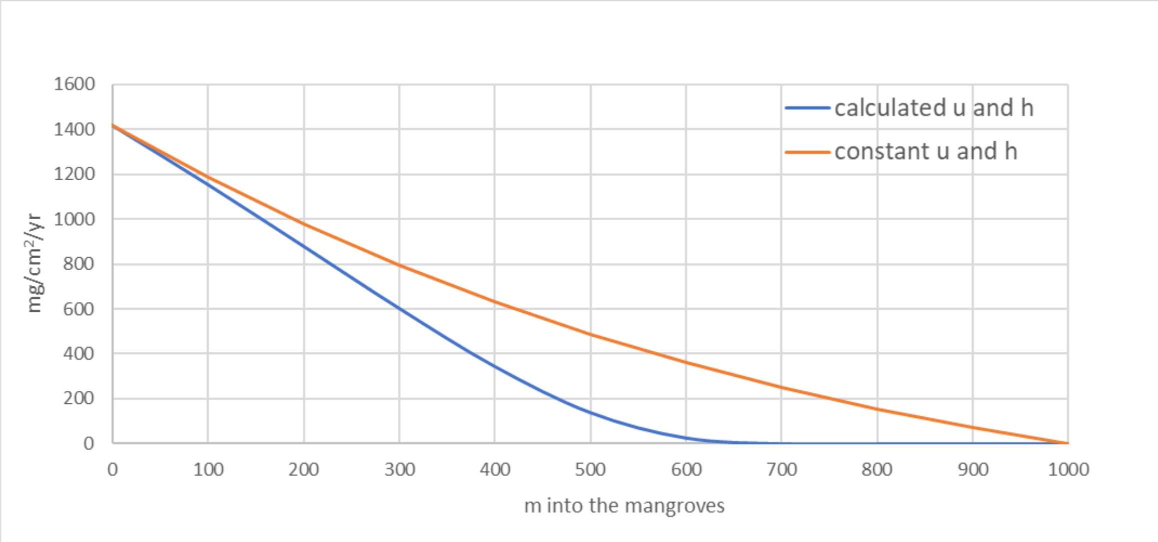

Figure 12: Sedimentation per year with a constant h and u (h =0.4m, u = 0.1m/s), SSC =0.03kg/m3, and w0=0.00003m/s (orange), vs sedimentation per year with the calculated h (h0=0.4m and h1000=0m, constant decline), SSC =0.03kg/m3, and u for every cell and w0=0.00003m/s (blue). Both curves are adjusted for inundation time

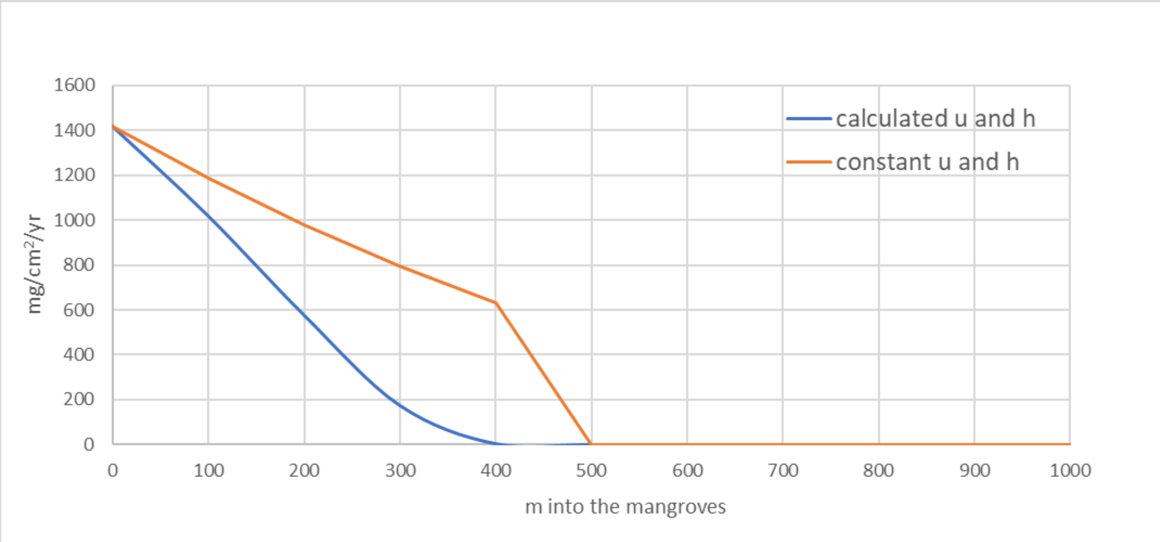

Figure 13: Sedimentation per year with a constant h and u (h =0.4m, u = 0.1m/s), SSC =0.03kg/m3, and w0=0.00003m/s and a dike at 500m (orange), vs sedimentation per year with the calculated h (h0=0.4m and h1000=0m, constant decline), SSC =0.03kg/m3, and u for every cell, w0=0.00003m/s and a dike at 500m (blue). Both curves are adjusted for inundation time

4.5 DMM Input

The input for the DMM has been divided by sedimentation input, initial elevation and subsidence input, and SLR input, a summary can be found in Table 11.

4.5.1 Sedimentation input

Suspended sediment concentration (SSC)

Marchesiello et al. (2019) modelled the SSC in the MRD in January and October 2014 and compared it to satellite data in January and October 2002-2012. The SSC values for each of these 4 graphs were estimated for all the profile locations and the average of the 4 values was taken (Table 9). It was determined that multiplying the SSC with a factor of 1.63 fitted shoreline change observations better during the validation modelling (4.9, validation) and this value was used in the actual modelling. Additionally, SSC was adjusted according to future scenarios (4.10, scenarios)

Table 9: The SSC input for the different profiles (Marchesiello et al. 2019).

Profile	*satellite SSC surface mg/l January 2002-2012,*	*satellite SSC surface mg/l October 2002-2012,*	*model SSC mg/l January 2014,*	*model SSC mg/l October 2014,*	*average SSC kg/m³*	*SSC*1.63 used in model kg/m³ (see validation)*
2	40	40	50	45	0.044	0.071
3	35	37.5	45	35	0.038	0.062
4	40	37.5	45	27.5	0.038	0.061
5	45	45	45	50	0.046	0.075
6	40	30	37.5	15	0.031	0.050
7	35	25	40	17.5	0.029	0.048
8	35	32.5	45	45	0.039	0.064
9	40	25	50	15	0.033	0.053
10	40	40	50	50	0.045	0.073

w (settle velocity)

At the MRD coast the SSC < 200mg/l (Table 9) this causes the sediment to settle in a "free settling regime" with a minimum of flocculation taking place. The settling velocity measurements for such regimes were w > 0.01mm/s, w < 0.02mm/s in the lab and w > 0.01mm/s, w < 0.08mm/s measured in the MRD (Gratiot et al. 2017). w_0 = 0.03mm/s was used in this study because it fitted both the approximation in the literature for measured values and fitted the validation modelling (Table 8 and 4.9, validation).

Average mangrove sediment density (RhoS)

Sedimentation within mangroves is almost entirely consistent of clay, fine silt and organic matter due to the low hydrodynamic energy within the mangroves due to friction caused by the high vegetation density (Furukawa and Wolanski 1996). Van Santen et al. (2007) used 1000-1200 kg/m^3 for mangrove and tidal flat sediments in Vietnam, due to the large amount of water in these sediments. The heavier 1200 kg/m^3 was used in this research for a more conservative sedimentation estimate.

Tidal range

Tides In the South China Sea near the southeastern part of the MRD have a semidiurnal character with tidal ranges of 2 m at mean tide to 4 m at spring tide (Phan et al. 2015). The 4m tidal range was used because the study uses MHHW which includes spring tide.

Base bio-accumulation inside mangroves

Perez et al. (2018) found that the average (conservative) organic matter accumulation in mangroves was 160g/m^2/yr. Breithaupt et al. (2017) used a packing density of organic matter in mangroves of 0.114g/cm^3. 160/0.114/1000000 = 0.0014m/yr. Therefore, this study used 1.4mm/yr as a conservative estimate.

Average high tide duration

The hight tide was thought to be ~ 6 hours * 2 times a day = 12 hours in a day, assuming a perfectly sinusoidal semidiurnal tide (Phan et al. 2015).

Base sedimentation (or erosion) in the unvegetated foreshore of the profile

0, Sedimentation outside the mangroves was not modelled during this research

Maximum slope before erosion occurs

The slope was set at 1/1 = 45 degrees. This unrealistic value was chosen to prevent any erosion taking place, because erosion was not modelled in this research (45 degrees was never reached in the modelling)

4.5.2 Initial elevation and subsidence input

Initial elevation data

Elevation data was extracted along the profiles as shown in Figure 9 from the files from Minderhoud et al. (2019). The extracted data was linearly interpolated between datapoints along the profiles in excel to include an elevation value every 100 m, and the 5km closest to the sea was used in this research (Table 10). Additionally, the 5-meter depth contour line from Liu et al. (2017) is used to calculate a constant slope from the furthest seaward known elevation from Minderhoud et al. (2019) to complete the profile. The profile coordinates, average elevation and seaward slope are given in the table below:

Table 10: The profile coordinates (WGS 1984 UTM zone 48N), their average hight and their seaward slope that was calculated. These coordinates were used to extract elevation data from the subsidence scenarios in Minderhoud et al. (2020).

profile	X start	Y start	X end	Y end	Average elevation land within 5km closest to sea (m)	Slope to 5m (m/m) depth (Liu et al. 2017)
1	716043.9	1156847	688407.5	1177923	-	-
2	694811.3	1130784	668082.5	1139732	1.37	$2.2 \wedge 10^{-4}$
3	695449.7	1120638	662523.4	1134749	1.96	$5.5 \wedge 10^{-4}$
4	684413	1092602	654449.2	1111512	0.96	$6.8 \wedge 10^{-4}$
5	678158.4	1084893	653721.9	1110057	1.21	$4.6 \wedge 10^{-4}$
6	667597	1059179	640458.3	1087593	0.90	$1.2 \wedge 10^{-3}$
7	598630.1	1025682	585540.4	1050934	0.59	$6.0 \wedge 10^{-4}$
8	571125.5	1013193	559591.4	1037056	0.88	$9.3 \wedge 10^{-4}$
9	512484.3	955658.4	502741.4	972526.7	1.99	$5.2 \wedge 10^{-4}$
10	477657	958807.4	497330.3	958989.5	0.68	$2.4 \wedge 10^{-4}$

Human induced subsidence

Human induced subsidence rates for the three scenarios used in this study were taken from Minderhoud et al. (2020). This consisted of a prediction of subsidence along the profile in 2100 and a subsidence factor detailing how much subsidence takes place every time step. For a further explanation see 4.10 (scenarios).

Natural induced subsidence

Natural subsidence at the MRD coast was determined to be ~20mm/yr (Zoccarato et al. 2018).

4.5.3 Sea level input

SLR

Time transient predictions of the three sea level rise scenarios for the MRD were retrieved from the IPCC AR6 report (IPCC, 2011) using the sea level projection tool (https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool?psmsl_id=1495). Data was obtained for the location of Vũng Tàu which lies just north of the MRD and was the closest that could be used from this database. The values represent the median of the likely range of sea level rise during these scenarios. for further explanation see 4.10 (scenarios).

Initial MSL

Initial MSL was taken as 0 in the modelling.

Table 11: summary of the input used in the DMM

input	**source**	**value**
Sedimentation and erosion	-	-
C_0 = Suspended Sediment Concentration (SSC)	Marchesiello et al. 2019	See Table 9 and scenarios (4.10)
w_0 = settling velocity	Gratiot et al. 2017, Le et al. 2020	0.03mm/s (0.00003m/s)
RhoS = Average mangrove sediment density	Van Santen et al. 2007	1200 kg/m^3
Average high tide duration	Phan et al. 2015	~ 6 hours, 2 times a day = 12 hours in a day
Base sedimentation (or erosion) in the unvegetated foreshore of the profile	-	0
Maximum slope before erosion occurs	-	1/1 = 45 degrees
td_0 = Tidal range	Phan et al. 2015	4m
Base sedimentation inside mangroves	Perez et al. 2018, Breithaupt et al. 2017	1.4mm/yr
Profile initial elevation/subsidence	-	-
Current profile land elevation (part of EL_0)	Minderhoud et al. 2019	See Table 10
Current profile shore depth (part of EL_0)	Liu et al. 2017	See Table 10
Profile height after subsidence in 2100 for the three future scenarios (part of *subhum*)	Minderhoud et al. 2020	See scenarios (4.10)
Subsidence factor, how fast does subsidence occur (part of *subhum*)	Minderhoud et al. 2020	See scenarios (4.10)
Subnat = natural induced subsidence	Zoccarato et al. 2018	20mm/yr
Sea level	-	-
SLR_t = Sea level rise	IPCC AR6 report (IPCC, 2011)	See scenarios (4.10)
MSL_0 = Initial MSL	-	0

4.6 DMM Output

The output of the model consists of a series of elevation profiles containing the location of the mangroves for every 10 years from 2020 (present) to 2100 for each scenario and location. Also, a summary plot is produced for every scenario and location containing: 1) the present elevation, 2) present mangrove location, 3) present MSL, 4) year 2100 elevation, 5) year 2100 mangrove location, and 6) year 2100 MSL (Figure 14). From this data the mangrove retreat at the seafront, the mangrove strip width percentage from present is calculated. For every time step it is additionally shown whether the entire profile has been submerged.

Figure 14: A typical raw excel output of the DMM in this case the summary figure of profile 7, SSP 2-4.5 output model according to input variables as seen in figure. On top is the present (left) and the 2100 (right) profile with the mangrove cover indicated with the thick green line. In 2100 the profile is entirely submerged and no mangroves are present. Below the two profiles are compared in one figure and the two MSL are also indicated. Here the mangrove sedimentation is visible in the 2100 profile.

4.7 Sensitivity analysis

To determine the sensitivity of the model to the different variables a simple sensitivity analysis was performed. The relative influence of profile elevation, RSLR, SSC, settling velocity, and dike placement on the DMM output has been analysed by testing their relative influence on the timing of the complete drowning of profile 2, scenario 2. The relative influence of the factors was visualised in Figure 16 according to their relative difference to each other; the relative difference: average year of submergence for results with the subject input variable - average year of submergence for all results / average year of submergence for all results.

The base input of the sensitivity analysis was profile 2, scenario 2 (4.10). Instead of using 1200kg/m^3 for sediment density, 1760 kg/m^3 was used. This change caused the average drowning year to drop to the year 2084. This allowed for a larger spread of relative differences and thus more accurate results, because the DMM only simulates until 2100 and therefore has a max drowning year of 2110. Additionally, instead of the adjusted SSC, the original SSC values of before the validation results were used (Table 9). For every input variable used (profile elevation, RSLR, SSC, settling velocity, and dike placement) a low, high, and control value were tested. The control value represented the most probable value that was found in the literature for profile 2 and scenario 2 (4.10). The high value was 2 times the control value and the low value was half the control value. The different input variables are shown in the table below. The different input for RSLR is visualized in Figure 15.

Table 12: The different input variables used for the sensitivity analysis.

Input variables	Value low	Value control	Value high	Notes/explaination
SSC	0.022 kg/m^3	0.044 kg/m^3	0.088 kg/m^3	Based on observations and modelling of Marchesiello et al. 2019 (Table 9). This study assumed this spread to be sufficient, it all still falls within the thresholds for a free settling regime on which the settling velocity is based (<200mg/l)
Settling velocity	0.000015m/s	0.00003m/s	0.00006m/s	Falls within the measurements of a free settling regime in the MRD 0,01mm/s-0.08mm/s Gratiot et al. 2017
Profile elevation	Elevation of profile 2/2	Elevation of profile 2 (Table 10)	Elevation of profile 2*2	(Minderhoud et al. 2019)
RSLR	RSLR for scenario 2, profile 2/2	RSLR for scenario 2, profile 2	RSLR for scenario 2, profile 2*2	see Figure 17, see 4.10, scenarios
Dike placement	No dike placement change (dike at 5km in the model)	Dike 2.5 km back (dike at 7.5km in the model)	Dike 5 km back (dike at 10km in the model)	See 4.10, scenarios

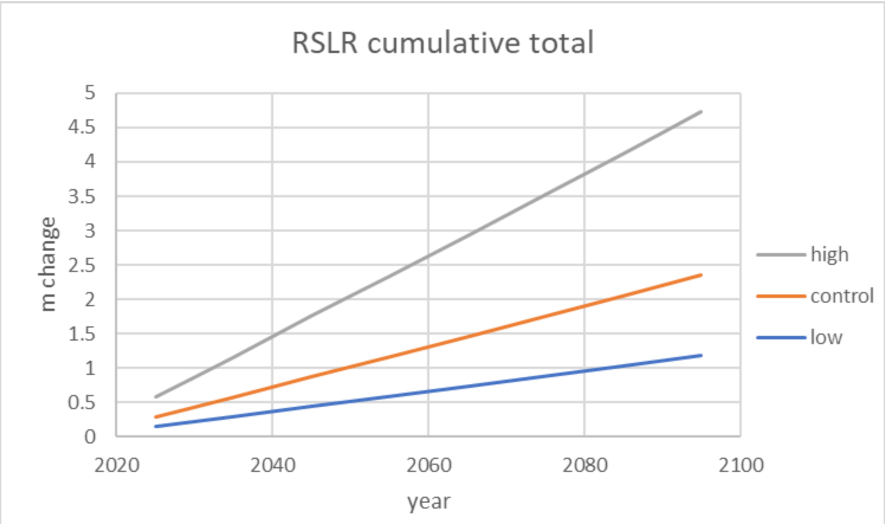

Figure 15: the cumulative RSLR used in the sensitivity analysis.

The results of the sensitivity analysis are summarized in Figure 16:

Conclusions:

- **(decreasing sensitivity):1) RSLR, 2) profile elevation, 3) SSC, 4) settling velocity, 5) dike placement.**
- The DMM is the most sensitive to RSLR and profile elevation. This makes sense because the model is inundation based, and RSLR and profile elevation are therefore dominant factors.
- Dike placement has a low impact, mostly because the elevation increase further landward in the MRD is very low.

- High scenarios result in a larger relative difference in drowning year than low scenarios for SSC and settling velocity. This is because the profile elevation that needs to be flooded for the profile to be completely inundated is the same for all these runs, however every year that the profile is drowned earlier is caused by exponentially more RSLR/yr. E.g: to drown a profile in 70 years instead of 80 is a time reduction of 12.5%, but from 50 to 40 years is a reduction of 20%. Because of a non-linearly increasing profile hight, this pattern is not so strong in the dike placement scenario.
- Low elevation scenarios result in a larger relative difference than high scenarios. This is because there is a maximum year in the DMM when the profile drowns. The model only runs to 2100 so if the profile is still not drowned at that moment the output value will be 2110, even if it means that in 2110 the profile is still not drowned. The same effect is visible in RSLR, only reversed because a high RSLR causes a profile to drown faster, while a high elevation causes a profile to drown slower.

The results of this sensitivity analysis seem realistic. RSLR and elevation have already been identified as the most important factors controlling future mangrove persistence in the MRD in chapter 2. Additionally, subsidence and SLR are some of the main threats to mangroves in the future along with direct human influence (chapter 2). Dike placement influence is relatively low because of the flat MRD geomorphology. Sedimentation plays an important role, but since sediment input into the MRD is low this factor is also of lesser relative importance to mangrove sustainability in the MRD than the RSLR and initial elevation of the area (Dunn and Minderhoud 2022).

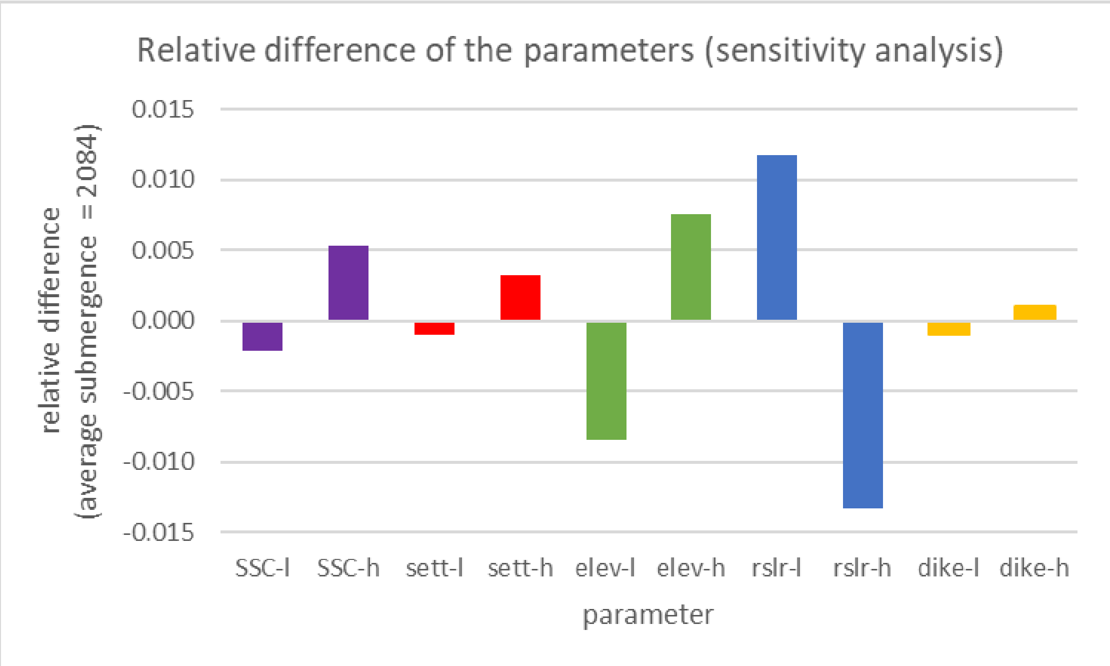

Figure 16: the relative difference of the different results obtained with the input variables used in the sensitivity analysis (l = low h = high); relative difference: average year of submergence for that input variable - average year of submergence of the profile with all input variables / average year of submergence of the profile with all input variables.

4.8 Calibration of the model

The most useful historical data that was available to test the accuracy of the DMM model was historic shoreline change data. Because shoreline change in the MRD during the last decades can be relatively easily measured using satellite data. When the shoreline change of the 9 profiles was modelled for the 1990-2015 period, using the sensitivities analysis' control input parameters (Table 12) and the DMM, and were compared to the actual shoreline change data from that time period (Marchesiello et al. 2019;

Anthony et al. 2015), a large discrepancy was visible (on average -29.17m/y shoreline change difference) (Table 13). First the DMM had to be calibrated to historic shoreline change data, to know which model parameters guarantied the best result.

4.8.1 Focus of the calibration modelling; profile 7 and 8 + SSC values

To accomplish the most accurate calibration possible, this study focussed on profiles 7 and 8 during the 1990-2015 period, because these profiles are mainly influenced by subsidence and profile elevation, and sedimentation and erosion plays a relatively small role (Marchesiello et al. 2019) (Figure 9). The effects of sedimentation and erosion in this study are relatively uncertain, since sedimentation outside mangroves and erosion is not considered. On the contrary, subsidence and elevation can be easily incorporated into the DMM, using data of the 1990-2015 period that has been measured in the MRD (the effects of these factors are thus relatively certain). Therefore, profiles 7 and 8 are most suited for calibration.

As stated, most of the model input variables of the DMM to model the 1990-2015 were assumed to have a relatively low uncertainty because measured data was available for elevation, subsidence and SLR during that period (4.5 input). Even though sedimentation had a lower impact in profile 7 and 8, sedimentation inside the mangroves was the most uncertain factor in the modelling of these profiles, because it still makes a significant impact, while there were no measurements of this process available. The sedimentation in the DMM is a function of settling velocity (w) and suspended sediment concentration (*SSC*). Because the study already did an analysis of the settling velocity (Table 8), it was decided to vary the *SSC* to obtain the desired shoreline changes. Additionally, the *SSC* data gathered by this study has a relatively high uncertainty because it consists of offshore surface satellite measurements and offshore modelled values (Marchesiello et al. 2019). It is safe to assume that *SSC* at the shoreline is significantly higher than *SSC* offshore.

The actual modelled average m/yr shoreline changes with the original *SSC* input for profile 7 and 8 were off by about 20 m/yr when compared to observed values (Table 13). However, in both the DMM calculation and the historic data, the same comparison did show a similar average difference between both profiles (Table 13). Additionally, the study assumed that higher *SSC* offshore would translate on average to higher *SSC* at the shoreline. Because of these reasons it was decided to multiply the input *SSC* (that was obtained by Marchesiello et al. 2019) with a factor determined in the calibration modelling.

4.8.2 The input of the calibration modelling

As stated, the calibration modelling was done for the period 1990-2015 and input of the calibration modelling consisted mostly of the values as specified as control in the sensitivity analysis for profile 7 and 8. For SLR the present value was taken (4.10, scenarios), but human-induced subsidence was reduced when compared to the present in the same manner as is done in scenario 1 (4.10, scenarios), because recent water extraction has increased human-induced subsidence (Minderhoud et al. 2020). No dike was implemented, since infrastructure has been greatly increased since this period (Veettil et al. 2019). The current profile height was taken, because only an indication of the profile slope was relevant in the calibration modelling (because only change in shoreline is measured instead of direct values). The *SSC* baseline was taken from Marchesiello et al. (2019) (Table 9) because their measurements are from data that ranged from 2002-2014 and thus fall within the calibration time range.

4.8.3 Methods of calibration

Because the DMM uses cells of 100m in length that can be either inundated or not inundated at MSL and a timestep of 10 years, the smallest increment possible of shoreline change is 100m/10 years = 10m/yr. To more accurately predict average shoreline change, and thus more accurately tune the DMM to historical data, the same conditions were modelled over a 40-year run and the average of those 40 years was taken (e.g. y10:0m, y20:0m, y30:10m, y40:0m = 2.5m average shoreline change). In this way the smallest unit of shoreline change the DMM could calculate was 2.5m/yr.

Additionally, because of the absence of sedimentation outside mangroves in the DMM modelling, the shoreline cannot move seawards. This means that the maximum amount of growth in the DMM is 0m/yr shoreline change (Figure 17). However, there is a difference between different 0m/yr shoreline change values. In some runs profiles are just able to keep above MSL while in other runs the profile is far above MSL but not accreting. It is visible that with a higher *SSC* multiplier there is an apparent linear increase in shoreline change/yr in both profile 8 and profile 7 calculated by the DMM (Figure 17). This linear increase in m/yr change would also be logical considering *SSC* has a linear effect on the sedimentation formula used in the DMM (4.4, DMM detailed calculations). Although, profile 8 caps of at 0m/yr at 1.8 SSC multiplier, the trend can be assumed to continue. If it is assumed this trend is linear, it is possible to infer an estimate of the positive meter per year change in profile 8. This value can be calculated to be +4.17m/yr average shoreline change/ +0.2 *SSC* multiplier ((5+2.5+5)/3 = 4.17) for profile 8 (Figure 17), and a 3.93m average shoreline change for profile 7 ((2.5+5+2.5+5+5+5+2.5)/7 =3.93).

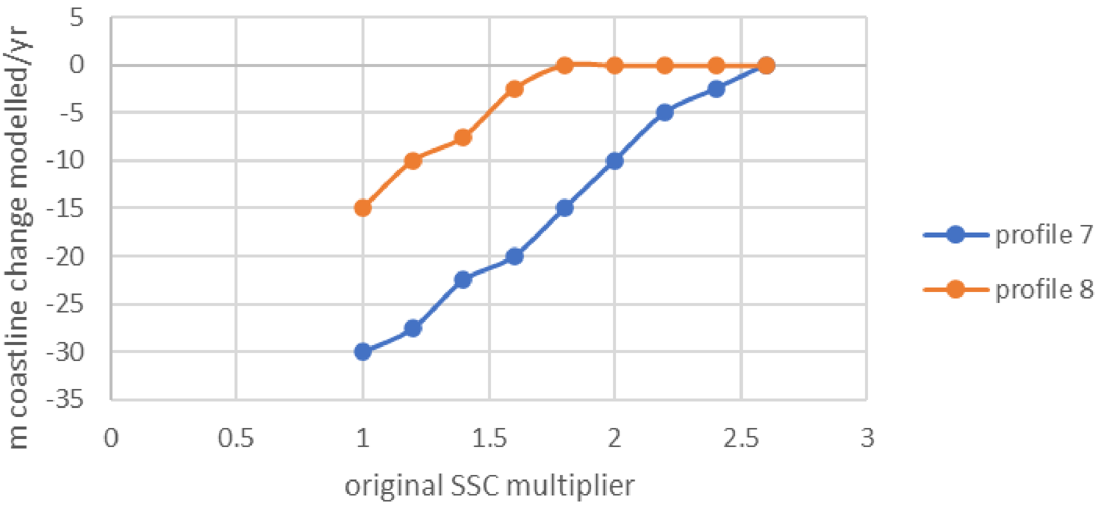

Figure 17: The DMM modelled shoreline, 40 year average change per year for different SSC multipliers for profile 7 and 8. Note that both profiles have a similar linear trend that stops at 0m/yr for profile 8 because the DMM is incapable of seaward expansion without sedimentation outside mangroves. A SSC multiplier of 2 was found to be the best representation of reality.

4.8.4 Results calibration

Using these methods, the most optimal calibration input is reached at a 2.0 *SSC* multiplier (Figure 17). Here profile 7 modelled = -10m/yr compared to -11m/yr measured, while profile 8 is estimated at a 5.83m/yr change (modelled: SSC*1.6 = -2.5 + 2*4.17 = 5.83m/yr) compared to an 8m/yr change measured. Both DMM results are within 2.5 m/yr difference of their measured counterparts, which is considered sufficient due to the minimum m/yr shoreline change possible being 2.5m/yr in this validation exercise. In the table below the measured results are compared to the initial DMM results obtained with sensitivity analysis' control values (average 40 years) and the results for the DMM modelled with the *SSC* multiplier of 2 (average for 40 years) results for all profiles.

Table 13: Measured vs DMM modelled with initial input (average 40 years) vs DMM modelled with SSC multiplier of 2 (average for 40 years) results for all profiles and the explanation .

profile	Measured m/yr shoreline change 1990-2015 (Marchesiello et al. 2019, Anthony et al. 2015)	Modelled m/yr shoreline change 1990-2015 initial input DMM (average 40 years)	Modelled m/yr shoreline change 1990-2015 SSC*2 DMM (average 40 years)	Explanation, of the difference between modelled SSC*2 and measured m/yr changes (Marchesiello et al. 2019)
2	-9	-25	0	Erosion dominant (and erosion is not accounted for)
3	-5	-25	0	Erosion dominant (and erosion is not accounted for)
4	-25	-22.5	0	Erosion dominant (and erosion is not accounted for)
5	43	-27.5	0	No growth simulation possible in the model + sedimentation dominant (sedimentation outside mangroves is not accounted for)
6	-1	-17.5	-5	Correct (within <5m/yr difference)
7	-11	-30	-10	Correct (within <5m/yr difference)
8	8	-15	0	No growth simulation possible in the model (sedimentation outside mangroves is not accounted for)
9	-25	-30	-2.5	Erosion dominant (and erosion is not accounted for)
10	25	-70	-10	Sedimentation dominant(sedimentation outside mangroves is not accounted for)
total	Sum = 0 Average = 0	Sum = -262.5 Average = -29.17	Sum = -27.5 Average = -3.06	3.15m in Li et al. (2017) for the whole SE MRD (Table 14)

4.8.5 Discussion and conclusion calibration

A 2.0 SSC multiplier calibrates the model based on the average conditions in 1990-2015, however since then *SSC* values have dropped and therefore the average shoreline change per year has dropped (Table 14). The results from Wackerman et al. (2017) indicate an average drop of 1% per year from 2001-2015 in Mekong River SSC and show that the SSC halfway through 2001 represents the average SSC for 1990-2015 (Figure 18). If we assume that the drop of 1% per year continued to 2020 (which is also consistent with Dunn and Minderhoud (2022)), and that the Mekong River *SSC* input is directly related to MRD *SSC* values (chapter 2), the average MRD *SSC* value for 1990-2015 would have dropped by about 18.5% in 2020. 18.5% of 2 = 0.37, 2 - 0.37 = 1.63. This thus results in a 1.63 final *SSC* multiplier. The calibration of the DMM is thus considered optimal with the initial control values used in the sensitivity analysis plus an *SSC* multiplier of 1.63.

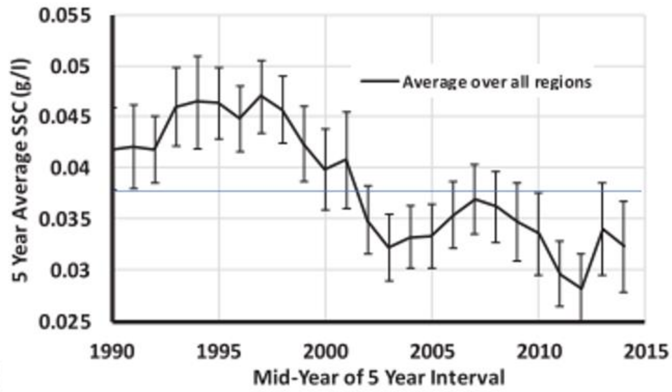

Figure 18: average SSC over all regions measured by Wackerman et al. (2017) in the Mekong River. The blue line represents the average of this period.

4.9 Evaluation of the DMM

This chapter will elaborate to which extend the calibrated DMM results are reliable.

4.9.1 Observations concerning model validity

Average shoreline change of modelled profiles is relatively reliable

It is clear that the calibrated DMM gives better results than the initial calculations (Table 13). In the results that used the initial input parameters the average shoreline change value is -29.17m/yr vs 0m/yr measured. Using the calibrated input variables, the average is almost an order of magnitude lower at -3.06m/yr. This value is still not the same as the 0m/yr measured, however it has to be noted that 5/9 profiles were not eroding. Thus, some of these profiles would have accreted if this was possible in the DMM. As explained in "notes on obtaining calibration results" for example profile 8 would have had an expected seaward shoreline change of 5.83m/yr if the trend from Figure 17 is followed. This factor explains at least part and probably most of the average shoreline change difference observed between the calibrated DMM result and the measured values in Table 13. However, in the original input values DMM results there are no profiles with a 0m/yr shoreline change present. So, in this case the observed difference can not be accounted for.

Modelled profile specific shoreline change not reliable

Another observation is that the individual profile shoreline changes are not reliably predicted even in the calibrated DMM results (Table 13). This is probably because of the absence of erosion in the DMM, and the absence of sedimentation outside of the mangroves which causes the DMM to be incapable of simulating shoreline accretion. This hypothesis is supported by the fact that the strongest accreting (5, and 10) and strongest eroding (4, and 9) profiles are the profiles that are predicted the worst in the DMM.

The average measured shoreline change of the chosen profiles is representative of the SE MRD coast

To test the validity of the results of the DMM it also necessary to test if the average result of the 9 profiles that were tested in the DMM were representative for the whole SE MRD. This was done by taking the total average shoreline change from 1990-2015 from Li et al. (2017) (Table 14) and comparing it to the total average shoreline change for the 9 profiles from Marchesiello et al. (2019), and Anthony et al. (2015) (Table 13) for that same period. The result of 3.15m/yr and 0m/yr respectively was comparable.

Table 14: The average shoreline change m/yr for the SE MRD, divided into three segments from Li et al. (2017). Under the total average is calculated adjusted for the length of each segment.

Time period	**Segment 1 (estuarine coast) average m/yr**	**Segment 2 (Ca Mau east coast) average m/yr**	**Segment 3 (Ca Mau west coast) average m/yr**
1991-1995	14	-27	15
1995-2000	17	-21	39
2000-2005	7.0	-18	8.0
2005-2010	6.0	-22	12
2010-2015	2.0	-23	17
average	9.0	-22	18
lenght segment (km)	300	115	75
	Total 1991-2015	*segment 1+2*	*Total 2010-2015*
average	3.15	0.410	-1.57

4.9.2 Evaluation Discussion

Redistribution of sediment within the SE MRD is not well modelled in the DMM, but can be partly negated when the average of all profiles in the SE MRD is used instead of individual profiles

The high variability of measured shoreline change between profiles, which is not well modelled in the DMM, is linked to the redistribution of sediment in the SE MRD, which comprises most of the sediment movement in this area (Marchesiello et al. 2019). However, sediment redistribution does not affect the average shoreline change in the SE MRD. The DMM does not take sediment redistribution into account and instead focusses more on the total input of sediment, which is mostly linked to the Mekong River sediment input (Marchesiello et al. 2019) (chapter 2). The total sediment input into the SE MRD system will help to predict the average shoreline change in the MRD, but will not be particularly accurate when looking at one location when redistribution of sediment is such an important mechanism as at the SE MRD coast.

The maximum elevation of a profile at any time period is better suited to be used as main output of the DMM than shoreline change

Although shoreline change is not particularly effectively modelled by the DMM because of The inability of the DMM to model erosion or a seaward accreting shoreline can for the most part be nullified by interpreting the results based on maximum profile elevation. This is because even without sedimentation outside the mangroves and erosion at the edge of the mangrove area (the area identified as being affected by erosion the most in chapter 2), profile elevation inside the mangrove area is mostly correctly calculated according to the model calibration on profile 7 and 8. Additionally, because by definition the area landwards of the mangroves is not regularly flooded in the DMM (due to being behind a dike or above MHHW) there is no significant sedimentation and/or erosion in those areas. This means that the maximum elevation of a profile (that is almost always located in/or behind the mangroves, due to the coastal morphology and high sedimentation in mangrove areas) is relatively reliably calculated in the DMM.

4.9.3 Conclusion

The results of the DMM can be useful, but only when the results are handled correctly and with caution. This is because 1) the profiles are shown to be on average more or less representative for the SE MRD coast, and because 2) there is a good case to be made that the average shoreline change and especially maximum elevation is relatively reliably calculated.

How to interpret DMM results

Based on these observed strengths and weaknesses of the DMM it is possible to create a strategy that uses DMM results in the most accurate way possible and in this way to maximise the potential of the DMM. This strategy consists of 2 actions.

1) ***Use maximum profile elevation for the interpretation of DMM results instead of shoreline change.***
   The inability of the DMM to model erosion or a seaward accreting shoreline can for the most part be nullified by interpreting the results based on maximum profile elevation.
2) ***Wherever possible base conclusions on the average results instead of specific profiles.***
   The use of the average result for all profiles helps to negate the model inaccuracies in individual profiles. It is especially effective for inaccuracies caused by the redistribution of sediment at the SE MRD coast that is not effectively modelled by the DMM.

4.10 Definition of Future Scenarios

To model the future of the SE MRD I decided to follow three IPCC scenarios for future global socio-economic development and associated GHG emissions: Scenario 1: SSP1-2.6, representing a sustainable future, Scenario 2: SSP2-4.5, with a 'middle of the road' projection, and scenario 3: SSP5-8.5, with strong economic development and associated GHG emissions (IPCC 2022). These scenarios have been extended to also include subsidence scenarios and a possible dike retreat in the MRD in a way that is as consistent as possible with the IPCC global SSP scenario's (Minderhoud et al. 2020). The different scenarios and their accompanying model input is given in the table below.

Table 15: Overview of the Scenarios used in this research (SSC: suspended sediment concenmtration).

SCENARIO	SSP	RCP	SUBSIDENCE SCENARIO *(Minderhoud et al. 2020)*	SSC *(Dunn and Minderhoud 2022)*	DIKE PLACEMENT
1	1. *Sustainability*	2.6	M3, *75% total extraction reduction*	*SSC increase linear to 150% in 2100*	*Dike retreat of 5 km*
2	2. *Middle of the Road*	4.5	M1, *stable extraction*	*Stable SSC*	*Dike retreat of 2.5 km*
3	5. *Fossil-Fuel Development*	8.5	B1.5, *3% annual extraction increase*	*SSC linear decrease to 50% in 2100*	*No dike retreat*

Input from these scenarios differ for the 4 crucial factors for mangrove persistence in the MRD that can change in the future, that were determined in chapter 2: 1) human-induced subsidence, 2) sea level rise, 3) SSC, and 4) dike placement. The different input for these input variables is elaborated below and shown in Figure 21.

4.10.1 Human-induced subsidence

How human-induced subsidence will change in the coming century is dependent on the amount of groundwater extraction. Minderhoud et al. 2020 calculated the subsidence rate according to 4 mitigation (M1, M2, M3, M4) and two non-mitigation (B1, B2) scenarios (Figure 7). For these 6 scenarios total human-induced subsidence was calculated by Minderhoud et al. (2020) over the whole MRD until 2100 (Figure 8).

This study coupled S1 (SSP1-2.6) with M3, S2 (SSP2-4.5) with M1, and S3 (SSP5-8.5) with B1.5 following Dijkstra (2020). Scenario B1.5 is exactly the average of B1 and B2 (thus equal to a 3% annual extraction increase). Figure 19 shows the average human-induced subsidence rate in the MRD per scenario modelled by Minderhoud et al. (2020). This study used the modelled data of Minderhoud et al. (2020) extracted along the 9 profiles to determine the total human subsidence in an area in 2100. Using Figure 19, the study then calculated how much (percentage that was translated to a factor) of the total subsidence in 2100 was caused in the specific decade of the timestep in the DMM: "the subsidence factor". The input in the DMM consisted thus of the profile and scenario specific human subsidence total for 2100 (Figure 8) and the scenario specific and time step specific "subsidence factor" that was calculated from Figure 19.

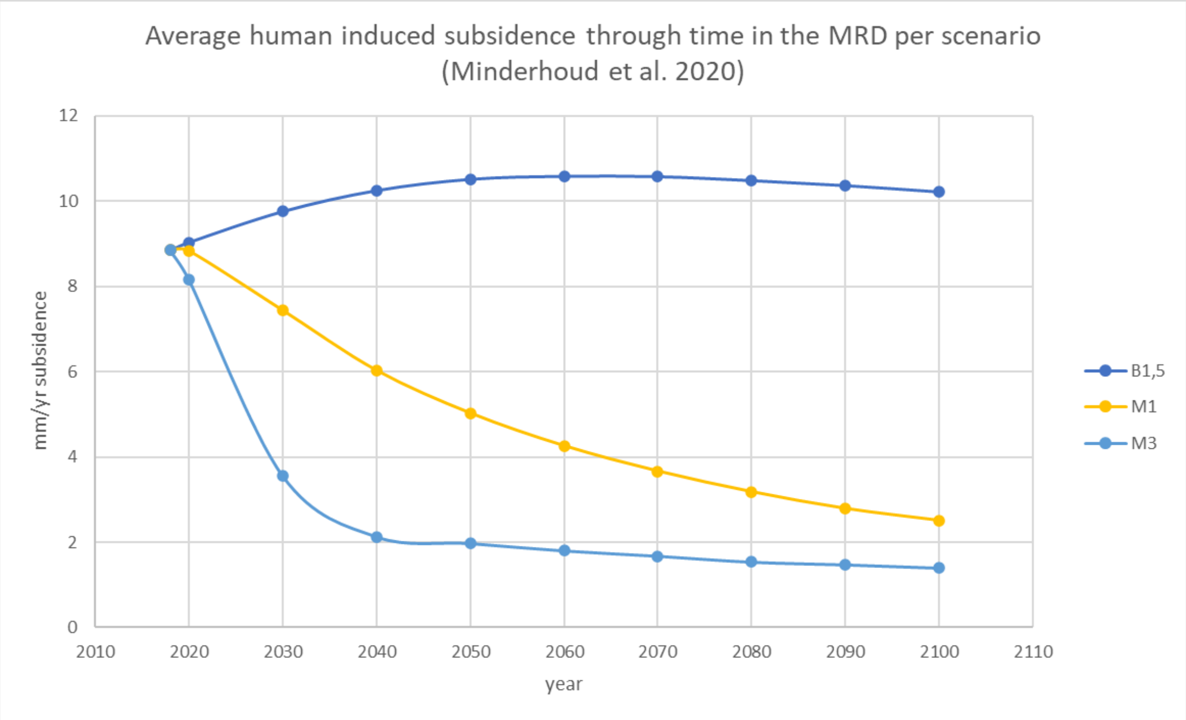

Figure 19: calculated average subsidence rates per scenario through time for the MRD from Minderhoud et al. (2020). Note that scenario B1.5 is the average of scenario B1 and B2. Scenario 1 corresponds to M3, Scenario 2 to M1, and scenario 3 to B1.5.

4.10.2 Sea level rise (SLR)

Time transient predictions of the three sea level rise scenarios for the MRD were retrieved from the IPCC AR6 report (IPCC, 2022) using the sea level projection tool (https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool?psmsl_id=1495). Data was obtained for the station of Vũng Tàu (see link) which lies just north of the MRD and was the closest station that could be used in this database. The values represent the median of the likely range of sea level rise during these scenarios (Figure 20). In this report the IPCC predicted a total SLR from 2020 to 2100 of 0.43m, 0.55m, and 0.76m for the scenarios: scenario 1(SSP1-2.6), scenario 2(SSP2-4.5), and scenario 3(SSP5-8.5) respectively. The input of the model consisted of the predicted m SLR per decade following Figure 20. In contrast to Figure 20, the DMM results were obtained with a starting SL of 0 in 2020 (however, there is an option in the DMM to start at a different SL elevation in 2020).

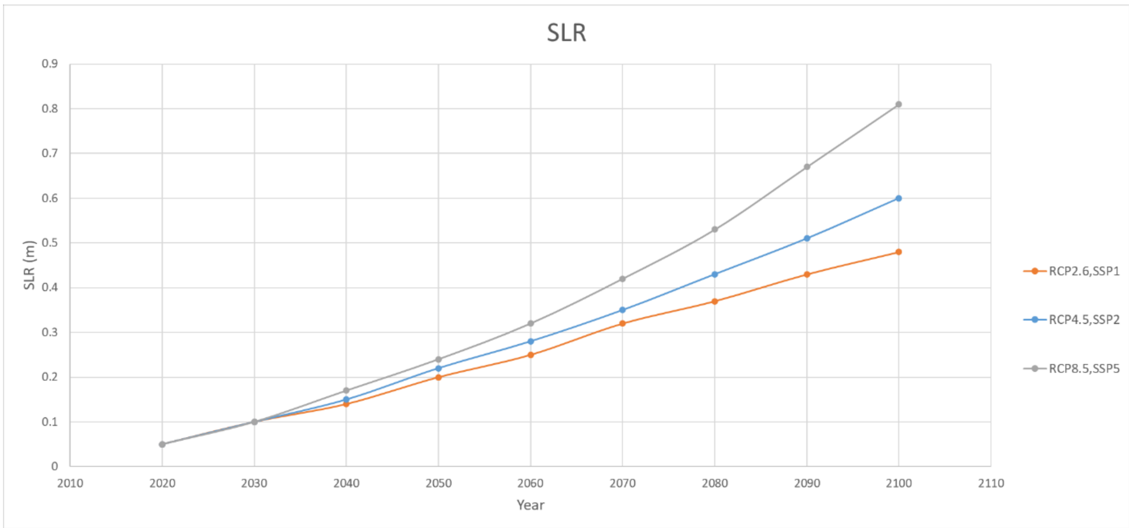

Figure 20: the IPCC predicted sea level rise in Vũng Tàu till 2100. Notice the SLR starts at 0.05m already in 2020. Scenario 1=(SSP1-2.6), scenario 2=(SSP2-4.5), and scenario 3=(SSP5-8.5).

4.10.3 Suspended sediment concentration

The overall sediment budget at the SE MRD coast is dependent on sediment input of the Mekong River as discussed in chapter 2 and chapter 4.9. Therefore, SSC changes along the MRD coast in the future are linked to Mekong River sediment input (Li et al. 2017). From 2001-2016 it was observed by Wackerman et al. (2017) that the *SSC* concentration in the Mekong River dropped by about 1% per year mostly due to the damming of the Mekong. A further drop in *SSC* scenario 3 (strong economic development, worst case) is expected due to continued Mekong River damming. Scenario 3 assumes therefore a linear decrease of *SSC* that culminates in a 50% reduction by the year 2100. Conversely, under scenario 1 (representing a more sustainable future) it is assumed that damming in the Mekong will be reduced (best case scenario) and *SSC* may again increase. Dunn and Minderhoud (2022) showed that when the largest 10% of dams are removed in the Mekong River in 2050, the sediment delivery to the delta mouth could increase by about 75% by the end of the 21st century. Thus, as a conservative estimate, a linear increase in *SSC* occurs under scenario 1 up to a 50% *SCC* increase in the year 2100. In scenario 2, *SSC* is kept constant over the full modelling period, hereby representing the average of these two extreme scenarios.

4.10.4 Habitat borders/Dike placement

Dikes are placed right at the coast (border between profile of Minderhoud et al. (2019) data and the slope towards the 5 m depth (4.5, input)) for scenario 3. This is mostly the current situation (chapter 2). It is assumed that for scenario 2 dikes are placed landwards 2.5 km in the SE MRD in 2020. In scenario 3, dikes are moved 5 km landwards in 2020.

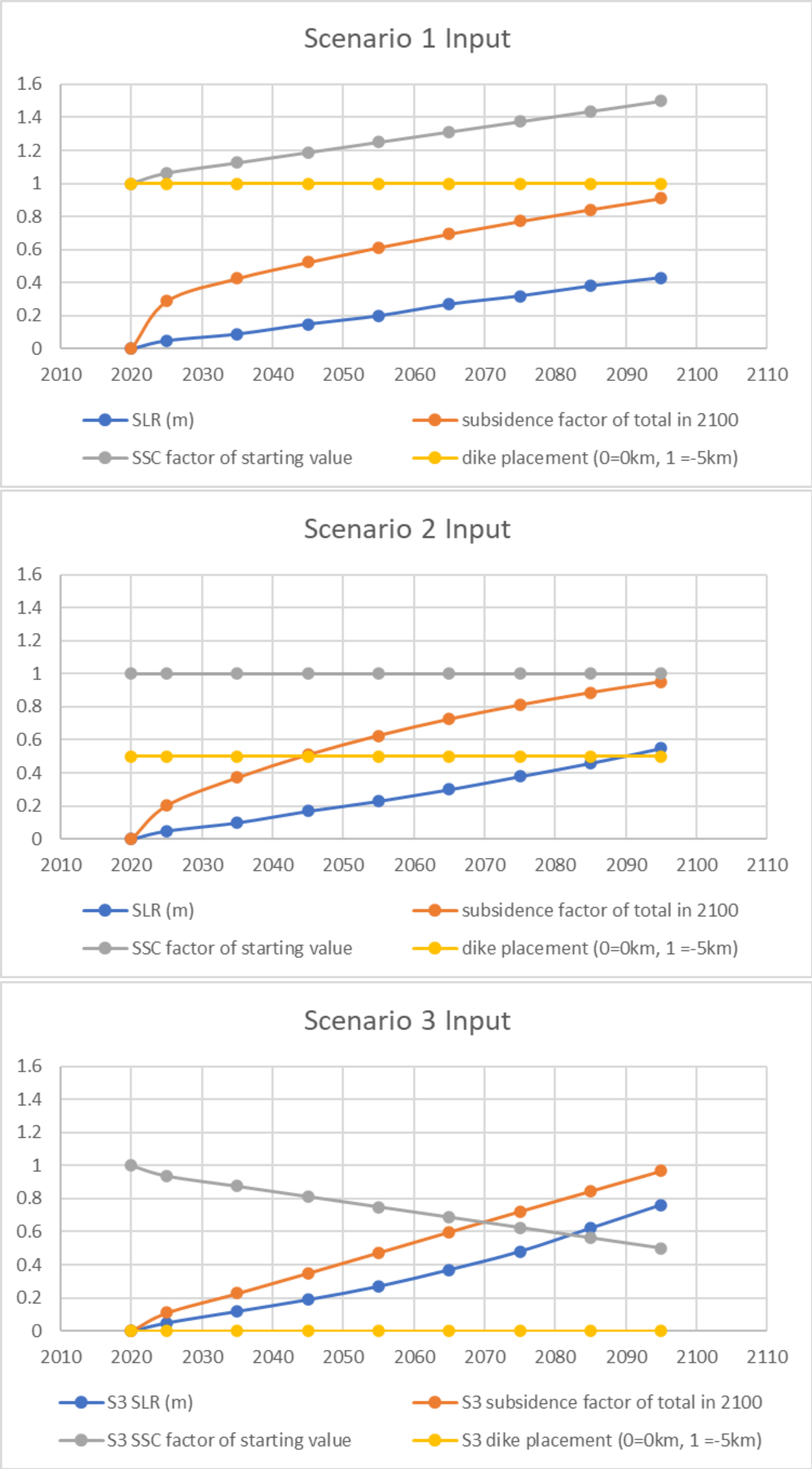

Figure 21: top: the input variables of scenario 1, middle: the input variables of scenario 2, bottom: the input variables of scenario 3.

5. Results; future mangrove persistence in the SE Mekong River Delta

It was determined in chapter 4.9 that the maximum elevation (and thus the presence or absence of mangroves) in a profile at any time period is better suited to be used as main output of the DMM than shoreline change and/or exact position of the mangrove forest in a profile. Therefore, for the results the study modelled firstly for every scenario (1) when the 9 profiles which represented the first 5-10 km of SE MRD coast will be below MSL: "*the inundation date*" of all profiles, (2) when mangroves disappear from these profiles and (3) when profiles will drown without any sedimentation or mangroves. In this manner, it could approximately be determined A) how long mangroves would be present in the SE MRD in the different scenarios and B) if mangroves actually aid against flooding in the MRD in all scenarios. For B the study assumes that mangroves act as flood protection if (1) sedimentation delays the "inundation date" ***and*** (2) if mangroves are present (chapter 2). The results are visualized below: (Figure 22 = S1, Figure 23 = S2 and Figure 24 = S3).

Secondly, 1) the average "inundation date", 2) year of disappearance of mangroves and 3) year of disappearance without sedimentation are compared in one figure (Figure 25). Because it was determined in chapter 4.9 that redistribution of sediment within the SE MRD is not well modelled in the DMM, but that this factor can be partly negated when the average of all profiles in the SE MRD is used instead of individual profiles.

Thirdly, the influence of additional possible measures to increase MRaC solution space in scenario 1 and 2 on the model results are visualized (Figure 26).

5.1 SSP 1-2.6

Figure 22 shows the result for scenario 1 (SSP1-2.6: subsidence = M3, SSC = +50% by 2100, dike placement = 5km landwards). The numbered thin lines perpendicular to the coast represent the profiles. As seen in Figure 22, all of these profiles were still above MSL in the year 2100 (the maximum year calculated in the DMM). That means that, when using the 10-year time step that is used in the model, the earliest “inundation date” for the profiles is 2110. However, because most of the profiles still had a large elevation margin by 2100 the “inundation date” is expected to be later than 2110 on average. Therefore, this category and the average “inundation date” has been labelled 2110+.

Assuming that the profiles are representative of the local coastline, The result of the individual profiles is taken as a baseline for a prediction for the first 5 km (minimum initial depth land above MSL in a profile) of the entire SE MRD coastline (the thick coloured line that hugs the coastline) which is thus also expected to stay above MSL until at least 2100. Mangroves are also present in every profile until at least 2100.

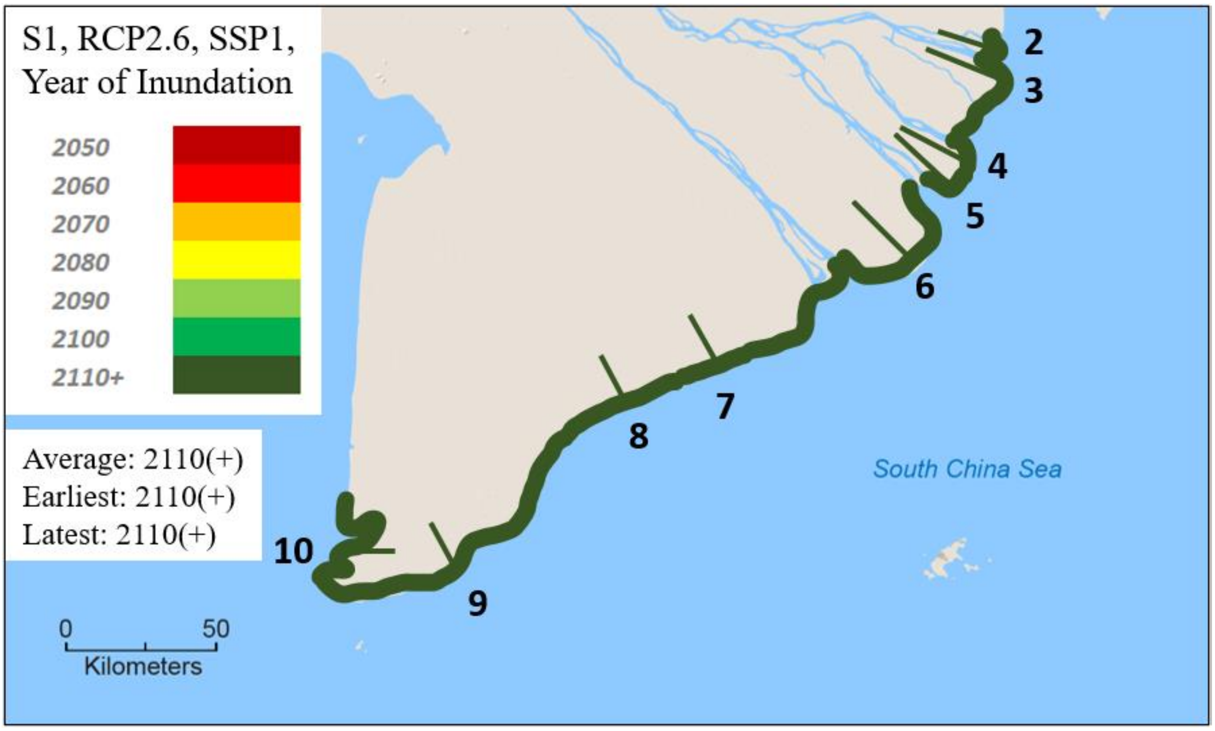

Figure 22: The year of complete inundation of all the profiles (numbered) in scenario 1 (SSP1-2.6: subsidence = M3, SSC =+50% by 2100, dike placement = -5km, see 4.10 for input variables). Assuming that the profiles are representative for the local coastline the result of the profiles is projected over the whole SE MRD coastline.

5.2 SSP 2-4.5

This figure shows the result for scenario 2 (SSP2-4.5: subsidence = M1, SSC = constant, dike placement = -2.5km). The numbered thin lines perpendicular to the coast represent the modelled profiles. For scenario 2 only profile 2, 3 and 9 stay above MSL until at least 2110 (the latest year that the DMM can calculate). The rest of the profiles will be below MSL prior to this date in scenario 2 starting with profile 10 that will be below MSL in 2070 according to the DMM. The average "inundation date" for this scenario is somewhere around 2095. This date is at the low end of estimates as 3 of the 9 profiles persist until at least 2110 (maybe longer) and therefore are not properly accounted for (for this estimate 2110 was taken for these profiles). Because in most cases in the SE MRD the highest point of elevation lies within 5km of the coastline a MSL above this elevation would mean large scale flooding of the entire MRD (Minderhoud et al. 2019) (Figure 5).

In scenario 2 dikes/mangrove barriers are placed 2.5 km landwards, because in all profiles the highest elevation falls within this range at time of inundation, the mangrove forests will disappear at the same time as the year the entire profile falls below MSL. Mangroves thus persist in 3 of the 9 profiles until at least 2110.

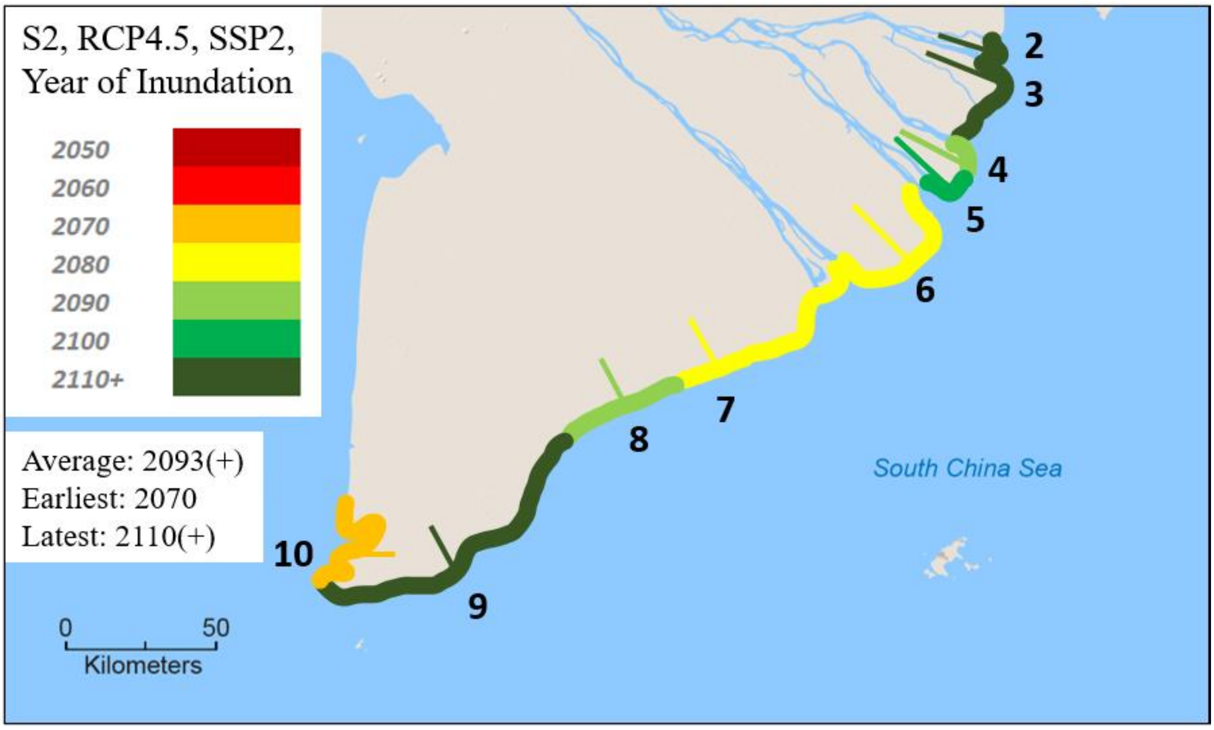

Figure 23: The year of complete inundation of all the profiles (numbered) in scenario 2 (SSP2-4.5: subsidence = M1, SSC = constant, dike placement = -2.5km, see 4.10 for input variables). Assuming that the profiles are representative for the local coastline the result of the profiles is projected over the whole SE MRD coastline.

5.3 SSP 5-8.5

This figure shows the result for Scenario 3 (SSP5-8.5: subsidence = B1.5, SSC = =-50% by 2100, dike placement = no dike retreat). The numbered thin lines perpendicular to the coast represent the modelled profiles. For scenario 3 every profile will be below MSL in 2090. The average "inundation date" for this scenario is around 2065. The profiles that will be below MSL first are 6,7,8 and 10 in 2050. This would mean large scale flooding of the entire MRD (Minderhoud et al. 2019) (Figure 5).

In scenario 3 dikes/mangrove barriers prevent mangroves to retreat landwards. This causes the mangroves to disappear slightly earlier than the average profile "inundation date" around 2060.

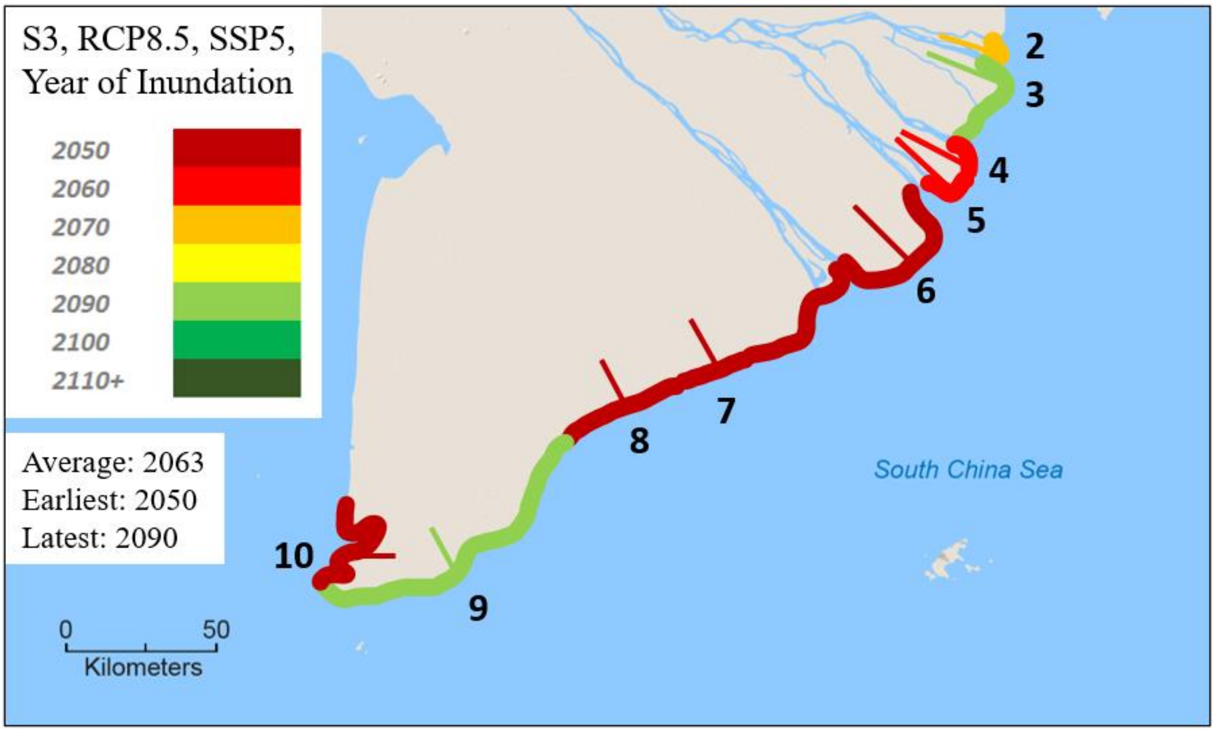

Figure 24: The year of complete inundation of all the profiles (numbered) in scenario 3 (SSP5-8.5: subsidence = B1.5, SSC =-50% by 2100, dike placement = no dike retreat, see 4.10 for input variables). Assuming that the profiles are representative for the local coastline the result of the profiles is projected over the whole SE MRD coastline.

5.4 Average Result per Scenario

The average results for all profiles under the three scenarios are summarized in Figure 25. Indicated are 1) the complete submergence of the profile beneath MSL, 2) the disappearance of mangroves in the profile, and 3) the submergence of the profile without sedimentation.

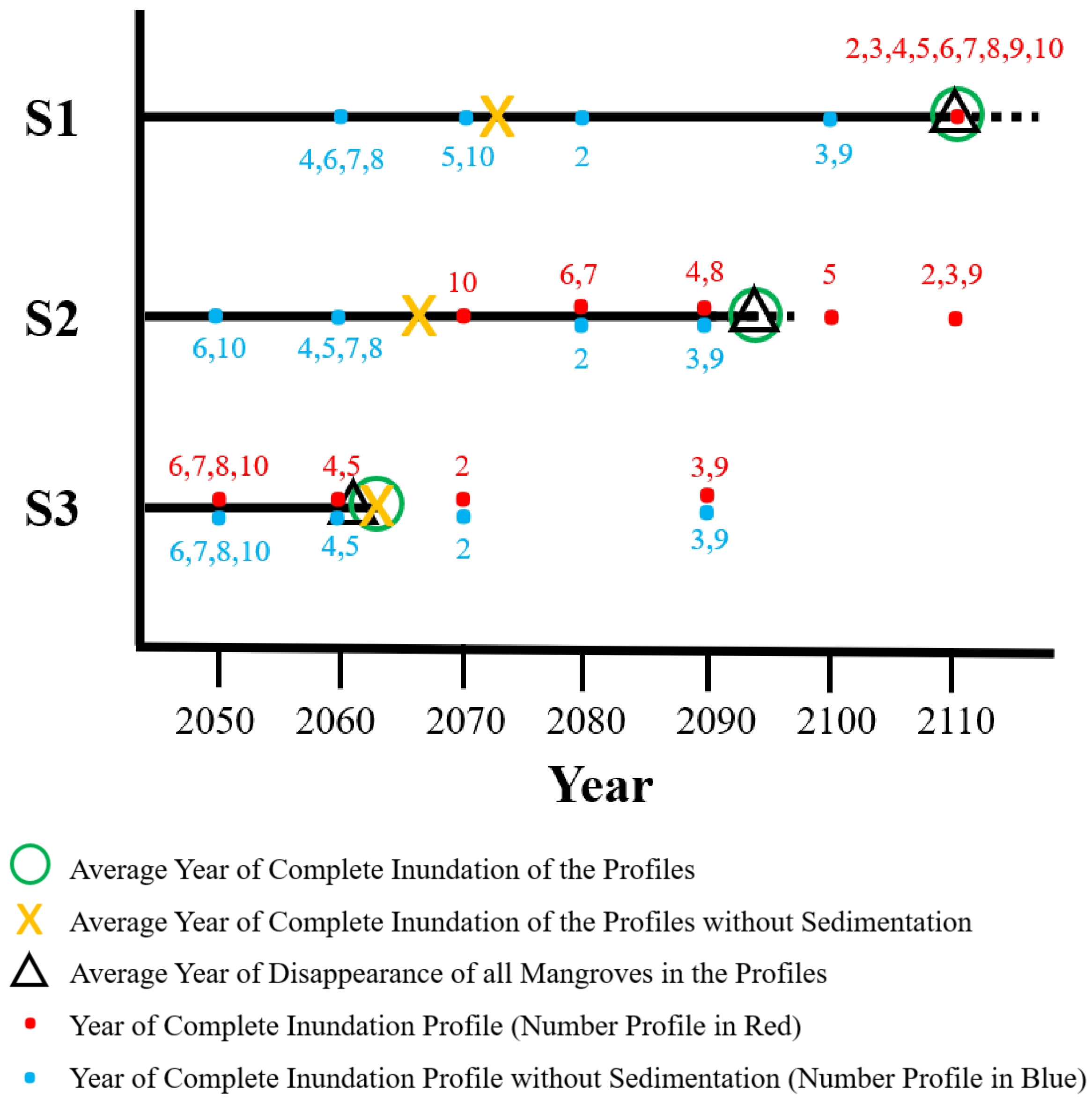

Figure 25: Average result per scenario: indicated in this figure are the average year for all profiles of 1) the complete submergence of the profile beneath MSL, 2) the disappearance of mangroves in the profile, and 3) the submergence of the profile without sedimentation per scenario. The averages for S1 and S2 are open ended (dashed line) due to the maximum time range of the DMM and show the minimum value that is calculated by the DMM.

The results can be summarised in the following manner:

S1: No complete inundation of any profile in scenario 1 until the end of the DMM simulation (2110). Sedimentation was found to be a large aid against flooding in this scenario with at least a ~40-year difference in average "inundation date" in a run with and without sedimentation and mangroves.

S2: Flooding of the entire profile in 6 out of 9 profiles before 2110 (average "inundation date" = ~2095). Mainly the most western part (west of Cà Mau, profile 10) and the middle part of the SE MRD is vulnerable (around Thạnh Hải to Gành Hào, profile 4-8). Profile 10 was calculated to be the first to drown in 2070. The end of mangrove persistence in all profiles in this scenario was simultaneous with the drowning of all profiles. Mangroves thus persisted in 4 out of 9 profiles until at least 2110. Sedimentation was found to be a large aid against flooding in this scenario with at least a ~30-year difference in average "inundation date" in a run with and without sedimentation and mangroves.

S3: all profiles are completely below MSL in the year 2090 (average "inundation date" = ~2065) starting with profile 6, 7, 8 (Dân Thành to Gành Hào) and 10 (the far west of the SE coastline) in 2050. So, we see that the same areas as in S2 are extra vulnerable. Profile 9 (most southern coast of the MRD) and profile 3 (around Bình Đại) are the last profiles to fall below MSL. These areas seem to be the least vulnerable to flooding in the coming decades. Mangroves persisted on average a little shorter than the average "inundation date" with an average disappearance date of ~2060. The last mangroves disappear in profile 3 in 2090.

Interestingly, the average "inundation date" with mangroves and sedimentation is the same as the average "inundation date" without mangroves and sedimentation in scenario 3 (~2065). In this scenario the profiles drown so fast that not enough sedimentation can take place to make a significant difference. Also, in scenario 3 dikes/mangrove barriers prevent mangroves to retreat landwards. This causes the mangroves to disappear slightly earlier than the average "inundation date", in ~2060 instead of ~2065. Mangroves in this scenario thus don't significantly help to protect the SE MRD against flooding. However, in scenario 1 and 2 mangroves do protect the SE MRD against flooding. In both cases mangroves provide a favourable sedimentation environment that have enough time to significantly make a difference compared to a non-sedimentation scenario. In both scenarios the mangrove forest area due to sedimentation comes to include, or already includes the highest point of elevation. Which causes the "inundation date" and the "disappearance of mangroves date" to be the same.

5.5 Influence of Additional Measures

Figure 26 shows the effect of additional measures that may be taken to support against flooding and promote mangrove sedimentation on the average "inundation date" of all profiles. Results are shown for scenario 2 and 3. Scenario 1 is not taken in consideration, because in this scenario all profiles stay above MSL until at least 2110 (the maximum time range of the DMM). Additional measures thus can not extend the simulated mangrove persistence any further into the future. For this assessment the study analysed what effect of mitigation measures targeting all major factors that will change and influence MRaC in the future, that were determined in chapter 2. These are: 1) SLR, 2) SSC, 3) human-induced subsidence, and 4) dike/human barrier placement. The study assumes that problems that have a local cause are easier to solve than large scale problems, and that a potential policymaker in Vietnam would start with tackling the smallest scale problem. It was determined that SLR = global cause (global warming), SSC = international (basin wide) cause (Mekong River damming and sand mining in China and Laos and Vietnam), human-induced subsidence = regional cause (regional groundwater extraction), and dike placement = local (see chapter 4.10). Following this reasoning the measures in Figure 26 are applied in an increasing problem cause scale order: 1) dike/human barrier placement, 2) human-induced subsidence, and 3) SSC. SLR is left out because the study presumes that there is no realistic possibility that decision makers in Vietnam could significantly influence this factor, and that it is directly tied to the scenario modelled.

The mitigation measures used in this assessment are the same as have been used in the previous S1 and S2 scenarios, as these have been shown to be realistically possible in chapter 4.10. Because scenario 2 already has most half of these measures implemented, it only adds 3 mitigation measures.

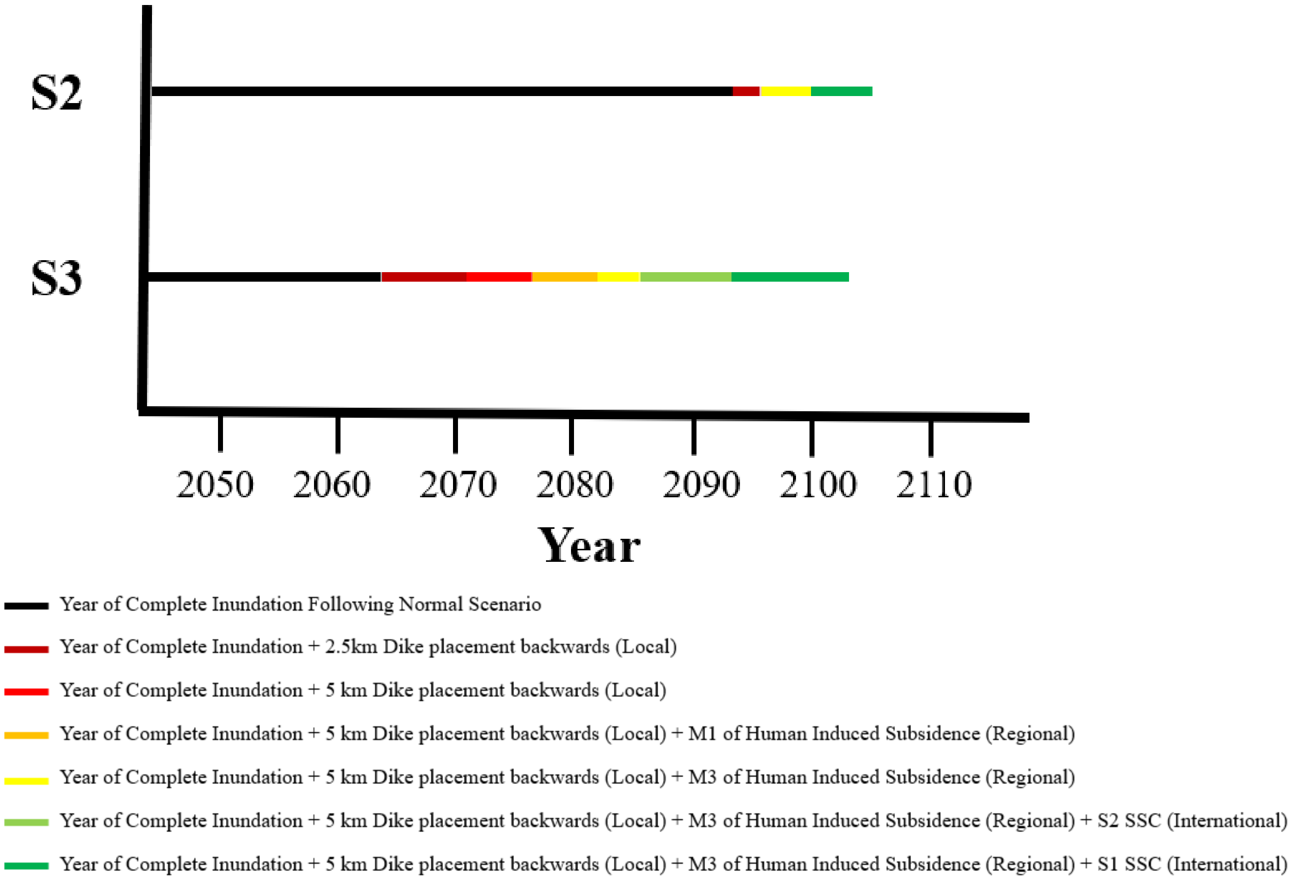

Figure 26: the average "inundation date" per scenario plus additional possible mitigation measures, from a local to a international scale. It is clear that these extra mitigation measures can make a large difference. Every measure has an influence, even doubling the MRD lifespan in scenario 3. It is worth noting that the averages for S2 and S3 are open ended due to the maximum time range of the DMM and show the minimum average value that is calculated by the DMM. For an explanation of M1, M3, and S1 and S2 SCC (chapter 4.10).

The simulation results show that all measures proposed have at least some impact in both S2 and S3. Every measure adds at least 3 years to the “inundation date”. Overall, SSC seems to be the most impactful mitigation measure in both S3 and S2. In S3 dike placement seems to have more impact than subsidence mitigation, while in S2 it is opposite. It is hard however, on the basis of these results, to quantify exactly how much the impact of each measure has individually because their cumulative effect may be greater than the sum of the individual impacts. Additionally, there was a maximum “inundation date” (of 2110) in the DMM that influenced the data. These factors are elaborated in chapter 6.

Below, the most important results of the simulated influence of mitigation measures on the average “inundation date” of all profiles, are described in more detail (sorted by type of measure):

Dike retreat

- Dike retreat to create more mangrove habitat has the biggest impact in S3, a 5km dike retreat will add at least 10 years to the “inundation date” in every profile. With a 13-year average addition across the profiles. In S2 the impact of an extra 2.5 km dike retreat is smaller (average = 3 years added to the “inundation date”). Part of the reason for this difference might have to do with the fact that 3 out of 9 profiles already reached the maximum “inundation date” possible in the DMM in S2. Therefore, their “inundation date” can not increase. It is possible that these profiles would benefit from dike retreat the change would be similar as seen during a 2.5km dike retreat in S3. However, this also might have to do with positive feedback of other measures implemented in S2.
- The results do not show a clear trend of which profiles profit most from dike retreat. In S3 profile 2, 5, and 8 profit most (5km retreat = 20 extra years added to “inundation date”). In S2, profile 4 and 5 profit most (2.5 km extra retreat = 10 extra years added to “inundation date”)
- Interestingly, elevation behind the initial dikes does not seem to have a large influence on the “inundation date” because the profiles in this research that have higher elevation behind the S3 initial dike placement (2, 3, 9) do not experience more (or less) benefit from dike retreat. Additionally, a profile with significantly lower elevation behind the initial S3 dike (profile 7) still benefits from dike retreat.

Subsidence mitigation

- Human-induced subsidence mitigation in S3 from B1.5 to M3 has an impact in every profile except profile 2 and 9. The profile that profits most from the measure is profile 8, here it adds 20 years to the “inundation date”. On average years added to the “inundation date” by the mitigation from B1.5 to M1 is 6 years, and by the mitigation from M1 to M3 is 3 years, totalling an extra of 9 years average for subsidence mitigation as a whole in S3. In S2, profile 6, 8 and 10 benefit from subsidence mitigation M1 to M3 by an average of 4 years added to the “inundation date”. This is relatively high considering the 4 profiles that already have reached the DMM maximum “inundation date”. The higher impact from M1 to M3 subsidence mitigation in S2 than in S3 could be an indication that this factor is extra sensitive to feedback processes and works better in conjunction with other measures (chapter 6).
- Subsidence mitigation does seem to have the most influence on the SE MRD coastline that is most affected by human-induced subsidence. Profile 8 profits most from this measure in the results of this study, and this profile indeed experiences the largest amount of extraction subsidence due to its closeness to Cà Mau city (Minderhoud et al. 2020).
- Profile 2 and 9 experience the least amount of benefit from this measure, this fits with the observation that these areas (southwest of Cà Mau, and the most Eastern MRD coast) experience the least amount of human-induced subsidence, due to those areas being relatively more remote.

SSC increase

- A *SSC* increase benefits all profiles in both S2 and S3 scenarios. In the results of this research, it seems to have the largest individual impact of all mitigation measures. This, however, may be partly caused by the positive feedback of the cumulative mitigation measures, because the SSC increase measure is the last measure to be added in this research (chapter 6).
- In S2, all profiles that have not already reached the maximum "inundation date" of the DMM, benefit when the S1 scenario for SSC (from constant SSC to a gradual increase of SSC to +50% of present value in 2100) is added as a mitigation measure. These profiles consist of profile 4, 5, 6, 7, and 10. In all cases this measure added 10 extra years to the "inundation date".
- The study observes the same trend for S3. All profiles (except profile 10) that have not already reached the maximum "inundation date" of the DMM benefit when the S2 scenario for SSC (from a gradual decline to -50% SSC in 2100 to a constant SSC) is added as a mitigation measure. This benefit is 10 added years on the "inundation date" for all profiles (except profile 10 where no change of the "inundation date" was observed). Also, the second SSC mitigation (S2 to S1) causes an addition of at least 10 years on the "inundation date" in profiles that have not yet reached the maximum "inundation date" in the DMM. Profile 6 however experiences 20 years before inundation after this measure.
- In S3 the study observes that the first SSC mitigation measure (S3 to S2 SSC) (a), has a slightly smaller effect than the second SSC mitigation measure (S2 to S1 SSC) (b). This is due to profile 10 (for which 0 years added to the "inundation date" was observed in mitigation a, and 10 years added to the "inundation date" was observed in mitigation b) and profile 6 (where 10 years added to the "inundation date" is observed in mitigation a, and 20 years added to the "inundation date" is observed in mitigation b). This effect could also be caused by the positive feedback of the cumulative mitigation measures, because the SSC increase measure is the last measure to be added in the modelling (chapter 6).

6. The physical solution space of mangrove restoration and conservation in the Mekong River Delta

6.1 Current solution space

This study used all data gathered in the previous chapters to shape and quantify the physical solution space of mangrove restauration and conservation (MRaC) in the MRD. The physical solution space of MRaC is shaped by biophysical dimensions (y axis) at a given moment in time (x axis). The physical solution space of MRaC represents the boundaries of what is biophysically possible within restauration and conservation of mangroves (or “room to manoeuvre”), and is constantly changing its form due to new insights, views and opportunities. Change in the solution space is possible in two ways: First, due to exogenous changes beyond the direct influence of the actors. Second, solution space can be intentionally changed by planned actions for adaptation, unless hard limits occur. In the case of MRaC solution space, if it is known, for example, how mangroves in the MRD react to a range of probable climate and social scenarios, it is possible to deduct how the solution space of this measure is shaped. Future MRaC solution space may shrink (less “room to manoeuvre”) due to rapid climate change that causes large SLR, but planned actions could increase space or “room to manoeuvre” by e.g. a sediment supply program that adds new sediment to the MRD coast.

6.1.1 The critical factors that determine physical MRaC solution space

Therefore, to determine the physical solution space of MRaC in the MRD, first the physical dimensions/factors, and “hard” (unsurpassable) and “soft” (surpassable) limits that mainly control MRaC in the MRD should be known and understood. What determines physically, at a long-term delta wide scale in the MRD, if mangrove forests can persist or not? This question was the focus during the literature research of the mangrove system in the MRD in chapter 2. A visual summary of the conclusions of this chapter can be found in Figure 2. The 6 physical factors with the largest potential impact on the shape of the physical solution space of MRaC in the MRD were determined to be: (1) SLR, (2) elevation of the MRD (geomorphology), (3) subsidence (natural and human-induced), (4) tidal range, (5) human-induced mangrove barriers and mangrove destruction, (6) sedimentation within mangroves that is dependent on suspended sediment input (SSC), and organic matter accumulation.

6.1.2 The critical factors that determine physical MRaC solution space that will change in the future

Only 4 of those factors are thought to be able to significantly change in the future, thereby affecting future solution space (chapter 2; Dunn and Minderhoud 2022): (1) SLR, (2) human-induced subsidence (natural subsidence will stay more or less constant (zoccarato et al. 2018)), (3) suspended sediment input and thus sedimentation within mangroves, and (4) the location of human-induced mangrove barriers. The tidal range will stay constant (Dang et al. 2022), while elevation is an initial condition. The change of these 4 factors is dependent on climate change and how people will act in the future, therefore it was linked to 3 future scenarios: (S1) SSP1-2.6, (S2) SSP2-4.5, (S3) SSP5-8.5. S3 acts as a “minimum” boundary for possible future solution space change, while S1 act as a “maximum” boundary and S2 illustrates the most probable future solution space of MRaC in the MRD. How these scenarios influence the factors that control solution space is described in chapter 4.10.

6.1.3 Calculation of the physical MRaC future solution space using the DMM

To calculate the impact of the changing factors through time on the physical solution space of MRaC in the MRD until 2100, the study modelled firstly for every scenario (1) when the 9 profiles which represented the first 5-10 km of SE MRD coast will be below MSL: “*the inundation date*” of all profiles, (2) when mangroves disappear from these profiles and (3) when profiles will drown without any sedimentation or mangroves. In this manner, it could approximately be determined A) how long mangroves can be present in the SE MRD in the different scenarios and B) if mangroves actually aid against flooding in the MRD in all scenarios. For B the study assumes that mangroves act as flood protection if (1) sedimentation delays the "inundation date" ***and*** (2) if mangroves are present. The probable time range how long mangroves can physically be present on the MRD coast, and if they helped against flooding during that time period, is the estimated time range when the solution space shrinks to zero (T0). Secondly, the influence of additional possible measures to increase MRaC solution space in scenario 1 and 2 was modelled to understand how these extra measures will influence T0 (Figure 26).

6.1.4 The general shape of the physical MRaC solution space, impact of critical factors on physical MRaC solution space

From the results obtained by the DMM, it becomes clear that solution space for MRaC in the MRD is narrowing in every scenario, with T0 being reached around the year 2090 in the most likely scenario (S2). This is because in every scenario relative sea level (RSL) is increasing. This RSL rise can mostly be attributed to human-induced subsidence future increase and SLR future increase, while sediment input stays low. This set of conditions is present in all future scenarios. However, both of these factors will influence S3 significantly more negatively than S1. Suspended sediment input influences the solution space of MRaC positively in S1, no influence in S2 and negative in S3. Human-induced mangrove barriers have a neutral effect on the solution space of MRaC in S3 and a positive effect in S2 and S1. All other factors such as tidal range and settling velocity are constant in the DMM and thus do not affect future solution space.

6.1.5 Feedback mechanisms and their influence on the physical MRaC solution space

It is hard to quantify the importance on the MRaC solution space of every individual factor considered in the paragraph above, because of the presence of feedback mechanisms. The feedback mechanisms observed in the DMM model were linked to the presence of mangroves and sedimentation in general. Namely, these feedback mechanisms are caused by the fact that the amount of sediment deposited in the MRD in the DMM is dependent on the amount of time that mangroves provide a favourable environment for sedimentation to take place, which is in term influenced by the amount of sediment deposited. The feedback mechanisms work in both directions: "more sedimentation → more time to deposit sediment → more sedimentation", but also "less sedimentation → less time to deposit sediment → less sedimentation". These feedback mechanisms are the main reason for the large difference in "inundation date" between scenarios. Without sedimentation and mangroves, the "inundation date" for S1, S2, and S3 is respectively the year ~2075, ~2070, and ~2065 (an average of 5 years difference). With sedimentation and mangroves, the "inundation date" for S1, S2, and S3 is respectively the year ~2110, ~2095, and ~2065 (an average of 22.5 years difference, which would undoubtedly be much higher if the DMM calculated beyond the year 2110). Additionally, these feedback mechanisms cause the very limited effect of MRaC in S3, where the "inundation date" with mangroves and sedimentation is the same as the "inundation date" without mangroves and sedimentation. With this data one can argue that, without additional measures (see next paragraph) T0 in S3 is already reached at present, because MRaC has no significant impact. Contrary to S3, the "inundation date" is significantly extended using MRaC due to these feedback mechanisms in S2 and S3 (with at least a 30- and 40-year difference respectively). In conclusion, no single factor seems to be dominant in its control over the MRaC solution space. Because of powerful feedback mechanisms, MRaC solution space is most affected by a combination of factors changing in the same direction.

6.1.6 Difference in physical MRaC solution space between DMM profiles

The difference in solution space between the profiles is mostly dictated by the initial solution space that is present, instead of different rates of solution space change between scenarios. Often initial elevation is the best indicator if a particular profile has a large or a small solution space (Figure 27). A higher elevation equals more years before a profile is drowned and thus also more sedimentation years and time to adapt before drowning. Sediment input and human-induced subsidence also differ between profiles in the modelling but have a smaller impact. with these factors there is no clear correlation visible between high and low values and longer or shorter periods before T0. This is thought to be partly caused by relatively smaller sedimentation and subsidence differences than elevation differences between the profiles. This result is also in accordance with the sensitivity analysis (4.7).

Because the larges elevation of the MRD coast is found in the southeast (Minderhoud et al. 2019), it is safe to assume that the solution space for MRaC is the largest in this area. For this reason, the study focussed on this area to observe which areas within the southeast MRD coast have the largest potential for MRaC (largest solution space). The results indicate that especially profile 2 (the most Eastern MRD coast), 3 (around Bình Đại) and 9 (the most southern point in the MRD) possess a large MRaC solution space (T0 is likely to be beyond 2110), due to their high elevation. Interestingly the most southern part of the MRD (east of Cà Mau Cape) (profile 9) seems to have large MRaC potential according to DMM results, even though it lies in a highly erosive area (Marchesiello et al. 2019). Since the impact of erosion on mangroves has been largely ignored in the DMM the results for this profile should be handled with caution. Profiles with moderate solution space (and moderate elevation) (T0 likely to be around or later than the year 2090) are 4, 5(around Thạnh Hải to Thạnh Phong) and 8 (around Xóm Vàm Cái Cùng) and mostly possess an intermediate average elevation. Profile 6 and 7 (around Dân Thành and east of Bạc Liêu respectively) and profile 10 (most western part of Cà Mau Cape) have the least solution space in S2 according to the DMM and possess relatively low elevation.

Interestingly, while profile 10 enjoys high sediment input and relatively low human induced subsidence it is the first profile to reach T0 in 2070 in S2. This is probably caused by its maximum elevation which is the lowest of all profiles. However, in the most positive scenario (S1) the low subsidence and high sediment input are starting to make a larger difference and its T0 is reached 10 years later than profile 4,6,7 and 8 (indicating a larger solution space). In profile 4,6,7 and 8 especially subsidence is a larger problem, but also sediment input to these profiles is lower. This indicates that elevation is especially important in scenarios where the drowning of the delta happens fast. If there is more time for sedimentation to take place the amount of sediment input and human induced subsidence is relatively more important due to its influence on the more powerful sedimentation feedbacks of the system in this scenario. Unfortunately, the drowning of the MRD seems to be so fast that, according to the DMM, it is most likely that the high sedimentation values in profile 10 (and in extension the extreme west of Cà Mau Cape) will not make much of a difference. Since the SSC in profile 10 is the second highest of all profiles it is most likely that the same applies to the whole MRD.

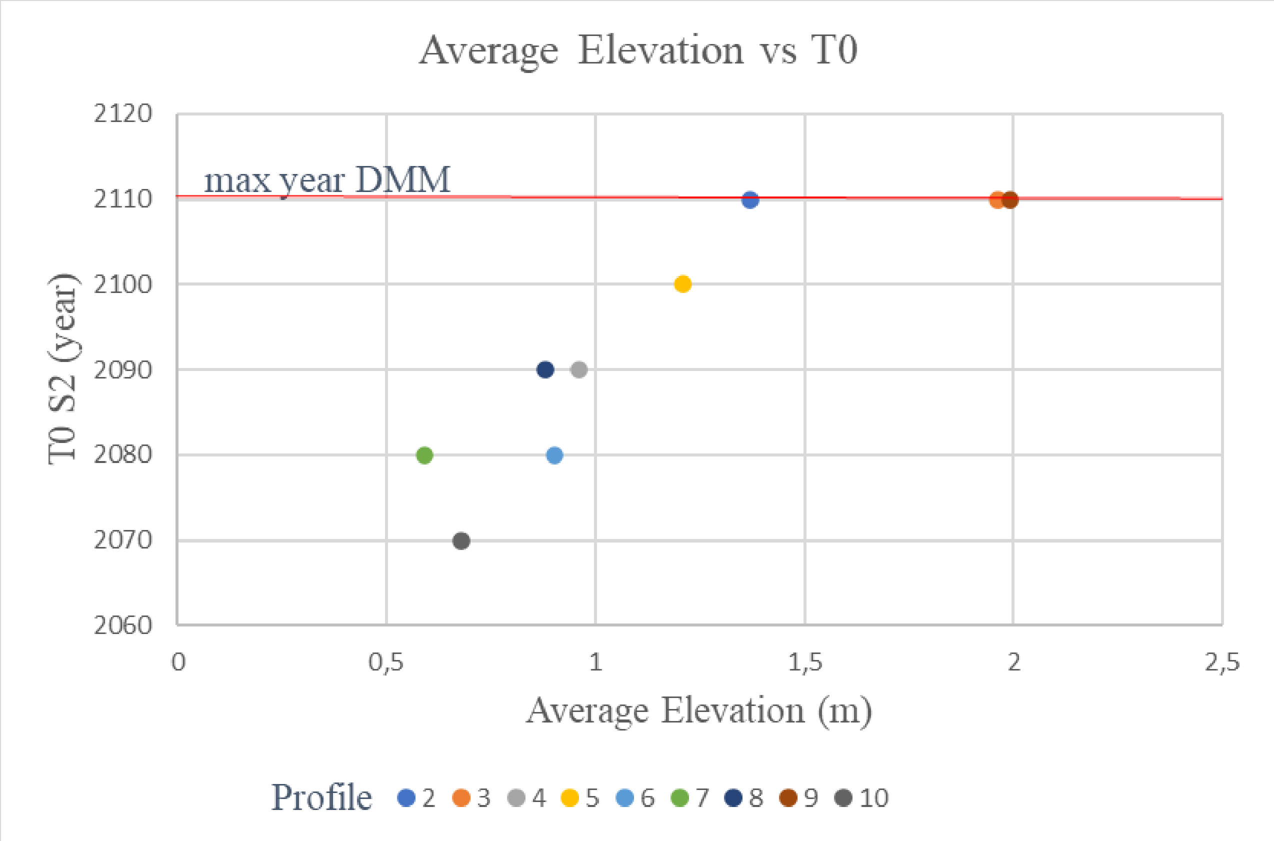

Figure 27: The average elevation (m) of the profiles used in this research vs the calculated time range when the physical MRaC solution space shrinks to 0 (T0).

6.2 Measures to increase solution space

To research what can be done to increase future solution space for MRaC in the MRD, an assessment was made of the influence of measures that may be taken to influence one of the four important factors of the DMM that influence the solution space of MRaC: 1) mangrove retreat space (determined by dike placement), 2) human-induced subsidence, 3) SSC, and 4) SLR. It was decided that, because SLR is a global problem, this should form the base of the modelled scenarios and that future measures would be added in the same sequence as described above (from local, to regional, to international measures). The "inundation date" of S1 is already over the maximum date the DMM could calculate so no mitigation measures were added in this scenario. S2 added all S1 measures, and S3 added all S2 and S1 measures (Figure 27).

The simulation results show that all measures proposed have at least some impact on both S2 and S3. Every measure adds at least 3 years to the "inundation date". Overall, SSC seems to be the most important value in both S3 and S2. However, in S3 dike placement is more important than subsidence mitigation, while in S2 it is opposite. As stated in the results, this may be a product of multiple feedback loops and different starting conditions for every measure imposed (see 6.1). Additionally, there was a maximum "inundation date" (of 2110) in the DMM that influenced the average "inundation date".

The influence of every additional measure (1. dike retreat, 2. subsidence mitigation and 3. sediment input increase) on the solution space of MRaC is described below in more detail:

6.2.1 Dike retreat

According to the results a dike retreat will increase the solution space for MRaC in the SE MRD in all scenarios. This measure has the highest positive impact on "T0" (end of mangrove presence) in areas where dikes are preventing mangroves to grow in higher elevation behind dikes. These areas are rare in the MRD because most of the highest elevation is right at the coast. The area around profile 9 (southwest of Cà Mau) has the most potential in this regard.

Interestingly, the "inundation date" did not show a similar trend to T0 (see chapter 5). I suggest this is mostly due to insufficient data. Secondly, DMM results indicate that a dike retreat has more impact if the mangrove width is small. Adding mangrove habitat to a mangrove forest that already has a large width seems to have a smaller influence. However, the ability of the DMM to correctly calculate this must not be overestimated since the sediment distribution through the mangrove forest has not been sufficiently validated (4.9). More research is needed to fully understand this part of the data.

6.2.2 Subsidence mitigation

The solution space for MRaC on the coastline in between Bac Liêu and Cà Mau city, where human induced subsidence is highest and which includes profile 7 and 8, would benefit most from subsidence mitigation measures, the most southwestern MRD tip (profile 9) and the most eastern part of the MRD (profile 2) coast, where human induced subsidence is lowest, will benefit the least. However, subsidence mitigation would positively influence the whole SE MRD coastline.

6.2.3 SSC increase

An increase in suspended sediment input, seems to be the mitigation measure that has the most positive influence, of the three researched in this research, on solution space for MRaC, in the SE MRD. However, more research needs to be done to untangle the effects of the SSC increase and the effect of feedback mechanisms.

6.3 conclusion; the physical MRaC solution space

The sedimentation feedbacks in both positive and negative scenarios result in a very large difference between scenario outcomes. Because of these powerful feedback mechanisms, the MRaC solution space is most affected by a possible change of multiple factors in the same direction. The impact of these factors on the MRaC solution space if they are acting together is higher than the sum of individual impacts of these factors on MRaC solution space. However, in general it can be said that, because SLR and subsidence will continue to affect the solution space of MRaC negatively in all scenarios, that solution space of MRaC will continue to decrease in the future.

Because the MRD is drowning so fast (there is not much time for sedimentation to take place), the DMM also predicts that, in the most likely scenario (S2 and S3), initial elevation instead of local sediment input and local subsidence is the most important factor in determining the MRaC solution space of that area. Thus, in general areas in the SE MRD with the highest elevation have the largest solution space for MRaC (profile 9 and 3) and areas with low initial elevation have the least amount of MRaC solution space (profile 6,7 and 10). This will only change if sediment input is significantly increased, and subsidence significantly decreased (such as in S1).

Following the results of the DMM it is likely that without mitigation measures the first stretches of SE MRD coastline and mangroves (probably starting at the far west of Cà Mau Cape) will have drowned by 2070, and that more than half of the SE MRD coastline will have drowned by 2100. Because the SE MRD possesses the some of the highest elevation in the entire MRD (Minderhoud et al. 2019), and elevation was determined to be critical for site specific solution space for MRaC, this will mean that most of the MRD will have drowned and the solution space of MRaC will have been decreased very significantly.

Possible mitigation measures to increase the “physical” MRaC solution space and slow the drowning of mangroves and MRD coastline include dike retreat, subsidence mitigation, and sediment input increase. The impact of individual measures will be quite small, on average a delay of 3-10 years to the “inundation date”. However, maximum positive impact on the MRAC solution space will be achieved if the measures are implemented together as soon as possible (due to positive feedback mechanisms). If all mitigation measures are implemented, this could translate to at least an addition of 40 years on top of the predicted average “inundation date” in the worst-case scenario (S3).

7. Discussion

In the discussion the study will first discuss the background on the critical factors. Secondly, the reliability of the DMM will be discussed. Thirdly, the DMM results will be compared to the literature. Finally, we touch upon the relevance of this research and give recommendations to decision makers based upon the findings.

7.1 The mangrove system, critical factors for physical MRaC solution space

Most of the literature was in consensus about which critical physical factors determined MRaC solution space and how they influenced that space (key sources for the formation of this chapter were: Besset et al. 2019; Lewis 2005; Lovelock et al. 2015; Phan et al. 2015; Proisy et al. 2009; Rogers 2021). Because of the relative consensus in the literature about the critical factors and processes that determine the MRaC solution space, the largest amount of uncertainty in this research is theorized to lie in the results of the DMM.

However, some disagreement among cited authors exists. Most notably, the possible existence of a critical minimum mangrove width in the MRD. Below this width the mangrove forests becomes unstable because it loses its ability to effectively regulate and promote sedimentation (Phan et al. 2015; Truong et al. 2017). Hereby these studies implied that mangrove forest strip width is a critical factor that controls the MRaC solution space on the long-term.

Although this study acknowledges that a thicker mangrove forest strip can more effectively dissipate hydrodynamic energy, thereby increasing flood protection and more effectively promoting sedimentation, it argues that the situation is more complex. This study argues that in reality mangrove strip width is a less important factor than factors such as subsidence, sediment supply, and SLR and in fact depends mostly on these other factors. Mangroves can not survive on the long-term without sufficient sediment supply and under prevailing erosion and/or extremely fast inundation no matter how wide the mangrove strip is (Besset et al. 2019). Additionally, a mangrove forest will generally accrete if the sediment supply is larger than the accommodation space created by RSLR, even if the mangrove forest strip is very narrow. Because of these reasons, this study argues that there is no such thing as a critical minimum mangrove strip width in the MRD. This is in line with the results from Besset et al. (2019), who did not support such a relationship in their study which was based upon a larger database than Phan et al. (2015). In fact, this study reiterates Besset et. al (2019) who warned that ignoring larger scale processes such as sediment supply and subsidence (i.e. the assumption that a certain mangrove width means accretion) may mean that high expectations from mangroves could be met with disappointment.

Another point of discussion was the influence of a suspected increase in storm frequency and intensity due to climate change on MRaC solution space. Sources generally agree that this factor will negatively influence mangroves (Lovelock et al. 2015), yet the impacts of this factor on mangroves is still very hard to quantify (Balke et al. 2013a). This factor is therefore not included in the critical factors that control MRaC solution space in chapter 2. However, it may be of critical future importance. More research on the effects of increasing intensity and frequency of storms in the MRD on mangroves is needed.

7.2 The Dynamic Mangrove Model (DMM)

As stated in 7.1 the largest uncertainties in this research are theorized to lie in the results of the DMM. This chapter will argue (1) why, and (2) to what extend the results of the DMM can be trusted.

The DMM is a large simplification of reality. This is especially so because of the use of a small number of 1D profiles and the simplistic sedimentation calculations. Additionally, no erosion and sedimentation outside the mangroves is present in the model. However, as discussed in chapter 3 a simplification of reality can be superior to more realistic modelling and in this case was unavoidable due to the long timescale, large model area, and lack of reliable input data. Results from such simplified models can still be valuable (Kirwan and Temmerman 2009; Wu et al. 2015).

7.2.1 Discussion of the processes included in the modelling

As discussed (7.1), not much disagreement existed among authors about the critical factors that control long term and large scale mangrove sustainability and the mangrove system. The DMM includes all of the critical factors and processes that were determined: 1) the ability of mangrove forests to retreat landwards, 2) mangrove growth between MSL and MHHW, (3) SLR, (4) detailed elevation of the MRD (geomorphology), (5) subsidence (natural and human-induced), (6) tidal range, (7) human-induced mangrove barriers, and (8) sedimentation within mangroves.

However, all of the other similar modelling research that has been done on this subject has excluded one or more of these processes or factors. As explained in chapter 3 one of the reasons for this is that most of these models are not specifically designed for mangroves, but for wetlands in general (and thus did not properly account for the influence of mangroves on sedimentation and their habitat range between MSL and MHHW). Studies that did focus on mangroves still missed one or more of the crucial factors and processes described.

Notable examples are:

1. Lovelock et al. (2015) did look specifically at mangroves and included the MRD in their assessment of South Asia. However, Lovelock et al. (2015) did not consider the (a) ability of mangrove forests to retreat landwards, (b) different subsidence rates in different parts of the MRD, (c) increased future subsidence and SLR, or (d) the elevation of the MRD.
2. Dang et al. (2022) did take into account the ability of mangrove forests to retreat landwards in the MRD and used a detailed elevation model. However, their model also did not consider the (a) increased future subsidence, (b) natural subsidence, or (c) different subsidence rates in different parts of the MRD.

Processes such as erosion or the influence of stochastic events such as an increase in storm intensity and frequency (as briefly discussed in 7.1), are not included in the DMM. There is consensus within the literature that these factors do influence MRaC solution space (Balke et al. 2013a; Doyle et al. 2003; Lovelock et al. 2015), so their absence is detrimental to the accuracy of the DMM. However, these factors were determined to be of lesser importance than the factors described above for MRaC solution space in chapter 2. Because of (1) their suspected lower importance, (2) the difficulty of including these complicated processes in simple models, and (3) limited knowledge about the exact influence of future stochastic events, these processes are also omitted in the two studies described above. Of all studies incorporated in the literature background in chapter 3 only Doyle et al. (2003) included the influence of storms on mangroves. However, their model did not include any sedimentation mechanisms and did not calculate for the long term (until 2100) or delta wide scale that was needed for this research.

Therefore, because of the inclusion of all the critical factors and processes that were determined in the thorough literature background of this study in the DMM, it is likely that the critical factor and process inclusion and their relation to each other in the DMM is reliable or at least comparable to- or better than other similar mangrove/tidal marshes modelling studies.

7.2.2 Reliability of DMM input

DMM input is limited to a few 1D profiles. However, because of the simplicity of these profiles the data input within the profiles into the DMM can be (and is) relatively detailed. Especially the elevation data and current and future human induced subsidence is of the highest quality and data density currently available in the MRD (Dunn and Minderhoud 2022). Also, *SSC* data (although it is for a large part reliant on remote sensing data) is site specific and subject to a future change that is consistent with the literature (Dunn and Minderhoud 2022; Marchesiello et al. 2019). In this way the DMM input is often more detailed than similar 2D studies discussed in chapter 3. For example, Dang et al. (2022) use a delta wide subsidence value that does not change through time and does not include natural subsidence. They also do not consider *SSC* and a declining sediment input from the Mekong River. Lovelock et al. (2015) use a delta wide RSLR value that does not change through time.

Because of these reasons, it is likely that the input of the DMM is relatively reliable or at least comparable to- or better than other similar mangrove/tidal marshes modelling studies.

7.2.3 Reliability of DMM output

To test the validity of the results the model has been calibrated and validated with historical data (chapter 4.8 and 4.9). The conclusion of the validation was the results of the DMM can be useful, but only when the results are handled correctly and with caution.

The DMM was shown to not be able to reliably calculate the exact shoreline position due to the absence of erosion and seaward accretion. Also, individual profile results could be off since sediment input was linked to the Mekong River sediment output and redistribution was largely ignored. However, it was shown that the maximum profile elevation output was relatively reliable and that the averaged result for all profiles was realistic. Based on these observed strengths and weaknesses of the DMM it was possible to create a strategy that uses DMM results in the most accurate way possible and in this way maximized the potential of the DMM. This strategy consists of 2 actions that have been applied in the results of this study:

1. ***Use maximum profile elevation in relation to SL for the interpretation of DMM results instead of shoreline change.***
2. ***Wherever possible base conclusions on the average results instead of specific profiles.***

The results obtained in this study using these two strategies do seem reliable when compared to other studies as will be elaborated below (chapter 7.3).

7.2.4 Possible improvements for the DMM

There are various ways to improve the DMM and the results of the research. As discussed above the biggest weaknesses of the DMM lie in the inability to correctly model sedimentation outside mangroves and erosion. This would be the most important addition to the DMM because it would enable more reliable shoreline changes to be modelled. Which would mean that the results do not have to rely anymore on mainly the maximum profile height.

The extra sedimentation and erosion functions should be easily applicable to all profiles. If possible, sedimentation and erosion also should be linked to the dominant redistribution mechanisms at the MRD coast instead of relying solely on measured *SSC* and incoming sediment from the Mekong River. Additionally, the sedimentation and erosion calculations could be complemented with field data that includes measured *SSC*. *SSC* input used in the DMM still relies for a large part on remote sensing data which is less reliable.

Furthermore, a study could be done to determine a more strategic placing of profiles. The profile selection in this study is supported in the validation of the DMM (chapter 4.10). This indicated a relatively representative profile selection to represent the SE MRD coast. However, this validation relies solely on the average measured shoreline change of all the profiles and needs further attention if the DMM is to be used in the future. Another option to address this problem is to use significantly more profiles in future research.

Finally, the DMM could be improved by the addition of the predicted influence of stochastic events such as storms which are thought to increase in frequency and intensity due to climate change.

The biggest challenge of these improvements will be to incorporate these functions in a simple manner that compliments the modelling approach, instead of too complicated calculations which can not be sufficiently practically or scientifically supported in the simple DMM profile-based modelling.

7.2.5 Conclusion: to what extend are the DMM results reliable?

In conclusion, on the basis of the before mentioned arguments, I argue that the results of the DMM can be trusted when used carefully and in a way that bases conclusions wherever possible upon maximum profile elevation and averages of multiple profiles. The results of the study were obtained with this conclusion in mind.

7.3 Model results and solution space comparison to literature

7.3.1 Timing the drowning of mangroves at the MRD coast (T0)

One of the most important results of this research is the timing of the drowning of the SE MRD coast and mangroves. The literature is divided on if- and when the mangroves and/or the MRD coast will drown. Kirwan et al. (2010) states that a 10 mm/y SLR seems to be a threshold for tidal marshes with a 1m tidal range and 20+mg/L SSC. Drowning in their model occurs 30-40 years after this threshold is exceeded. However this threshold is (by far) not exceeded in S2 SSC= 50-70 mg/l, tidal range = 4m, and SLR is 5-9mm/yr. Still a large part of the delta drowns before 2100 according to the results of the DMM. They also identify that a tidal marsh can survive a 20mm/yr SLR if it possesses a tidal range of at least 3 m, with more than 30mg/L SSC. Even in S3, this study’s worst case scenario, SSC is predominantly above 30mg/L (except for a small number of timesteps) in profile 7,8 and 9, tidal range = 4m, and SLR never rises above 14mm/yr. Still the entire delta drowns by 2090. The study concludes that at least part of the difference is caused by: (1) Kirwan et al. (2010) did not consider subsidence in their model: If the extra subsidence is added in the MRD, this study found that in S2 most profiles have ~30mm/yr subsidence + SLR RSL elevation drop. In S3 this cumulative drop regularly comes out at over 35mm/yr. Although subsidence is thought to be the main issue that sets apart the results, part of the observed difference still remains because some profiles still drown in S2 while the threshold is not exceeded. (2) Another reason may be that Kirwan et al. (2010) designed their model for tidal wetlands in general not specifically for mangroves. This may alter the result, although mangroves are thought to be in general more efficient in raising local elevation than most tidal marshes (Woodroffe et al. 2016).

Subsidence is often not properly accounted for in these studies while it clearly does play a critical role in the MRD according to this research and others such as Minderhoud et al. (2020), because human induced subsidence alone in the MRD currently often decreases RSL more than SLR (Minderhoud et al. 2017). Lovelock et al. (2015) did look specifically at mangroves and included the MRD in their assessment of South Asia. Just as Kirwan et al. (2010), Lovelock et al. (2015) based the calculations mainly on incoming sediment and tidal range. Increasing human induced subsidence in the MRD was omitted from calculations, instead taking a conservative constant RSL drop of only 6mm/yr, which was the average of their study sites across southeast Asia. The DMMs result varies per profile, per scenario and through time, however due to increasing SLR and subsidence and decreasing sediment input in the MRD this value lies around 14mm/yr. Another problem in the modelling of Lovelock et al. (2015) is that they assume that mangroves occupy the full (vertical) 2m tidal range that is present in the MRD, however in most cases the MRD max elevation is lower than 2m which makes this an impossibility. As a result, the risk for the drowning of mangroves in the MRD is argued by this study to be underestimated. Lovelock et al. (2015) estimate that there is little risk for the drowning of mangroves in the SE MRD until at least 2120 (the end of their simulation) even in the two worst case scenarios that are modelled (RCP8.5 and even a 1.4 m SLR by 2100 scenario). This is in contrast to the DMM and other more recent research that has focussed exclusively on the MRD and did take into account local subsidence and MRD elevation like Besset et al. (2019), Allison et al. (2017) and Dunn and Minderhoud (2022).

Dang et al. (2022), used SLAMM (chapter 3) to model the southwestern tip of the MRD (profile 9 and 10) with mangroves. They found that even in the worst-case scenario (RCP8.5) the mangrove area would only decrease by about 30% in 2100 (in contrast to this study's 100%). Subsidence is taken into account, however it again only uses a constant 6.5mm/yr total net subsidence (subsidence-accumulation), citing the mean value for the entire MRD. Additionally, Dang et al. (2022) use an additional mangrove sedimentation rate of 4mm/yr (that is on top of the 6,5mm/yr total subsidence-accumulation) that is constant until 2100 and based on sedimentological measurements from the undisturbed sedimentation regime in the Holocene (10-7ka) (Saintilan et al. 2020). Sedimentation input has since dropped by about 75% however (Dunn and Minderhoud 2022), due to extensive damming and sand mining, and it is therefore probable that actual accretion rates (on top of the accretion that counteracts the high natural subsidence at the MRD coast) will be lower.

Finally, in the above-mentioned studies (Dang et al. 2022; Lovelock et al. 2015) future increase in subsidence and future decrease in sediment delivery to the MRD coast is not taken into account and constant values are used. This is dangerous because sediment delivery to the Mekong River mouth has been steadily declining and human induced subsidence has been steadily rising over the past decades (Dunn and Minderhoud 2022).

The above-mentioned studies that do not agree with the DMM timing of mangrove drowning, all negate important factors. Most notably (1) high subsidence at the MRD coast, but also (2) low sediment income and (3) the probable future subsidence increase and sediment supply decrease. Because of these reasons, it is fair to assume that the results of the DMM, which show that mangroves will drown significantly earlier than these cited studies indicate, are still valid. When compared to Dunn and Minderhoud (2022), a recent study that focusses specifically on the MRD and does also take into account all above mentioned factors, this study's results are quite comparable. Dunn and Minderhoud (2022) predict a mean 45-50cm RSLR (all factors included) for the entire MRD in from 2020 to 2050 with RCP 4.5; subsidence: B1 (see chapter 4.10 for subsidence scenarios). When assumed to be a constant decline this would result in 120-133cm RSLR in 2100. Such a RSLR would result in the inundation of profiles 4,6,7,8 and 10 (profile 5 is only flooded with 122 cm RSLR) and profile 2,3, and 9 are not flooded (even with 133cm RSLR). This is exactly what is seen in the results of this research with RCP4.5 profiles 4,5,6,7,8 and 10 are flooded. With profile 5 being the last profile to flood (only in 2100). Similarly, the best-case scenario from Dunn and Minderhoud (2022) (RCP 2.6; subsidence: M3) predicted about 10cm RSLR in 2050 which would translate to about ~30cm in 2100. 30 cm of RSLR is similar to what this study observes in S1 and would not inundate any profile. The worst-case scenario from Dunn and Minderhoud (2022) (RCP8.5; subsidence: B2) results in about 70cm of RSLR by 2050. That is ~190 in 2100 when linearly interpolated. This amount of RSLR would submerge all profiles in this study except for profile 3 and 9, which both have a maximum elevation of about 2m in 2020. Profile 3 and 9 are inundated in this study's worst-case scenario (S3), being submerged by 2090. However, this difference can maybe be attributed to the fact that both SLR and subsidence both increase gradually over time in S3 (and the worst-case scenario of Dunn and Minderhoud (2022)), instead of staying more or less constant after 2050 like in S1 or a smaller increase in S2. This causes the estimated RSLR that is linearly interpolated from 2050 to 2100 for the most pessimistic scenario to be too low (because RSLR will be greater from 2050 to 2100 than from 2020 to 2050).

It is important to be careful when linearly interpolating the result from 2050 to 2100. Additionally, the result from Dunn and Minderhoud (2022) (1) calculated the mean RSLR for the whole MRD, while this study focusses on the MRD coast and mangrove sedimentation and (2) uses slightly different subsidence scenarios (B1 instead of M1 with RCP4.5, and B2 instead of B1.5 with RCP 8.5). This means that the profiles in this study experience on average more natural and less human subsidence, and more sedimentation on average than is accounted for in Dunn and Minderhoud (2022). However, these factors may balance each other out. It is promising that the results of the DMM and the most recent study that focussed entirely on the MRD, and incorporated the same factors from a slightly different (non-mangrove) perspective, came to such a similar conclusion.

Although the reader has to keep in mind the limitations of this study (7.2). Because the results generally agree with the most recent similar research (Dunn and Minderhoud 2022), and good reasons for disagreement that is found in other literature can be given, this research concludes that the timing of the drowning of the SE MRD coast and mangroves, produced by the DMM, is reasonable. Therefore it can be used for broad interpretations of the solution space of MRaC in the SE MRD.

7.3.2 The effect of implementation of extra measures to increase physical MRaC solution space

It is hard to quantify exactly how much the impact of each measure is individually because of sedimentation feedback loops ("more sedimentation → more time to deposit sediment → more sedimentation", but also "less sedimentation → less time to deposit sediment → less sedimentation") (chapter 6.1 and 7.3.3). Additionally, there was a maximum "inundation date" in the DMM that influenced the data. However, simulation results show that all measures proposed have a (small) impact on the "inundation date" in both S2 and S3. Every measure adds at least 3 years before inundation.

Overall, of the three measures proposed, SSC increase seems to have the most positive effect on the "inundation date" in both S3 and S2. On specifically this subject there was not a lot of literature available. Dunn and Minderhoud (2022) predict that the largest gains in elevation preservation lie in mitigating extraction induced subsidence, however their study focusses on the whole MRD. On the SE MRD coast human water extraction rates and thus extraction induced subsidence is relatively small (Minderhoud et al. 2020) while sedimentation is generally larger than inland areas. So there is still a good argument that for the solution space of MRaC SSC increase would have the largest positive influence.

However, the simulation results show that a decision maker should not focus too much on which is the best mitigation measure. By far the best results are obtained if the measures are implemented together. Because of the powerful feedback mechanisms at play, MRaC solution space is most affected by a combination of factors changing in the same direction. And no single factor seems to be dominant in its control over the MRaC solution space (chapter 6.1.5).

When all mitigation measures that are modelled in this research are combined, they can extend the life of the MRD with at least 40 years in the worst-case scenario (and thus have significant impact). This estimate is probably lower than the actual value since these results are negatively influenced by the maximum "inundation date" of the DMM. Since this is an important finding for decision makers it is discussed in its own paragraph below (7.3.3).

7.3.3 The effect of multiple measures vs the sum of each measures individual effect

Sedimentation feedback loops ("more sedimentation → more time to deposit sediment → more sedimentation", but also "less sedimentation → less time to deposit sediment → less sedimentation") are a dominant factor in the DMM results.

Because of the powerful feedback mechanisms at play, MRaC solution space is most affected by a combination of factors changing in the same direction. And no single factor seems to be dominant in its control over the MRaC solution space.

For maximum positive impact on the MRaC solution space, decision makers should focus on strategies that address subsidence, sediment starvation, and limited mangrove retreat space at the same time. Measures that are implemented alone seem to have a relatively limited impact. Dunn and Minderhoud (2022) come to the same conclusion. They stress that: *"... the most effective way to reduce RSLR and preserve elevation in the Mekong delta is to not focus on a single factor controlling delta elevation but to combine strategies that address multiple components simultaneously."* This conclusion is central to this research and crucial for future policies in the MRD.

7.4 Relevance and recommendations for decision makers

The results of the DMM indicate that even under the most optimal modelling scenario solution space of MRaC will continue to decrease (together with RSL) in the future. This view is supported by Dunn and Minderhoud (2022). These research results show that it is likely that without mitigation measures the first stretches of SE MRD coastline and mangroves will have drowned by 2070, and that more than half of the SE MRD coastline will have drowned by 2100. Because the SE MRD possesses the some of the highest elevation in the entire MRD (Minderhoud et al. 2019), and elevation was determined to be critical for site specific solution space for MRaC (chapter 6.1), this will mean that most of the MRD will have drowned, and the solution space of MRaC will have been decreased very significantly.

Mitigation measures that are implemented on their own will probably have limited positive effect on the future RSL and the future physical MRaC solution space in the MRD. **DMM results indicate that to achieve any substantial enlargement of MRaC solution space in the MRD, decision makers will have to (as soon as possible) implement strategies that address subsidence, sediment starvation, and limited mangrove retreat space at the same time.**

Even in this most optimistic scenario the DMM indicates that RSL and MRaC solution space will still have significantly decreased in 2100. However, this will significantly delay MRD drowning and give the delta more time to adapt (Dunn and Minderhpoud 2022).

To achieve this goal this research will elaborate below on recommendations to decision makers that can be made about each modelled mitigation measure, using DMM data.

7.4.1 Dike retreat

- Dike retreat will be easiest in relatively uninhabited parts of the delta: especially southwest of Cà Mau (profile 9 and 10) while it would be costlier for the more populated coastline: especially near Bac Liêu (profile 7 and 8).
- This measure seems to have the highest positive impact on MRaC solution space in areas where dikes are preventing mangroves to grow in higher elevation behind dikes. These areas are rare in the MRD because most of the highest elevation is right at the coast. The area around profile 9 (southwest of Cà Mau) has the most potential in this regard.
- **Although more research is needed to calculate the effects of such measures in more detail and compare the costs vs benefits, the research recommends to start applying this measure southwest of Cà Mau near profile 9, because it would probably have a significant impact here, while being relatively easy and cheap to implement.**

7.4.2 Subsidence mitigation

- Subsidence mitigation will not only increase MRaC solution space, but will also be crucial for overall MRD RSLR reduction (Dunn and Minderhoud 2022).
- **To make subsidence mitigation possible, large reductions of entire regions or mayor cities ground water extraction have to be made. This research recommends (preferably) an immediate reduction of 75% in the entire MRD (M3) (Minderhoud et al. 2020). A measure of this magnitude will be very challenging, but possible, since successful subsidence measures at a similar scale have been observed in other (more developed) countries (Cao et al. 2021).**

7.4.3 SSC increase

- Of the measures proposed, an *SSC* increase will likely be the most difficult to achieve because it will have to include the removal of dams in neighbouring countries. Dunn and Minderhoud (2022) found that if no new dams are built after 2020 and the largest 25 dams in the Mekong River (10% of dam total) would be removed, sediment delivery to the delta mouth could increase to half of the pre-Anthropocene levels (66Mt/y). This is an increase of about 75% of the 2020 37Mt/y sediment output (Dunn and Minderhoud 2022). If we assume that the total suspended sediment output would increase by a similar figure, that would be well over the 50% increase in suspended sediment needed for the S1 SSC mitigation measure. However, this would involve international cooperation between the riparian countries on a scale that is unprecedented (Dunn and Minderhoud 2022).
- Additionally, it is very questionable if a 75% increase in suspended sediment input in the MRD mouth would translate to a 75% increase in SSC for the entire SE MRD coast. Although almost all sediment input in the MRD consist of sediment from the Mekong River, most of this sediment is deposited Just west of- and at the mouth of the delta (Marchesiello et al. 2019). Some sediment will find its way to the western part of the delta, due to redistribution, however this involves a large time lag. The most eastern part of the MRD will, for the most part, not receive sediment that is delivered to the delta mouth. For these reasons it is thought that especially the MRD coast between the Cô Chiên tributary and just east of Bac Liêu city (profile 4, 5, and 6), will benefit most, while the other areas and profiles will be left behind.
- Finally, it is important to consider that the sediment that is transported to the Mekong River mouth, is maybe more efficiently used in inland sedimentation strategies as laid out by Dunn and Minderhoud (2022). In this way, the sediment is used exclusively for consolidation efforts instead of allowing the sediment to flow out to sea and potentially be lost or also partly be used for the expansion of part of the MRD, which is less desirable.
- **In conclusion, although increasing *SSC* at the SE MRD coast will be a measure that seems to increase the solution space of MRaC significantly, it is questionable if it will be possible or even desirable in the future. Nonetheless increasing sediment input to the MRD as a whole will be crucial to slow RSLR. More research is needed to be able to present a plan that will convince other riparian countries to remove a part of their dams to make this a reality.**

7.4.4 The place of MRaC in a possible MRD solution

In conclusion, the results of this study indicate that in conjunction with the other mitigation strategies (S2 and S1), MRaC will extend the lifetime of the MRD coastline significantly (at least 27 (S2) and 37 (S1) years due to mangrove supported sedimentation). Mangrove restauration and conservation can be done at a relatively low effort/cost compared to the other mitigation measures described above. Additionally, strategies that address multiple components simultaneously are simulated to be more effective for reducing RSLR and preserving elevation in the Mekong delta. **Therefore, MRaC should be a part of the MRD solution**.

However, since the DMM simulated that even in the best-case scenario and using all adaptation measures considered in this research, RSLR will occur at the SE MRD coast. Eventually, without extra action the SE MRD will drown. A popular alternative to soft/nature-based solutions such as MRaC is hard protection measures (Hinkel et al. 2014). These however, are much more expensive and do not work well in conjunction with other adaptation measures that are crucial for MRD survival such as sedimentation strategies, because they do not generate flood protection value over time like MRaC. Additionally, trying to preserve the entire sinking MRD coast will eventually become economically, if not technically infeasible. **At present a managed retreat in some areas seems unavoidable (Dunn and Minderhoud 2022). If this is to be the future, using MRaC is much more desirable, as it is much cheaper, and the mangrove ecosystem could, to an extent, migrate with the retreating coast. More research is needed to explore these kinds of possibilities, to optimize adaptation strategies and avoid catastrophic flooding events in the MRD.**

8 Conclusion

There is general consensus in the literature that mangroves help protect the Mekong River Delta (MRD) coast against erosion and support sedimentation processes. Under the right conditions (without too much sediment disturbance, erosion, sufficient sediment input and between MSL and MHHW), they can significantly help extend the lifetime of the MRD coast. The critical factors that were determined to control the mangrove restauration and conservation (MRaC) solution space were: (1) SLR, (2) detailed elevation of the MRD (geomorphology), (3) subsidence (natural and human-induced), (4) tidal range, (5) human-induced mangrove barriers, (6) sedimentation within mangroves.

Due to sedimentation feedbacks present in the system "more time to deposit sediment → more sedimentation (possibly supported by mangroves) → more time to deposit sediment→ etc", the longer the mangroves are able to persist in the MRD the greater is their influence. Because of this, it was determined that MRaC had the highest chance of success in the southeastern (SE) MRD, because of the higher elevation present and more RSLR needed to drown mangroves on this coast.

In the worst-case scenario (SSP5-8.5) it was shown that mangroves did not significantly extend the average inundation year of the SE MRD coast. Thus, in this scenario the MRaC solution space can be argued to have already (almost) reached zero. In this scenario the SE MRD coast was estimated to be completely drowned around the year 2090. Which areas will drown first is mostly determined in this scenario by the initial elevation of that area. Because of low initial elevation the middle (between approximately Dân Thành to Gành Hào) and the most western part of the SE MRD (profile 6,7,8 and 10) will drown first around the year 2050. However, "the middle of the road" scenario (SSP2-4.5), and the best-case scenario (SSP1-2.6) considered by this research, estimated that a future SE MRD coast with mangrove supported sedimentation can persist at least 27 and 37 years longer respectively, than the SE MRD coast without mangroves and sedimentation. In "the middle of the road" scenario the DMM projected that the first area to drown is the far west of the SE MRD (profile 10) around 2070, with most of the SE MRD coast being submerged by 2100. Only in the best-case scenario, the future SE MRD coastline is estimated to not drown until at least 2110 (the end of the simulation). But even in this case RSLR is still present and MRaC solution space will have been significantly decreased due to a decrease in RSL.

The most important physical factors that impede mangrove success in the MRD and can be changed in the future consist of 1) SLR, 2) decreasing sediment input, 3) human-induced subsidence, and 4) decreasing/limited space for mangroves to retreat. SLR will be hard to tackle, but making space for mangrove retreat and reduction of human-induced subsidence (however difficult) could be tackled at a national level. Another option would be to increase sediment delivery to the Delta mouth. This would probably have to include the removal of dams in the Mekong River. However possible, this would require unprecedented cooperation between riparian countries and is therefore less likely to succeed.

DMM simulations showed that individual mitigation measures only had a small positive effect on the MRaC solution space (mostly an apparent delay of 3-10 years before complete inundation). An *SSC* increase seemed to have the largest positive influence. However, because of the sedimentation feedback loops described, DMM simulation results showed that combining multiple mitigation measures will have a significantly greater positive total effect on the MRaC solution space, than the sum of the individual effects of each measure. It is thus crucial to implement a variety of adaptation measures as fast as possible to buy enough time for the MRD, for it to be able to adapt to the future.

In conclusion, the results of this study indicate that in conjunction with other mitigation strategies, MRaC will extend the lifetime of the MRD coastline significantly at a relatively low effort/cost. Therefore, MRaC should be a part of the solution. However, simulation results showed, that even in the best case scenario and using all adaptation measures considered in this research, RSLR will occur at the SE MRD coast. Eventually, without extra action the SE MRD will drown. A popular alternative to soft/nature-based solutions such as MRaC is hard protection measures. These however, are much more expensive and do not work well in conjunction with other adaptation measures that are crucial for MRD survival such as sedimentation strategies, because they do not generate flood protection value over time like MRaC. Additionally, trying to preserve the entire sinking MRD coast will eventually become economically, if not technically infeasible. At present a managed retreat in some areas seems unavoidable. If this is to be the future, using MRaC is much more desirable, as it is much cheaper, and the mangrove ecosystem could, to an extent, migrate with the retreating coast. More research is needed to explore these kinds of possibilities, to optimize adaptation strategies and avoid catastrophic flooding events in the MRD.

9. References

Adame, M. F., Neil, D., Wright, S. F., & Lovelock, C. E. (2010). Sedimentation within and among mangrove forests along a gradient of geomorphological settings. *Estuarine, Coastal and Shelf Science*, *86*(1), 21–30.

Albers, T., & Schmitt, K. (2015). Dyke design, floodplain restoration and mangrove co-management as parts of an area coastal protection strategy for the mud coasts of the Mekong Delta, Vietnam. *Wetlands Ecology and Management 2015 23:6*, *23*(6), 991–1004.

Allison, M. A., Nittrouer, C. A., Ogston, A. S., Mullarney, J. C., & Nguyen, T. T. (2017). Sedimentation and survival of the Mekong Delta: A case study of decreased sediment supply and accelerating rates of relative sea level rise. *Oceanography*, *30*(3), 98-109.

Alongi, D. M. (2008). Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Estuarine, Coastal and Shelf Science*, *76*(1), 1–13.

Alongi, D. M. (2015). The Impact of Climate Change on Mangrove Forests. *Current Climate Change Reports 2015 1:1*, *1*(1), 30–39.

Anthony, E. J., Brunier, G., Besset, M., Goichot, M., Dussouillez, P., & Nguyen, V. L. (2015). Linking rapid erosion of the Mekong River delta to human activities. *Scientific Reports 2015 5:1*, *5*(1), 1–12.

Balke, T., Bouma, T. J., Herman, P. M. J., Horstman, E. M., Sudtongkong, C., & Webb, E. L. (2013). Cross-shore gradients of physical disturbance in mangroves: Implications for seedling establishment. *Biogeosciences*, *10*(8), 5411–5419.

Balke, T., Bouma, T. J., Horstman, E. M., Webb, E. L., Erftemeijer, P. L. A., & Herman, P. M. J. (2011). Windows of opportunity: thresholds to mangrove seedling establishment on tidal flats. *Marine Ecology Progress Series*, *440*, 1–9.

Balke, T., Swales, A., Lovelock, C. E., Herman, P. M. J., & Bouma, T. J. (2015). Limits to seaward expansion of mangroves: Translating physical disturbance mechanisms into seedling survival gradients. *Journal of Experimental Marine Biology and Ecology*, *467*, 16–25.

Balke, T., Webb, E. L., Elzen, E. van den, Galli, D., Herman, P. M. J., & Bouma, T. J. (2013). Seedling establishment in a dynamic sedimentary environment: a conceptual framework using mangroves. *Journal of Applied Ecology*, *50*(3), 740–747.

Besset, M., Gratiot, N., Anthony, E. J., Bouchette, F., Goichot, M., & Marchesiello, P. (2019). Mangroves and shoreline erosion in the Mekong River delta, Viet Nam. *Estuarine, Coastal and Shelf Science*, *226*, 106263.

Biber, P. D. (2006). Measuring the effects of salinity stress in the red mangrove, Rhizophora mangle L. *African Journal of Agricultural Research*, *1*(1), 1–004.

Blasco, F., Aizpuru, M., & Gers, C. J. W. E. (2001). Depletion of the mangroves of Continental Asia. *Wetlands Ecology and Management*, *9*(3), 255.

Breithaupt, J. L., Smoak, J. M., Rivera-Monroy, V. H., Castañeda-Moya, E., Moyer, R. P., Simard, M., & Sanders, C. J. (2017). Partitioning the relative contributions of organic matter and mineral sediment to accretion rates in carbonate platform mangrove soils. *Marine Geology*, *390*, 170-180.

Cahoon, D. R., Hensel, P. F., Spencer, T., Reed, D. J., McKee, K. L., & Saintilan, N. (2006). Coastal wetland vulnerability to relative sea-level rise: wetland elevation trends and process controls. *Wetlands and natural resource management*, 271-292.

Cannon, D., Kibler, K., Donnelly, M., McClenachan, G., Walters, L., Roddenberry, A., & Phagan, J. (2020). Hydrodynamic habitat thresholds for mangrove vegetation on the shorelines of a microtidal estuarine lagoon. *Ecological Engineering*, *158*, 106070.

Cao, A., Esteban, M., Valenzuela, V. P. B., Onuki, M., Takagi, H., Thao, N. D., & Tsuchiya, N. (2021). Future of Asian Deltaic Megacities under sea level rise and land subsidence: current adaptation pathways for Tokyo, Jakarta, Manila, and Ho Chi Minh City. *Current Opinion in Environmental Sustainability*, *50*, 87-97.

Costanza, R., Sklar, F. H., & White, M. L. (1990). Modeling coastal landscape dynamics. *BioScience*, *40*(2), 91-107.

Cox, J., Paauw, M., Nienhuis, J., Dunn, F., van der Deijl, E., Esposito, C., Goichot, M., Leuven, J., van Maren, D.S., Middelkoop, H. & Naffaa, S. (2021). A global synthesis of the effectiveness of sedimentation enhancing strategies for river deltas.

D'Alpaos, A., Lanzoni, S., Marani, M., & Rinaldo, A. (2007). Landscape evolution in tidal embayments: Modeling the interplay of erosion, sedimentation, and vegetation dynamics. *Journal of Geophysical Research: Earth Surface*, *112*(F1).

Dang, A. T., Reid, M., & Kumar, L. (2022). Assessing potential impacts of sea level rise on mangrove ecosystems in the Mekong Delta, Vietnam. *Regional Environmental Change*, *22*(2), 70.

Dijkstra, H. J. L. (2020). Impact of land subsidence on the population and land use in the Mekong delta Applying environmental feedback to the Shared Socio-economic Pathways to provide projections for delta regions (*Master's thesis*).

Doyle, T. W., Girod, G. F., & Books, M. A. (2003). Modeling mangrove forest migration along the southwest coast of Florida under climate change. *Preparing for a Changing Climate: the Potential Consequence of Climate Variability and Change: Gulf Coast Region*, 211-222.

Doyle, T. W., Krauss, K. W., Conner, W. H., & From, A. S. (2010). Predicting the retreat and migration of tidal forests along the northern Gulf of Mexico under sea-level rise. *Forest Ecology and Management*, *259*(4), 770-777.

Dunn, F. E., & Minderhoud, P. S. (2022). Sedimentation strategies provide effective but limited mitigation of relative sea-level rise in the Mekong delta. *Communications Earth & Environment*, *3*(1), 2.

Ellison, J. C. (1999). Impacts of Sediment Burial on Mangroves. *Marine Pollution Bulletin*, *37*(8–12), 420–426.

Fagherazzi, S., Bryan, K. R., & Nardin, W. (2017). Buried alive or washed away: The challenging life of mangroves in the Mekong delta. *Oceanography*, *30*(3), 48–59.

Friess, D. A., Krauss, K. W., Horstman, E. M., Balke, T., Bouma, T. J., Galli, D., & Webb, E. L. (2012). Are all intertidal wetlands naturally created equal? Bottlenecks, thresholds and knowledge gaps to mangrove and saltmarsh ecosystems. *Biological Reviews*, *87*(2), 346–366.

Friess, D. A., Rogers, K., Lovelock, C. E., Krauss, K. W., Hamilton, S. E., Lee, S. Y., Lucas, R., Primavera, J., Rajkaran, A., & Shi, S. (2019). The State of the World's Mangrove Forests: Past, Present, and Future. *Https://Doi.Org/10.1146/Annurev-Environ-101718-033302*, *44*, 89–115.

Furukawa, K., & Wolanski, E. (1996). Sedimentation in mangrove forests. *Mangroves and Salt Marshes*, *1*(1), 3–10.

Gedan, K. B., Kirwan, M. L., Wolanski, E., Barbier, E. B., & Silliman, B. R. (2010). The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. *Climatic Change 2010 106:1*, *106*(1), 7–29.

Gijsman, R., Horstman, E. M., van der Wal, D., Friess, D. A., Swales, A., & Wijnberg, K. M. (2021). Nature-Based Engineering: A Review on Reducing Coastal Flood Risk With Mangroves. *Frontiers in Marine Science*, *8*.

Gratiot, N., Bildstein, A., Anh, T. T., Thoss, H., Denis, H., Michallet, H., & Apel, H. (2017). Sediment flocculation in the Mekong River estuary, Vietnam, an important driver of geomorphological changes. *Comptes Rendus Geoscience*, *349*(6-7), 260-268.

Ha, T. T. T., van Dijk, H., & Bush, S. R. (2012). Mangrove conservation or shrimp farmer's livelihood? The devolution of forest management and benefit sharing in the Mekong Delta, Vietnam. *Ocean & Coastal Management*, *69*, 185–193.

Haasnoot, M., Biesbroek, R., Lawrence, J., Muccione, V., Lempert, R., & Glavovic, B. (2020). Defining the solution space to accelerate climate change adaptation. *Regional Environmental Change*, *20*, 1-5.

Hai, N. T., Dell, B., Phuong, V. T., & Harper, R. J. (2020). Towards a more robust approach for the restoration of mangroves in Vietnam. In *Annals of Forest Science* (Vol. 77, Issue 1).

Hamilton, S. (2013). Assessing the role of commercial aquaculture in displacing mangrove forest. *Bulletin of Marine Science*, *89*(2), 585–601.

Hinkel, J., Lincke, D., Vafeidis, A. T., Perrette, M., Nicholls, R. J., Tol, R. S., ... & Levermann, A. (2014). Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proceedings of the National Academy of Sciences*, *111*(9), 3292-3297.

Hong, H. T. C., Avtar, R., & Fujii, M. (2019). Monitoring changes in land use and distribution of mangroves in the southeastern part of the Mekong River Delta, Vietnam. *Tropical Ecology*, *60*(4), 552–565.

Hong, P. N., & San, H. T. (1993). Mangroves of Vietnam (Vol. 7). Iucn.

Horstman, E. M., Bryan, K. R., & Mullarney, J. C. (2021). Drag variations, tidal asymmetry and tidal range changes in a mangrove creek system. *Earth surface processes and landforms*, *46*(9), 1828-1846.

Horstman, E. M., Dohmen-Janssen, C. M., Narra, P. M. F., van den Berg, N. J. F., Siemerink, M., & Hulscher, S. J. M. H. (2014). Wave attenuation in mangroves: A quantitative approach to field observations. *Coastal Engineering*, *94*, 47–62.

IPCC, 2022: *Climate Change 2022: Impacts, Adaptation, and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844

Jennerjahn, T. C., & Ittekkot, V. (2002). Relevance of mangroves for the production and deposition of organic matter along tropical continental margins. In *Naturwissenschaften* (Vol. 89, Issue 1, pp. 23–30). Springer.

Kirwan, M. L., Guntenspergen, G. R., D'Alpaos, A., Morris, J. T., Mudd, S. M., & Temmerman, S. (2010). Limits on the adaptability of coastal marshes to rising sea level. *Geophysical Research Letters*, *37*(23), 23401.

Kirwan ML, Murray AB (2007) A coupled geomorphic and ecological model of tidal marsh evolution. *Proc National Academy of Science* 104:6118–6122.

Krauss, K. W., Lovelock, C. E., McKee, K. L., López-Hoffman, L., Ewe, S. M. L., & Sousa, W. P. (2008). Environmental drivers in mangrove establishment and early development: A review. *Aquatic Botany*, *89*(2), 105–127.

Krauss, K. W., Mckee, K. L., Lovelock, C. E., Cahoon, D. R., Saintilan, N., Reef, R., & Chen, L. (2014). How mangrove forests adjust to rising sea level. *New Phytologist*, *202*(1), 19–34.

Lewis, R. R. (2005). Ecological engineering for successful management and restoration of mangrove forests. *Ecological Engineering*, *24*(4), 403–418.

Lewis, R. R., & Brown, B. (2014). Ecological Mangrove Rehabilitation: a field manual for practitioners. *Education*, 275.

Li, X., Liu, J. P., Saito, Y., & Nguyen, V. L. (2017). Recent evolution of the Mekong Delta and the impacts of dams. *Earth-Science Reviews*, *175*, 1-17.

Li, Z., Saito, Y., Mao, L., Tamura, T., Li, Z., Song, B., Zhang, Y., Lu, A., Sieng, S., & Li, J. (2012). Mid-Holocene mangrove succession and its response to sea-level change in the upper Mekong River delta, Cambodia. *Quaternary Research*, *78*(2), 386–399.

Liu, J. P., DeMaster, D. J., Nguyen, T. T., Saito, Y., Nguyen, V. L., Ta, T. K. O., & Li, X. (2017). Stratigraphic formation of the Mekong River Delta and its recent shoreline changes. *Oceanography*, *30*(3), 72-83.

Lovelock, C. E., Ball, M. C., Martin, K. C., & Feller, I. C. (2009). Nutrient Enrichment Increases Mortality of Mangroves. *PLOS ONE*, *4*(5), e5600.

Lovelock, C. E., Cahoon, D. R., Friess, D. A., Guntenspergen, G. R., Krauss, K. W., Reef, R., Rogers, K., Saunders, M. L., Sidik, F., Swales, A., Saintilan, N., Thuyen, L. X., & Triet, T. (2015). The vulnerability of Indo-Pacific mangrove forests to sea-level rise. *Nature 2015 526:7574*, *526*(7574), 559–563.

Marchesiello, P., Nguyen, N. M., Gratiot, N., Loisel, H., Anthony, E. J., San Dinh, C., ... & Kestenare, E. (2019). Erosion of the coastal Mekong delta: Assessing natural against man induced processes. *Continental Shelf Research*, *181*, 72-89.

Martin JF, White ML, Reyes E, Kemp GP, Mashriqui H (2000) PROFILE: evaluation of coastal management plans with a spatial model: Mississippi Delta, Louisiana, USA. *Environmental Management* 26:117–129.

Mazda, Y., Magi, M., Nanao, H., Kogo, M., Miyagi, T., Kanazawa, N., & Kobashi, D. (2002). Coastal erosion due to long-term human impact on mangrove forests. *Wetlands Ecology and Management*, *10*, 1–9.

McFadden, L., Spencer, T., & Nicholls, R. J. (2007). Broad-scale modelling of coastal wetlands: what is required? *Hydrobiologia 2007 577:1*, *577*(1), 5–15.

Mcivor, A., Spencer, T., Möller, I., & Spalding, M. (n.d.). The response of mangrove soil surface elevation to sea level rise Natural Coastal Protection Series: Report 3. *Natural Coastal Protection Series*. Retrieved October 4, 2021, from www.nature.org.

Minderhoud, P. S. J., Coumou, L., Erkens, G., Middelkoop, H., & Stouthamer, E. (2019). Mekong delta much lower than previously assumed in sea-level rise impact assessments. *Nature communications*, *10*(1), 3847.

Minderhoud, P. S. J., Erkens, G., Pham, V. H., Bui, V. T., Erban, L., Kooi, H., & Stouthamer, E. (2017). Impacts of 25 years of groundwater extraction on subsidence in the Mekong delta, Vietnam. *Environmental research letters*, *12*(6), 064006.

Minderhoud, P. S. J., Middelkoop, H., Erkens, G., & Stouthamer, E. (2020). Groundwater extraction may drown mega-delta: projections of extraction-induced subsidence and elevation of the Mekong delta for the 21st century. *Environmental Research Communications*, *2*(1), 011005.

Mitra, A. (2020). Ecosystem services of mangroves: An overview. *Mangrove Forests in India: Exploring Ecosystem Services*, 1-32.

Morris, R. L., Boxshall, A., & Swearer, S. E. (2020). Climate-resilient coasts require diverse defence solutions. *Nature Climate Change 2020 10:6*, *10*(6), 485–487.

Narayan, S., Beck, M. W., Reguero, B. G., Losada, I. J., Van Wesenbeeck, B., Pontee, N., Sanchirico, J.N., Ingram, J.C., Lange, G.M. & Burks-Copes, K. A. (2016). The effectiveness, costs and coastal protection benefits of natural and nature-based defences. *PloS one*, *11*(5), e0154735.

Nardin, W., Locatelli, S., Pasquarella, V., Rulli, M. C., Woodcock, C. E., & Fagherazzi, S. (2016). Dynamics of a fringe mangrove forest detected by Landsat images in the Mekong River Delta, Vietnam. *Earth Surface Processes and Landforms*, *41*(14), 2024–2037.

Nardin, W., Vona, I., & Fagherazzi, S. (2021). Sediment deposition affects mangrove forests in the Mekong delta, Vietnam. *Continental Shelf Research*, *213*, 104319.

Nardin, W., Woodcock, C. E., & Fagherazzi, S. (2016). Bottom sediments affect Sonneratia mangrove forests in the prograding Mekong delta, Vietnam. *Estuarine, Coastal and Shelf Science*, *177*, 60–70.

Osland, M. J., Feher, L. C., Griffith, K. T., Cavanaugh, K. C., Enwright, N. M., Day, R. H., Stagg, C. L., Krauss, K. W., Howard, R. J., Grace, J. B., & Rogers, K. (2017). Climatic controls on the global distribution, abundance, and species richness of mangrove forests. *Ecological Monographs*, *87*(2), 341–359.

Payo, A., Mukhopadhyay, A., Hazra, S., Ghosh, T., Ghosh, S., Brown, S., Nicholls, R. J., Bricheno, L., Wolf, J., Kay, S., Lázár, A. N., & Haque, A. (2016). Projected changes in area of the Sundarban mangrove forest in Bangladesh due to SLR by 2100. *Climatic Change 2016 139:2*, *139*(2), 279–291.

Pérez, A., Libardoni, B. G., & Sanders, C. J. (2018). Factors influencing organic carbon accumulation in mangrove ecosystems. *Biology letters*, *14*(10), 20180237.

Perry, C. T., & Berkeley, A. (2009). Intertidal substrate modification as a result of mangrove planting: Impacts of introduced mangrove species on sediment microfacies characteristics. *Estuarine, Coastal and Shelf Science*, *81*(2), 225-237.

Phan, L. K., Van Thiel De Vries, J. S. M., & Stive, M. J. F. (2015). Coastal mangrove squeeze in the Mekong Delta. *Journal of Coastal Research*, *31*(2), 233–243.

Pontee, N., Narayan, S., Beck, M. W., & Hosking, A. H. (2016, March). Nature-based solutions: lessons from around the world. In *Proceedings of the Institution of Civil Engineers-Maritime Engineering* (Vol. 169, No. 1, pp. 29-36). Thomas Telford Ltd.

Proisy, C., Gratiot, N., Anthony, E. J., Gardel, A., Fromard, F., & Heuret, P. (2009). Mud bank colonization by opportunistic mangroves: A case study from French Guiana using lidar data. *Continental Shelf Research*, *29*(3), 632–641.

Proske, U., Hanebuth, T. J. J., Gröger, J., & Diêm, B. P. (2011). Late Holocene sedimentary and environmental development of the northern Mekong River Delta, Vietnam. *Quaternary International*, *230*(1–2), 57–66.

Roelvink, J. A., & Van Banning, G. K. F. M. (1995). Design and development of DELFT3D and application to coastal morphodynamics. *Oceanographic Literature Review*, *11*(42), 925.

Rogers, K. (2021). Accommodation space as a framework for assessing the response of mangroves to relative sea-level rise. *Singapore Journal of Tropical Geography*, *42*(2), 163–183.

Rogers, K., & Saintilan, N. (2005). Surface Elevation Dynamics in a Regenerating Mangrove Forest at Homebush Bay, Australia *Article in Wetlands Ecology and Management*.

Rogers, K., Saintilan, N., & Copeland, C. (2012). Modelling wetland surface elevation dynamics and its application to forecasting the effects of sea-level rise on estuarine wetlands. *Ecological Modelling*, *244*, 148-157.

Rogers, K., Saintilan, N., & Woodroffe, C. D. (2014). Surface elevation change and vegetation distribution dynamics in a subtropical coastal wetland: Implications for coastal wetland response to climate change. *Estuarine, Coastal and Shelf Science*, *149*, 46–56.

Saintilan, N., Khan, N. S., Ashe, E., Kelleway, J. J., Rogers, K., Woodroffe, C. D., & Horton, B. P. (2020). Thresholds of mangrove survival under rapid sea level rise. *Science*, *368*(6495), 1118–1121.

Schmitt, K., & Duke, N. C. (2015). Mangrove Management, Assessment and Monitoring. In *Tropical Forestry Handbook* (pp. 1–29). https://doi.org/10.1007/978-3-642-41554-8_126-1

Schmitt, K., Albers, T., Pham, T. T., & Dinh, S. C. (2013). Site-specific and integrated adaptation to climate change in the coastal mangrove zone of Soc Trang Province, Viet Nam. *Journal of Coastal Conservation 2013 17:3*, *17*(3), 545–558.

Schmitt, R. J. P., Rubin, Z., & Kondolf, G. M. (2017). Losing ground-scenarios of land loss as consequence of shifting sediment budgets in the Mekong Delta. *Geomorphology*, *294*, 58-69.

Schuerch, M., Spencer, T., Temmerman, S., Kirwan, M. L., Wolff, C., Lincke, D., McOwen, C. J., Pickering, M. D., Reef, R., Vafeidis, A. T., Hinkel, J., Nicholls, R. J., & Brown, S. (2018). Future response of global coastal wetlands to sea-level rise. *Nature 2018 561:7722*, *561*(7722), 231–234.

Seddon, N., Chausson, A., Berry, P., Girardin, C. A., Smith, A., & Turner, B. (2020). Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B*, *375*(1794), 20190120.

Sippo, J. Z., Lovelock, C. E., Santos, I. R., Sanders, C. J., & Maher, D. T. (2018). Mangrove mortality in a changing climate: An overview. *Estuarine, Coastal and Shelf Science*, *215*, 241–249.

Spalding, M., Blasco, F., & Field, C. (1997). World mangrove atlas.

Spencer, T., Schuerch, M., Nicholls, R. J., Hinkel, J., Lincke, D., Vafeidis, A. T., Reef, R., McFadden, L., & Brown, S. (2016). Global coastal wetland change under sea-level rise and related stresses: The DIVA Wetland Change Model. *Global and Planetary Change*, *139*, 15–30.

Strauss, B. H., Ziemlinski, R., Weiss, J. L., & Overpeck, J. T. (2012). Tidally adjusted estimates of topographic vulnerability to sea level rise and flooding for the contiguous United States. *Environmental Research Letters*, *7*(1), 014033.

Sudmeier-Rieux, K., Arce-Mojica, T., Boehmer, H. J., Doswald, N., Emerton, L., Friess, D. A., Galvin, S., Hagenlocher, M., James, H., Laban, P., Lacambra, C., Lange, W., McAdoo, B. G., Moos, C., Mysiak, J., Narvaez, L., Nehren, U., Peduzzi, P., Renaud, F. G., … Walz, Y. (2021). Scientific evidence for ecosystem-based disaster risk reduction. *Nature Sustainability 2021 4:9*, *4*(9), 803–810.

Tamura, T., Horaguchi, K., Saito, Y., Nguyen, V. L., Tateishi, M., Ta, T. K. O., Nanayama, F., & Watanabe, K. (2010). Monsoon-influenced variations in morphology and sediment of a mesotidal beach on the Mekong River delta coast. *Geomorphology*, *116*(1–2), 11–23.

Temmerman, S., Meire, P., Bouma, T. J., Herman, P. M. J., Ysebaert, T., & De Vriend, H. J. (2013). Ecosystem-based coastal defence in the face of global change. *Nature 2013 504:7478*, *504*(7478), 79–83.

Terrados, J., Thampanya, U., Srichai, N., Kheowvongsri, P., Geertz-Hansen, O., Boromthanarath, S., Panapitukkul, N., & Duarte, C. M. (1997). The Effect of Increased Sediment Accretion on the Survival and Growth ofRhizophora apiculataSeedlings. *Estuarine, Coastal and Shelf Science*, *45*(5), 697–701.

Thampanya, U., Vermaat, J. E., & Terrados, J. (2002). The effect of increasing sediment accretion on the seedlings of three common Thai mangrove species. *Aquatic Botany*, *74*(4), 315–325.

Truong, S. H., Ye, Q., & Stive, M. J. F. (2017). Estuarine Mangrove Squeeze in the Mekong Delta, Vietnam. *Journal of Coastal Research*, *33*(4), 747–763.

Van, C. M., Ngo, A., Mai, T., & Dao, H. T. (2022). Bamboo fences as a nature-based measure for coastal wetland protection in Vietnam. *Coastal Wetlands Dynamics*.

Van Santen, P., Augustinus, P. G. E. F., Janssen-Stelder, B. M., Quartel, S., & Tri, N. H. (2007). Sedimentation in an estuarine mangrove system. *Journal of Asian Earth Sciences*, *29*(4), 566-575.

Veettil, B. K., Ward, R. D., Quang, N. X., Trang, N. T. T., & Giang, T. H. (2019). Mangroves of Vietnam: Historical development, current state of research and future threats. *Estuarine, Coastal and Shelf Science*, *218*, 212–236.

Wackerman, C., Hayden, A., & Jonik, J. (2017). Deriving spatial and temporal context for point measurements of suspended-sediment concentration using remote-sensing imagery in the Mekong Delta. *Continental Shelf Research*, *147*, 231-245.

Woodroffe, C. D., & Grindrod, J. (1991). Mangrove biogeography: the role of Quaternary environmental and sea-level change. *Journal of Biogeography*, 479-492.

Woodroffe, C. D., Rogers, K., Mckee, K. L., Lovelock, C. E., Mendelssohn, I. A., & Saintilan, N. (2016). Mangrove Sedimentation and Response to Relative Sea-Level Rise. *Annu. Rev. Mar. Sci*, *8*, 243–266.

Wu W., Yeager K. M. , Peterson M. S., Fulford R. S. (2015) Neutral models as a way to evaluate the Sea Level Affecting Marshes Model (SLAMM). Ecol Modell 303:55–69.

Zoccarato, C., Minderhoud, P. S., & Teatini, P. (2018). The role of sedimentation and natural compaction in a prograding delta: insights from the mega Mekong delta, Vietnam. *Scientific reports*, *8*(1), 1-12.