Effectiveness of Mangroves in Flood Risk Reduction

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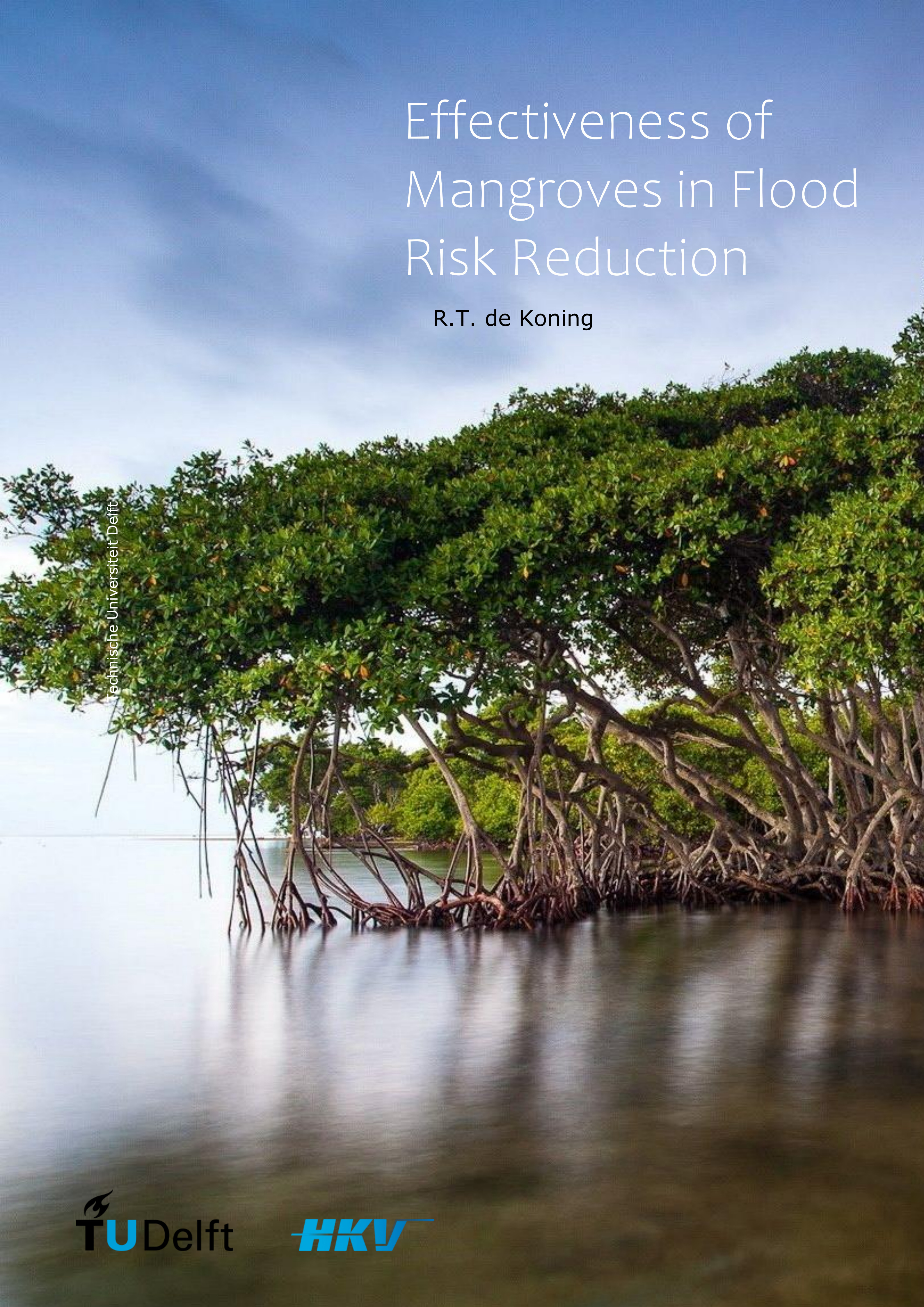

Effectiveness of Mangroves in Flood Risk Reduction

Master Thesis by

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to obtain the degree of Master of Science
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R.T. de Koning
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Summary

The risk of flood risk is increasing with global trends such as rising sea levels, land subsidence, increasing populations in coastal areas and economic growth.

Traditional solutions to reduce flood risk are a levee or a dam; however, the research on hydraulic engineering is increasingly promoting nature-based solutions for flood protection. Salt marshes and mangroves can attenuate waves and could thus help to reduce failure probability. This research focuses on the attractiveness of mangroves in flood risk reduction. The essence of the reasoning followed in this research is that mangroves in front of a levee enable a lower levee and therefore reduce costs while maintaining the same failure probability.

There are three aspects related to this assessment: the biological behavior of mangroves; the physical behavior of waves and storm surge in a mangrove forest; and the economics of flood risk, levees, and mangroves. Mangroves grow under specific conditions, such as high temperatures, saline water with fresh water input, between mean sea level and high tide, and with low wave impact. Mangroves attenuate waves, with the attenuation rates depending on mangrove height, stem diameter and density, in addition to the water depth, wave height and wave period. Lastly, the costs of restoring mangroves and building levees have been considered.

In this thesis a method has been developed to define the optimal configuration of a levee-mangrove system. The goal is to reach a desired safety level while keeping costs as low as possible. Costs consist of building a levee, restoring mangroves, and the expected annual damage and maintenance. This depends on the ratio of mangrove and levee costs, the ability of mangroves to attenuate waves, and levee characteristics.

Although all variables have equal significance in defining the mangrove forest width, the variety in levee and mangrove costs and significant wave height are the variables most likely to affect the optimal mangrove forest width. Mangroves are only useful to decrease the height of waves, thereby reducing wave run-up. This wave-attenuating effect decreases exponentially with the mangrove forest width. all Based on the literature, when considering common values for levee costs and mangrove restoration costs, levee characteristics and wave attenuation, wave attenuation is strong enough such that the optimal mangrove forest width is larger than zero.

The costs of restoring mangroves depend on the required measures to enable mangroves to grow back. Hydrological restoration involves returning the mangrove area to the natural condition where mangroves are able to grow. This could, for example, be restoring a fresh water source that has been blocked by human intervention. If hydrological restoration is required and can be done cheaply, then this is the most effective option. Planting mangroves can also be a cost-effective option. Sheltering the mangrove area by using a permeable structure requires more financial resources. If large-scale filling or excavation is required, costs may increase significantly, and it is likely to be too expensive to use mangroves in flood-risk reduction. However, this cost assessment may change if the ecosystem services of mangroves are taken into account.

As a rule of thumb, for mangroves to be economically effective, restoration costs [USD/m/m] in case of a 1 m wave height should remain below 0.003 times the variable levee costs [USD/m/m]. This value increases linearly with the wave height. For levee costs of 1 million USD/km/m, of which 0.6 million USD/km/m variable costs, the mangroves restoration costs should not exceed 1.8 USD/m/m, or 18,000 USD/ha.

For Kaback, Guinea, the optimal mangrove forest width and height of the levee are assessed. These are 900 meter and 1.1 meter respectively, with the levee located just behind the mangroves. 900 meter is the maximum width possible, considering the physical conditions where mangroves grow. Since mangroves are growing back naturally already, costs for mangroves restoration is limited to fixed costs.

The model developed in this study can be used to create a “mangrove opportunity map”. This map can indicate—based on physical attributes—the costs, hydraulic conditions such as storm surge and wave height, and whether mangrove restoration for flood risk reduction is effective. Governments or organizations such as the World Bank can use this method to explore whether mangrove-based strategies are an option.

Further research can focus on improving the cost estimates on levees and mangroves. In this study, costs are assumed to be linear with the levee height or mangrove area. In practice, levee costs might especially increase exponentially with the levee height, which would make mangroves more effective.

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Introduction

1.1. Background

Coastal areas have always been popular locations for populations to settle, because of their high potential for economic activities such as fishing, trade and agriculture. However, low-lying coastal areas are prone to flooding. Flood risk can be defined as the probability of failure multiplied by the consequences of flooding, expressed in terms of expected annual economic damage. The term “economic” is not limited to the financial aspects of damage but can be broadened to the wealth impact on a community in the coastal area.

Social trends such as an increasing population in coastal areas (either by a positive net birth rate or migration) and positive economic growth increases the consequences of flooding (Mendelsohn et al., 2012). With climate change and corresponding Sea Level Rise (SLR) and land subsidence, the probability of flooding increases (Syvitski et al., 2009). Higher consequences of flooding and a larger probability of flooding results in increased flood risk.

Traditional solutions to protect the land are a levee or dam, which are built to withstand the forces of tides, storm surges and waves. These traditional solutions need to be increased in height or strength because of higher forces, a higher required safety level or degradation of the structure.

Over the last decades, ecosystem engineering has become increasingly popular as an alternative to traditional flood protection solutions (Wesselink et al., 2015). Salt marshes and mangroves can attenuate waves and could thus help in preventing floods. Incorporating nature-based solutions as a flood-risk measure may be an autonomous solution or combined with a traditional flood risk measure (e.g. a levee) as a hybrid solution. Figure 1.1 shows how mangroves are decreasing the required levee height.

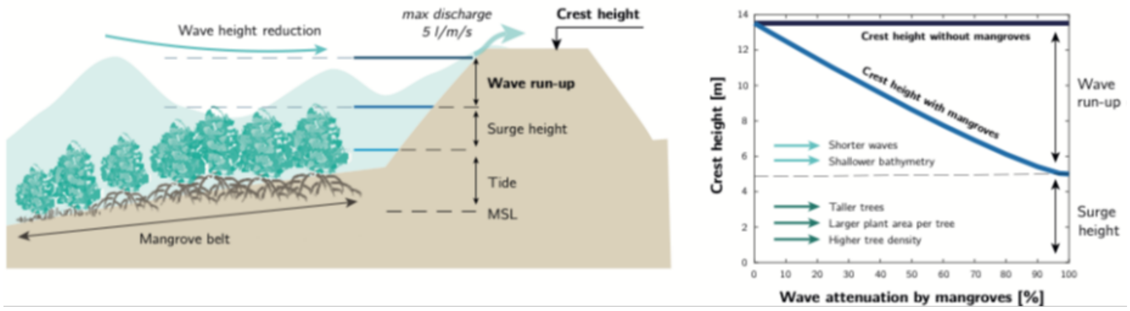

Figure 1.1: Overview of how mangroves decrease the required levee height, from Van Berchum et al. (2018)

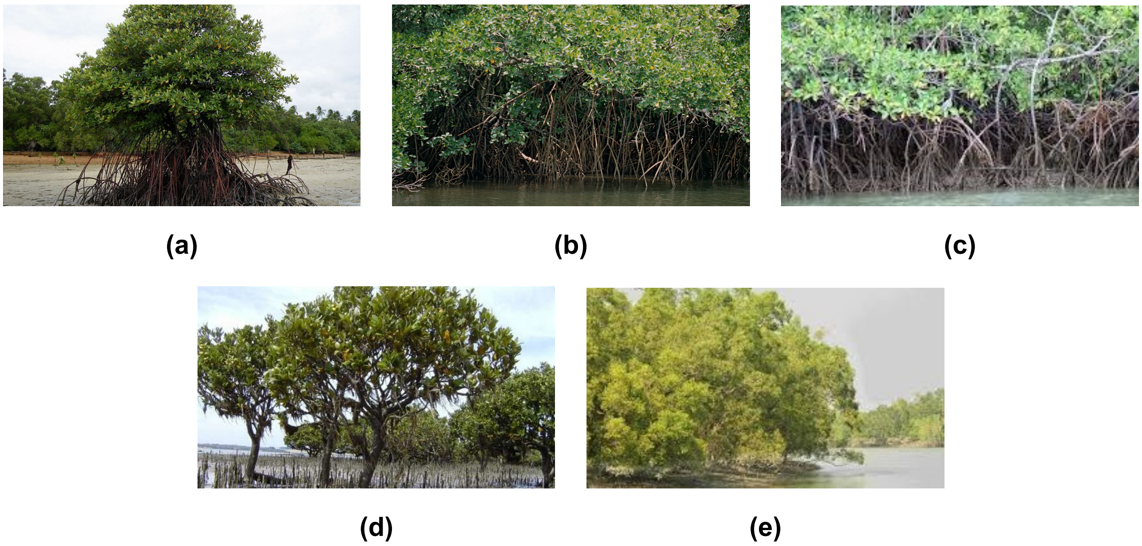

Figure 1.2: Overview of the most common mangrove species used for mangrove restoration: **(a)** Rhizophora apiculata **(b)** Rhizophora mucronata **(c)** Rhizophora mangle **(d)** Avicennia marina **(e)** Sonneratia apetala. Pictures from Ron Yeo, Wikimedia, Wikipedia, Chris Harty and Sagar Adhurya, respectively.

The most common types of mangroves are presented in Figure 1.2. Mangroves grow in the region between 32°N and 38°S, where water temperatures are high (Quisthoudt et al., 2012). For mangroves to grow, other requirements must also be met, such as the presence of a fresh water input, sediment and low wave energy (Alongi, 2009). Mangroves apply drag forces on waves, which reduces the wave energy and attenuate the waves(Menéndez et al., 2020).

1.2. Problem Statement

Existing literature on mangroves focuses on wave attenuation (Bao, 2011; McIvor et al., 2012a; Quartel et al., 2007; Suzuki et al., 2012; Vo-Luong and Massel, 2008), restoring mangroves (Hashim et al., 2010; Indonesia and Hakim, 2016; van Bijsterveldt et al., 2020; Van Cuong et al., 2015; Winterwerp et al., 2020) and ecosystem services (Costanza et al., 1997; De Groot et al., 2012; Karanja and Saito, 2018). However, the contribution of mangroves on failure probability, expected damage and the impact on building with nature business cases has not been assessed quantitatively, to the best of the author's knowledge.

Although the literature shows that mangroves attenuate waves (McIvor et al., 2012a; Suzuki et al., 2012), it remains unclear when a levee-mangrove system is also a more cost-effective flood risk reduction measure than a traditional stand-alone levee.

Over the years, methods have been developed to design levees, including probabilistic analyses (Vrijling, 2001), which enables designing a levee with well-defined uncertainties. Mangrove forests vary for example in density, height of trees and stem diameter (Alongi, 2009; Suzuki et al., 2012), such that uncertainty is inherent in using mangroves as a flood risk reduction measure. However, a probabilistic analysis for levee-mangroves systems has not been done before, as of our knowledge.

Besides the wave attenuation property of mangroves, they also provide ecosystem services, such as functioning as habitat for wildlife including fish, water purification and preventing erosion (Alongi, 2009; Costanza et al., 1997; De Groot et al., 2012; Karanja and Saito, 2018). To assess the economic effectiveness of mangroves in flood risk reduction, these ecosystem services must also be considered.

Roughly two situations may prompt an assessment of a levee-mangroves system: (1) mangroves have to be restored to be able to use them as a flood risk reduction measure, and (2) mangroves are existing in the area already, but there is pressure from the local community to economically exploit the area at the expense of mangroves. Both situations involve a levee-mangroves system, but the essential difference between them can be described as restoring versus maintaining mangroves.

For flood risk engineers and governments to define the effectiveness of levee-mangrove systems, the cost-effectiveness of a levee-mangroves system must become clear, including the ecosystem services and the option for a probabilistic assessment.

Including ecosystem services is especially important from the point of view of the social planner[1], who wants to maximize aggregate welfare rather than choosing the financially cheapest solution, implying that the ecosystem services provided by mangroves are also considered, in addition to the costs of restoration.

1.3. Objective

This study aims to assess the effectiveness and optimization of a levee-mangroves system. To reach this goal, several models have been developed which define the optimal mangrove forest width and optimal levee height, as depicted in Figure 1.3.

This report will answer the question: How can mangroves be incorporated into the design of flood risk reduction measures? This question can be segmented into several sub-questions:

1. Which indicators can be applied to estimate the economic effectiveness of levee-mangroves systems?

[1] A social planner is a decision-maker who attempts to achieve the best result for all stakeholders, which implies maximizing social welfare (Mankiw and Mankiw, 2007). Note that this definition implies that financial assessments are about costs only, while economic assessments also include the effect on social welfare such as ecosystem services.

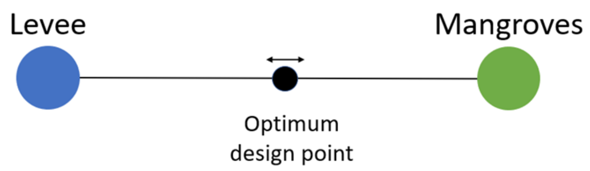

Figure 1.3: Objective of this study is to find the optimum design values for a levee-mangroves system as flood risk reduction measure.

2. Which approaches are applicable to assess the economic effectiveness of levee-mangrove systems?
3. What is the optimal combination of mangroves and levee for flood risk reduction?
4. What is the optimal combination of mangroves and levee for land use?
5. What is the optimal levee-mangroves combination in Kaback, Guinea, and what is the optimal location for a levee?

The costs of mangrove restoration, levee costs, and ecosystem services are estimated on the basis of a literature study. Wave attenuation by mangroves is also estimated by a literature study, as well as by modelling mangroves in the numerical model Simulating Waves Nearshore (SWAN). The input variables to schematize mangroves are based on the literature. For a probabilistic assessment, a First Order Reliability Method (FORM) is used, which is a semi-probabilistic reliability analysis method devised to evaluate the reliability of a system (Verderaime, 1994).

1.4. Report Structure

The report first presents a literature study in Chapter 2. This chapter elaborates on the theoretical background of mangroves, such as the physical conditions in which they grow, their wave-attenuating capabilities and restoration. Moreover, the background on flood risk and the economic analysis of mangroves and a levee are included. Chapter 3 explains the methodology, describing two different decision problems and two possible approaches to solve these problems. Chapter 4 describes how the problem is solved analytically, whereas Chapter 5 presents the solution to the problem using a numerical model developed for this study. Chapter 6 uses the model for the average values based on the literature. This chapter includes a sensitivity analysis, showing how the range of variable values may affect the optimal mangrove forest width. Chapter 7 applies the model to the situation in Kaback, Guinea. Chapter 8 discusses the insights and limitations of this research. Chapter 9 and Chapter 10 conclude the report with conclusions and recommendations.

2

Literature Study

The existing literature gives an overview of the mangroves, flood risk, and financial and economic costs of mangroves and traditional solutions. This literature forms the basis of the model that has been developed in this thesis.

2.1. Mangroves

Mangroves can be used for flood protection. They grow at locations where specific conditions are favorable. Mangroves contribute to the protection measure by attenuating waves. Mangroves also provide ecosystem services that can be evaluated in monetary terms. Costs of restoring mangroves must be considered.

2.1.1. Ecosystem Services

Mangroves provide multiple ecosystem services. According to, among others, the United Nations (Gilman et al., 2008; United Nations, 1994) these are:

- Utilization of wood products
- Utilization of non-wood resources
- Fauna/biodiversity
- Coastal protection
- Recreation and ecotourism
- Erosion prevention
- Water quality
- Carbon capturing

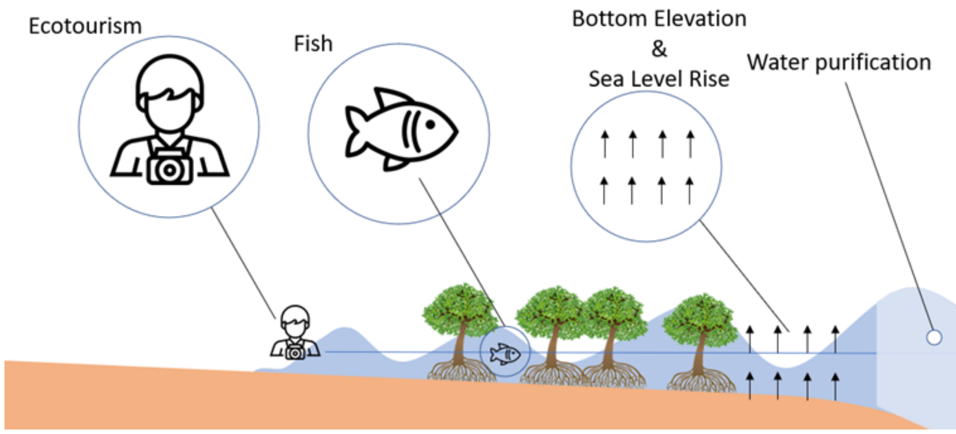

Figure 2.1: Beside wave attenuation, mangroves also provide other ecosystem services. These ecosystem services should be considered when defining the optimal mangrove forest width in a levee-mangroves system. Examples of ecosystem services are habitat for fish, ecotourism, water purification and the ability to grow with sea level rise.

Wood products contain timber for construction, charcoal, and firewood. Non-wood products are, for example, medicines made from mangroves resources. Some of the ecosystem services are shown in Figure 2.1. The monetary value of the ecosystem services is elaborated in Section 2.3.

2.1.2. Physical Conditions

Physical conditions must be favorable enough for mangroves to grow. These conditions are preferably naturally present, but also human intervention can create these circumstances to some extent. Loss of mangroves could be due to human distortion of these physical conditions. The sensitivity for these conditions may vary per mangrove species.

Alongi (2009) identified the different mangrove species. They elaborated that there are roughly 70 species of mangroves. Segmenting species results in 27 genera, 20 families and nine orders. Major ocean currents and the 20 degrees seawater isotherm in winter define the distribution of mangroves. Each mangrove species has an indicator of its salt tolerance and their relative frequency with tidal zonation.

Globally the distribution of mangroves is limited by temperature. At the local scale, mangrove forests vary by sediment availability, rainfall, tides, waves, and rivers (Alongi, 2002). The largest percentage of mangroves occur between 5 degrees latitude, both South and North (Giri et al., 2011). Typically, mangrove forests are located from mean sea level (MSL) to the highest spring tide and several tree species exist parallel to the shore, rather than only one specific species (Alongi, 2009). Low wave energy is a prerequisite for mangroves to grow, since under these circumstances, mangrove seedlings can establish. Sediment deposition is relevant for mangroves as they grow on this soil. Moreover, a freshwater input is required since water should not be too saline.

Mangroves face several natural enemies, such as cyclones or pests. Human threats to mangrove forests are, for example, the extensive utilization for wood or transformation to pond aquaculture. A future threat to mangrove forests is rising sea levels, which may shift mangroves landwards. Damaged mangrove forests may take decades to recover; it is challenging to restore. Natural rehabilitation programs require sufficient undisturbed forests nearby to supply seed stocks.

2.1.3. Wave Attenuation

Mangroves can attenuate incoming waves. Several studies have been done to identify the amount of wave attenuation caused by mangroves, which depends on the type of the mangrove species, mangrove forest characteristics, the type of waves, and other characteristics (Bao, 2011; McIvor et al., 2012a; Quartel et al., 2007; Suzuki et al., 2012). This multi-dependency of wave attenuation makes it difficult to estimate the wave attenuating capacity of mangroves. Some characteristics that might influence the wave attenuating capacity of mangroves are:

- Mangrove height and whether it has a (fully grown) canopy
- Width of mangrove forest
- Density of mangrove forest
- Species of mangroves
- Wave height
- Bed slope

Knowledge about wave attenuation by mangroves is scattered. McIvor et al. (2012a) have assessed several studies about wave attenuation by mangroves. They found that wave attenuation is affected by variables such as mangrove species, bed slopes, forest widths, and wave height. This wide range in wave attenuation values complicates the applicability of mangroves into flood defense calculations. Modelling waves in the presence of vegetation has been done by Suzuki et al. (2012). They added to the Simulating Waves Nearshore (SWAN) (Booij et al., 1997) model the possibility to model vegetation in separate horizontal and vertical layers, which addresses the vertical heterogeneity in mangrove trees. Wave attenuation can be assessed by using field observations or experiments, statistical analyses or numerical modelling.

Bao (2011) applied a statistical model to observe the significance of different parameters related to the wave height. The model contains data of wave heights at two regions in Vietnam, segmented into five different locations. At each location, a plot of the mangrove forest has been set up, and of these plots transects have been made to measure the wave height. Wave attenuation is then analyzed concerning distances, initial wave height, and mangrove forest structures. He found that wave height decays exponentially to distance. The density of mangrove trees explains the exponential relationship; at the trunks, branches, and above-ground roots. A higher density implies higher bed roughness, more friction and wave dissipation. He showed that wave-height reduction could be well estimated by considering the wave height, forest width, average tree height, tree density, and canopy closure. Naturally, a smaller forest width is required when the density, canopy closure, and tree height are higher.

2.1.4. Modelling Wave Attenuation

Suzuki et al. (2012) used a SWAN model and Vo-Luong and Massel (2008) applied a model called WAve PROpagation in MANgrove Forest (WAPROMAN). Suzuki et al. (2012) made an addition to the SWAN model by including vegetation. They built onto the research of Mendez and Losada (2004) who applied a cylindrical approach for determining the bulk drag coefficient for vegetation. This coefficient considers the diameter, density, and height of the vegetation. Additionally, the possibility is added to the model to apply both vertical and horizontal layers. Since mangroves consist of the root, stem, and canopy, all shaped differently, this vertical layer differentiation made the model appropriate to model mangroves. This layer differentiation has a significant effect when peak periods are small (e.g., $T_p = 1s$) but becomes less apparent for longer peak periods (e.g., $T_p = 8s$). Suzuki et al. (2012) introduced the parameter vegetation factor that seizes vegetation's overall effect on wave attenuation. This vegetation factor is defined as in Equation (2.1):

$$V_f = b_v N \widetilde{C}_D \tag{2.1}$$

where b_v is the plant area per unit height of vegetation [m], N the number of plants per square meter [units/m2], and $\widetilde{C}_D$ the bulk drag coefficient [-]. Wave dissipation depends on the vegetation factor and the bathymetry.

McIvor et al. (2012a) assessed several wave attenuation studies. They mention several factors affecting wave attenuation by mangroves:

- The distance a wave travels through the mangroves
- The water depth compared to the structure of the mangrove trees
- Shore slope and topography
- Wave height and period

Roots, trunks, branches and leaves, and the age of the trees define the structure of mangrove trees. At shallow depths, the roots reduce waves more due to higher friction. At deeper water depths, water is higher than the roots and waves experience less drag, and less wave attenuation. For even higher water depths, waves reach the branches and leaves, which increases wave attenuation. The drag coefficient C_D increases exponentially with the projected cross-sectional area of the underwater obstacles up to a certain water depth (A) (Quartel et al., 2007). $C_D = 0.6exp^{0.15A}$ approximates this relation. As expected, the wave attenuation ability of mangroves increases with the age of the trees. For older trees, wave friction became less critical, and leaves and branches became more important in attenuating waves. Both short and long waves attenuate at similar rates. Branches and leaves reduce the wave height more (Mazda et al., 2006).

McIvor et al. (2012a) conclude that wave attenuation rates vary between 0.0014 per meter and 0.011 per meter, which is equivalent to a wave reduction of 0.14% and 1.1% every meter. These rates imply a wave reduction of 50 to 99% for a 500-meter mangrove forest width. However, most studies measure wave attenuation for only small waves, which has to be considered when using the acquired results for higher waves.

Table 2.1: Summary of wave attenuation and storm surge reduction research. Storm surge is relatively unknown, while wave attenuation has been studied often and provides a wide range of outcomes.

	Author	Method	Main take-away
Waves	Bao (2011)	Statistical analysis	Exponential decay of waves
	Suzuki et al. (2012)	SWAN modelling	Vertical layer schematization
	Vo-Luong and Massel (2008)	WAPROMAN modelling	Specifically designed for waves in mangroves
	Quartel et al. (2007)	Drag coefficient	Exponentially increasing with underwater obstacle area
	McIvor et al. (2012a)	Meta-analysis	0.14% and 1.1% wave reduction every meter
Storm surge	Krauss et al. (2009)	Observations	storm surge reduction of 4.2 to 9.4 cm per km
	Xu et al. (2010)	Hurricane modelling	Equivalent of Manning's coefficient of 0.15
	Dean and Bender (2006)	Storm surge and mangroves modelling	Mangroves can reduce wave set-up

Dean and Bender (2006) modelled wave set-up included in wave reduction by mangroves. They found that for the linear wave theory, wave height is small compared to water depth and wavelength. Vegetation can reduce the wave set-up by one-third of the situation where no vegetation was present.

Modelling is a suitable method when assessing the effectiveness of wave attenuation by mangroves in a probabilistic manner, with the right boundary conditions and a realistic depiction of the mangroves. Being limited to specific locations and events constrain the usefulness of field observations and statistical analyses.

Wave attenuation depends on the maturity of the trees. In the model, it must either be assumed that mangroves are grown to maturity, or the distribution of mangrove characteristics must consider the first years of mangrove restoration when mangroves are still small.

Next to wave attenuation, storm surge is also a relevant factor in flood risk. Mangroves' abilities to reduce storm surge water levels have been measured in Florida for three different hurricanes (Krauss et al., 2009). They concluded that the mangroves reduced peak water-level height by an average of 4.2 to 9.4 cm per km. However, field observations are site-specific, and the conclusions may not necessarily be applicable to other sites. The mangrove species they assess are, for example, mangrove interior marsh and riverine mangrove sites. The width of the mangroves varies along with these two locations. Additionally, they measured at three riverine mangrove and four mangrove-interior marsh sites at separate locations inland. Seven sites in total is a limited amount and is prone to errors. For example, an exponential decay remains unnoticed in such measurements. Although insightful, field observations may not be suitable enough for probabilistic analyses due to its specific circumstances. Mangroves seem to reduce storm surges, but this happens at a significantly lower rate than wave attenuation, since the reduction of storm surge is in the order of cm per km.

Xu et al. (2010) modelled the storm surge from Hurricane Andrew in Florida (USA). They noticed that storm surge water levels were lower where mangroves were present. Their findings are that their model aligned with measurements when applying a Manning's coefficient for mangroves of 0.15, which is a typically high coefficient and suggests that mangroves can reduce storm surges, next to wave attenuation. Manning's coefficient is one of the parameters describing water flow over surfaces quantifying

Figure 2.2: Mangrove restoration options can be segmented into three main options: building a permeable structure, planting mangroves and hydrologic restoration in the form of excavation/filling. A permeable structure can be in the form of a bamboo fence and reduces wave energy such that mangroves are able to grow again. For planting mangroves mainly seedlings or propagules are used.

resistance or drag force caused by vegetation (McIvor et al., 2012b).

2.1.5. Existing or Restored Mangrove Forests

Existing or restored mangrove forests can reduce flood risk. Both options have consequences for the certainty of the physical characteristics of mangroves and the costs of applying mangroves in flood risk reduction measures.

When restoring a forest, it is significant to assess the timeframe, what share will survive and which mangrove species are being used. Mangroves typically grow from mean sea level to highest spring tide (Alongi, 2002). This area limits the potential width of the forest.

Naturally, mangroves mature from the initial pioneering, rapid early growth and development, to maturity and ultimately death. As mangroves get older, densities decline, but larger trees lead to more above-ground biomass (Alongi, 2002). This above-ground biomass may be important to attenuate high waves.

Restoring mangroves basically comes in three forms: (1) building a permeable structure (Van Cuong et al., 2015), (2) planting (Hashim et al., 2010) or (3) hydrologic restoration (van Bijsterveldt et al., 2020) in the form of excavation or filling. These options are shown in Figure 2.2.

The standard approach for mangrove restoration is to allow propagules into the area of restoration (Hashim et al., 2010). In the event of loose soil, storm surges or high energetic waves, these propagules may be washed away, which limits their viability. Another possibility in these circumstances is to plant pre-grown seedlings, as Hashim et al. (2010) did. Planting pre-grown mangroves turned out not to be preferred, however (Winterwerp et al., 2020).

Restoring mangroves is possible when a short inundation-free period is followed by a wave-free period to allow propagule anchoring and subsequently, a sheet-erosion-free period to allow seedling growth (Balke et al., 2011, 2015; van Bijsterveldt et al., 2020). Van Bijsterveldt et al. (2020) assessed the settings where abandoned fish ponds can restore mangroves. At the locations where mangroves

Table 2.2: Restoration has several initial conditions, requirements and risks to take into account

	Restoration
Situation	Abandoned fishponds or near existing mangrove forest
Requirements	Low wave energy Between MSL - High tide Inundation time <40% Low slope
Risk	Low survival rate

expanded, the slope was generally low (0-2 cm per m, or negative slopes), whereas steep slopes (2-5 to 5-18 cm per m) faced mangrove retreat, due to the level of protection from waves. Low slopes are better protected against waves, since they are less vulnerable to wave breaking. Soil chemistry appeared not to be a significant driver of seedling establishment. Enhancing soil stability and decreasing inundation stress through bed level accretion, with inundation times below 40% per day, support seedling establishment.

Wave exposure is important when restoring mangroves. Areas prone to strong wave action are vulnerable to seedling loss. One option to control this risk is to dampen the wave height. Hashim et al. (2010) tested the functioning of a detached homogeneous rubble mound breakwater on the west coast of Malaysia. It sheltered the restoration area for mangroves to grow by limiting the wave energy. Since mature mangroves are more resilient against waves, a breakwater is no longer required. A wave transmission coefficient of 0.4 under typical storm conditions and at mean high water was an optimal choice, considering the costs. In this setting, pre-grown seedlings were used due to the wave energy.

Hard wave barriers are typically expensive. Van Cuong et al. (2015) applied a soft coastal engineering solution by planting Melaleuca fences in front of the mangrove restoration site. A Melaleuca tree is native to Vietnam. Three methods are distinguished to define which circumstances restore mangroves best. The first method builds a fence, which acts as a wave barrier, the second method is a fence which acts as a wave barrier and a silt trap fence. The third method is the benchmark situation with only a single fence.

Permeable dams are used to decrease wave energy, and also to restore the local sediment balance along eroding coastlines (Winterwerp et al., 2020). They mention the need for these permeable dams to stay until mangroves take over. In Demak (Indonesia), this is a period of 3 - 5 years (Winterwerp et al., 2020).

Behind the fences mud accumulation took place, while no significant mud accumulation was seen in the control area. At the location behind the wave barrier and silt trap fence, the survival rate of seedling was considerably higher than at the location with only the wave barrier fence. Moreover, the species richness behind the double fence was comparable to the richness in nearby mangrove forests. The tree heights and biomass of a double fence outperformed the control area and the single fence area. Additionally, seedling mortality is enhanced by refuse and near shore fishing. These fences can protect the restoration areas from floating waste and human intervention (Van Cuong et al., 2015). They investigated two different mangrove species, namely Rhizophora appiculata and Avicennia alba. The latter species were found to outperform the former considerably, underlining the importance to select the best species for mangrove restoration.

When the circumstances of planting seedlings or propagules directly on the projected cultivation area are too hostile, an option may be to grow mangroves in a nursery first. A reason for adverse conditions may be that there is a mismatch between the availability of propagules and the optimal planting period, affected by the time soil accretion or erosion occurs. Mangroves can be planted in the field after having grown to around 35 to 50 cm in the nursery (Hoang and Pham, 2010).

In Vietnam, failed planting programmes were due to planting seedlings accretion, erosion washing away seedlings or young trees, barnacles killing trees by clinging to their stems, and fishers disturbing plant growth by pulling ground nets through the planted areas (Thinh et al., 2009).

To conclude, the determinants of proper mangrove restoration are:

- Low wave exposure
- Low slope
- In the case of abandoned fishponds: proper drainage, high bed level

Threats

Mangroves face several threats from the environment and humans, summarized in Table 2.3. Cyclones and environmental diseases threaten and destroy mangroves and may take decades to recover. Local communities threaten mangroves by using the wood for construction or heating; when harvesting is done sustainably, it will not threaten the forest growth. However, when timber extraction becomes commercial exploitation, mangrove forests cannot sustain themselves. Converting mangrove forests to aquaculture is the biggest human threat to mangrove forests. It effaces the mangroves and alters, for example, tidal flows, which can influence the sensitive ecological system of mangroves (Alongi, 2002). A combination of human and natural threats can be due to human intervention, salinity, or flow change which are detrimental to the growth and survival of mangroves.

The rise of sea level may cause mangroves to move landwards if accretion rates are below the rate of SLR. Historically, mangroves adapted to SLR up to at least 3 mm/year (McIvor et al., 2013). There are several other studies mentioned where mangroves kept up with the SLR. Additionally, more recent evidence shows that mangroves keep up with SLR in some locations. However, the maximum rate at which mangroves can keep up with SLR remains unclear. Mangroves near Florida, for example, shifted inland in the presence of a SLR of 2.3-2.7 mm/year (Alongi, 2008). The sedimentation processes

Table 2.3: Both humans and nature pose threats to the survival and restoration of mangroves

Nature	Human
RSLR	Conversion to aquaculture
Cyclones	Excessive wood exploitation
Diseases	
Flow/salinity changes	

in mangrove areas are not yet fully understood (McIvor et al., 2013). Sources of sediment roughly come from either allochthonous or autochthonous matter (Alongi, 2008). Allochthonous materials from outside of the forest are for example sediment from rivers or the sea. Autochthonous material is, for example, leaves and twigs from the trees. For salt marshes, storms bringing sediment to the shore are also important input sources of sediment, which may have the same function for mangrove forests.

A safe choice would be to assume no capability of keeping up with SLR, implying that in the light of coastal defenses, where there might be a fixed location for a levee at the land-side of the forest, this can decrease the forest width that one can effectively use for wave attenuation. Assuming mangroves keep up with SLR implies that the width of the forest is not affected by SLR. The probability is higher that mangroves are somewhere in-between.

2.2. Flood Risk

Flood risk of nature-based solutions involves the variability of vegetation and the variability on the traditional parameters for flood risk reduction. A thorough flood risk analysis involves the distribution of each parameter in the flood risk analysis.

2.2.1. Definition of Risk

Before assessing flood risk, it is helpful to define risk as used in this research. The adopted definition of risk is the probability of an undesired event multiplied by the consequences (Jonkman et al., 2020). Risk is a set of scenarios containing a probability and a consequence. One can define an optimal accepted level of safety, considering the costs of implementing flood risk reduction measures and the risk.

2.2.2. Flood Risk for Nature-Based Solutions

Concerning levees, risk as a function over time is described by the bathtub curve, presented in Figure 2.3 (Jonkman et al., 2020). It distinguishes three phases: 1) the beginning phase: failure is high due to structural and design flaws, 2) the middle phase: calamities and extreme circumstances define the risk, 3) the end phase: an increased rate of failure because of deterioration or wear.

Using mangroves for flood risk reduction, the state of the mangrove forest will play a role in all

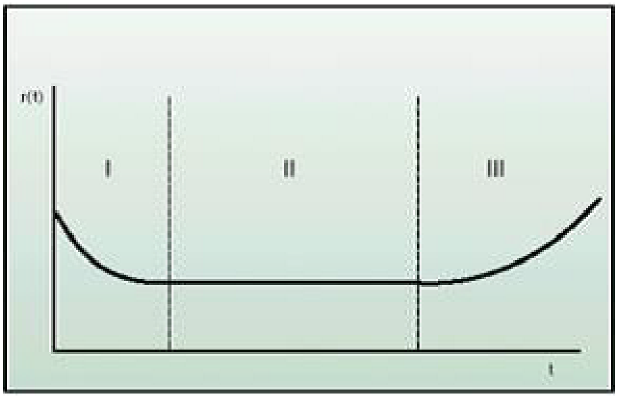

Figure 2.3: Bathtub curve showing risk as a function of time from Jonkman et al. (2020).

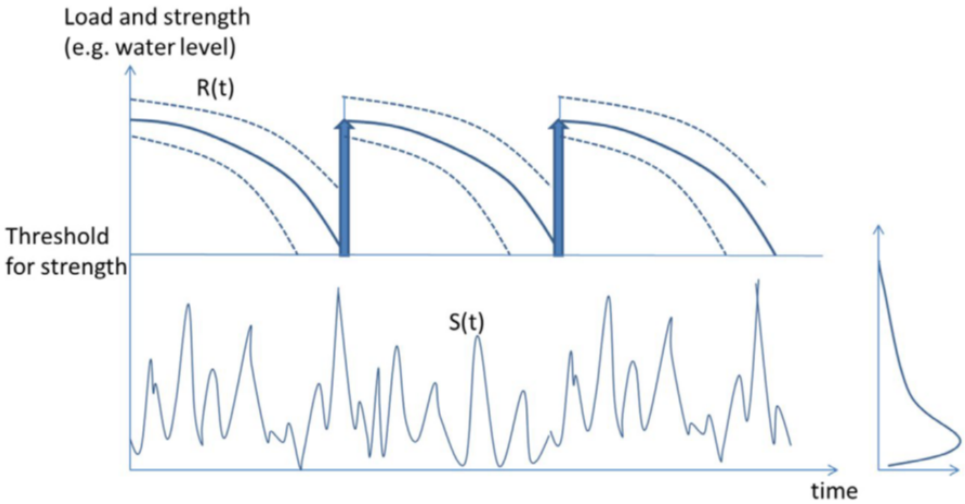

Figure 2.4: Load and strength of a levee schematized over time. Figure copied from Jonkman et al. (2018).

phases. In phase 1, it is about restoring mangroves or using an existing forest. In phase 2 and 3, the state of the mangroves is relevant to assess its ability to attenuate waves. Thus, while the traditional bathtub curve faces a specific level of risk when including mangroves in the protection measure, the risk may oscillate depending on the state of the mangroves. Since mangrove's geographical areas do not know seasons, the seasonal state of the mangroves does not play a role.

Jonkman et al. (2018) illustrated in Figure 2.4 how strength of a levee and load on a levee develops over time. Mangrove strength develops in another way. Mangroves need to grow from seedlings to a mature, dense forest. This process will take some years to occur. This implies that Figure 2.4 is not applicable for mangroves. Mangroves will provide little safety in the beginning, while providing more safety later in time. This can be influenced by damage caused by nature or humans, which makes mangroves addition to safety less predictable. On the other hand, this additional strength in the beginning allows for mangroves not to fully be developed yet. This way, a levee and mangroves are acting in a complementary manner.

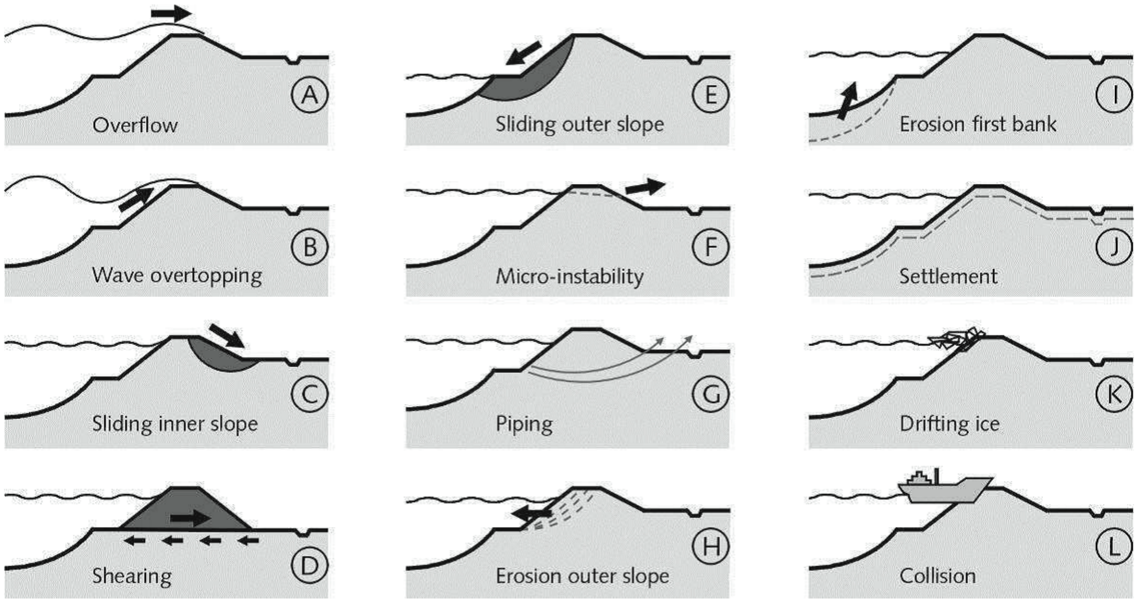

Figure 2.5: Possible failure mechanisms (Jonkman et al., 2020). This thesis focuses on the failure mechanism of wave overtopping (B). Failure occurs if the discharge of water over the levee is higher than the critical discharge for which the levee fails.

2.2.3. Calculating Probabilities

In determining whether a failure occurs, a Limit State Function (LSF) can be set up. If this function reaches a specific value, failure occurs. The LSF may be a non-linear function. Probabilities can be calculated in several ways. First, one can calculate it in a deterministic manner, defined as level 0, which requires nominal values of the variables. Level 1 makes use of safety factors to take into account the probabilistic distributions of certain parameters. Level 2 makes use of an LSF which is linearized, and the variables are transformed to standardized normal distributions. Level 3 uses non-normally distributed variables and a non-linear LSF. The probability can then be calculated by applying Monte Carlo simulations which applies random sampling on the variables.

Level 2 methods can be calculated by a First Order Reliability Method (FORM). Such a method consumes considerably less computational time than a Monte Carlo simulation. Applying a probabilistic approach has the advantage that it gives insight into the absolute importance of parameters and relative importance in obtaining an uncertainty level.

2.2.4. Failure Mechanisms

For flood risk reduction, the failure of a levee or another water blocking structure is the moment flooding occurs. In this respect, one can identify the failure of a levee as the critical failure mechanism.

For a traditional or hybrid flood defense solution, a levee has to be built. There are several mechanisms that lead to the failure of a levee, as shown in Figure 2.5.

Vuik et al. (2018) assessed flood risk protection by applying a vegetated foreshore in combination with a dike. He considered two failure mechanisms. First, erosion of the crest and inner slope of the levee due to wave overtopping. Second, erosion of the levee cover on the outer slope due to the impact of breaking waves.

The formula for wave overtopping can be taken from the EurOtop Manual 2018. This manual provides design formulas for wave overtopping, based on European research, but can be applied worldwide (Van der Meer et al., 2016). According to the manual, wave overtopping discharge q decreases exponentially as the crest freeboard R_c increases. Since locations where mangroves grow are typically shallow foreshores, the formula for these shores is being used and described in Equation (2.2).

$$\frac{q}{\sqrt{gH_{m0}^3}} = 10^{-0.50}\exp\left(-\frac{R_c}{\gamma_f\gamma_\beta H_{m0}\left(0.33+0.022\zeta_{m-1,0}\right)}\right) \tag{2.2}$$

where H_{m0} [m] stands for the significant wave height, γ_f [-] is the influence factor for roughness elements on a slope, γ_β [-] the influence factor for oblique wave attack and $\zeta_{m-1,0}$ [-] the breaker parameter.

De Waal and Van Hoven (2016) assessed wave impact due to wave breaking further. Equation (2.3) describes this failure type.

$$Z = D_{crit} - D_{load} \tag{2.3}$$

D is here defined as the cumulative overload. If D_{crit} is reached, the grass cover of the levee will start to erode (De Waal and Van Hoven, 2016). According to their report the erosive load at a certain level is determined by the front velocity U of the uprunning wave i. If the effective front velocity load $\alpha_M U^2$ of wave runup i at level z exceeds a critical velocity load $\alpha_S U_C^2$, the wave adds to the cumulative overload D_{load} at level z. De Waal and Van Hoven (2016) describe this in their formula in Equation (2.4).

$$D_{load,z} = \sum_{i=1}^{N} \max\left(\alpha_{M,z}U_{i,z}^2 - \alpha_{S,z}U_c^2; 0\right) \tag{2.4}$$

2.2.5. Parameters and their Distributions

The hydraulic load on the levee starts with offshore wave characteristics. These are defined by tide and wind, with water level and offshore wave conditions as boundary conditions (Vuik et al., 2018). Waves then enter the foreshore zone, which is defined by its bathymetry, and affects the wave conditions, wave impact, water-level and run-up, according to a wave energy balance. Eventually, at the levee location, there is a certain wave load and a levee strength that are used as input variables in the LSF (Vuik et al., 2018). He identified the following system components in the probabilistic analysis of a nature-based coastal defense:

- Levee characteristics
- Wave load model
- Wave model
- Foreshore bathymetry

- Vegetation properties
- Vegetation model
- Stability properties
- Stability model

For each of these components, a probability distribution needs to be defined to perform a probabilistic analysis. Costs and benefits of a traditional levee solution and the mangroves has to be included to make the link to the feasibility analysis. This does not necessarily have to be within the probabilistic model.

A one-dimensional wave energy balance can be used as Vuik et al. (2018) showed in Equation (2.5).

$$\frac{dEc_g}{dx} = S_{in} - S_{ds,w} - S_{ds,b} - S_{ds,f} S_{ds,v} \tag{2.5}$$

where $E = (1/8)\rho g H_{rms}^2$ is wave energy density $[J/m^2]$, H_{rms} root mean square wave height $[m]$, ρ density of water $[kg/m^3]$, g gravitational acceleration $[m/s^2]$, c_g group velocity [m/s], and x distance [m] along the foreshore.

2.2.6. Flood Damage

In flood risk analyses, damage can be segmented into direct and indirect effects (Messner and Meyer, 2006). Direct damage is related to physical contact with flood water. Indirect damage concerns flood damage like disrupted economic and social activities, and affects regions outside the inundated regions. One can measure this damage potential in monetary or non-monetary units. Vulnerability to flooding depends on the elements which are at risk, how much these are exposed, and how susceptible these are, measuring how sensitive an element at risk behaves when confronted with flooding. Messner and Meyer (2006) divide exposure into the kind of exposure (i.e. closeness to inundation areas) and in general flood characteristics such as duration and inundation depth.

They describe that damage can either be expressed in an absolute manner, showing the total damage of valuable property, or relative damage (mostly on a scale from 0 to 1, implying no damage and total loss, respectively) and is often related to inundation depth. Damage analyses can be categorized as macro-, meso- and micro-scale analyses. Macro-analyses relate to national or international scale, meso-scale analyses relate to regional scale (e.g. river basins or coastal areas) and micro-scale analyses look into a single flood protection measure on a local level. Meso-scale analyses use categories of valuables within a municipality to obtain a more realistic measure of damage. For example, residential, industrial or agricultural areas. By intersecting a map of an inundation area and valuables, the value of a region can be determined. Linking the damage level to the inundation depth is the most common approach to define damage levels.

Messner and Meyer (2006) address several limitations in damage estimation methods. First, they consider the tangible flood effects while the economic welfare effects such as health, loss of life and environmental effects are ignored. Second, the indirect effect of reduced economic activity in the affected region may affect for sectors outside of the inundated region. The conventional method to estimate damage is by relating it to the inundation depth. Other flood characteristics, such as velocity, flood duration or sedimentation can impact flood damages. This effect is limited, since these factors are strongly linked to inundation depth. Socio-economic susceptibility may also influence the damage level, such as individual or public preparedness prior to flood events.

The social planner needs to identify these steps in flood risk reduction:

1. Presence of an inadequately protected coast
2. Determine the probability that flooding occurs
3. Determine occurring damage in the event of flooding
4. Determine current flood risk
5. Determine economic optimization considering the investment costs and desired protection level or flood risk
6. Build flood risk measures
7. Maintain flood risk measures

This research focuses on the last three steps. The implicit assumption is that there is a need for building a flood risk measure, as is concluded from the first steps.

2.3. Financial and Economic Analysis

In the analysis of nature-based flood risk reduction, both financial and economic aspects can be considered. Financial aspects refer to the costs of the investments to build and maintain a flood risk measure. The economic aspects include the societal values or externalities derived from a specific flood defense solution, such as ecosystem services.

2.3.1. Financial Analysis: Costs of Levees and Mangroves

The financial analysis discusses the costs of both mangroves and levees. A levee has a straight forward cost structure, while the cost structure of mangroves is more complex. Certain costs of mangroves may not be relevant in some locations. Table 2.5 illustrates the difference in complexity of the cost structure for levees and mangroves.

Traditional levee solution

(Hillen et al., 2010) described five general costs factors:

1. Planning and engineering costs
2. Material costs
3. Labor costs
4. Costs for implementation in the environment (urban or rural)

Table 2.4: Costs and benefits of mangroves and levee. Mangroves provide additional benefits.

	Mangroves	**Levee**
Costs	Seedlings/propagules	Material (sand, stones, etc.)
	Bamboo fences/breakwater	Machines
	Maintenance	Maintenance
	Acquiring of land	Acquiring of land
	Protection	
Benefits	Wood	Flood risk reduction
	Fish	Infrastructure
	Fresh water	
	Flood risk reduction	
	Decrease in damage level	
	Ecotourism, recreation	
	Carbon capturing	
	Sediment trapping	

Table 2.5: Different costs for levees and mangroves. The costs for mangroves may not all be necessary.

Levee	**Mangroves**
Construction	Restoration
Maintenance	Maintenance
	Permeable structure
	Landfill/Excavation

5. Costs for management and maintenance

Jonkman et al. (2013) assessed the costs of raising a dike for The Netherlands, United States of America (USA), and Vietnam. For these countries, costs to implement a coastal defense measure differed between urban or rural areas. In The Netherlands, it ranged from 4.5 to 22.4 million Euro per kilometer per meter raising (M.EUR/km per m). In the United States this was 5 to 8 M.EUR/km per m, while in Vietnam, dikes were only built in rural areas and the costs ranged from 0.7 to 1.2 M.EUR/km per m. Maintenance was estimated at 0.1 M.EUR/km per year in The Netherlands while 0.02 M.EUR/km per m in Vietnam. There is a significant difference in costs between developed countries (e.g. The Netherlands and USA) and developing countries (e.g. Vietnam).

Sand is a significant building material in the construction of a levee. Kok et al. (2008) used a price of 3 EUR/m3, while in their sensitivity analysis a value of 5 EUR/m3 was applied. Jonkman et al. (2013) noted that the price of 3 EUR/m3 in the Netherlands is relatively low due to large raw material resources available and the large volume of beach nourishment.

For the Pearl River Delta in China, He et al. (2020) estimated the costs of one kilometer dike heightening of 1 m to cost 0.39 million USD (2019 price level). These costs are linear, without an intercept, based on observations in The Netherlands and Canada. This estimate included all investment costs: groundwork, construction, engineering, land compensation and project management.

Mangrove Solution

Costs for mangroves depends on whether the mangrove forest has to be restored or exists already. If mangroves must be planted, costs will depend on whether the physical or hydraulic circumstances are favorable as elaborated on in Section 2.1.2. If the circumstances are inadequate to grow mangroves, one must take measures to create these beneficial circumstances. Measures to decrease the height of the waves are most common, such as applying a breakwater made from bamboo (Van Cuong et al., 2015).

Lewis III (2001) identified three types of restoration. The first one is planting alone, which has a relatively high risk of failure since circumstances are insufficient. The second option is hydrologic restoration, which could be done by restoring abandoned aquacultural fish ponds. Planting may be necessary and would double the costs. The third option is an excavation or fill and involves large scale earth moving, making it the most expensive option. He found that the costs for restoring mangroves differ from several hundreds to several hundreds of thousand US Dollar per hectare, and depends on the local situation. Reasons for this difference of several magnitudes are:

- The amount of soil that needs to be excavated or restored
- Using natural secondary succession without planting a nursery development or planting young seedlings or trees.

Bayraktarov et al. (2016) did a meta-analysis study on the cost of coastal marine restoration of coral

Table 2.6: Costs of the several components of mangrove restoration. The cost estimates differ considerably.

Cost element	Cost	Source	price level
Seedlings	2,510 - 22,400 USD/ha	Teas (1997)	1994
Propagules	1,140 - 10,175 USD/ha	Teas (1997)	1994
Young plants	87,500 - 216,130 USD/h	Teas (1997)	1994
Bamboo fence building	50-60 USD per meter	Thao et al. (2014)	2008
	21,000 USD/km	Van Cuong et al. (2015)	2014
	70 USD per meter	Indonesia and Hakim (2016)	2016
Bamboo fence maintenance	4,200 USD/km per year	Van Cuong et al. (2015)	
	30 USD per meter	Indonesia and Hakim (2016)	2016
Reduced maintenance on dike	7.3 M USD after investment of 1.1 M USD in mangroves	Brown et al. (2006)	2006
Restoration in general	186,000 USD/km2	Huq et al. (2010)	2010

reefs, seagrass, mangroves, saltmarshes and oyster reefs. The costs they defined were adjusted to 2010-dollar price levels and adjusted for the local value of a dollar in developing countries by using GDP and purchasing power parity (PPP). PPP enables comparing costs in developed and developing countries. In total, Bayraktarov et al. (2016) analysed 54 studies on mangroves. He only included observations where both capital and operating costs were reported. The costs for restoration of mangroves in developing countries are 30 times lower than in developed countries. When considering GDP and PPP, costs in developing countries were 226 times lower, which shows the large uncertainty in cost estimations. One reason for this could be that restoring mangroves requires manual labour, which is more expensive in developed countries.

Most successful mangrove restorations were those with natural mangrove recovery through planting seeds, seedlings and propagules (Bayraktarov et al., 2016). Planting small trees, reconversion of aquaculture ponds and hydrological restoration were considerably less successful. Lewis III (2001) expresses the range of estimates of mangrove restoration. He finds a range from 225 - 216,000 USD/ha in 2001 price levels. He explains the upper bound due to overly expensive landfills or land exclamation and planting young trees. He points out that these restoration approaches are not successful (especially planting young trees) or not a good choice in developing countries (land fill or exclamation). Restoration of the environmental conditions, such as wave energy or using propagules and seedlings are considered the most viable options for a successful long-term restoration.

Teas (1997) identified the costs for three different scenarios: planting propagules, planting seedlings, and planting 3-year old trees. At 1997 price levels, costs would be 1,140 - 10,175 USD/ha for propagules, 2,510 - 22,400 USD/ha for seedlings, and 87,500 - 216,130 USD/ha for the already grown trees. The costs depend on the density of the planted mangrove forest.

To restore mangrove forests, one needs to reduce wave energy by building traditional breakwaters or bamboo fences. A breakwater is a more expensive solution than bamboo fences. Bamboo T-fences are 50-60 USD per meter (2008 price levels), according to Thao et al. (2014). These costs add to the restoration of mangrove forests. After the mangroves have been restored, the mangroves take over the role of the bamboo fences. Other benefits of the bamboo fences are that local labourers can build these without machinery.

The costs of the trap fences as described in Van Cuong et al. (2015) cost 21,000 USD/km initial investment and 4,200 USD/km per year of maintenance. The planners used local material, melalueca for these fences.

Indonesia and Hakim (2016) estimated the costs of planting mangroves at 1,221 million IDR as investment cost and 122.1 million IDR as yearly maintenance costs (2016 price level), which is equivalent to 80,000 USD and 8,000 USD respectively. These costs involved mangrove seedlings, bamboo fences, rope, labour and boat costs. These values apply to a mangrove restoration project of 102 ha. The material cost and installation of the bamboo fences cost 995 thousand and 416 thousand IDR per meter, respectively. This equals approximately 70 and 30 USD per meter.

Huq et al. (2010) assessed the rehabilitation of mangroves in Bangladesh and set the costs of planting mangroves at 168,000 USD per km2. Further specifications about how this number is reached have not been made.

Brown et al. (2006) also note that mangroves reduce levee maintenance costs. They state that an investment of 1.1 million USD in mangroves prevented maintenance on the levee of 7.3 million USD. Whereas storms damaged the levee, it was not (as severely) damaged in places where mangroves grew. It shows how mangroves may support a lower levee and decrease maintenance costs.

To summarize, costs of mangroves depend on the following characteristics:

- An existing forest
- Adequate physical conditions. If not, a breakwater or a sand exclamation and reclamation need to be built
- Need to plant propagules, seedlings or small trees in-situ
- The density of the forest
- Maintenance cost

Several costs have not been considered until this point (explicitly), such as labour costs, training of labourers building and maintaining the mangrove forest. However, these costs could be beneficial to the local economy.

2.3.2. Economic Analysis

The financial aspects of mangroves include investment and maintenance costs and prevented maintenance costs for the levee. However, mangroves may supply other direct or indirect economic values. Economic values do not directly influence the investment or maintenance cost of the flood defense. The most apparent economic benefit is the prevented damage in the event of flooding. When assuming both flood-defense solutions offer the same level of protection, this economic benefit is equal. Section 2.1 already described the ecosystem services. These services do not directly affect the costs of the flood defense, but provide monetized values. Although this monetizing of values is subject to subjectivity, it is necessary to include for the full picture to make a complete judgment between the possible flood defense solutions.

A well-functioning market for these services does not exist (e.g., ecosystem services are often not traded), making the valuation of these economic analysis challenging (Brander et al., 2018). Two main methods for the valuation of ecosystems are the primary-valuation and value-transfer methods. Primary-valuation methods can use either cost-based approaches that use a measure of costs associated with an ecosystem service or based on inputs into production or consumer behaviour. Value-transfer methods use results from existing primary studies to predict an ecosystem value for other locations or ecosystems. Both methods have several options to calculate the value. One could calculate how much it costs to replace an ecosystem with manufactured equivalents, people can be asked to state their willingness to pay for an ecosystem service (possibly in groups of stakeholders), or estimate the influence of an ecosystem on the price of marketed goods (e.g., real estate) (Brander et al., 2018). Each method has its advantages and limitations.

Costanza et al. (1997) gave the example of a forest. Let us assume one would be willing to pay 50 USD for the timber production of a forest. Additionally to this timber production, the forest provides non-marketed values, such as aesthetics and conservation values at 70 USD. The total value would be 120 USD, but the contribution to the economy is 50 USD. According to classical economic theory, when evaluating ecosystems, it can be expressed by the supply and demand curves. Applying a linearly increasing supply curve and a linearly decreasing demand curve implies a substitutable good. However, many ecosystem services would have different supply and demand curves: a vertical supply curve and an exponentially decreasing demand curve. The value of the ecosystem (the area captured by the supply and demand curve) would then go to infinity. The former supply and demand curves provide a more useful approach but underestimate the total value.

One can make several caveats. The willingness to pay of individuals determine the supply and demand curves. However, these individuals may not incorporate social fairness, ecological sustainability, or be ill-informed, leading to an undervaluation of ecosystem services. The values also assume no sharp thresholds, discontinuities, or irreversibility in the ecosystem response function, which leads to another underestimation of the value. Another issue is the inter-country comparisons of valuation, which are affected by income differences. The authors consider these comparisons by addressing the

Table 2.7: Value of ecosystem services of mangroves according to Costanza et al. (1997) in USD/ha/year in 1994 price levels.

Ecosystem service	Mean value
Food	466
Raw materials	162
Waste treatment/purification	6,696
Habitat/refugia	169
Opportunities for recreation and tourism	658
Total	**8,151**

relative purchasing power (GNP per capita) of countries relative to the USA, even though it is a crude correction (Costanza et al., 1997).

The authors describe their eventual results for the value of mangrove ecosystems as a lower bound, presented in Table 2.7 in 1994 USD. Their approach is based on economic theory and is limited by the caveats described above.

Mangroves attenuate waves and enhance sedimentation or reduce erosion. Phan et al. (2015) assess the effect of mangroves in relation to sedimentation and erosion. They find that long waves particularly play a role in sedimentation rates since these waves penetrate relatively deep into the mangrove forest. In a meta-analysis study, Shepard et al. (2011) concluded that coastal marshes such as mangroves could lead to accretion or reduced erosion at the shoreline. Relative Sea Level Rise (RSLR) may lead to erosion of coasts. If mangroves lead to accretion of the soil at a rate equal to or larger than RSLR, erosion due to RSLR may be prevented. This (prevented) erosion is difficult to express in monetary terms, but the difference between a mangrove forest and a traditional levee could be significant.

By assessing numerous studies of ten different biomes, De Groot et al. (2012) also estimated the value of coastal wetlands, where mangroves grow. The services are segmented into provisioning services, such as food, water and raw materials, and regulating services, such as waste treatment and erosion prevention, habitat services, and cultural services. In total, they estimated the value of coastal wetlands at 193,845 USD/ha/year at 2007-price levels. However, a significant segment of this amount is based on the value of waste treatment or water purification in the United States. One could argue that this value translated to a developing country is considerably less. Nevertheless, it shows that this economic value of mangroves should not be neglected. This value consists of several components, including extreme events moderation. When excluding the latter (the alternative, a traditional levee, should provide the same value) and other relatively small components, these components are summarized in Table 2.8.

Karanja and Saito (2018) did a smaller study to assess the ecosystem services of mangroves in Kenya. First, they mentioned the difference in damage after flooding. They refer to the study by Dahdouh-Guebas (2006), who concluded that the villages protected by the mangroves had minimal

Table 2.8: Most relevant services provided by coastal wetlands according to De Groot et al. (2012) in USD/ha/year at 2007 price levels. The main section derives from a study about waste treatment in the USA. The value differs from Costanza et al. (1997) mainly in waste treatment.

Ecosystem service	Mean value
Food	1,111
(Fresh) water supply	1,217
Raw materials	358
Waste treatment/purification	162,125
Erosion prevention	3,929
Lifecycle maintenance	10,648
Gene pool protection	6,490
Opportunities for recreation and tourism	2,193
Total	**188,071**

Table 2.9: Ecosystem services in USD/ha/year, according to Karanja and Saito (2018). Flood protection (740 USD/ha/year) is not included in this analysis. This estimate is relatively low due to taking into account only direct economic benefits.

Ecosystem service	Mean value
Firewood	36
Timber	25
Herbal medicine	17
Thatch	13
Fishing	38
Fodder	175
Ecotourism	15
Total	**304**

damage (i.e., 7% of the villages). The villages not protected by mangroves had severe damage in 80 to 100% of the villages, which shows the protective value of mangroves.

Karanja and Saito (2018) mention and evaluate several other ecosystem services, summarized in Table 2.9. These services consist of direct economic benefits, such as firewood bought or (sustainably) taken from the mangrove forest. This estimate is on the lower bound when not including the indirect, intangible, economic benefits, especially compared to Costanza et al. (1997) and De Groot et al. (2012). Additionally, the flood protection (740 USD/ha/year) is not considered, as elaborated on above.

One may calculate the present value for an infinite lifetime by dividing the annual values by the discount rate. An infinite lifetime is reasonable since a mangrove habitat can exist for many years. However, it might be necessary to maintain the mangrove forest frequently. If assuming an interest rate of 10%, the present values of the mangroves are shown in Table 2.10.

Table 2.10: Summary of studies defining the value of ecosystem services of mangroves. The present value is calculated by dividing the value per year by the interest rate of 10%. (Karanja and Saito, 2018) has the most conservative approach, taking into account mainly the direct economic benefits.

Source	Context	USD/ha/year	Present Value USD/ha
Costanza	Study from 1994 in which the value is determined using supply and demand curves and willingness to pay. Differences in GDP per country are taken into account.	8,151	81,510
De Groot	(De Groot et al., 2012) did a meta-analysis, looking into several studies that assessed the ecosystem services value. A large part of the value comes from water treatment.	188,071	1,880,710
Karanja	Rather conservative approach by considering only the direct economic benefits.	304	3,040

3

Methodology

This chapter explains the research methodology. The report is separated into two problem definitions and two methods of solving the problem. The two decision problems are either based on flood risk or opportunity costs. In the flood-risk problem, the choice is between applying mangroves and a levee while considering the effect on Annual Expected Damage (AED). The opportunity costs assessment considers using a land area where mangroves can grow for commercial exploitation and protection.

The flood risk problem will be addressed in Chapter 7 with specific reference to Kaback, Guinea (West-Africa).

3.1. Two Decision Problems

3.1.1. Flood Risk Problem

In the flood risk problem, investments in mangroves and a levee reduce the flood risk, but this needs to be done in a cost-efficient manner. The investments need to be minimized while decreasing the annual expected damage. The reasoning behind the flood risk problem is presented in Figure 3.1

In the opportunity costs problem, the focus is not on building a levee, but rather how much of the mangroves should be maintained. The question is to what extent mangroves may be used for economic production while maintaining enough protection such that the damages are do not eradicate the economic production. More mangroves provide more safety, but they also provide less opportunity for economic exploitation such as the production of rice. These two problems are summarized in Table 3.1 and schematized in Figure 3.2.

An example of the flood risk problem could be the preference for restoring mangroves, which means the levee height does not need to be raised much while maintaining a sufficient low failure probability

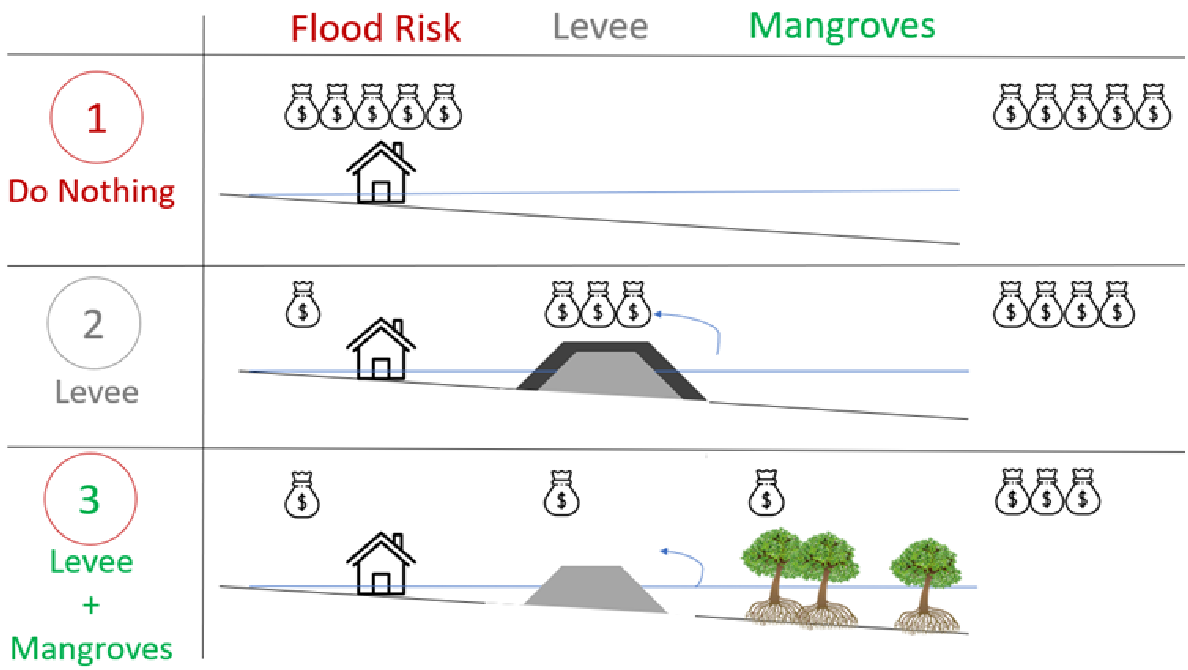

Figure 3.1: This figure shows the reasoning behind applying levee-mangroves systems. When doing nothing, the flood risk is high, leading to high annual expected damage. An investment can be made to reduce the flood risk by building a levee. By restoring mangroves, investment costs of the levee can be minimized, leading to the most economically effective flood risk reduction measures.

and therefore the expected annual damage stays sufficiently low.

3.1.2. Opportunity Costs Problem

The opportunity costs problem is about the trade-off between maintaining mangroves with their protective capacity and ecosystem services versus economic exploitation of the land (e.g. for agricultural use). These two problems are summarized in Table 3.1 and visually presented in Figure 3.2.

3.2. Two Possible Approaches

There are two approaches - analytical and probabilistic - to addressing the problems mentioned above.

3.2.1. Analytical Approach

First, the problem will be derived analytically in Chapter 4. In this approach, the problem is schematized, simplified and expressed in mathematical terms. Next, the optimum is found by deriving the mathematical equations for the variables. In these mathematical models, some simplifications are applied to enable a derivation, ensuring clear, simple relations.

Table 3.1: Two decision problems and their considerations. The flood risk problem involves a levee, mangroves and annual expected damage. The opportunity costs problem involves the alternative economic exploitation of the mangrove area and the annual expected damage.

Kind of problem	Considerations
Flood Risk	Mangroves Levee Annual Expected Damage
Opportunity Costs	Mangroves Economic Exploitation Annual Expected Damage

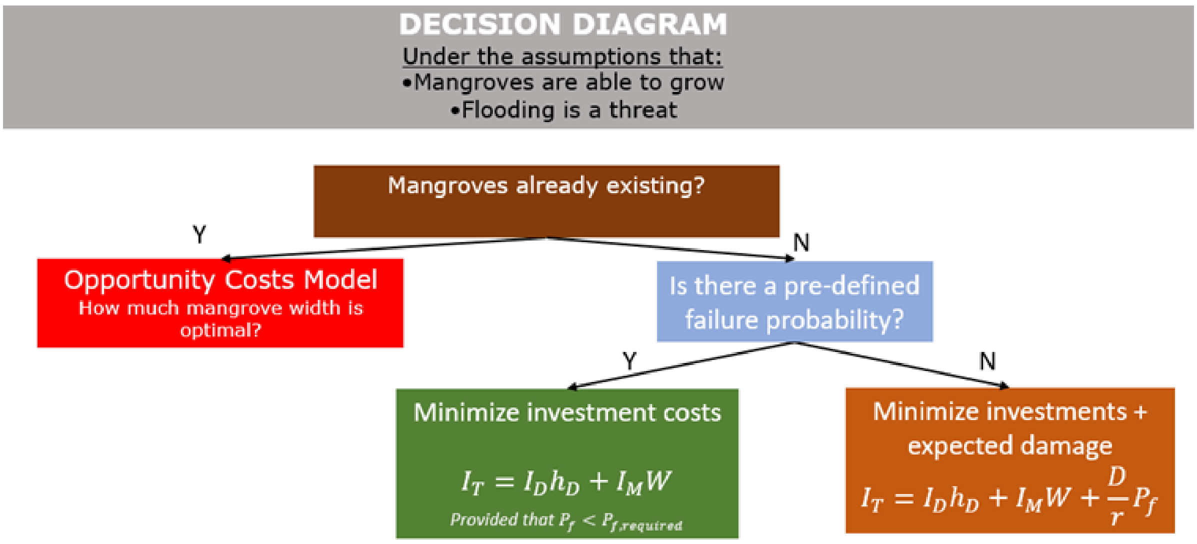

Figure 3.2: Decision diagram for either the flood risk problem or opportunity costs problem.

3.2.2. Probabilistic Approach

Second, this study will develop a model to solve a complete set of equations in a probabilistic manner in Chapter 5. A FORM analysis was included to account for the probability of flooding. In the FORM analysis, the distributions of relevant parameters may be included rather than the deterministic values of, for example, storm surge and wave height. Including distributions enables the possibility to find optimal solutions for a set of variables on their specified distribution. For the flood risk assessment in this model, wave attenuation can be included as a fixed value or by modelling waves from onshore to offshore using SWAN software. In SWAN, mangroves and their wave attenuation are modelled according to the latest findings in the literature (Dalrymple et al., 1984; Janssen, 2016; Suzuki et al., 2012).

3.2.3. Expansions of the Model

More advanced modelling could be done on both the hydraulic and the economic side.

On the hydraulic side, sea-level rise could be considered. Sea-level rise increases the water level and therefore increases the required height of the levee. At the same time, mangroves are able to increase the soil elevation, on which they grow as the sea-level rises (McIvor et al., 2013). However, it is not known what level of sea rise is the point beyond which mangroves cannot continue growing.

Concerning the economic side of the model, one advanced method to consider is the growth rates of the economy, which could be affected by additional flood safety measures. If an area is less prone to flooding, it may attract a larger population to settle in the area. A larger economy would again require more safety against flooding. Other additions to the model could consider inflation, the effect of labor used during the construction of a levee, and the restoration of mangroves.

3.3. Application of the Models

In Chapter 6 the analytical model is applied to gain insight into how the variables in the model affect the optimal mangrove forest width. Based on the literature, a range in values is defined for each variable: a low, common and high value. This shows the sensitivity of each variable on the optimal forest width.

Both the analytical and probabilistic models are applied in Chapter 7, where the case study of Kaback, Guinea is assessed. In this case, the coast has been prone to flooding ever since mangroves disappeared (Reeskamp et al., 2017). By applying both the analytical and probabilistic approaches, a comparison between the results of both models can be made.

4

Economic Optimization of Levee-Mangroves Systems: Analytical Approach

In this chapter, the problem of levee-mangroves systems described in Chapter 3 is derived analytically. This analytical derivation is later applied in Chapter 6 and in a case study of Kaback, Guinea (West-Africa).

4.1. Flood Risk Problem

One can address the trade-off between applying levees and mangroves as flood risk reduction measures from two different angles. The first approach is a trade-off between a levee and mangroves to reach a specific level of safety for minimum investment costs. The second approach is a trade-off between the costs of building a levee, the costs of restoring mangroves and flood risk in terms of expected annual damage. The two approaches are schematized in Figure 4.1.

$H_{s,0}$ is the wave height at the toe of the levee in the situation without mangroves and defines wave-overtopping. The levee has to be high enough to reduce the wave-overtopping to a sufficiently low discharge that the failure probability is as required. Mangroves decrease the wave height and therefore the wave-overtopping discharge, which allows for a lower levee height, while preserving the same failure probability as a higher levee without mangroves. Figure 4.2 shows this scenario with and without mangroves.

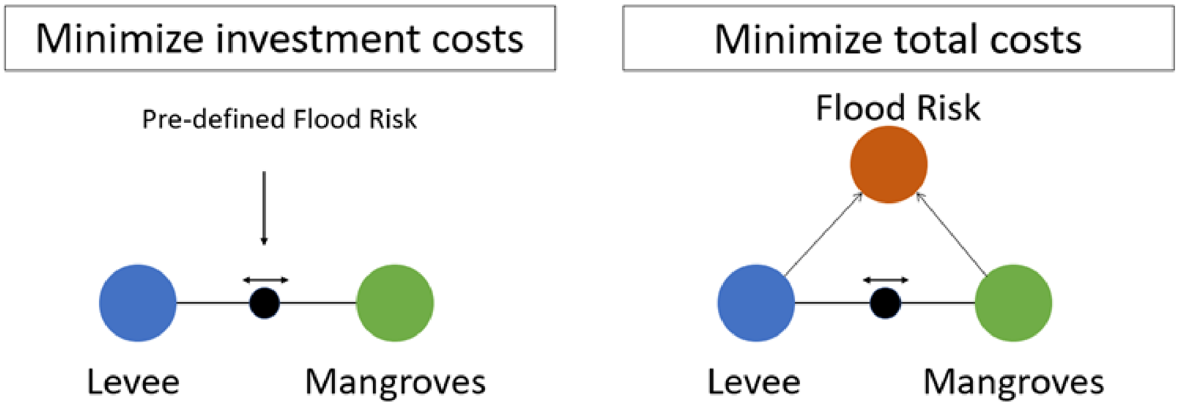

Figure 4.1: Two approaches to assess the flood risk problem. One is to minimize investment costs, while the other minimizes the total costs, including the effect of the levee and mangroves on flood risk in terms of annual expected damage.

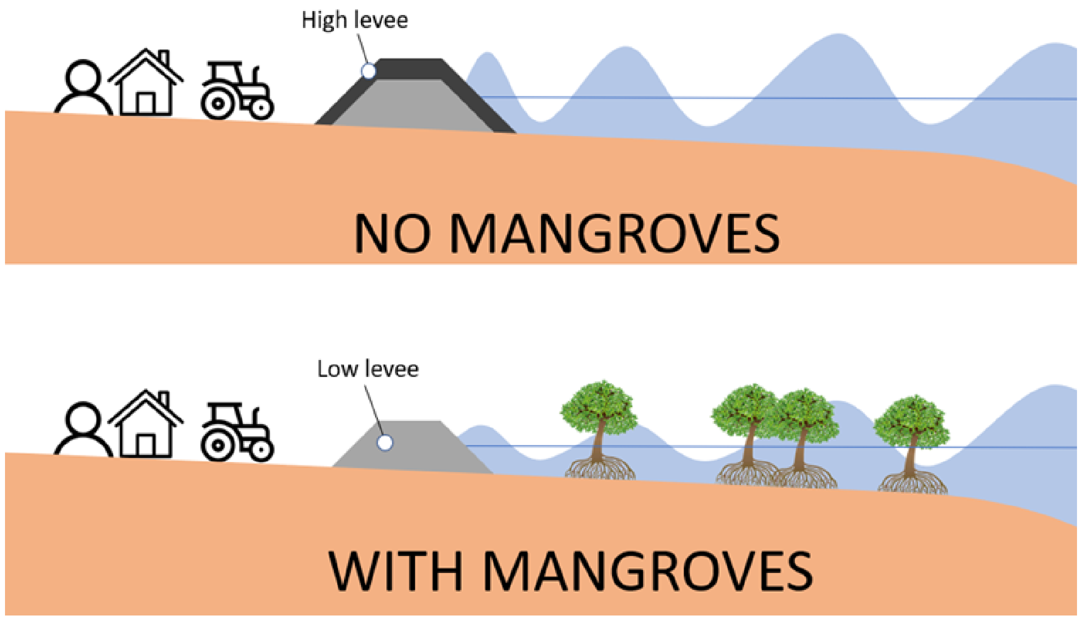

Figure 4.2: Sketch of the situation with and without mangroves. Without mangroves, the wave is not attenuated by vegetation: the levee has to withstand the unaffected wave run-up. With mangroves, the wave height is attenuated, reducing the wave run-up and as a result a lower levee height suffices.

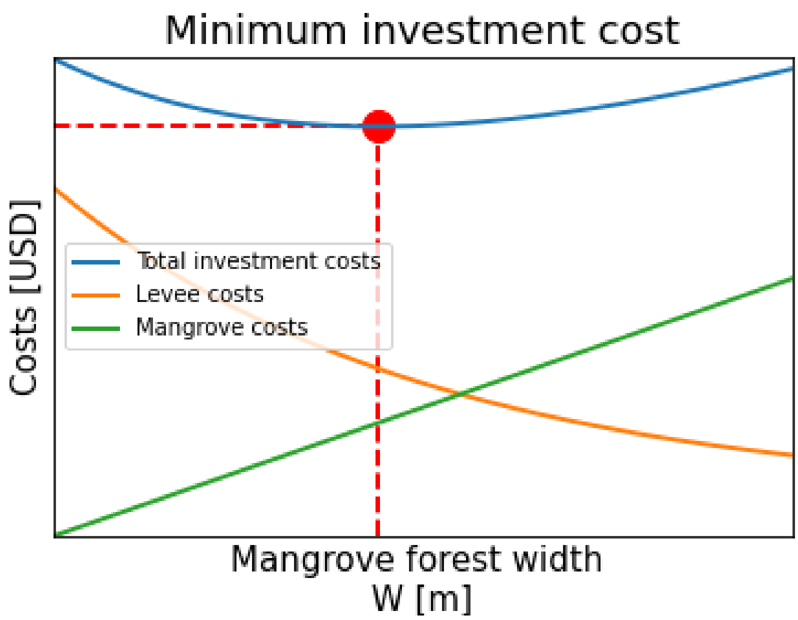

Figure 4.3: The essence of the model is to minimize investment costs by finding the optimal combination of levee and mangroves for a given safety level. A wider mangrove forest reduces the required height of the levee.

4.1.1. Minimize Investment Costs

The first analysis considers the investment costs to reach a predefined safety level. The objective is to find the minimal investment costs between a levee and mangroves. The total costs of both components must be assessed, including their interaction. Figure 4.3 visualizes the minimization problem.

Costs for building a levee are generally provided in USD/km per m raising, and costs for restoring mangroves generally in USD/ha. To be able to compare both options in a model, the costs have to be converted into USD/m/m dimensions, see Figure 4.4.

The formula of total investment I_T is defined as:

$$I_T = I_D h_D + I_M W \tag{4.1}$$

in which I_T is the total investment costs per meter coast, I_D and I_M the variable investment costs of the levee [USD/m/m] and of restoring mangroves [USD/m/m], respectively. h_D and W are the height of the levee and the mangrove forest width, respectively.

Since there is a predefined safety level, the storm surge and wave height can be determined according to this safety level. The required height of the levee may then be calculated by taking the sum of storm surge (S_S) and wave run-up ($R_{u,2\%}$), minus the initial elevation of the land:

$$h_D = -E_0 + S_S + R_{u,2\%} \tag{4.2}$$

Wave run-up is calculated using Equation (4.3) (Asbeck, 1953; Van der Meer et al., 2016). It is based on the 2% wave run-up and has been used in the Netherlands until 1980. If only 2% of the waves reach

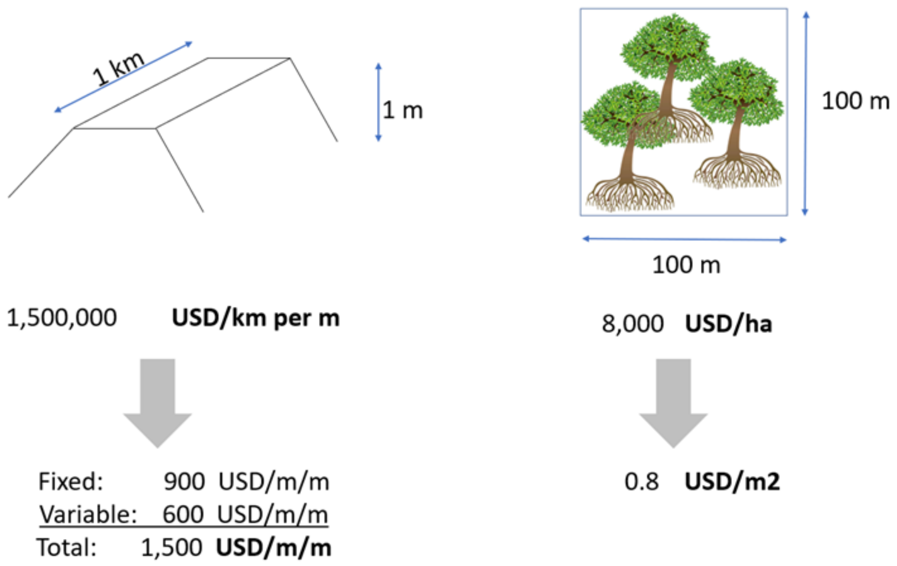

Figure 4.4: Conversion of the conventional dimensions of levee and mangrove costs to USD/m/m dimensions. This is required to compare the costs of levees and mangroves.

the crest of the levee, the crest and inner slope do not need specific protection measures other than clay or grass (Van der Meer et al., 2016). ϕ is the constant which depends on the strength of the levee (how much discharge the levee can take) and on the shape of the levee. In Asbeck (1953), $\phi = 8$, see Figure 4.5. This value corresponds to a maximum discharge of 0.1 l/m/s. This is a conservative value, since levees can generally withstand higher discharges.

$$R_{u,2\%} = \phi H_{s,0} \tan(\alpha) e^{-cW} \tag{4.3}$$

in which E_0 is the initial elevation, S is the storm surge [m], $H_{s,0}$ the wave height at the toe of the levee in case of no mangroves, c the wave attenuation by mangroves $[m^{-1}]$ and W the mangrove forest width. For the wave attenuation, an exponential distribution is chosen, based on the literature, where the wave attenuation rate is given in percentage per 100 m mangrove forest width (McIvor et al., 2012a; Suzuki et al., 2012). The initial elevation refers to the height of the land relative to the reference level. The initial elevation refers to the height of the land relative to the reference level. If this is, for example, below mean sea level, a levee will always be necessary for flood risk reduction. If this is above mean sea level, a levee might be redundant. The mangroves reduce the offshore wave height towards the coast. The required height of the levee is the sum of the storm surge and wave run-up, minus the initial bottom elevation:

$$h_D = -E_0 + S + \phi H_{s,0} e^{-cW} \tan(\alpha) \tag{4.4}$$

Equation (4.1) can be redefined in terms of the mangrove forest width:

$$I_T = I_D \left(-E_0 + S + \phi H_{s,0} e^{-cW} \tan(\alpha)\right) + I_M W \tag{4.5}$$

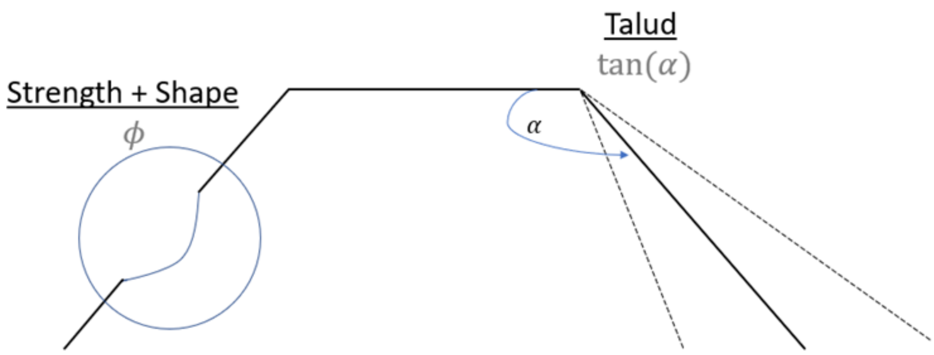

Figure 4.5: Maximum wave overtopping and therefore maximum wave run-up depends on the shape and strength of the levee. ϕ represents the shape and strength of the levee (Van der Meer et al., 2016), while $\tan(\alpha)$ represents the talud of the levee. These are design choices and may affect the costs of the levee. In this thesis, $\phi = 8$ is applied based on Van der Meer et al. (2016) and $\tan(\alpha) = 0.25$.

By taking the derivative to W, and set it equal to zero, $\frac{\partial TC}{\partial W} = 0$, the optimal mangrove forest width is found:

$$\frac{\partial I_T}{\partial W} = -cI_D\phi \tan\alpha H_{s,0}e^{-cW} + I_M \tag{4.6}$$

$$W_{opt} = \max\left[\frac{1}{c}\ln\left(\frac{cI_D H_{s,0}\phi\tan\alpha}{I_M}\right), 0\right] \tag{4.7}$$

The ecosystem services (S) can eventually be deducted from the variable mangroves restoration costs. Ecosystem services are provided in USD/ha/year, or USD/m/m/year. To deduct these from the variable costs, the present value has to be calculated by dividing it by the discount rate:

$$\text{PV } S = \frac{S}{r} \tag{4.8}$$

Substituting this in the mangrove forest width equation results in the following expression for the optimal mangrove forest width:

$$W_{opt} = \max\left[\frac{1}{c}\ln\left(\frac{cI_D H_{s,0}\phi\tan\alpha}{I_M - \frac{S}{r}}\right), 0\right] \tag{4.9}$$

From this relation, mangroves are attractive in case the factor within the natural logarithm is larger than 1. This implies that mangroves are attractive ($W_{opt} > 0$) if the following relation holds:

$$\frac{I_M - \frac{S}{r}}{I_D} < c\phi H_{s,0}\tan(\alpha) \tag{4.10}$$

Mangroves can contribute to reduce wave run-up, and is an effective solution if the variable costs of the mangroves compared to the variable costs of the levee are smaller than the wave attenuation rate c and the wave run-up $R_{u,2\%}$. If this relation does not hold, the W_{opt} in Equation (4.9) becomes negative. In that case, the optimal width is zero.

The essence of this optimization is:

- Water level and wave height need to be withstanded
- Water level is counteracted by the height of the levee. Wave height can be fully counteracted by a levee or after being reduced by mangroves first.
- Equation (4.9) gives the optimal mangrove forest width

4.1.2. Economic Optimization Including a Levee, Mangroves and Flood Risk

The second approach addresses the economic optimization and takes flood risk into account in the analysis of flood protection, next to the investment costs. In the first approach this is implied by imposing a height of the levee which is able to withstand a storm surge and wave height combination with a specific probability.

The total cost function including flood risk becomes:

$$TC = I_D h_D + I_M W + \frac{D}{r} P_f \tag{4.11}$$

The failure probability can be approximated by an exponential distribution, derived by Van Dantzig (1956). Failure occurs if the water level exceeds some critical value. The water level is given by the storm surge.

$$P_f = P(H > h) = exp^{\left(-\frac{h-A}{B}\right)} \tag{4.12}$$

with A and B constants of the exponential distribution [m]. Since the levee height is a function of the storm surge, as given in Equation (4.4), the failure probability can be expressed as to the levee height. The effect of the storm surge is incorporated in the exponential distribution of the water level, and thus represented by the constants A and B.

$$P_f = P(h + R_{u,2\% > E_0 + h_D}) = e^{-\frac{1}{B}(E_0 + h_D - R_{u,2\%} - A)} \tag{4.13}$$

The total costs of investments and flood risk can be expressed as:

$$TC = I_D h_D + I_M W + \frac{D}{r} e^{-\frac{1}{B}(E_0 + h_D - \phi H_{s,0} \tan(\alpha) e^{-cW} - A)} \tag{4.14}$$

From this equation it becomes apparent that building a levee or restoring mangroves increases the total costs directly, but decreases the total costs via the reduced failure probability P_f. For an investment to be profitable, construction costs need to be less than the present value of prevented expected annual damages. The dimensions of the variables are per meter coast width, thus I_M and I_D in [USD/m/m], and D in [USD/m] [1].

[1] These dimensions might not align with the conventional presentation of these variables, but enables an equation with clear variables. A different approach would be to define the total costs not per meter coast, but in absolute numbers, and damage D, I_D and I_M in their conventional dimensions. This would lead to the equation $TC = 1{,}000 h_D L + \frac{I_M}{10{,}000} WL + \frac{D}{r} e^{-\frac{1}{B}(E_0 + h_D - \phi H_{s,0} \tan(\alpha) e^{-cW} - A)}$, in which L the coast length in [m], D in [USD], I_D in [M USD/km per m raising], and I_M in [USD/ha].

The total cost function in Equation (4.14) should be optimized in relation to W and h_D to obtain the global minimum costs.

To optimize for both W and h_D, the equations $\frac{\partial TC}{\partial h_D} = 0$ and $\frac{\partial TC}{\partial W} = 0$ need to be solved. By substituting both results, an expression is found of h_D as a function of W. These equations are given below:

$$\frac{\partial TC}{\partial W} = I_M - \frac{D}{r}\frac{\phi H_{s,0}\tan(\alpha)ce^{-cW}}{B}e^{-\frac{1}{B}\left(E_0+h_D-\phi H_{s,0}\tan(\alpha)e^{-cW}-A\right)} = 0 \tag{4.15}$$

$$\frac{\partial TC}{\partial h_D} = I_D - \frac{D}{rB}e^{-\frac{1}{B}\left(E_0+h_D-\phi H_{s,0}\tan(\alpha)e^{-cW}-A\right)} = 0 \tag{4.16}$$

Combining Equation (4.15) and Equation (4.16) leads to a function of levee height h_D as a function of W (derived in Appendix A):

$$h_{D,opt} = -E_0 + \phi H_{s,0}\tan(\alpha)e^{-cW} + A + B\ln\left(\frac{D\left(1 - 8H_{s,0}\tan(\alpha)ce^{-cW}\right)}{rB\left(I_D - I_M\right)}\right) \tag{4.17}$$

However, since $c = \mathcal{O}(10^{-3})$ and $8H_{s,0}\tan(\alpha)ce^{-cW} = \mathcal{O}(10^{-3})$, $I_M = \mathcal{O}(1)$ and $I_D = \mathcal{O}(10^2)$, it is reasonable to apply the following relations: $8H_{s,0}\tan(\alpha)ce^{-cW} \ll 1$ and $I_M \ll I_D$. These relations justify a simplification of Equation (4.17) to Equation (4.18).

$$h_{D,opt} = -E_0 + \phi H_{s,0}\tan(\alpha)e^{-cW} + A + B\ln\left(\frac{D}{rI_D B}\right) \tag{4.18}$$

By rewriting the equation, the formula for the optimal mangrove forest width W as a function of h_D is found.

$$W_{opt}|_{h_D} = \frac{-E_0 - h_D + A + B\ln\left(\frac{cD\phi H_{s,0}\tan(\alpha)}{rI_M B}\right) + \phi H_{s,0}\tan(\alpha)e^{-cW_{opt}}}{cB} \tag{4.19}$$

With Equation (4.18), the levee height h_D can be expressed in terms of mangrove forest width W for the economic optimization including flood risk. The question remains, however, what mangrove forest width is optimal. The economic optimization is an exercise of reducing flood risk with minimal investment costs. The latter analysis has been done in Section 4.1.1 and shows how mangroves lowers wave run-up and decreases the required height of the levee. The optimal mangrove forest width for minimum investment costs can be calculated using Equation (4.9). In Figure 4.6, the qualitative relationship between W and h_D is shown. For c and $H_{s,0}$, the sensitivity on this relationship is shown qualitatively. Corresponding to Equation (4.18), a higher wave attenuation rate c or wave height $H_{s,0}$ makes mangroves more effective.

Optimal mangrove forest width in the economic optimization

For the economic optimization, the steps in Section 4.1.1 remain the same but are expanded:

1. Water level and wave height need to be counteracted

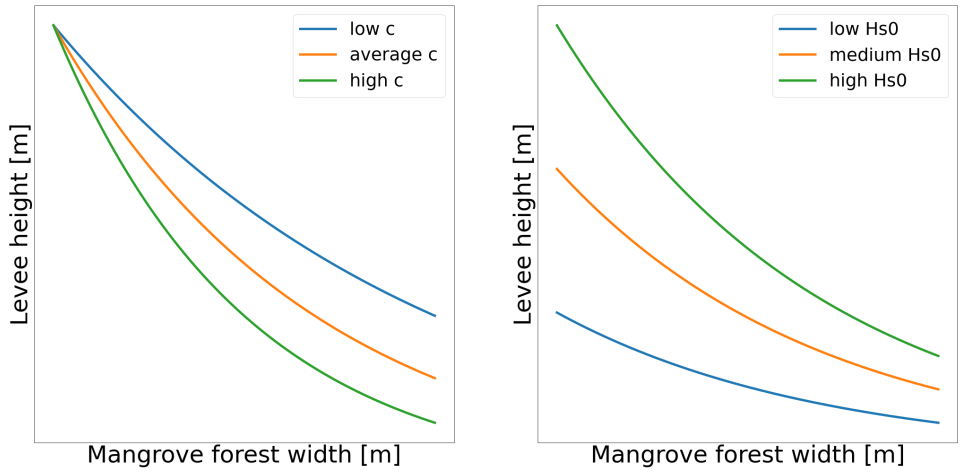

Figure 4.6: These graphs represent the optimal combinations of levee height and mangrove forest width, and how it changes for c and $H_{s,0}$. Corresponding to Equation (4.18), a higher c or $H_{s,0}$ makes mangroves more attractive.

2. The more water level and wave height are counteracted, the less flood risk, but the higher the investment costs
3. Water level will be withstanded by the height of the levee. Wave height can be counteracted by either a levee or mangroves.
4. Equation (4.9) gives the optimal mangrove forest width to withstand the wave height
5. Given W_{opt}, the optimal levee height can be calculated, which is an optimization between investment costs and reduced flood risk by withstanding water level and (mangrove-reduced) wave height

W_{opt} is expressed in Equation (4.9) in Section 4.1.1:

$$W_{opt} = \max\left[\frac{1}{c}\ln\left(\frac{cI_D H_{s,0}\phi\tan\alpha}{I_M - \frac{S}{r}}\right), 0\right]$$

There are three cases that could be distinguished related to W:

1. $W = W_{opt}$
2. $W = W_{opt} = 0$
3. $W \neq W_{opt} \neq 0$

In case 1, the optimal mangrove forest width in Equation (4.9), derived in Section 4.1.1, can be substituted into the optimal levee height formula in Equation (4.18). In cases 2 and 3, Equation (4.18) gives the optimal levee height.

In case 1, if $W = W_{opt} > 0$, W_{opt} can be substituted into Equation (4.18), and the optimal levee height is presented as in Equation (4.20). The advantage of this representation is that the W falls out of the equation of $h_{D,opt}$. W is implicitly taken into account in the ratio of mangrove costs, wave attenuation and levee costs. This is only valid if W_{opt} is physically possible, and not restricted by the range of MSL and high tide in between mangroves grow.

$$h_{D,opt}|_{W=W_{opt}>0} = -E_0 + \frac{I_M}{cI_D} + A + B\ln\left(\frac{D}{I_D rB}\right) \tag{4.20}$$

In case 2, $W = W_{opt} = 0$, the total cost equation reduces to the optimization between investment costs of the levee and expected annual damage. Substituting this $W = 0$ in Equation (4.18), the optimal levee height becomes:

$$h_{D,opt}|_{W=W_{opt}=0} = -E_0 + \phi H_{s,0}\tan(\alpha) + A + B\ln\left(\frac{D}{I_D rB}\right) \tag{4.21}$$

In case 3, the Equation (4.18) remains unchanged. This case may occur when the optimal width is larger than the possible mangrove forest width, constrained by physical restrictions. For example, if the optimal mangrove forest width is 1000 meters, but the horizontal distance between MSL and high tide is only 500 meters, W_{opt} is constrained by these 500 meters.

$$h_{D,opt}|_{W\neq W_{opt}\neq 0} = -E_0 + \phi H_{s,0}\tan(\alpha)e^{-cW} + A + B\ln\left(\frac{D}{rI_D B}\right) \tag{4.22}$$

These functions for W_{opt} and $h_{D,opt}$ imply that flood risk does not influence the mangrove forest width. However, if the height of the levee is somehow restricted, the optimal mangrove forest width will increase in case of high damage, since the mangrove forest width is the only option left to decrease the flood risk.

To conclude, if the levee height and mangrove forest width can be freely chosen, W_{opt} is given as Equation (4.9), and $h_{D,opt}$ is given as Equation (4.18). If the levee height is fixed or limited due to which the outcome of Equation (4.20) or Equation (4.21) is not possible, W_{opt} is given as in Equation (4.19). This could be the case if a higher levee faces resistance from the local community, or a higher levee is technically not possible. If W is fixed or limited, the outcome of Equation (4.9) is not possible and the optimal levee height is given as Equation (4.18). This could be the case if there is a natural boundary, such as mean sea level.

An analysis of a cost minimization could look as in Figure 4.7. More mangroves lead to more costs to restore them, but decreases the required height of the levee. A higher levee costs more to build, but decreases expected annual damage.

4.1.3. Result

To obtain the optimal mangrove forest width and levee height, first the mangrove forest width has to be determined with the following formula:

$$W_{opt} = \max\left[\frac{1}{c}\ln\left(\frac{cI_D H_{s,0}\phi\tan\alpha}{I_M - \frac{S}{r}}\right), 0\right] \tag{4.23}$$

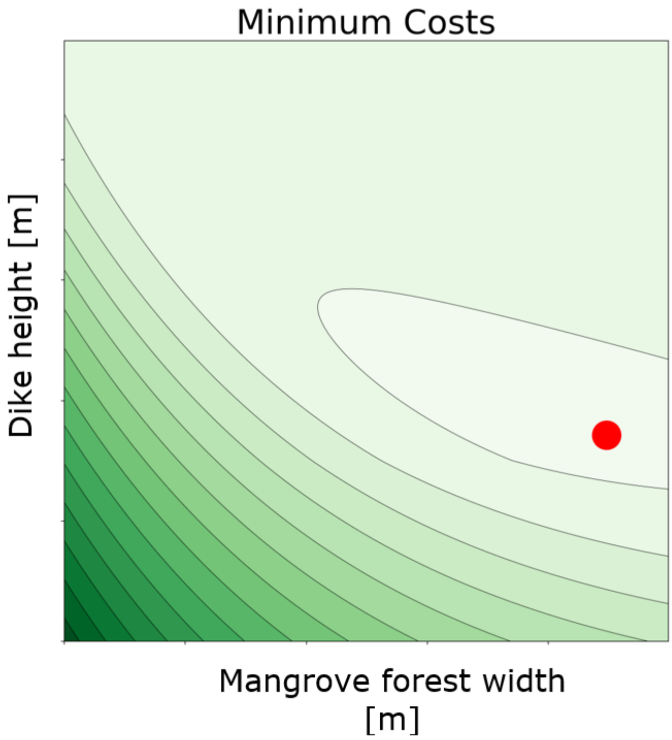

Figure 4.7: Qualitative representation of a combination of levee height and mangrove forest width where the combination at minimum costs is indicated by the red dot. Costs consist of building a levee, restoring mangroves, annual expected damage and maintenance. More mangroves leads to more costs to restore them, but decreases the required height of the levee. A higher levee costs more to build, but decreases expected annual damage.

Next, the optimal levee height is found with the following formula:

$$h_{D,opt} = -E_0 + \phi H_{s,0} \tan(\alpha) e^{-cW} + A + B \ln\left(\frac{D}{rI_D B}\right) \tag{4.24}$$

For both the optimal mangrove forest width and levee height, it must be physically possible and reasonable.

From these formulas, we can draw the following implications:

- The optimal wave height is a balance between variable costs of a levee and mangroves, and between wave height and wave attenuation. A higher wave height and stronger wave attenuation increases the effectiveness of mangroves.
- Wave attenuation has two contradicting effects. A high wave attenuation increases the necessity of mangroves, but decreases the necessary width in meters.
- Optimal mangrove forest is found by minimizing investment costs, whereas the optimal levee height also depends on the flood risk.
- The optimal mangrove forest width and levee height also depends on the strength and shape of the levee, in the formulas expressed in the variables ϕ and $\tan(\alpha)$.

The results in the table can be expressed in quadrants, distinguishing investment costs only, and an economic optimization. in Figure 4.8 it becomes clear that both analyses are similar. If the costs of mangroves compared to the costs of a levee is small enough relative to the wave attenuation by mangroves, mangroves are an attractive measure.

The results derived in this chapter are presented in Figure 4.8. If the bottom elevation is sufficiently high for the optimal failure probability, no levee is required. If storm surge and wave run-up is higher than the bottom elevation, and thus threatening the land, a flood risk reduction measure is required. Then if the cost ratio of mangroves and levees are low relative to the attenuated wave run-up, mangroves are an effective measure for flood risk reduction.

In Appendix A several numerical examples are shown. It shows how variables change the optimum mangrove forest width and optimal levee height.

4.2. Opportunity Costs Model

The problem changes into an opportunity costs problem if a mangrove forest is already present. In this case, there is a trade-off between mangroves and the agricultural exploitation of the same area. Finding a balance between ecosystem services, agricultural yield and annual expected damage will provide the optimal location of a levee.

Figure 4.9 schematizes the problem. Mangrove growth is restricted by MSL and high tide. In the opportunity costs model, the levee is placed between MSL and high tide, at the expense of either the mangroves, or agriculture. Equation (4.25) defines the annual total net gains which have to be optimized depending on the levee location, which defines both the mangrove forest width and agriculture width. In this equation, P_f is the failure probability of the levee, assuming there is no yield in the year in which

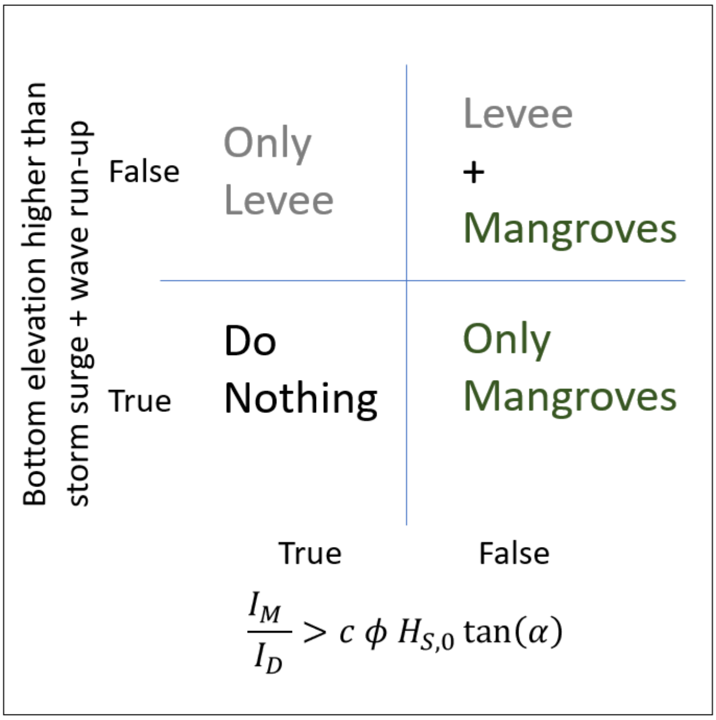

Figure 4.8: Requirements for each solution for flood risk reduction. If storm surge and wave run-up is higher than the bottom elevation of the land, a levee is required. If the costs of mangroves relative to the costs of levees and wave attenuation is sufficiently low, mangroves become an effective measure for flood risk reduction.

the levee fails. W_a is the width of agricultural land in meters and W_m the width of mangroves in meters. Y represents the yields of agricultural land in $USD/km/m$ and S represents the ecosystem services provided by mangroves in $USD/km/m$. The failure probability is a function of the levee shape and strength, its position, mangrove forest width, and the storm surge and wave height, which is assumed to be 50% of the water level in front of the levee.

Agricultural yield depends on both the yield in terms of production in tonne/ha/year, but also on the price of a tonne of cultivated crops. In Guinea (West-Africa), rice production is around 1.35 tonne/ha/year, and is sold for around 200 USD/tonne. This implies a yield of 270 USD/ha annually, or 27 USD/km/m annually. In Vietnam, for example, production yields are higher - around 4 tonne/ha annually (Tri et al., 1998). At 2020 price levels, this is sold for around 400 USD/tonne (FAO, 2021), equivalent to a yield of 160 USD/km/m annually.

$$ATG = (1 - P_f)YW_a + SW_m \tag{4.25}$$

A numerical example of the opportunity costs model is presented in Table 4.1, with the results presented in Figure 4.10. As the mangrove forest width increases, the ecosystem services also increase. The potential agriculture yield decreases, but the annual expected damage does as well. The ecosystem services in these examples are set at 50% and 75% of the yields of the agricultural yield. For these ratios the maximum total gains are at around 400 and 800 meters mangrove forest width of the 1000

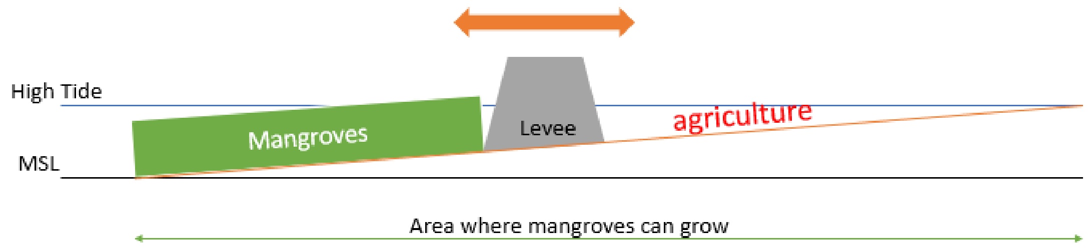

Figure 4.9: Situation sketch for the trade-off between mangroves and agriculture of the mangrove area. More mangroves imply less opportunity to reap benefits from commercial use. Mangroves provide a decreased failure probability and therefore more protection to the land, and ecosystem services.

Table 4.1: Values of opportunity costs example. The yield is based on a return of 400 USD/ha, similar to the yield in Guinea. The ecosystem services are based on Karanja and Saito (2018), and these are 300 USD/ha. Levee costs are neglected, since they do not change if the levee is placed at another location.

Variable	**Dimension**	**Value**
Levee height	m	1
High Tide	m +MSL	1
Agricultural Yield	USD/km/m	40
Ecosystem services	USD/km/m	(a) 20, (b) 30
Slope	1V:xH	1000
Storm surge	m, distribution	Exponential(λ=1, γ=0)
Wave attenuation	m^{-1}, distribution	Normal($1.46 \cdot 10^{-3}$, $0.2 \cdot 10^{-3}$)

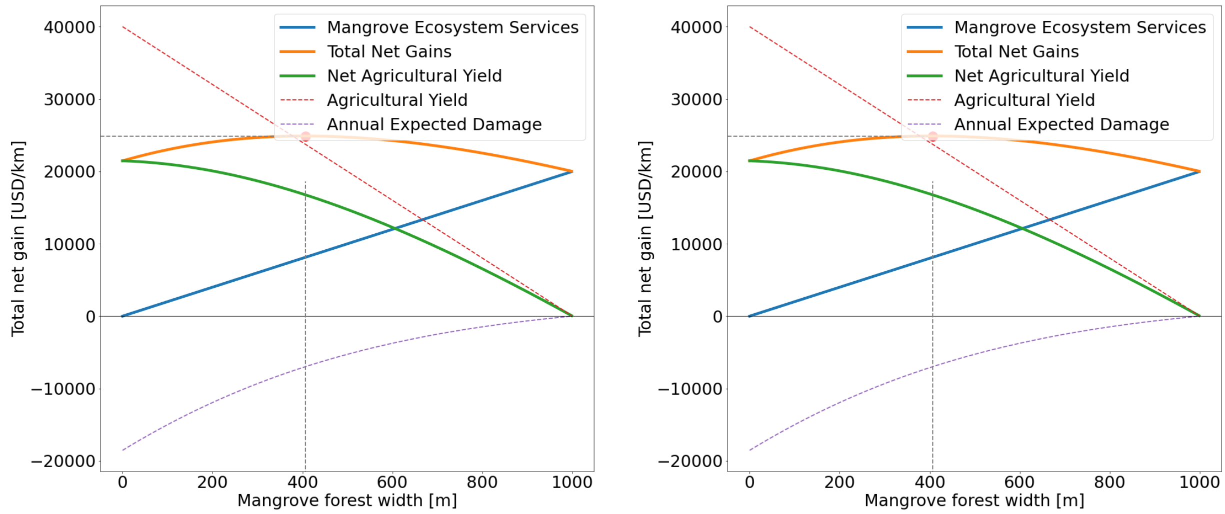

Figure 4.10: Results of the opportunity costs model. The solid blue line represents the ecosystem services and increases with the mangrove forest width. The solid green line represents the net agricultural yield, defined as the potential agricultural yield minus annual expected damage (dashed lines). The solid yellow line represents the total net gains. The optimal location of the levee is where these total net gains are maximum.

meters maximum, respectively. The net total gain is, in this example, at a mangrove forest width of 380 meters. For a different distribution of storm surge and levee height, this optimum shifts. For a higher levee height, the failure probability decreases and therefore more land may be used for agriculture.

Figure 4.11 presents how the optimal mangrove forest width changes for the ratio of ecosystem services relative to the agricultural yield. If the ecosystem services fall between 85% and 100% of the agricultural yields, it is not feasible in this example to give up mangroves, due to the annual expected damage that must be deducted from the agricultural yields. For decreasing ecosystem services, the optimal mangrove forest width decreases exponentially to “no mangrove forest” if the ecosystem services are below 5% of the agricultural yield.

Although this graph will be different for different levee heights and distributions of the storm surge and wave attenuation rate, it nevertheless shows how the ecosystem services do not need to be as high as the agricultural yield in order to maintain the entire mangrove forest.

4.2.1. Risks of Agriculture at Mangrove Areas

Although giving up mangroves in favor of agriculture might seem appealing at first for local communities to maximize their wealth, in the long-term this might not hold. Due to the disappearance of mangroves, the coast might erode, which makes the land useless for both agriculture and mangroves (Van Wesenbeeck et al., 2015). Agricultural soil might also be prone to salinization due to occasional flooding or sea water seepage, which makes the soil unfit for crop cultivation (Hamilton and Snedaker, 1984). Moreover, agricultural yields on reclaimed mangrove soil typically are lower than other agricultural soil

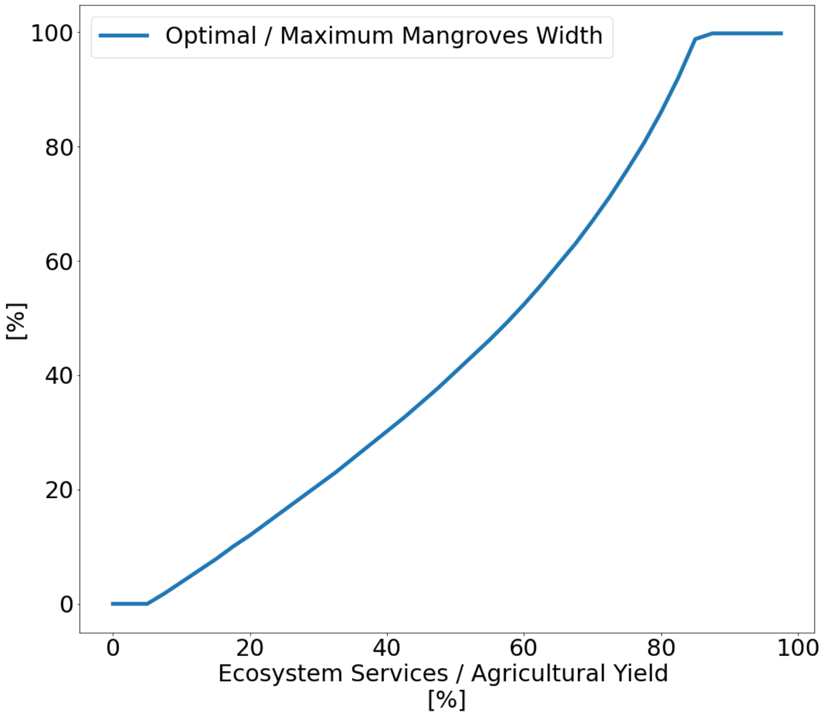

Figure 4.11: This graph presents the optimal mangrove forest width as a percentage of the maximum mangrove forest width, depending on the ratio between ecosystem services and agricultural yield. The basis of this graph is the values in Table 4.1. Giving up mangroves for agriculture becomes feasible if the ecosystem services are below 85% of the agricultural yield.

(Hamilton and Snedaker, 1984). Lastly, examples of reclaiming mangrove areas in favor of agriculture show this might be an irreversible practice (Hamilton and Snedaker, 1984). These risks while taking into account that agricultural yields are disappointing, or even nonexistent should be considered when reclaiming mangroves.

5

Economic Optimization of Levee-Mangroves Systems: Modelling Approach

5.1. Flood Risk Model

Chapter 4 the model used to find the optimal mangrove forest width and levee height. In this chapter, the same approach is followed as in the analytical model, which consists of the following steps:

1. Define the hydraulic conditions such as storm surge and wave height.
2. Define the costs for levee construction, mangrove restoration, and flood damage.
3. Calculate the optimal mangrove forest width
4. Calculate the optimal levee height by considering the mangrove forest width.

Compared to the analytical model, the modelling approach includes distributions of variables which enable a probabilistic analysis with a FORM analysis. This FORM analysis makes it possible to deal with uncertainty in levee-mangroves systems. By incorporating SWAN calculations, wave attenuation is modelled instead of using a decay factor c.

5.1.1. Model Input Formulas

Total costs are optimized by choosing the optimal combination of levee height, mangrove forest, and Annual Expected Damage (AED). Analytical functions need to express the costs of the levee, mangroves, and the associated damage to optimize the flood risk reduction measure. Since mangroves

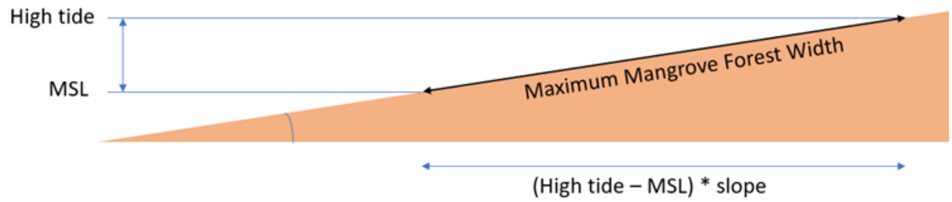

Figure 5.1: Schematization of the maximum mangrove forest width. Mangroves grow between MSL and high tide. Depending on the slope of the coast and difference between MSL and high tide, the maximum mangrove forest width can be calculated, presented by Equation (5.1)

grow from MSL to the highest tide water level, the maximum mangrove width can be expressed as a function of these levels and the average bed slope, as schematized in Figure 5.1:

$$\text{maximum mangrove forest width} = \sqrt{((\text{high tide} - MSL) * slope)^2 + (\text{high tide} - MSL)^2} \tag{5.1}$$

The optimal mangrove forest width will be between zero and this value. If the mangrove forest width is constrained by other reasons, such as a physical obstacle, this maximum mangrove forest width should be included manually.

Figure 1.1 shows that the crest height of the levee depends on the surge height and allowed wave run-up, similar to the analytical approach in Chapter 4. Wave run-up decreases when mangroves can successfully attenuate waves and thereby decrease the crest height of the levee. Wave set-up depends on the breaking wave height, relying on the water depth and the significant wave height ($H_{s,0}$). The wave height and the wave run-up decreases with wave attenuation by mangroves.

In the analytical approach taken in Chapter 4, the levee height was set equal to the sum of the water level and wave run-up. In the numerical model, wave overtopping discharge determines failure, according to Van der Meer et al. (2016). Equation (5.2) gives the wave overtopping for design or assessment approaches. The wave overtopping can be chosen freely and should be based on the strength and shape of the levee. A maximum discharge of 0.1 l/m/s corresponds to a value of $\phi = 8$ in the wave run-up formula applied in the analytical approach - a conservative assumption. A maximum discharge of 10 l/m/s corresponds to a multiplication factor of $\phi = 5$. The formula in Equation (5.2) shows an exponential relation to the wave height, whereas in the analytical model this is a linear relationship. If the wave height is above 1 m, this increases the need for wave attenuation by mangroves. However, if the wave height is below 1 m, this decreases the impact of wave height on wave overtopping and therefore failure probability.

$$q = \left(\frac{0.026}{\sqrt{\tan(\alpha)}} \gamma_b \zeta_{m-1,0} \exp\left[-\left(2.5 \frac{R_c}{\zeta_{m-1,0} H_{m0} \gamma_b \gamma_f \gamma_\beta \gamma_v} \right)^{1.3} \right] \right) \sqrt{g H_{m,0}^3} \tag{5.2}$$

5.1.2. Costs of the Levee

In the numerical model, the costs of the levee can be split up into three categories: fixed, variable, and maintenance costs. Costs of the levee can be calculated either from a bottom-up or top-down approach. In the bottom-up approach, each segment of costs is considered, such as labor, material, construction, purchase of land, and rocks or revetment to protect the levee. In the top-down approach, the levee costs are consolidated to costs per kilometer levee, per meter raising. The total costs of the levee also depend on the length of the coast. The total costs of the levee can be expressed as follows:

$$\text{total levee costs} = (F_{D_{m}^{-1}} + V_{D_{m}^{-2}} h_D + M_D) L_C \quad (5.3)$$

F_D represents the fixed costs in USD per meter width, V_D the variable costs in USD per m width and m height, and M_D stands for the maintenance costs of the levee in USD per meter width.

Since a top-down approach was used, variable costs increase linearly. There is no distinction between the first meter and the final meter raise of the levee. When a levee is being built for the final meter, more material (sand) and stronger revetments (larger rocks) are needed. This may lead to above-linear increases in costs. In a more advanced version of the model, this could be considered.

5.1.3. Costs of the Mangroves

For the mangroves, the same two approaches as for the levee costs can be applied - either bottom-up or top-down. As noted, a top-down approach was used, segmented into planting (or restoration), a permeable structure, and hydrologic restoration. The approach is case-specific in that measurements (planting, a permeable structure, or hydrologic restoration) are required. Once again, maintenance is, considered separately. Under the right circumstances, a mature forest can be self-sufficient.

The maintenance is calculated similarly to Equation (5.5). The planting depends on the mangrove forest area, while the costs of the breakwater depend on the length of the coastline which must be defended. Hydrologic restoration consists of filling or excavating soil, which depends on the necessary changes to the coast. The maintenance of the breakwater is required only as long as the mangroves cannot decrease the wave energy sufficiently. Mangroves also provide ecosystem services, and these services can be deducted from the total costs. The total cost of mangroves can be expressed as follows:

$$\begin{aligned} \text{total mangrove costs} &= (F_{M_{m}^{-1}} + V_{M_{m^{-2}}} W + M_M) CL \\ &+ \text{breakwater costs incl. maintenance} \\ &- \text{ecosystem services} \end{aligned} \quad (5.4)$$

$V_{M_{m^{-2}}}$ represents the restoration costs in USD/m^2 and M_M the mangrove maintenance costs in USD/m.

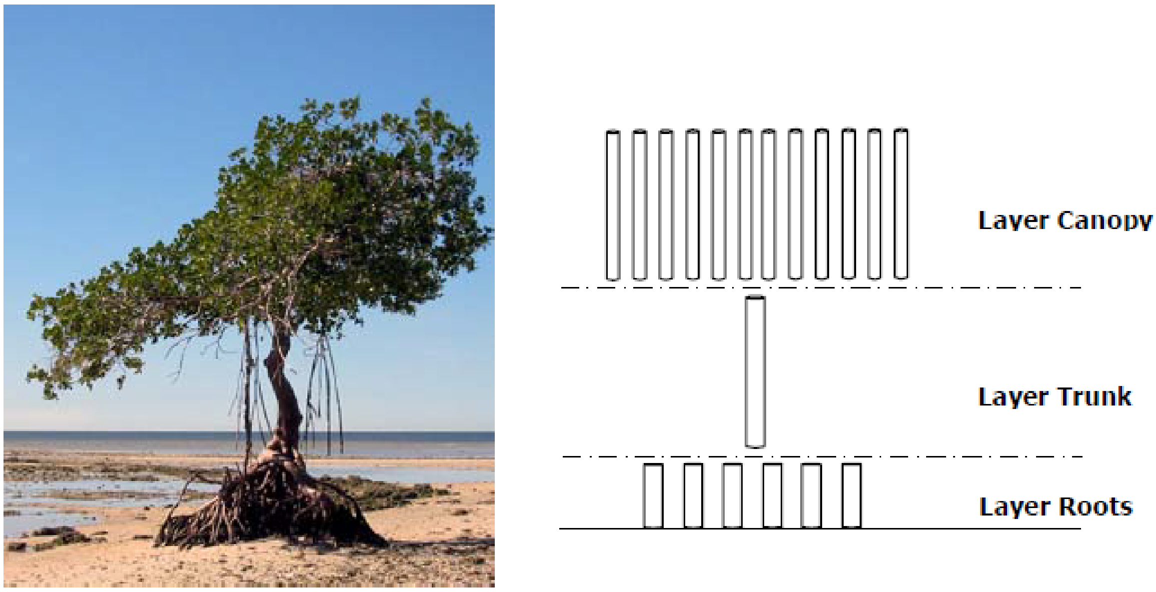

Figure 5.2: Schematization of mangroves in the model by Burger (2005). The roots, trunk and canopy are distinguished and can be incorporated into the model separately.

5.1.4. Maintenance costs

Maintenance costs are considered by calculating the net present value, which can be described using the structure's lifetime, and a yearly discount factor.

$$PV = \sum_{t=t_1}^{n} \frac{M_t}{(1+r)^t} \tag{5.5}$$

M_t represents the maintenance costs in year t in USD, n the lifetime of the structure, and r the yearly discount rate. Since the yearly maintenance is taken into account and transformed to the present value, the lifetime is a required variable and thus influences the optimal level of mangrove width. A higher discount rate r leads to a lower present value of the maintenance costs. When the maintenance costs of a levee are higher than the maintenance costs of mangroves, a higher discount rate will make mangroves more effective as a flood risk reduction measure.

5.1.5. SWAN Modelling

SWAN is a third-generation wave model developed at the Delft University of Technology. Vegetation in SWAN modelling is incorporated as structural elements, in the shape of cylinders (Dalrymple et al., 1984; Suzuki et al., 2012). Figure 5.2 gives a schematization of the mangroves. According to Janssen (2016), mangroves can be segmented into seven layers instead of three.

Four relevant parameters define the wave attenuation capacity of the mangroves in SWAN:

- Height of the mangroves [m]
- Stem diameter [m]

Table 5.1: Input values for the modelling of mangroves into SWAN, according to Janssen (2016).

	Root			**Stem**			**Canopy**		
	V_{fac}	h_v	C_D	V_{fac}	h_v	C_D	V_{fac}	h_v	C_D
Red	0.2-2.1	0.3-1	0.6-1.0	0.1-0.7	2-8	0.6-1.0	0.4-4.5	10-12	0.5
Black	0.2-2.1	0.15-0.8	0.6-1.0	0.01-0.8		0.6-1.0	0.5	9-13	0.5
Pioneer	2	1	0.6-1.0	-	-	-	1	2	0.5

- Total number of stems [$stems/m2$]
- Drag coefficient [-]

These variables are based on Dalrymple et al. (1984) and (Mendez and Losada, 2004), in which the variables are defined for each layer distinctively. These can be segmented into three main layers:

- Roots
- Trunk
- Canopy

SWAN modelling can be used to calculate the significant wave height at the toe of the structure. In order to calculate this, offshore waves are propagated towards the coast, including processes such as shoaling, local wind generation, white capping, bottom friction, depth-induced wave breaking, and wave attenuation by aquatic vegetation. For this model, a 1D SWAN model is used, with only variations in depth towards the coast. This modelled wave height at the toe of the structure can be used as a wave height input variable in Equation (5.2) to determine whether failure occurs due to overtopping.

Wave attenuation can be directly estimated based on the literature or modelled using SWAN. Although assuming a certain wave attenuation per meter, SWAN modelling makes it possible to find the wave attenuation for this specific location. However, the numerical parameters of the vegetation would still have to be assumed from the literature.

Janssen (2016) investigated wave attenuation by mangroves using SWAN modelling, based on Suzuki et al. (2012). Table 5.1 shows the parameters for red, black, and pioneer mangroves (the mangrove species in the case study area is the black mangroves). The vegetation layers are separated into seven layers to allow for the canopy changes in volume across the height of the mangrove trees.

Janssen (2016) modelled black mangroves in SWAN. Based on the SWAN adaptation of Suzuki et al. (2012) and mangrove characteristics based on the literature, he divided the mangroves into three layers and then subdivided the second and third layers again into three layers each. He used parameters given in Table 8.7 for modelling mangroves in SWAN. In the SWAN model, the diameter is multiplied by the number of stands per m^2. Janssen (2016) varied the diameter instead of the number of stands per m^2, leading to the number of stands per m^2 is being set to 1.

Table 5.2: Input values for the mangrove modelling of black mangroves in SWAN, according to Suzuki et al. (2012) and Janssen (2016). The layers correspond to the roots (1), trunk (2) and canopy (3). The trunk and canopy layers are subdivided into three separate layers.

Variable/Layer	**1**	**2**	**2**	**2**	**3**	**3**	**3**
Height	0.4	3.4	5.067	6.733	8.4	10.067	11.733
Number of stands/m2	1	1	1	1	1	1	1
Diameter	1.2	0.1	0.4	0.7	1	0.667	0.333
Drag coefficient	0.6	0.6	0.5	0.5	0.5	0.5	0.5

5.1.6. FORM Analysis

The FORM analysis requires a limit state function (LSF) to determine when a failure occurs. In the model, the failure mechanism is wave overtopping discharge, but another failure mechanism could be the wave impact. Equation (5.6) shows that failure occurs if the LSF is below zero. This occurs when the wave overtopping is higher than the critical wave overtopping which the levee can withstand.

$$Z = q_{crit} - q < 0 \tag{5.6}$$

The results of the FORM analysis are a β indicating the failure probability, and an α for each variable included as distribution instead of a deterministic value. If the LSF responds strongly to changing a variable, its alpha in absolute terms will be large. A high alpha therefore indicates the high relative importance of this variable in the failure probability. The sum of the alphas squared is equal to 1.

The calculations start with an initial estimate of the design point. The eventual design point represents the set of variable values leading to failure.

6

Application of the Analytical Model

In this chapter, first the mangrove restoration costs and levee costs are assessed, based on literature. Other variables which detremine the optimal mangrove forest width are also defined in literature. With these common values based on literature, the model is applied to see how the variety in estimates changes the outcome of the optimal mangrove forest width.

6.1. Mangrove Costs

In this section the model is applied for values representing possible cases. All parameters, provided as a bandwidth, are based on prior studies in the literature. An analysis is done in which average values are used, except for one variable that was varied. This enables seeing the variety in parameter values and its effect on the optimal mangrove forest width. Thirty years are assumed for the lifetime, used in the calculations of the net present value of costs.

Three methods can be distinguished for determining the costs of mangrove restoration:

- Planting
- Permeable structure
- Hydrologic restoration

Only one of the three methods is necessary. These costs include maintenance costs, which is required only for the first four or five years, after which the mangrove forest can sustain itself.

Bayraktarov et al. (2016) analyzed the mangrove restoration costs based on the restored area (see Section 2.1). For a higher restoration area, lower average costs per hectare might be expected. The data is presented in Figure 6.1. If the restoration area is low, costs per hectare are relatively high.

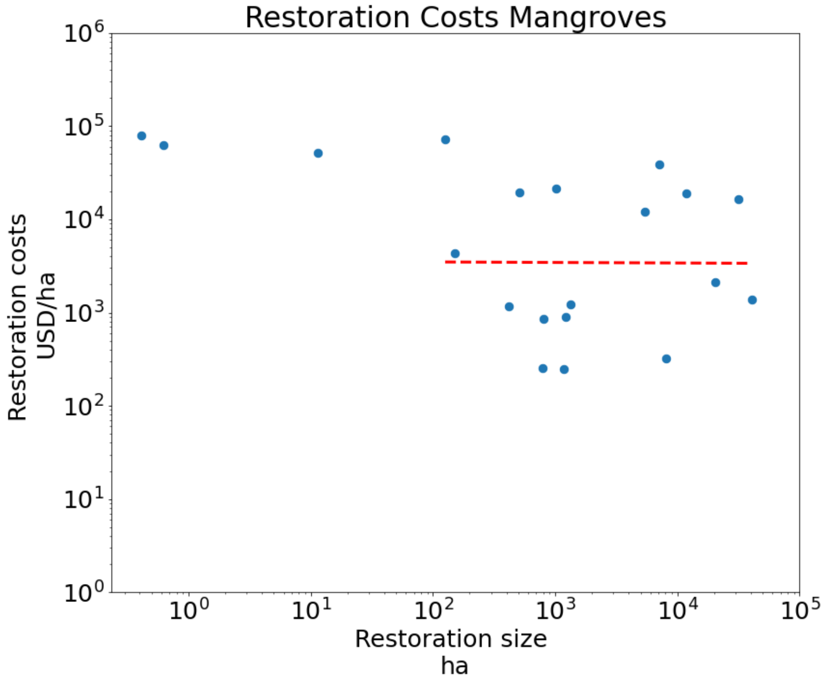

Figure 6.1: Relationship between total cost per unit area (USD/ha) and area restored (ha) for the restoration of mangroves. The costs for small restoration areas until 10 ha are not included in the fitting line. The points are remade from Bayraktarov et al. (2016).

A trend in to lowering costs in the case of a larger restoration area can be observed. However, it is unlikely that a mangrove area for flood risk reduction would be around 10 ha. No downward trend can be found in the costs of mangroves, considering the larger restoration areas.

For the data points larger than 100 ha, a normal distribution was defined. This distribution is shown in Figure 6.2. The median costs for mangrove planting are 3,434 USD/ha. The 85th and 15th percentiles give costs of 22,116 USD/ha and 533 USD/ha, respectively.

The median survival rate of mangroves was 51.3% (Bayraktarov et al., 2016). This rate is lower for developing countries, standing at 44.7%, implying that it is necessary to redo restoration projects once to achieve a full restoration. Another important ratio involves deciding which parts of the costs are fixed and which are variable. Since the trade-off between a higher levee and more mangroves depends on the variable costs, this strongly determines the attractiveness of mangroves.

Since mangroves are less capital intensive but more labor intensive, and the costs do not differ considerably for larger restoration areas, it is assumed that the costs are all variable costs. Using local labor for the restoration is preferred so as to improve the local communities' connection with a project and to make it beneficial for the local economy, where low-skilled labor is often highly available. These factors underpin the reasoning to assign all costs as variable.

Maintenance and monitoring of the forest is necessary for the first four years after restoration (Narayan et al., 2016). These yearly costs are approximately 10% of the investment costs before applying the survival rate. The present value of the total costs would increase by 33% to account for

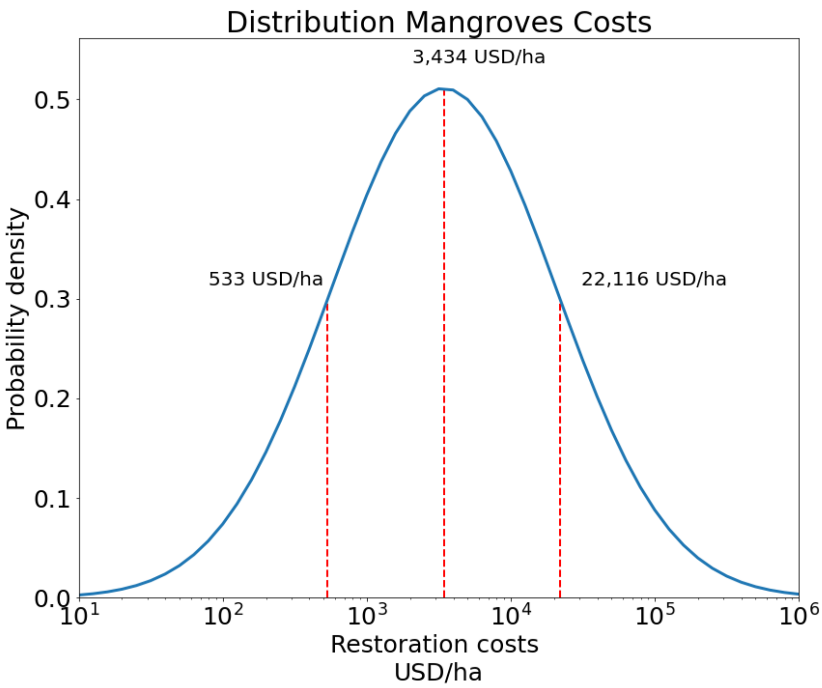

Figure 6.2: Normal distribution derived from the mangroves cost data found in Bayraktarov et al. (2016), including the restoration areas of above 100 ha. Note the logarithmic scale at the x-axis. This implies that the costs vary around the mean exponentially. This distribution forms the basis of the costs of mangroves.

Table 6.1: Low, average, and high scenarios for costs of restoring mangroves in USD/ha, based on the distribution presented in Figure 6.2. A survival rate of 50% is assumed, such that restoration needs to be done twice.

Costs/Scenario	**low**	**average**	**high**
Costs per ha $	533	3,434	22,116
Maintenance costs per ha $	178	1,145	7,372
Costs per ha after survival rate in $	1,066	6,868	44,232
Total costs per ha $	**1,244**	**8,013**	**51,604**

the maintenance and monitoring costs. Table 6.1 shows an overview of the costs for mangroves.

Mangroves cannot grow if wave energy is high. A permeable structure is often used to decrease wave energy, such as a bamboo fence (Van Cuong et al., 2015). The permeability enables sediment to pass through, which is an essential element for mangrove growth, while sufficiently decreasing the wave energy, ensuring that seedlings or propagules are not washed away, and mangroves can grow.

First, a bamboo fence has to be built and then maintained for some years until mangroves have grown sufficiently enough that they can reduce wave energy and grow simultaneously. According to Indonesia and Hakim (2016); Thao et al. (2014); Van Cuong et al. (2015), the costs of a bamboo fence are 21, 55, and 70 USD per meter, respectively. Although the cost will depend on local circumstances, such as wages and availability of labor, a projected cost per meter of 60 USD/m seems a reasonable estimate based on the literature. The maintenance costs are estimated to be 4.2 and 30 USD/m

Table 6.2: Costs of different measures to enable mangroves to be restored. Generally, only one intervention measure is required, depending on the location. It is possible, however, that, for example, restoration and a permeable structure are both required. The different dimensions per measure makes it harder to assess the total costs for mangroves restoration.

Type	Unit	Average costs	Low	High
Planting	USD/ha	8,013	1,244	51,604
Permeable structure	USD/m	130	35	200
Hydrologic restoration	USD/m3	fill: 6 excavation: 3	fill: 5 excavation: 2	fill: 20 excavation: 20

(Indonesia and Hakim, 2016; Van Cuong et al., 2015). If assuming a yearly maintenance cost of 25 USD/m for four years to maintain the bamboo fence with an inflation rate of 4%, the present value of the maintenance costs is 100 USD/m. The total costs of a bamboo fence are therefore estimated at 130 USD/m.

Costs for landfill or excavation differ (Aerts, 2018). Costs for nourishments range from 4.3 to 20.6 USD/m. In developing countries such as Vietnam, costs are 5.8 USD/m. Costs for excavation or dredging are lower. Dredging and transport in the Netherlands cost 14.1 to 19.4 USD/m, but dredging in Bangladesh costs 2 USD/m. Since mangroves often grow around the equator where mostly developing countries are located, this lower limit seems more reasonable than the upper limit. Thus, costs for landfill or excavation are estimated to be 6 and 3 USD/m, respectively. However, it does depend on local circumstances, such as the availability of necessary equipment to excavate or nourish.

To conclude, the cost estimates for mangroves are given in Table 6.2. An average, low, and high value are given. Only one cost type is necessary, depending on the location. However, it is possible that planting and constructing a permeable structure are both necessary.

6.2. Levee Costs

Levee costs are estimated in the study by Jonkman et al. (2013), and a meta-analysis of levee costs was done in the research by Aerts (2018). A distinction can be made between developed and developing countries.

Table 6.3 shows that the costs for raising a levee 1 m per kilometer for developed countries is a factor 10 to 20 higher than for developing countries. From this table and studies such as Jonkman et al. (2013); Van Berchum et al. (2018), it can be estimated that the costs of raising a levee in developing countries are around 1, 1.5 and 3 USD/km per m for a low, average, and high scenario. Van Berchum et al. (2018) estimate that around 60% of the costs are fixed, while around 40% of the costs are variable.

The maintenance and management costs for levees is approximated at 1-2% of the construction costs (Jonkman et al., 2013). For a lifetime of 30 years, a hypothetical construction cost of 100 USD/m/m and maintenance and management costs of 1.5%, the present value of these hypothetical investment and maintenance costs become 112 USD/m/m. The investment costs have to be multiplied

Table 6.3: Overview of costs for levees in developed and developing countries (Aerts, 2018). Price levels are in 2016 USD.

Country	Flood Protection	Design Water Level	Unit Cost Average per m raising [Mln]
Netherlands	Sea levee	4-6m	22.9
United States	Sea levee	7m	26.4
European Cities	Sea levee	varying	26.5
Vietnam	Sea levee	n.a.	2.3 M/km (not per m raising)
Vietnam	Sea levee	3-5m	1.3
Netherlands	Rural levee	4-6m	9.5
Canada	Rural levee	n.a.	1.9
Vietnam	Rural levee	n.a.	1.35

Table 6.4: Low, average and high scenarios for costs raising a levee one meter per km. These are based on Table 6.3. The costs are then differentiated into fixed and variable costs.

Costs/Scenario	low	average	high
Construction costs per m raising per km M$	1	1.5	3
Maintenance costs per m raising per km M$	0.12	0.18	0.36
Fixed costs M$ (60%)	0.67	1.01	1.8
Variable M$ (40%)	0.45	0.67	1.34
Variable USD/m/m	448	672	1344

by 1.12 to allow for the management and maintenance costs. These costs are added to the variable and fixed costs in the same proportion as the investment costs. Table 6.4 summarizes the costs for levees in developing countries.

6.3. Sensitivity Analysis

6.3.1. Results Based on Common Values

Based on Chapter 4 and Chapter 6, a sensitivity analysis was performed to gain insight into how the different variables influence the optimal mangrove forest width.

For each variable in Table 6.5, common, low, and high values are defined. The range of values for these variables indicates how sensitive each is when calculating the optimal mangrove forest.

The common values are based on the literature and were used to calculate the optimal mangrove forest width and optimal levee height. For the variables that are relevant to determine the optimal levee height, but not the mangrove forest width (A, B, D and r), reasonable values are chosen. Note that in the analytical approach A and B, related to storm surge, are not influencing the optimal mangrove forest width: but since offshore wave height is dependent on the water level, are, in reality important to determine the optimal mangrove forest width.

Table 6.5: Low, common and high values for the variables in the analytical approach. These lower and upper bounds are based on calculations in Chapter 6 or the literature. The ecosystem services can be deducted from the mangrove costs.

Variable	**Dimension**	**Low values**	**Common values**	**High values**
c	m^{-1}	0.00126	0.00146	0.00167
$H_{s,0}$	m	0.5	1.5	3
ϕ	-	5	8	9
$\tan(\alpha)$	-	0.2	0.25	0.4
I_D	USD/m/m	448	672	1344
I_M	USD/m/m	0.12	0.80	5
ecosystem services	USD/m/m	0	0.3	0.8

Table 6.6: Outcome for the optimal mangrove forest width and levee height, derived from the analytical approach. The values are derived from the literature studies. The first W_{opt} and $h_{D,opt}$ are calculated excluding the ecosystem services. The second W_{opt} and $h_{D,opt}$, shown in the last two rows, include the ecosystem services which mangroves provide.

Variable	**Symbol**	**Dimension**	**Values**
Wave attenuation rate	c	m^{-1}	0.00146
Initial elevation	E_0	m	0
Storm surge variable	A	m	1
Storm surge variable	B	m	0.5
Wave height	$H_{s,0}$	m	1.5
Levee parameter	ϕ	-	8
Levee talud	$\tan(\alpha)$	-	0.25
Damage	D	USD/m	500
Discount rate	r	%	10
Levee costs	I_D	USD/m/m	672
Mangroves costsI_M	USD/m/m	0.80	
W_{opt}	m	892	
$h_{D,opt}$	m	3.2	
Mangrove ecosystem service	S	USD/m/m/year	0.03
W_{opt} incl. ecosystem services	m	1214	
$h_{D,opt}$ incl. ecosystem services	m	2.9	

For mangroves to be an attractive option, the following inequality must hold:

$$\frac{I_M}{I_D} < c\phi H_{s,0}\tan(\alpha) \tag{6.1}$$

The optimal mangrove forest width can then be calculated with the following mathematical relation:

$$W_{opt} = \max\left[\frac{1}{c}\ln\left(\frac{cI_D H_{s,0}\phi\tan\alpha}{I_M - \frac{S}{r}}\right), 0\right] \tag{6.2}$$

in which I_M the mangrove costs in USD/m/m, I_D the levee costs in USD/m/m, c the wave attenuation in m/m, ϕ a constant depending on the dimensions and strength of the levee, and $H_{s,0}$ the wave height at the toe of the levee in case of no mangroves. S are the ecosystem services in USD/m/m/year and r the discount rate. When substituting average numbers in Equation (6.2), the inequality as in Equation (6.3) leads to a minimum wave height of 0.4 m for mangroves to be an effective measure for flood risk reduction. Following the same reasoning, for an optimal mangrove forest width of 1 km, the wave height to be attenuated by mangroves would need to be 1.76 m (excluding the ecosystem services).

$$\frac{0.8}{672} < 1.46\cdot 10^{-3}\cdot 8\cdot H_{s,0}\cdot 0.25 \tag{6.3}$$

For common values of wave attenuation ($c = 1.46\cdot 10^{-3}m^{-1}$), $\phi = 8$ and $\tan(\alpha) = 0.25$, the variable mangrove restoration costs [USD/m/m] must remain below 0.003 times the variable levee costs [USD/m/m] for each meter of significant wave height:

$$I_M < 0.003H_{s,0}I_D \tag{6.4}$$

To protect 1 km of coast with a wave height of 1 meter and variable levee costs of 600,000 USD/km per m raising, variable mangrove costs should remain below 1,800 USD/km/m, equivalent to 18,000 USD/ha.

Figure 6.3 shows how combinations of wave height and wave attenuation affects the allowable ratio in costs of mangroves and levees. For a high wave height and high wave attenuation, mangrove costs may be relatively high compared to levee costs and remain economically effective.

Figure 6.4 shows how the optimal mangrove forest and corresponding minimum costs and failure probability change for different storm surge levels. In situations of a high storm surge and low levee height, mangroves add most value because wave height can become high, and the protection level is low due to the low levee height.

6.3.2. Sensitivity Analysis of the Variables

The figures below show how each range of values affects the optimal mangrove forest width. In this analysis, the optimal mangrove forest width and optimal levee height are calculated using the common values based on literature, shown in Table 6.6, except for one variable which is varied in the calculations.

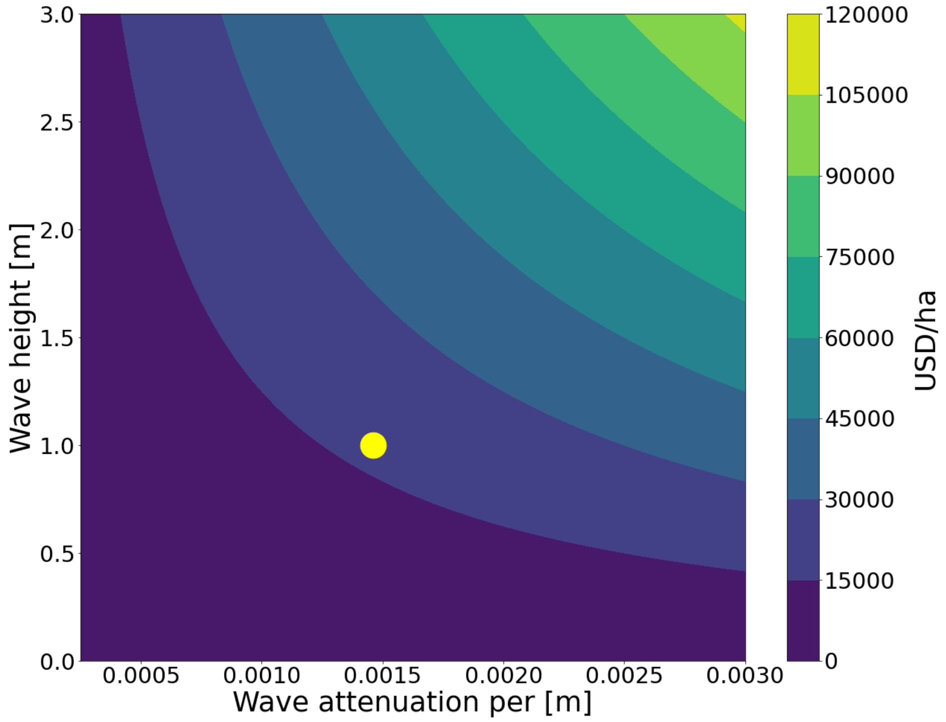

Figure 6.3: This graph shows the maximum mangrove costs for which it is economically effective to restore mangroves. This graph is based on variable levee costs of 600,000 USD/km per m raising, and common values for levee strength ($\phi = 8$) and levee talud ($\tan(\alpha) = 0.25$). The maximum mangrove costs depend on the combination of wave height and wave attenuation. The example of wave attenuation of $c = 1.46 \cdot 10^{-3} m^{-1}$ and wave height of 1 m is indicated by the yellow dot.

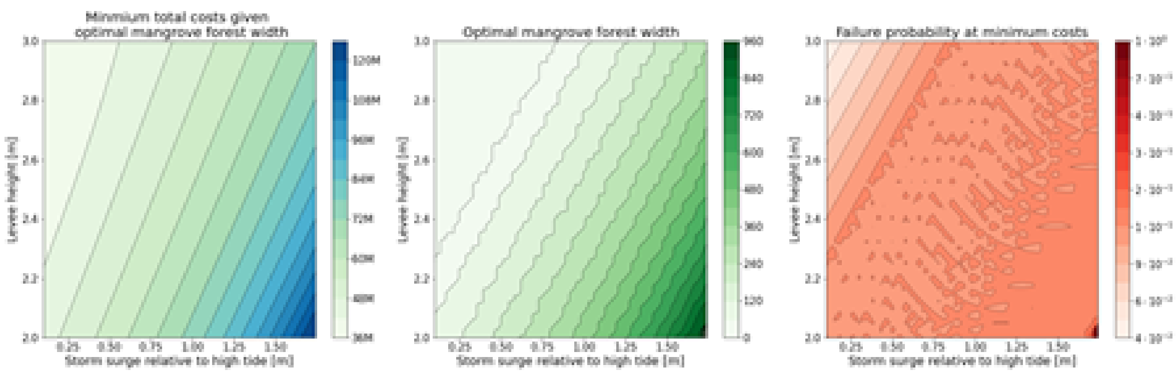

Figure 6.4: These graphs show how an a higher storm surge (x-axis) changes the total costs (left graph), optimal mangrove forest width and the failure probability at the optimal combination of levee and mangroves. Higher storm surge increases the optimal mangrove forest width (middle graph), and increases the failure probability corresponding to minimum costs (right graph). The right figure containing the failure probability at minimum costs is a blurred due to the linear extrapolation to visualize the values.

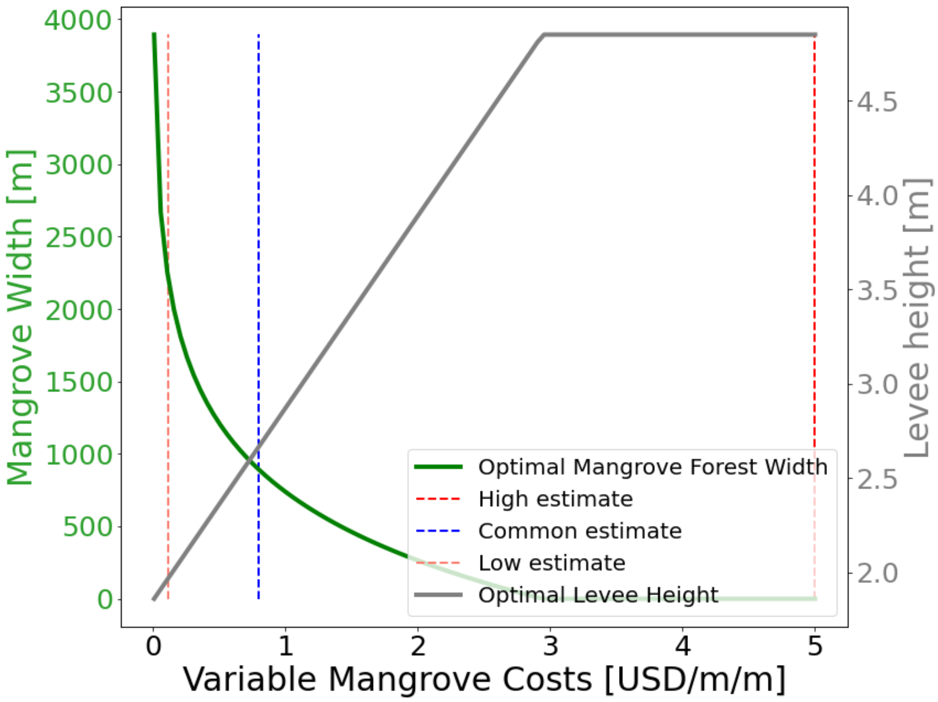

Figure 6.5: Optimal mangrove forest width and optimal levee height for varying variable mangrove costs [USD/m/m], according to the analytical model. For a common estimate of the mangrove restoration costs based on literature, the optimal mangrove forest width is around 900 meters. The optimal width decreases exponentially with the costs for restoration. The dashed lines represent the low, common and high estimates for variable mangrove restoration costs, based on literature. The wide range shows the need to assess mangrove restoration costs locally and depends, for example, on what measures are required to restore mangroves: a permeable structure, planting or hydrologic restoration.

In this analysis, any restrictions on the maximum levee height or mangrove forest width or levee height are ignored.

First, the optimal mangrove forest width is calculated according to Equation (4.9):

$$W_{opt} = \text{max}\left[\frac{1}{c}\ln\left(\frac{cI_D H_{s,0}\phi\tan\alpha}{I_M - \frac{S}{r}}\right), 0\right]$$

Second, using this optimal mangrove forest width, the optimal levee height is calculated according to Equation (4.18):

$$h_{D,opt} = -E_0 + \phi H_{s,0}\tan(\alpha)e^{-cW} + A + B\ln\left(\frac{D}{rI_D B}\right)$$

Figure 6.5 shows how the optimal mangrove forest width decreases exponentially with variable costs of mangrove restoration. For zero variable costs, the optimal forest width goes to infinity. However, mangrove cost estimates range from 0.12 USD/m/m to 5 USD/m/m, equivalent to 1,200 USD/ha and 50,000 USD/ha, respectively. This is a broad range and therefore leads to uncertainty in the assessment of whether restoring mangroves for flood risk reduction is feasible. Local assessments have to determine what the costs are for a specific location. This will depend, for example, on what measures

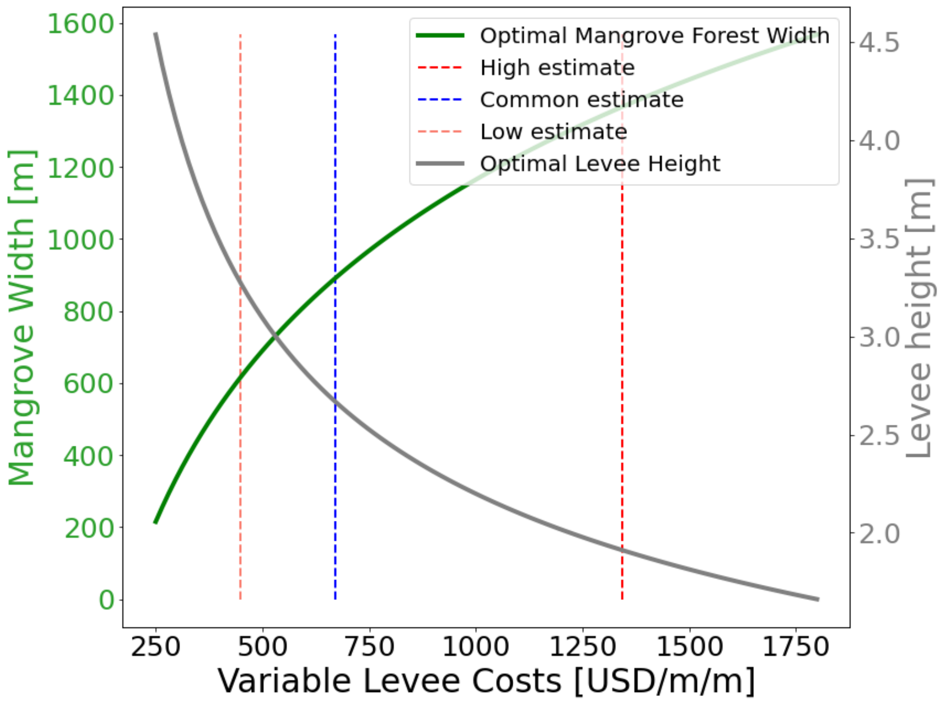

Figure 6.6: Optimal mangrove forest width and optimal levee height for varying variable levee costs [USD/m/m], according to the analytical model. For a common value of variable levee costs based on literature, the optimal mangrove forest width is around 900 meters. The optimal mangrove forest width increases with levee costs. The curvature in the optimal mangrove forest width line represents the exponential decay of wave height as a function of the forest width. The dashed lines represent the low, common and high estimates for variable levee costs, based on literature. These estimates relate to costs of a levee in developing countries.

are required to restore mangroves: a permeable structure, planting, or hydrologic restoration.

Figure 6.6 shows how the optimal mangrove forest width increases with variable levee costs. For very low levee costs, the optimal mangrove forest width is zero. For these variable levee costs, in order to decrease failure probability, it is more cost-efficient to increase the height of the levee than to increase the restored mangrove forest width. Variable levee cost estimates range from 448 to 1344 USD/m/m, equivalent to total (fixed and variable) costs of 1 to 3 million USD/km. These estimates relate to costs of a levee in developing countries. Within this range, and for common values of the other variables in the model, the optimal mangrove forest width varies from around 500 to 1300 m.

Figure 6.7 shows how the optimal mangrove forest width and optimal levee height change depends on the wave attenuation rate. For very low wave attenuation rates, the optimal mangrove forest width is zero, implying that mangroves are too expensive for the advantage they provide (decreasing wave height and therefore wave run-up). For increasing wave attenuation, the optimal mangrove forest width increases rapidly to its peak, after which it decreases gradually again. This gradual decrease is due to the exponential decay in wave height reduction by mangroves. The wave attenuation rates range from $1.26 \cdot 10^{-3} m^{-1}$ to $1.67 \cdot 10^{-3} m^{-1}$, equivalent to a 12% to 15% wave reduction for the first 100 m of mangroves. For common values of the other variables in the model based on the literature, the wave

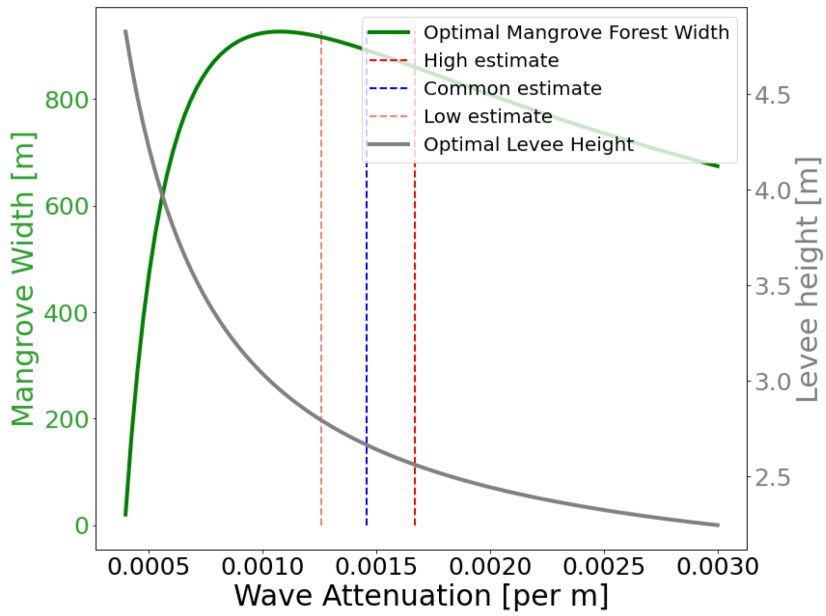

Figure 6.7: Optimal mangrove forest width and optimal levee height for varying wave attenuation rates [m^{-1}], according to the analytical model. The green line represents the optimal mangrove forest width, the grey line represents the optimal levee forest width. The vertical lines represent the low, common and high estimate of the wave attenuation rate, based on SWAN modelling. First, W_{opt} is calculated and is then substituted into the calculation of the optimal levee height. For very low wave attenuation rates, the economic effectiveness of mangroves disappear. However, when the threshold of sufficient wave attenuation is passed, the optimal mangrove forest width decreases rapidly. If wave attenuation rates increase beyond a certain value, in this graph around $1.0 \cdot 10^{-3} m^{-1}$, then the optimal mangrove forest width gradually decreases, since fewer mangroves are then sufficient to decrease the wave height. The levee height remains the same, since mangroves are a more cost-effective measure to reduce the wave height than increasing the levee.

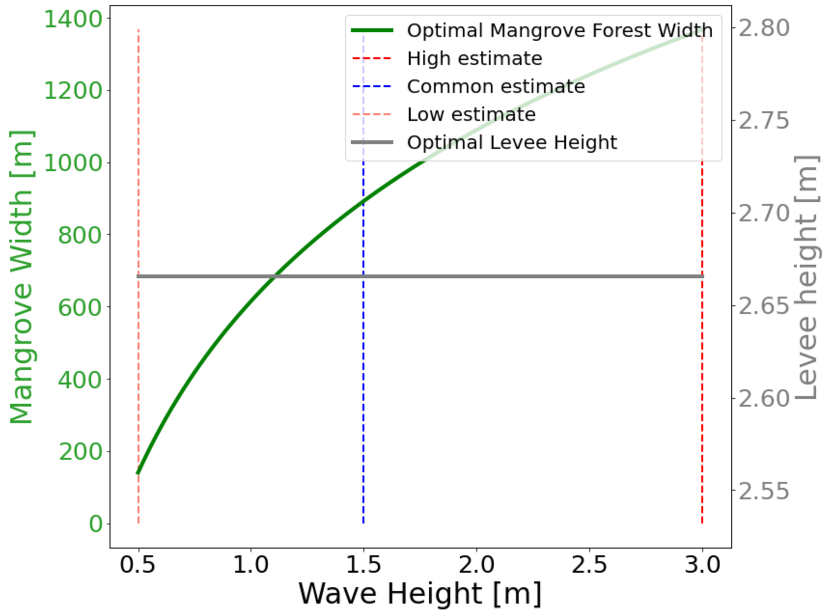

Figure 6.8: Optimal mangrove forest width and the corresponding optimal levee height for varying values of wave height [m]. The wave height has a strong influence on the optimal mangrove forest width. The green line represents the optimal mangrove forest width, the grey line represents the optimal levee forest width. The vertical lines represent the low, common, and high estimates of the wave height.

attenuation rate is sufficiently high such that the mangrove forest width is positive and beyond its peak.

Figure 6.8 shows how the optimal mangrove forest width and optimal levee height change for varying wave heights. In this analysis, the ratio between variable mangrove costs, variable levee costs and wave attenuation is favorable for mangroves. Due to this, the most cost-effective measure to withstand an increase in wave height is to increase the mangrove forest width. Because of this, the optimal levee height remains unchanged. Note, however, that this is predicated on the assumption that the mangrove forest width is unrestricted, which is not a realistic assumption. However, this graph shows how mangroves can help to limit the required height of a levee. Note also that the wave height eventually increases with storm surge. In this analysis, therefore, a higher storm surge would lead to a higher levee to withstand a higher water level and more mangroves to reduce the wave height and therefore wave run-up.

ϕ represents the strength and shape of the levee to wave run-up. A high value showing a low discharge is allowed over the levee. Low maximum discharge emphasizes the need to reduce the wave height and lower the optimal mangrove forest width. Thus, building a stronger levee decreases the effectiveness of mangroves. The same reasoning applies to $\tan(\alpha)$, which relates to the slope of the levee.

Figure 6.10 shows how the optimal mangrove forest width increases with ecosystem services provided by mangroves. If the ecosystem services are higher than the costs of restoring mangroves, the optimal mangrove forest width goes to infinity, since restoring mangroves is economically effective, irrespective of its flood risk reduction function. At the same time, the optimal levee height decreases,

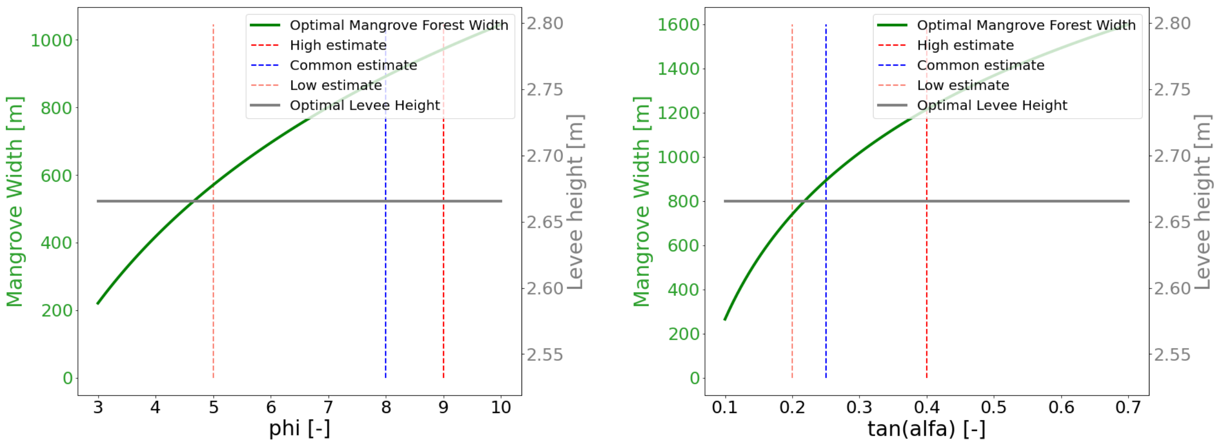

Figure 6.9: Optimal mangrove forest width and corresponding optimal levee height for varying values of (a) ϕ [-] and (b) $\tan(\alpha)$ [-]. The green lines represent the optimal mangrove forest width, the grey lines represent the optimal levee forest width. The vertical lines represent the low, common and high estimate of the ϕ and $\tan(\alpha)$. ϕ represents the strength and shape of the levee, $\tan(\alpha)$ represents the slope of the levee.

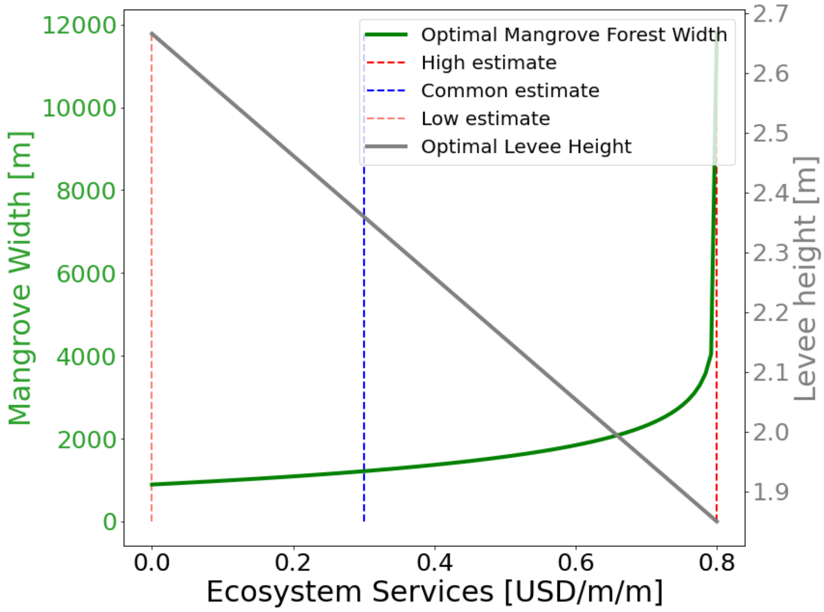

Figure 6.10: Optimal mangrove forest width and corresponding optimal levee height for varying values of ecosystem services [USD/m/m]. The green line represents the optimal mangrove forest width, the grey line represents the optimal levee forest width. The vertical lines represent the low, common and high estimate of the ecosystem services. If the ecosystem services are equal to or higher than the costs of restoring mangroves, the optimal mangrove forest width goes to infinity.

since for an infinite mangrove forest width the wave height reduces to zero at the toe of the levee.

6.4. Conclusion

The sensitivity analysis leads to the following conclusions:

- The variety in $H_{s,0}$, I_M, I_D and the ecosystem services have a large impact on the optimal mangrove forest width. These variables differ locally, which underlines the need to assess each local situation separately.
- If a large area needs to be excavated or filled with soil, I_M will become high. Planting or building a permeable structure for mangrove restoration is sufficiently cheap for mangrove restoration to be an effective measure.
- In areas where building a levee is not expensive, mangroves become a less effective option. Mangrove solutions, therefore, are more effective in high value areas where giving up land for a levee is undesirable. However, the costs of a levee must be assessed relative to the costs of mangroves. It might be that in areas where a levee is relatively inexpensive, restoring mangroves is also relatively cheap.
- Variable costs of mangroves I_M $[USD/m^2]$ should remain below $0.003 \cdot H_{s,0}$ of variable levee costs $[USD/m^2]$.
- Variation in c seems to be irrelevant for the assessment whether or not to apply mangroves. Only for low $H_{s,0}$ and high I_M this may become relevant.
- The optimal mangrove forest width depends primarily on the trade-off in investment costs. If the levee is fixed at a specific height, only then the value of the protected area becomes relevant in determining the optimal mangrove forest width.

7

Kaback (Guinea) Case Study

7.1. Introduction

Chapter 4 described the method regarding the trade-off between a higher levee and mangroves. This trade-off depends on the potential economic damages and the effectiveness of reducing the failure probability by the levee and mangroves.

7.1.1. Overview of the Location

Around 1997 a levee has been built at the ocean side of the mangroves. As a result, mangroves disappeared and agricultural land appeared. Around 2012, the levee breached and the agricultural area got flooded. After some time, the mangroves are now growing back naturally, see Figure 7.1.

The coast of Kaback is prone to flooding, since the existing levee has been breached. Mangroves by themselves do not provide sufficient protection, so a levee is required. The problem at hand is how flood risk can be reduced by a levee-mangrove combination, as described in Chapter 3.

Mangroves exist in the area in front of the coast; however, there are locations where the mangrove forest has disappeared altogether. Those are the areas where the coast is vulnerable, and restoration must occur for the mangroves to be part of the flood risk reduction. The blue area is found behind the third sandy ridge and thus offers extra protection from flooding.

Table 7.1 gives an overview of the area covered in mangrove forests, the length of the coastline, and the extend of the damaged area. There are existing mangrove forests along the entire width perpendicular to the coast. This implies that for each meter of extra mangrove forest width, a constant percentage is already there and does not have to be restored. This percentage is 35%, and this leads to the inference that 35% less restoration would be necessary to reach a certain mangrove forest width.

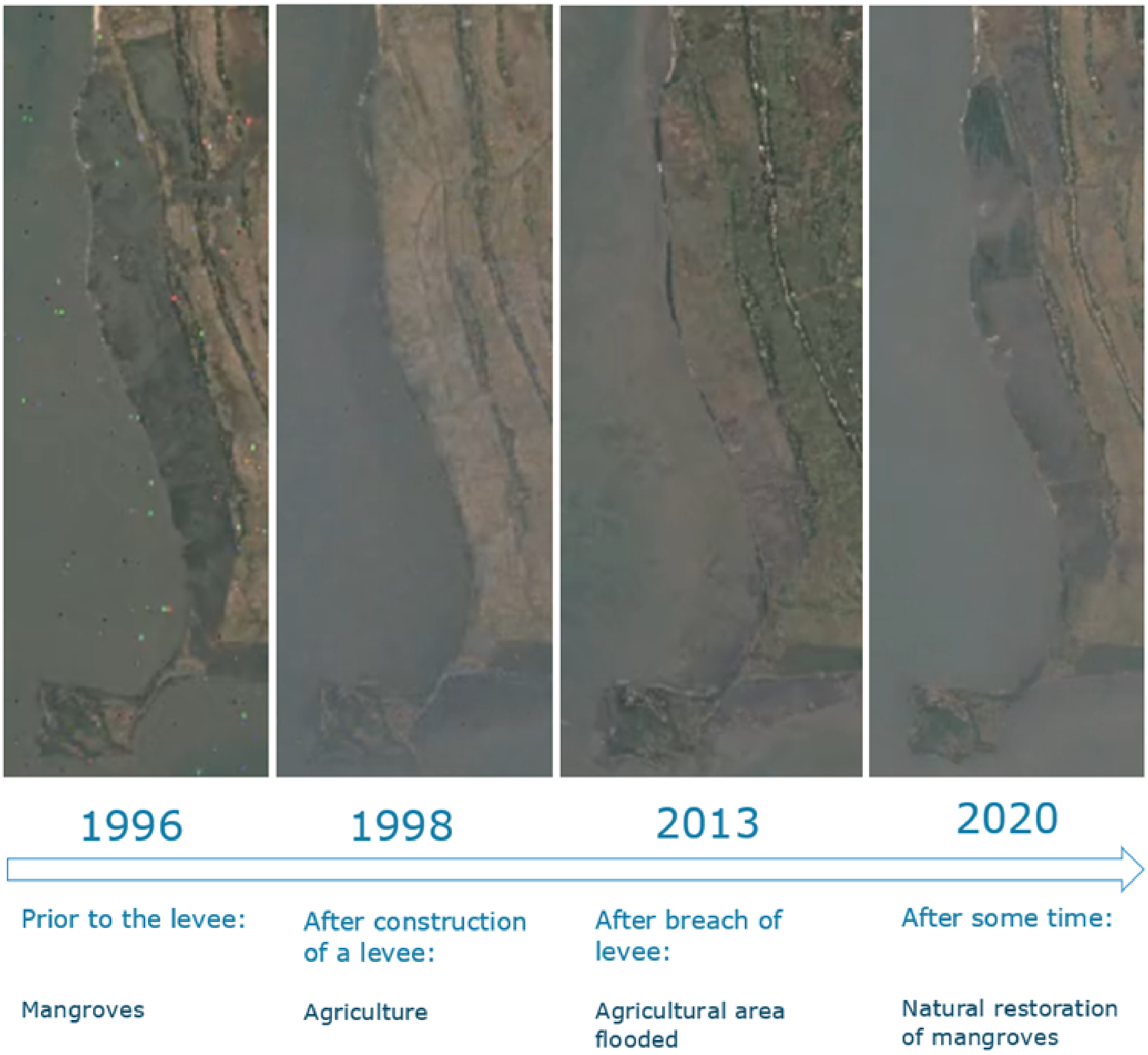

Figure 7.1: Timeline of the situation at the coast of Kaback. In 1996, a mangrove forest was present. After building a levee in 1997, the mangroves disappeared. After the levee breached in 2012, the agricultural area flooded and mangroves grew back naturally.

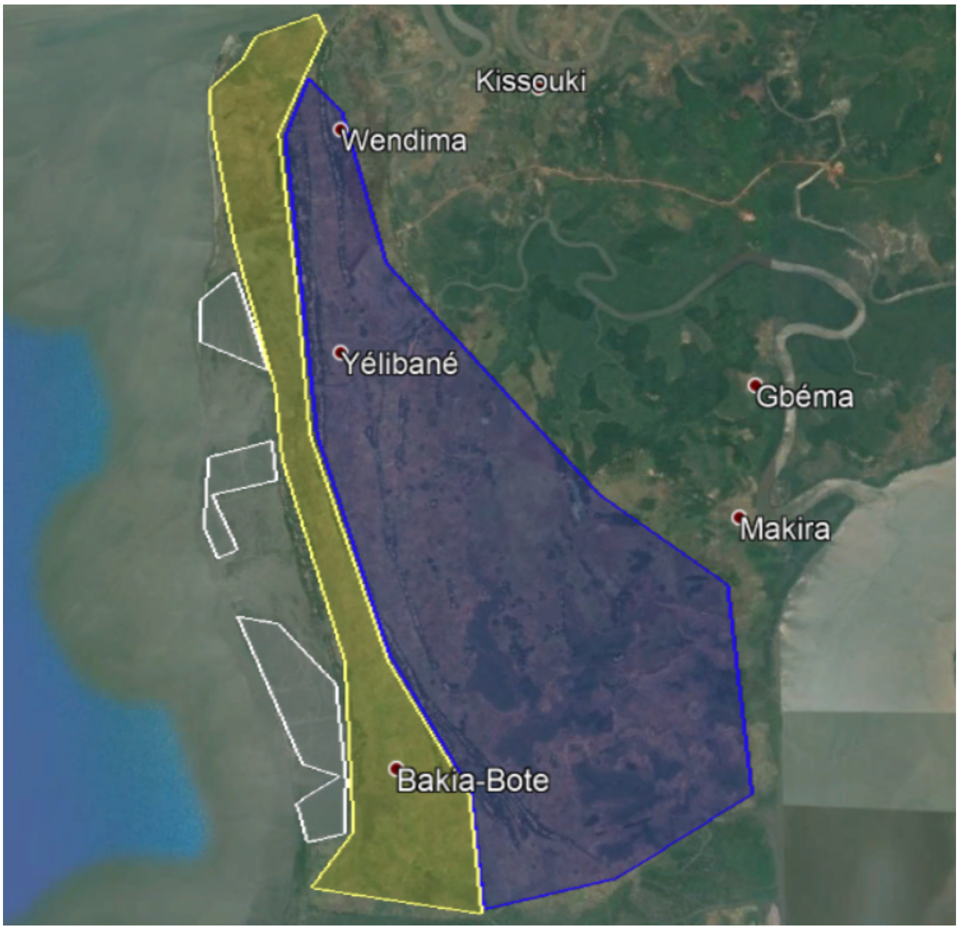

Figure 7.2: Coastal area of Kaback. The white areas show where the mangroves already exist. In between these areas, mangroves must be restored. The yellow area is the damaged area located behind the mangroves and in front of the levee. The blue area is the area behind the third sandy ridge.

Table 7.1: This table describes the current situation of the mangroves and coast near Kaback. The existing mangroves decrease the costs of restoring an extra meter of mangrove forest width.

Parameter	Unit	Value
Existing mangrove area	ha	350
Mangrove forest width	m	900
Coast length	m	11,000
Average % existing mangroves	-	35
Small damage area (yellow)	ha	1,100
Large damage area (yellow+blue)	ha	3,700

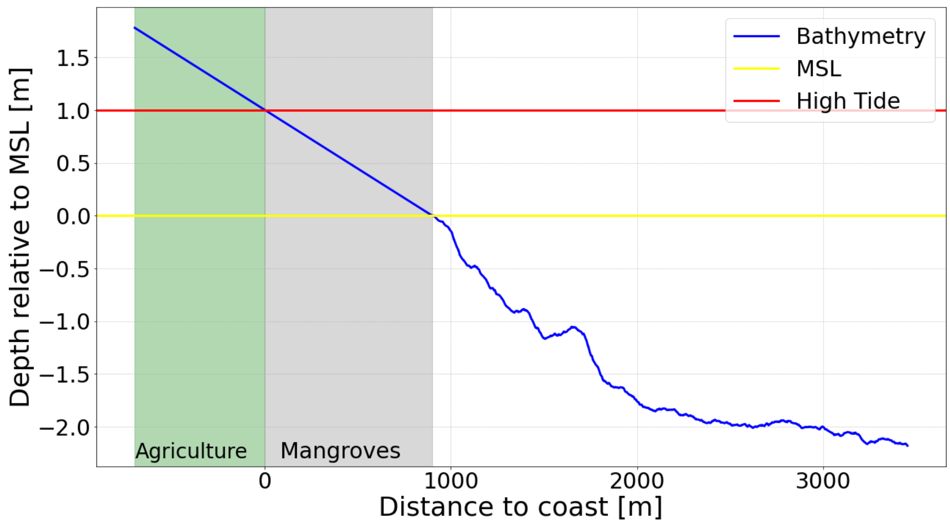

Figure 7.3: Bathymetry at the coast of Kaback. Mangroves start growing at MSL. The coastal profile from the mangroves land inwards is estimated based on measurements.

The costs to reach a certain mangrove forest width are only 65% of the total costs given in Section 7.3.1.

Figure 7.3 shows the bathymetry at the coast of Kaback. The bathymetry has been measured from the oceanside of the mangrove forest towards the ocean. Since mangroves start to grow from MSL onwards, this position is assumed to be at MSL. Based on measurements at the sandy roads through the mangrove forest, the slope at the mangrove forest is calculated at 1:900.

7.1.2. DRR-Mission to Kaback in 2017

In June 2017, a Dutch Risk Reduction (DRR) Team evaluated the coastal protection and resilience at the coast near Kaback (Reeskamp et al., 2017). The team's goal was to identify short- and long-term solutions for flood safety. The committee found that after the disappearance of the extensive mangrove forest, the living conditions in the area decreased due to frequent flooding in the area. The current levee was too weak to withstand the forces of extreme weather conditions. Flooding of the land with saltwater leads to salinization, making the area unsuitable for agriculture and the extraction

(a) (b)

Figure 7.4: Current situation of Kaback. The deforestation of the mangrove forest and previous levee breaches become clear from figure (b). There are three sandy ridges in the area. One in front of the mangroves at the sea side, one behind the mangroves at the landside, and one more inland.

of drinking water (Reeskamp et al., 2017).

Figure 7.4 presents a visual of the location. The dark green cover near the coast represents the mangroves. The mangrove forest will need to be restored so as to use it for flood risk measures.

A small village lies behind the mangrove forest that primarily cultivates rice. Even though the rice may not have a high monetary value, the local communities may depend on it. Currently, an area of around 1,500 ha remains unused (Reeskamp et al., 2017). The species Avicennias Germinans of the black mangrove family grows here. The current levee has been breached several times. The largest breach was 200 m wide in 2017 and is still growing (Reeskamp et al., 2017).

7.2. Four Options for Kaback

For the flood protection of Kaback, four scenarios are defined:

1. Do Nothing
2. Levee in front of the mangroves (yellow line in Figure 7.5)
3. Levee just behind the mangroves (red line in Figure 7.5)
4. Levee land inwards (blue line in Figure 7.5)

Figure 7.5 and Figure 7.6 show the location of the levee in the last three options. Table 7.2 summarizes the advantages and disadvantages of each location.

Table 7.2: Four different options to locate the levee, and their advantages and disadvantages.

#	Description	Advantages	Disadvantages
1	Do Nothing	No investment costs	High damage High negative social impact
2 (yellow)	Levee in front of the mangroves	More area for economic exploitation (rice)	Vulnerable for waves No mangroves
3 (red)	Levee just behind the mangroves	Mangroves can grow freely	No economic exploitation of mangrove area
4 (blue)	Levee land inwards	Mangroves can grow freely Located at a higher elevation, therefore better resistant to SLR	Area in front of levee remains unprotected

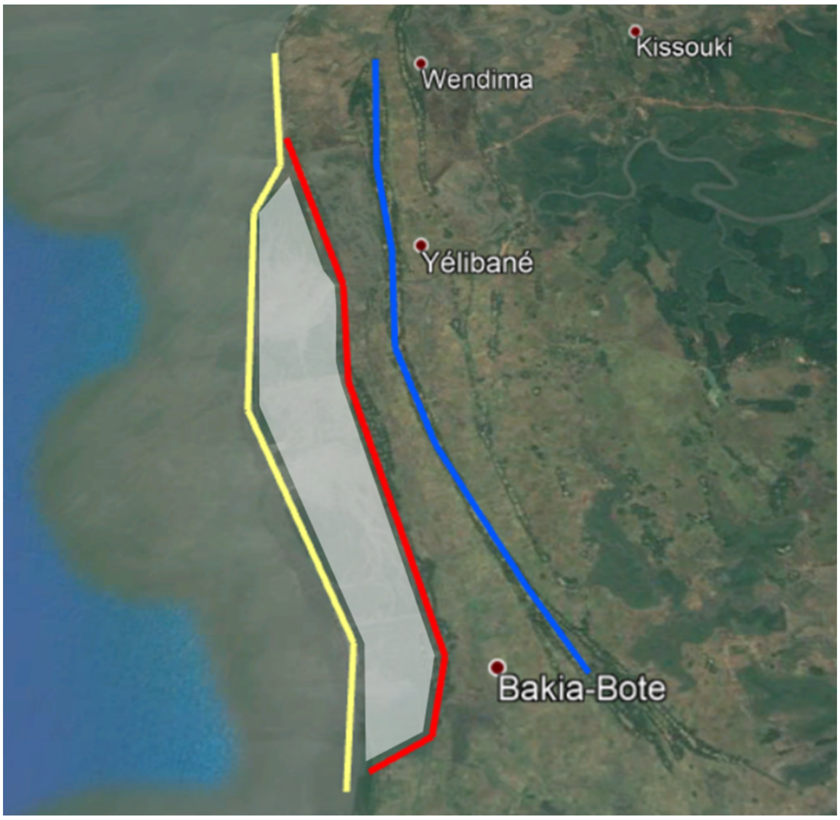

Figure 7.5: Three possible positions of a levee as incidated by the colored lines. **yellow** = in front of the mangroves, **red** = just behind the mangroves, **blue** = land inwards. The white shaded area represents the area where mangroves can grow.

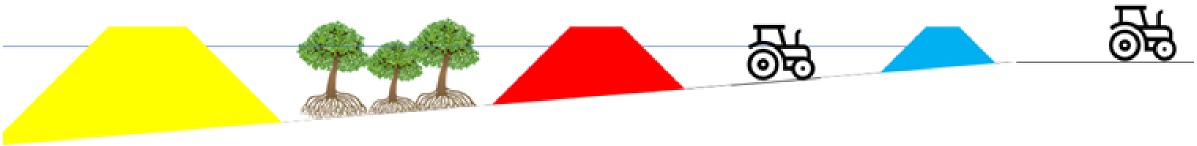

Figure 7.6: Three locations to build a levee. The colors of the levees correspond to those in Figure 7.5. The yellow levee does not allow mangroves to grow. The red levee receives protection from mangroves. The blue option is protected by mangroves and is positioned higher, such that a smaller levee suffices and it is more resilient to sea level rise. However, the agricultural land in front of the blue levee is lost due to salinization.

Table 7.3: Costs of mangroves and levee in Kaback. Due to the natural favorable circumstances for mangroves, variable costs are zero. Hydrological restoration can be achieved rather inexpensively. Due to the existing sandy ridges, building a levee is also relatively inexpensive.

	Dimension	**Fixed**	**Variable**
Mangroves	USD	64,800	
	USD/m^2		0
Levee	$MUSD/km$	0.33	0.22
	$USD/m/m$	333	224

7.3. Input Variables in the Model

7.3.1. Levee and Mangrove Costs

This section calculates the costs of the mangroves and levee. Thirty years for the lifetime are assumed, and this is used in the calculations of the net present value.

Section 2.3 and Chapter 6 discussed the costs of mangroves and levees. Since Guinea is a developing country, labor costs will be relatively low. Therefore, the costs of the levee are estimated to be on the lower end, being 1.12 million USD/km per m raising, including maintenance. The costs can be segmented into fixed and variable costs, which are 0.67 and 0.45 million USD/km per m raising, respectively, equivalent to 448 USD/m/m used in the analytical model. However, at the locations of the levee, a sandy ridge is already present. This sandy ridge acts as a natural levee, thus reducing the building costs of a levee against flooding. For this reason, the variable levee costs for Kaback are reduced by 50%, leading to 224 USD/m/m in variable costs for a levee in Kaback. This 50% represents an assumption, and the actual number could be higher. Further research is required for a more precise estimate.

When considering the costs of the mangroves, the local circumstances of Kaback must be examined. Over the last few years mangroves have been naturally regenerating on the coast of Kaback, indicating that restoration is unnecessary since enough seedlings are available to let mangroves grow. Additionally, a permeable structure is unnecessary since the wave energy is sufficiently low. However, gaps in the mangrove forest canopy are still visible. At these locations, the mangrove forest is divided by a sandy elevation with a road. These sandy elevations must be breached in order to restore water flow and allow sedimentation to flow freely through the forest. Therefore, in order to restore the mangrove forests, excavation needs to be done. Overall, there are four sandy elevations, each approximately 900 m long, 1.5 m high and 4 m wide. The total excavation of 21,600 m^3 may be needed if these sandy elevations require excavation to restore the hydrological situation and enable water and sediment flow. Chapter 6 estimates excavation at 3 USD/m^3, implying a total initial cost for mangrove restoration of 64,800 USD. These are fixed costs for incorporating mangroves into the flood defense system. Since mangroves are growing back naturally, neither planting nor a porous structure is required. The variable costs for mangroves would therefore be zero.

7.3.2. Hydraulic Variables

The storm surge is derived from the Global Tide and Surge Reanalysis (GTSR) dataset, which combines wind speed, atmospheric pressure from the ERA-Interim global atmospheric reanalysis (Muis, 2018), and tides from the Finite Element Solution hydrodynamic model (FES2012). Storm surge is then modelled based on the Delft3D Flexible Mesh software developed by Deltares. The GTSR reference level is the Mean Sea Level. The GTSR database underestimates extreme values by 0.2 m, especially around the tropics, and this underestimate is added to the extremes (Muis et al., 2017).

After applying a peak-over-threshold analysis on both dataset dates from 1979 to 2020, exponential distributions were found for tide + storm surge. The location and scale parameters in the exponential distribution are 1.95 and 0.18 for the tide + storm surge. Figure 7.7 shows this distribution.

7.3.3. Damage and Discount Rate

In the Kaback area, rice production is the primary source of income. Figure 7.8 presents the yield and price of rice in Guinea over the last few years, according to the Food and Agriculture Organization of the United Nations (FAO) (FAO, 2021). Although the yield has historically been around 1.7 tonnes/ha, it is currently around 1.35 tonnes/ha. The price has been higher in the past, but it is fluctuating. Currently, it is around 200 USD/tonne. For an area of 1,110 and 3,700 ha and 90 and 80% agricultural land, the total rice production value is estimated at 267,000 and 800,000 USD for the small and large areas, respectively. Flooding may destroy rice production for at least the year in which flooding occurs, but may be affected for a longer period of time if salinization becomes an issue.

The population of Guinea can be divided into a rural and urban population, as shown in Table 7.5 (World Bank, 2019). The agricultural area is also given, which is lower than the total rural area. It is assumed that the entire rural population is on agricultural land. The total population of the areas can be determined from these agricultural numbers. According to the population density on agricultural land, the author concludes that the population in the small and large area are 550 and 1,650 people, respectively.

The societal impact of flooding should also be considered. The GDP per capita in Guinea was 960

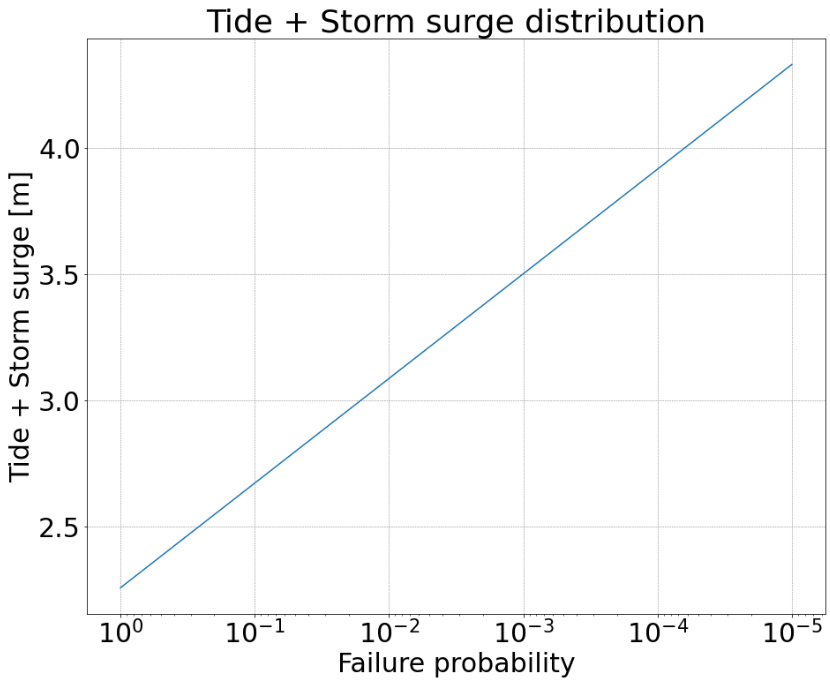

Figure 7.7: Tide + storm surge with location parameter (A) of 1.95 and scale parameter (B) of 0.18, based on data derived from the Global Tide and Storm Surge Reanalysis (GTSR) (Muis, 2018).

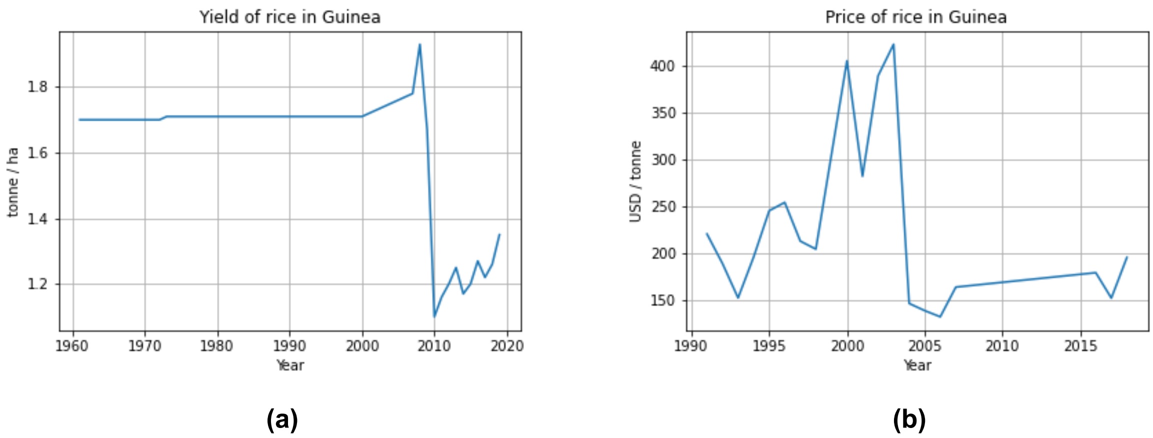

Figure 7.8: Yield (tonne/ha) and price (USD/tonne) of rice production in Guinea according to the FAO. Source: FAOSTAT Database.

Table 7.4: Rice Production in Guinea for the Kaback area. The yield and price of rice are derived from Figure 7.8.

Parameter	Unit	Value
Yield	tonne/ha/year	1.35
Price	USD/tonne	200
Small damage area (yellow)	ha	1,100
Large damage area (yellow+red)	ha	3,700
Agricultural part (small area)	%	90
Agricultural part (large area)	%	80
Total rice production (small area)	USD/year	267,000
Total rice production (large area)	USD/year	800,000

Table 7.5: Population of Guinea. For the analysis, the rural density is used (World Bank, 2019).

Area	**Land area**	**Population**	**Density**	**Density**
	$[km^2]$	[*people*]	$[km^{-2}]$	$[ha^{-1}]$
Rural	243,431	8,109,741	33	0.33
Urban	1,474	4,661,505	3,162	31.62
Guinea	245,720	12,771,246	52	0.52
Agricultural	145,000	8,109,741	56	0.56

USD in 2019 (World Bank, 2019). If the local community were to face damages of one-third of their annual income on average, damages for 550 and 1,650 people living in the two areas would result in financial losses of 176,000 and 528,000 USD for the two areas, respectively.

For the discount rate r, a general approach is to set the rate equal to the sum of economic growth and inflation. According to the World Bank, inflation in Guinea was around 10% from 2013 to 2019. Since economic growth has fluctuated around 4% since 1990, this is a reasonable assumption. Therefore, the discount rate is set at 14%.

7.3.4. Wave Attenuation

Based on the bathymetry data, a slope of 1:900 is derived at the location where mangroves grow, the maximal mangrove forest width is 900 meters, implying that the highest tide is at 1 m above MSL. According to the distribution of tide and storm surge given in Figure 7.7, storm surge is assumed to be 2.1 m (3.1 m, including tide) based on a 1/100 year water level. The wave height is limited to 50% of the water depth.

The wave attenuation by mangroves is calculated by comparing the levee height at the toe of the levee in case of a mangrove forest with the case of no mangroves at all. To take into account that

Table 7.6: Total damage of the Kaback area, for both the larger and smaller areas.

	Dimension	Small area	Large area
Agricultural value	USD	267,000	800,000
Societal damage	USD	176,000	528,000
Total value	USD	443,000	1,328,000
Coast length	m	11,000	11,000
Damage per m	USD/m	40	121

different combinations of wave height and wave period result in different wave attenuation rates (Suzuki et al., 2012), the SWAN runs are performed for significant wave heights varying from 0 to 4 m, and wave periods of 2 to 9 s. The mangrove characteristics are based on black mangroves as presented in Janssen (2016).

Figure 7.9 shows the varying wave heights and wave periods results in wave attenuation. Wave attenuation rates vary from $c = 1.67x10^{-3}m^{-1}$ to $c = 1.26x10^{-3}m^{-1}$, and is on average $c = 1.46x10^{-3}m^{-1}$. This value falls within the range of values found in the literature, as summarized in Table 2.1.

7.4. Results

7.4.1. Analytical Approach

Apart from the first "Do Nothing" approach, the three other options result in different combinations of optimal mangrove forest width W_{opt} and optimal levee height $h_{D,opt}$. For the levee in front of the mangroves, the mangrove forest width is zero. For the levee inland, the elevation of the land is higher than just behind the mangroves; thus, the levee height can be lower while providing sufficient protection. The optimal mangrove widths and levee heights can be found in Table 7.8. Since the mangroves are regenerating naturally, the variable costs of the mangroves are zero. Therefore, the optimal mangrove forest width is equal to the maximum mangrove width, from MSL to the high tide - in this case 900 m.

The total costs can be calculated for each option using these numbers. The costs are made up of fixed and variable costs for the levee and mangroves as well as the expected total damages. If an area is not protected, the land value may reduce to zero due to salinity and may cause societal damage. The inland levee implies that the area in front of the leveeis lost, and this is added to the expected damage. Table 7.9 gives the total costs for all four options. A levee in front of the mangroves requires a higher levee to withhold the storm surge and waves; behind the mangroves and land inwards, by contrast, the levee can be sufficiently lower due to decreased wave run-up by the mangroves. Since Kaback is an economically deprived area, the costs for the 'Do Nothing' option compares closely to the options involving a levee. For an area with a more valuable hinterland, the "Do Nothing" option may be less suitable. The lowest cost option for Kaback is building a levee just behind the mangroves because of the decreased wave height by the mangroves, which makes a lower levee sufficient. This option will

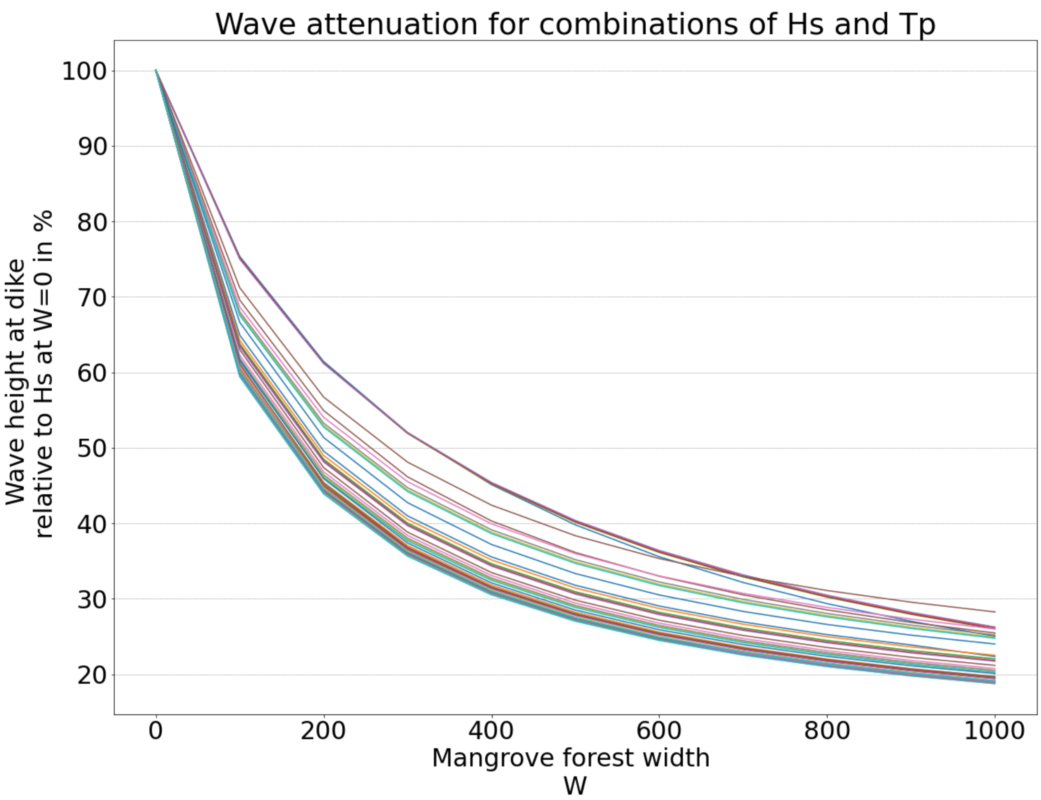

Figure 7.9: Wave attenuation for different H_S (0-4 m) and T_p (2-9 s), based on modelling black mangroves in SWAN, for a water level of 2 m. The wave reduces to 18 to 28% of the wave height in case of a mangrove forest of 1000 meter. This corresponds to a $c = 1.67 \cdot 10^{-3} m^{-1}$ to $c = 1.26 \cdot 10^{-3} m^{-1}$, and on average $c = 1.46 \cdot 10^{-3} m^{-1}$.

Table 7.7: Variables for the levee options at hand given in Figure 7.5. The wave height is based on half the water level for a 1/100 probability of storm surge.

Variable	Dimension	levee in front of mangroves	levee behind mangroves	levee inland
c	m^{-1}	0	0.00146	0.00146
E_0	m +MSL	0	1	1.7
A	m +high tide	0.95	0.95	0.95
B	m	0.18	0.18	0.18
$H_{s,0}$	m	1.55	1.05	0.7
ϕ	-	8	8	8
$\tan(\alpha)$	-	0.25	0.25	0.25
D	USD/m	121	121	121
r	%	14	14	14
I_D	USD/m/m	224	224	224
I_M	USD/m^2	n/a	0	0
W_{opt}	m	0	900	900
$h_{D,opt}$	m +E_0	4.6	1.1	0.2

Table 7.8: Results of the analysis following the analytical approach, and using the variables as in Table 7.7. The failure probability is once every 21 years for all situations. This failure probability is based on the marginally prevented damage and the marginal costs to increase the levee. For each case this is the same, but the levee needs to increase towards the sea, because of a lower bottom elevation and wider mangrove forest.

Variable	Dimension	levee in front of mangroves	levee behind mangroves	levee inland
W_{opt}	m	0	900	900
$h_{D,opt}$	m +E_0	4.6	1.1	0.2
P_f	once every x year	21	21	21

Table 7.9: Costs for each flood risk reduction measure in Kaback. A levee just behind the mangroves is most cost-efficient. In the “Do Nothing” scenario, the value of the area is lost entirely. A levee in front of the mangroves is expensive since it requires a relatively high levee due to the low elevation and high wave height. A smaller height is sufficient for the levee inland, but part of the inland area with agricultural value is lost. The levee behind the mangroves benefits from the mangroves while not giving up agricultural land. Levee costs are taken as 50% compared to the low-cost estimate in Chapter 6. The expected damage includes loss of rice production.

Costs	**Do Nothing**	**Levee in front of mangroves**	**Levee behind mangroves**	**Levee inland**
Fixed levee construction costs	-	3,685,000	3,685,000	3,685,000
Fixed Mangrove costs	-	-	64,800	64,800
Variable levee construction costs	-	11,338,614	2,626,797	438,469
Variable Mangrove costs	-	-	-	-
Expected damage	12,650,000	590,138	590,138	3,606,806
Total	**12,650,000**	**15,613,752**	**6,966,735**	**7,795,075**

also protect the agricultural land behind the red line and in front of the blue line (Figure 7.5). It is taken into account that when a levee that is positioned further inland fails, less damage results, since the hinterland consists of a smaller area. However, it is also assumed that the area in front of the levee suffers from salinity and loses its value. Figure 7.10 gives a schematization of the optimal solution.

If the costs of the levee are reduced to 10% due to the existing sandy ridges, the conclusions will remain similar (Table 7.10): the costs of the levee, however, reduce significantly, leading to higher levees.

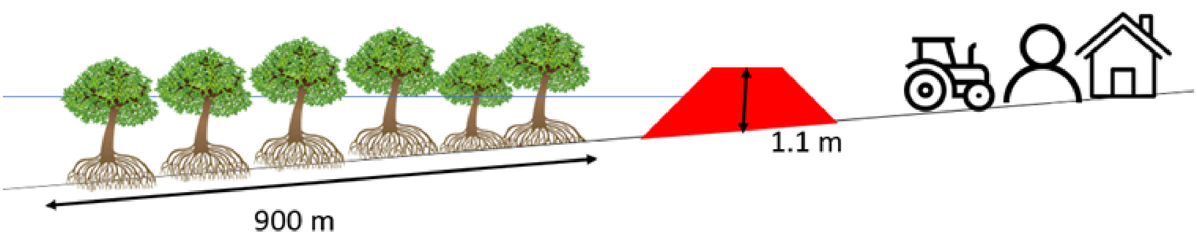

Figure 7.10: Schematization of the optimal solution for Kaback. A levee just behind the mangroves of 1.1 m combined with a mangrove forest of 900 m is optimal.

Table 7.10: Costs for each flood risk reduction measure in Kaback with levee costs taken as 10% compared to the low-cost estimate in Chapter 6. In this lower-cost case, the differences between the options increase considerably.

Costs	Do Nothing	levee in front of mangroves	levee behind mangroves	levee inland
Fixed levee construction costs	-	737,000	737,000	737,000
Fixed mangrove costs	-	-	64,800	64,800
Variable levee construction costs	-	2,410,486	668,123	230,457
Variable mangrove costs	-	-	-	-
Expected damage	12,650,000	118,028	118,028	3,252,790
Total	**12,650,000**	**3,265,514**	**1,587,951**	**4,285,047**

7.4.2. Modelling Using a Fixed Wave Attenuation

After gaining insight into the effectiveness of the four options combined with the analytical model, the numerical model can also be used to calculate the optimal mangrove width and levee height. The numerical model can either be used with a fixed wave attenuation per meter or by modelling the wave height using SWAN. For both methods, a FORM analysis is used, with a distribution of the parameters instead of deterministic values.

For the wave attenuation rate c, a normal distribution is assumed, as modelled previously in SWAN for black mangroves in Figure 7.9. The storm surge and wave height are used, as shown in Figure 7.7. The model with a fixed wave attenuation can be used in two ways: taking the wave height as a distribution or the wave height limited by depth-induced wave breaking. The influence factors (α) are one result of the FORM analysis, one factor for each variable included in the LSF as a distribution. The higher the alpha, the more weight the deviation in the variable contributes to the state of failure.

In the analysis where the wave height is maximized to half the storm surge due to depth-induced wave breaking, the optimal mangrove forest width is again 900 m, which is the maximum mangrove forest width possible. The optimal levee height is 0.7 m, which is lower than the analytical result; this could be because the wave height in the analytical model is given as a fixed parameter, while in the model, wave height is related to the storm surge. The costs increase again for a higher levee height. In these areas (upper part of the graph), the additional construction costs are higher than the annual damage prevented due to a lower failure probability. Figure 7.11 (b) shows how the failure probability decreases for a higher levee and wider mangrove forest. The exponential decay in failure probability for wider mangrove forests is in line with the exponentially decaying wave attenuation by mangroves. This graph shows how for the same failure probability, a lower levee is required if a wider mangrove forest is used in flood risk reduction. It also shows how the failure probability reduces to zero for certain combinations of levee height and mangrove forest width.

In Figure 7.11 (c), the alpha for the storm surge depends on the combination of levee height and mangrove forest width. The storm surge is highly relevant, which is expected, since wave attenuation cannot reduce storm surge, and storm surge determines the significant wave height at the offshore boundary and the wave breaking over the sloping bathymetry. Therefore, a change in the storm surge increases the failure probability due to a higher water level and wave height. The relevance of wave attenuation increases for a higher levee height. A higher levee requires a higher storm surge, which implies a higher wave height to reach the state of failure. Since wave attenuation is more effective for a higher wave height, a change in wave attenuation can significantly reduce the threat from wave height.

Figure 7.12 shows the model results with a fixed wave attenuation rate per m, c, and a wave height unlimited from the water depth. In (a), the total costs are shown. The optimal levee height is 1.2 m for the levee at position yellow in Figure 7.5 - higher than the results in the analytical model. The optimal mangrove width is 900 m, similar to the analytical model.

Lessons can be drawn from the figures (b), (c) and (d), in which the alphas for the storm surge, wave height, and wave attenuation are shown, changing per combination of levee height and mangroves. Since the storm surge does not limit the wave height, the wave height can play a dominant role in the failure. Due to this role of the wave height, the storm surge reduces in dominance, contributing to failure. This relevance of the wave height can be understood by looking at the formula for wave run-up in Equation (4.3). The wave height is taken to the power three, adding significantly to a state of failure of the levee. Wave attenuation c is dominant in the failure analysis for smaller mangrove forest widths. Since wave attenuation decreases the wave height exponentially, the first meters of mangroves have the greatest impact. For higher levee heights, the dominance of the wave height to reach a state of failure is so high that a slight change in wave attenuation does not affect the failure probability significantly.

7.4.3. Modelling Using SWAN

When modelling the failure probability using SWAN, the fixed wave attenuation is replaced by the mangrove characteristics needed for modelling: the drag coefficient, vegetation height, and the diameter of the stems.

$\mu = 0$, and $\sigma = 1$ describe the lognormal distribution of the drag coefficient. On average, the drag coefficient is 0.5, similar to the values in Janssen (2016) - as presented in Table 5.1. The vegetation height is taken as a normal distribution with a mean of 11 m, and a standard deviation of 2 m. The distribution of the diameter of the stems is set to be a normal distribution with mean 1.2 m and a

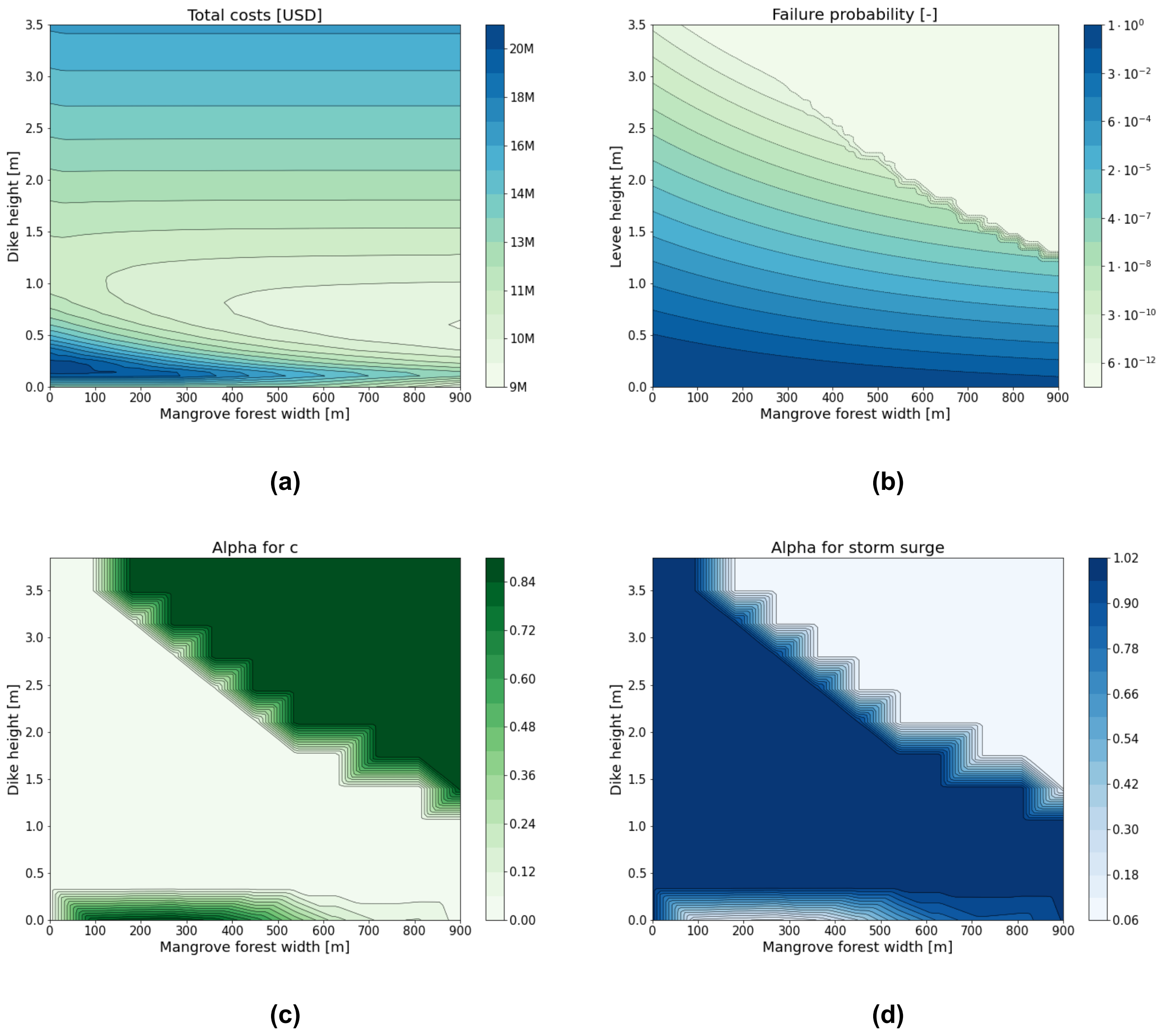

Figure 7.11: Total costs, P_f and alphas for modelling with a fixed wave attenuation. Since the wave height is related to the storm surge, storm surge and wave attenuation are the dominant factors. The area at the upper right part of the failure probability is where the FORM analysis does not give a solution anymore due to unstable behavior of the FORM analysis.

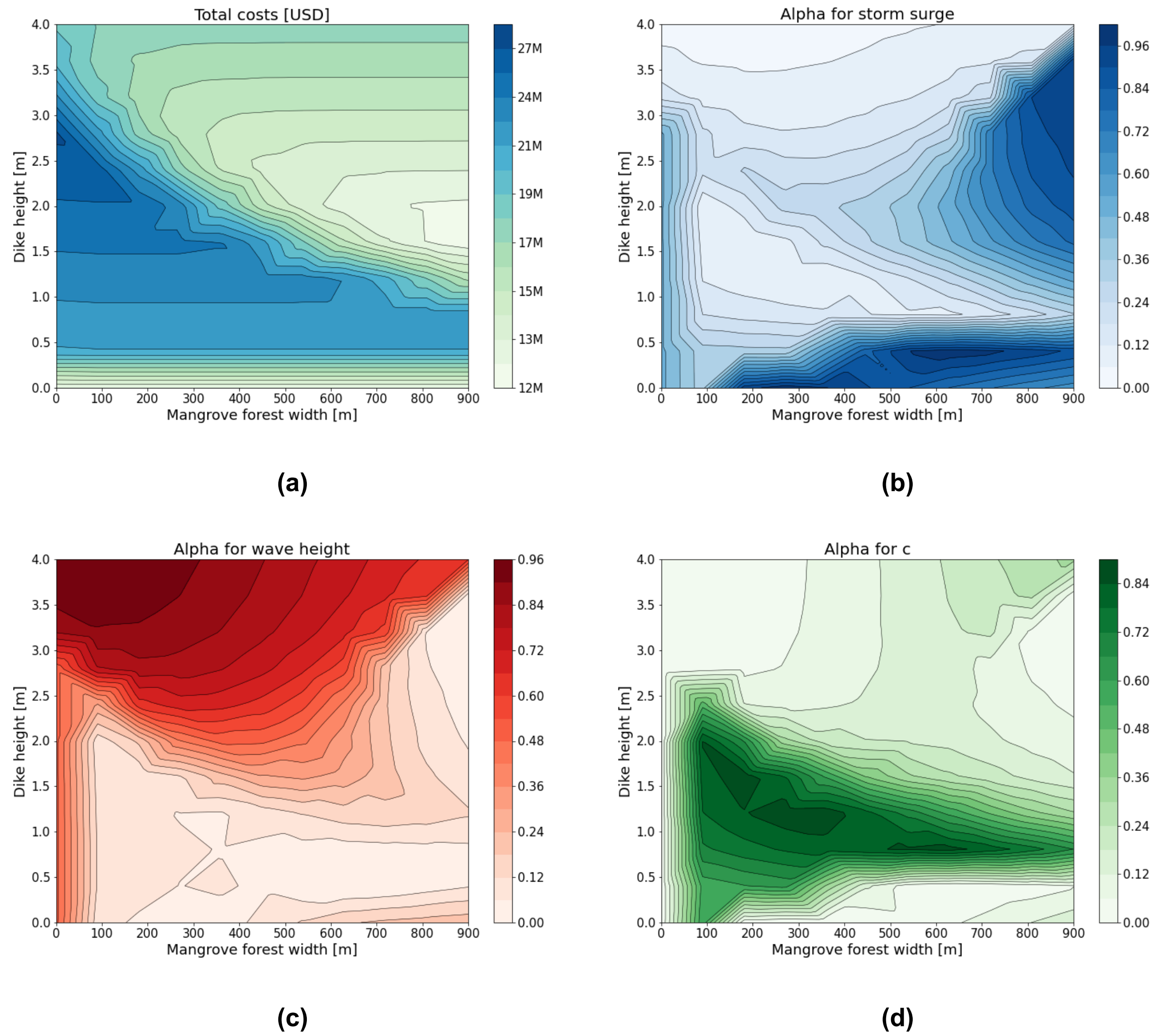

Figure 7.12: Results for modelling with a fixed wave attenuation, and a wave height which is unrelated to the storm surge. Although in practice it is likely these are related, it gives insight in when which variable is relevant.

standard deviation of 0.2 m.

Moreover, for SWAN modelling, the storm surge is the most dominant factor, with the relevance factor (alpha) going up to 0.96 out of 1. For low levee heights, the wave height at the toe of the levee is limited by depth-induced wave breaking. With higher levee heights, where the water level is higher due to the storm surge, waves can become higher and are more relevant for failing. Since the wave height becomes more relevant, the mangrove characteristics also become more relevant in reaching a state of failure. These mangrove characteristics lead to wave attenuation and reduce the failure probability. The vegetation height is moderately important, with the relevance factor alpha going up to 0.15. If the water level is so high that it submerges the mangroves, the height would probably become more relevant. The vegetation diameter is relevant up to an alpha factor of 0.28 and thus has more effect on wave attenuation than the height of the mangroves. The drag coefficient, whose exact definition is harder to estimate since it is seen as a bulk parameter, is the most relevant factor in determining the wave attenuation properties of mangroves. The alpha for the drag coefficient is mostly around 0.5. Only for low levee heights and a moderate mangrove forest width does the drag coefficient become highly relevant at the costs of the storm surge. The SWAN modelling gives similar results compared to the fixed wave attenuation, where the wave height is limited by depth-induced wave breaking.

7.5. Risks of Mangroves as Flood Risk Reduction Measure in Kaback

Several risks threaten the sustainability of the mangroves as an effective measure against flood risk.

First, the mangroves forest has not yet reached maturity. Part of the restoration process is to establish the mangroves, and this has to be guaranteed as it is used in the flood risk assessment. Since levees are designed to eventually decrease in strength to provide sufficient protection at the end of their lifetime, the strength will be sufficient to counteract the waves at an early stage without mangroves. Mangroves become stronger if maintained well, thus providing a good natural balance in flood risk reduction measures.

The quality of the mangrove forest leads to the next risk when applying mangroves. A threat to the mangroves is unsustainable wood chopping. Especially during economic downturns due to a failed harvest, selling wood for heating to the nearby city Conakry is a viable source of income for the local communities.

If mangroves are commercially harvested, they could become unsustainable and negatively affect the quality of the mangrove forest. This threat could be diminished by developing an economy resilient to failed harvests or through the issuance of insurance policies for the agricultural sector. Governments need to ensure that local communities understand the protective function that mangroves serve and create the circumstances in which local communities do not feel the need to undermine this function when an economic downturn threatens their livelihood.

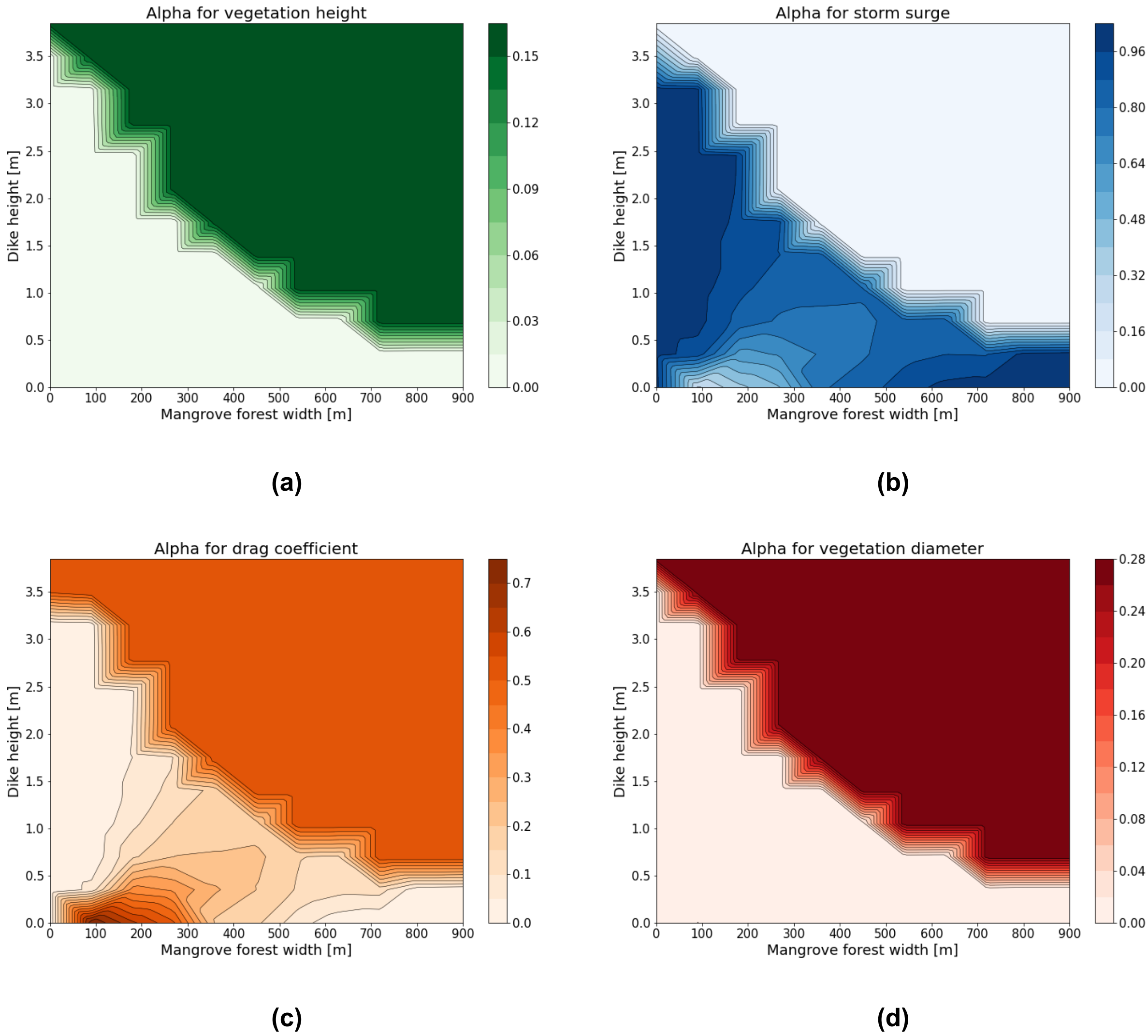

Figure 7.13: Results of modelling with a wave attenuation found by using SWAN modelling. The results are similar to those in the model with a fixed wave attenuation. Instead of wave attenuation, the variables representing the mangroves in SWAN are included in the model.

Table 7.11: Conclusion on the Kaback case. Based on the models it can be concluded that the mangroves should be used as much as possible, due to zero variable costs. The levee should be located just behind the mangroves to enable agricultural yield behind the levee.

	Mangroves	Levee	Position levee	Analysis vulnerabilities
Kaback analysis: conclusion	900 m	1.1 m	Just behind mangroves	Low fixed costs for mangroves No variable costs for mangroves Maturity of mangrove forest

7.6. Conclusion on Using Mangroves in Kaback

The most cost-effective solution for Kaback is to restore mangroves and build a levee of 1.1 m height, placed just behind the mangroves. Restoring mangroves is inexpensive in this case, since they are already growing back. This implies that the conditions for mangroves to grow, such as the availability of sediment and seedlings, are favorable. There is a lack of mangroves only in those areas where the water flow (and thus sediment flow) is disturbed by roads built on perpendicular elevations. Removing those barriers should be sufficient to restore the mangroves. Building a levee further inland would reduce the required height of the levee, since the bottom elevation is higher. However, this would also imply a loss of agricultural land in front of the levee due to salinity, which costs more than the savings gained from building a lower levee.

Incorporating mangroves into the flood risk reduction measure involves some risks. Mangroves will need to grow back into a mature mangrove forest, which takes time; therefore, a level of safety will be reached only after some years. Also, the mangroves will need to be maintained properly, and not be damaged by the local community. This must especially be prevented during economic downturns.

The economic damage in case of flooding might be underestimated. Higher economic damages will result in an increase in levee height for lower failure probability, and the differences with the ”Do Nothing” scenario will increase. If the mangrove width is uncertain, it could be considered to increase the height of the levee, such that there is a buffer for lower functioning mangroves.

8
Discussion

8.1. Costs of Mangroves and Levee

The sensitivity analysis in Section 6.3 shows how the costs of mangroves restoration and levee costs fall within a broad range of estimates and therefore strongly influence the optimal mangrove forest width. The first reason for the wide range in mangrove restoration costs are different restoration requirements and corresponding solutions: a permeable structure [USD/m] (Bayraktarov et al., 2016; Indonesia and Hakim, 2016; Thao et al., 2014; Van Cuong et al., 2015); planting [USD/ha] (Bayraktarov et al., 2016; Teas, 1997); or hydrologic restoration [USD/m3] (Aerts, 2018; Bayraktarov et al., 2016). All three options have different dimensions in which costs are defined. The second reason for the wide range in restoration costs involve the location-specific circumstances. Restoration options are for for example a permeable structure [USD/m]. The levee costs are estimated from a meta-analysis of levee costs (Aerts, 2018) and case studies in the Netherlands, Vietnam, the U.S. (Jonkman et al., 2013) and Bangladesh (Van Berchum et al., 2018). These costs are assessed in an overall approach, rather than a bottom-up approach. This approach requires an estimate of the ratio of fixed and variable costs. A bottom-up estimate could give insight into how the levee costs are segmented into sub-costs and are location-specific.

Moreover, the models assume that the costs of mangrove restoration and building a levee are linear with the forest width and levee height. This might be too simplified an analysis, since mangrove and levee costs might increase or decrease exponentially with width and height, respectively. For a levee, including costs of a revetment into the cost analysis might have an impact on the total levee costs.

8.2. Ecosystem Services

Inherent in an economic optimization - in contrast to a financial optimization - are the ecosystem services that lead to social welfare additionally on the flood risk reduction. However, some practical limitations arise when considering ecosystem services.

First, the literature provides a broad range of estimates for ecosystem services provided by mangroves (Costanza et al., 1997; De Groot et al., 2012; Karanja and Saito, 2018). Aslo, these estimates sometimes consist of global assessments (Costanza et al., 1997; De Groot et al., 2012), whereas levee-mangroves systems are applied locally.

Second, the ecosystem services provide social welfare in terms of direct economic benefit (e.g., fishing) but also indirect economic benefit (e.g., water purification). The estimates are prone to a broad range of economic research methods and subjectivity, which impact the estimates themselves (Costanza et al., 1997). For (local) governments there could be a tension between short-term aspects of financial considerations and long-term aspects of incorporating ecosystem services into the economic optimization.

8.3. Mangroves and Levee Design

In the analytical model derived in Chapter 4, the shape and strength of the levee can be adjusted with the variables ϕ (strength and shape) and $\tan(\alpha)$ (shape, slope of the levee) (Van der Meer et al., 2016). However, a levee could be adjusted in more ways than only by changing these variables. For example, a berm or revetment might have implications on the levee that are not captured well by ϕ and $\tan(\alpha)$, and may lead to a different critical discharge as wave overtopping (applicable for the probabilistic model).

In this study, mangroves are considered to be mature forests. However, mangrove restoration takes time, and mangroves will therefore not provide the wave attenuation assumed in the model during the first years. A levee, however, is designed to provide sufficient protection even after some deterioration (Jonkman et al., 2018). This way, the mangroves and levee behave in a complementary manner. An improved probabilistic model should include this uncertainty in restoration in the dynamics between mangroves and levee.

Sea level rise could also affect the design of a levee and mangroves. A levee might need to be increased in height to keep up with sea level rise, whereas mangroves might keep up with sea level rise naturally up to certain rates (McIvor et al., 2013).

8.4. Levee-Mangroves System

The levee-mangroves system can be assessed using the analytical model or the probabilistic model. The analytical model suffices for a first estimate. However, for design approaches, the probabilistic model is more suitable. The analytical model only considers variable costs, whereas probabilistic models also consider fixed costs. If fixed costs for mangroves are high, it is better to use the probabilistic model.

For both models, wave overtopping is the underlying failure mechanism. However, other failure mechanisms may also lead to failure, such as wave impact. It might be difficult to incorporate wave impact as a failure mechanism into the analytical model, but in the probabilistic model this would be a possible improvement.

8.5. Economics

In this study, the economic part of the models in addition to the financial costs implications consists of ecosystem services. However, reducing flood risk (protection effect) may also generate additional benefits through more investment and economic activity (wealth effect) (Hallegatte, 2017). This wealth effect, or economic growth in general, may require a higher flood risk protection level in which a higher levee or wider mangrove forest could be useful.

Another issue to consider is the productivity of agricultural land. In the analyses in this research, it was assumed that the agricultural yield is lost in the year in which flooding occurs. However, if this flooding leads to salinization of the land, crops might not be able to grow anymore - leading to a loss of income not only for those years in which flooding occurs, but also for the years that follow (Dasgupta et al., 2018).

Lastly, a levee-mangroves system is part of a local community. If a local community threatens the existence of mangroves (Barbier and Cox, 2002) - for example, by commercially chopping wood in an unsustainable manner - mangroves might not be a durable element in flood risk reduction measures. When assessing the risks of mangroves in a levee-mangroves system, this should be considered.

8.6. Kaback

The conclusion drawn from the case study in Kaback is that the optimal mangrove forest width is equal to the maximum (900 m), and the optimal position of the levee from an economic perspective is just behind the mangroves. This maximum mangrove forest width is the result of no variable costs for mangroves. This estimate is based on the fact that mangroves are growing back naturally in the area. However, it is possible that mangrove restoration will decline in the coming years, such that the aimed mangrove forest maturity is not reached naturally. In this case, mangrove costs will not be zero.

The numerical outcomes from the Kaback case should be used with caution. Although bathymetry data are available at the sea side of the mangroves, data were not available at the mangrove area and on the land behind the mangroves. Therefore, estimates were made to define the elevation.

The storm surge data are based on the Global Tide and Surge Reanalysis (GTSR) model, at the geographically nearest point to Kaback. However, this global model might not provide the most accurate estimate locally. Therefore it might be feasible to focus additional effort into developing better data on storm surge and tide.

The potential damage in case of flooding is based on the agricultural yield for national levels in Guinea. Locally, in Kaback, this estimate may not hold, since production efficiency can differ from the national average. Moreover, the flooded area in case of flooding may be different compared to the estimates in this thesis. A lower flooded area would decrease the required failure probability and therefore lower the required height of a levee. However, this will not alter the results qualitatively.

9 Conclusion

In this chapter, the research questions are answered. The answers to these questions present how mangroves can be included in the design of flood risk reduction measures. Managers, local governments, and organizations such as the World Bank can now systematically implement building with nature solutions when addressing flood risk problems.

9.1. Research Questions

1. *Which indicators can be applied to estimate the economic effectiveness of levee-mangroves systems?*

   The indicators to estimate the economic effectiveness of levee-mangroves systems are the following:

   - Variable levee costs I_D [USD/m/m]
   - Variable mangroves restoration costs I_M [USD/m/m]
   - Wave attenuation rate c $[m^{-1}]$
   - Wave run-up $\phi H_{s,0}\tan(\alpha)$ [m]
   - Storm surge [m]
   - Ecosystem services [USD/m/m]

   The effectiveness of mangroves comes from reducing the wave run-up. The wave run-up depends on the wave height $H_{s,0}$ [m], the talud of the levee $\tan(\alpha)$ [-] and strength and shape of the levee ϕ [-] (Van der Meer et al., 2016). A high wave run-up increases the economic effectiveness of mangroves. The wave height, in turn, depends on the water level. During storm conditions, the wave height is restricted by around 50% of the water level. Therefore, the storm surge indirectly defines the economic effectiveness of mangroves. If the ratio between mangrove costs relative to levee costs and wave attenuation is favorable, then additional wave run-up is reduced by increasing the mangrove forest width, rather than increasing the height of the levee.

The ratio between variable levee costs, wave run-up and wave attenuation relative to the variable mangroves restoration costs determine the optimal mangrove forest width.

As a rule of thumb, for mangroves to be economically effective, restoration costs [USD/m/m] in case of a 1 m wave height should remain below 0.003 times the variable levee costs [USD/m/m]. This value increases linearly with the wave height. For levee costs of 1 million USD/km/m, of which 0.6 million USD/km/m variable costs, the mangroves restoration costs should not exceed 1.8 USD/m/m, or 18,000 USD/ha.

To summarize, in order to assess the economic effectiveness of mangroves, the following steps should be followed:

(a) Define the storm surge. A high storm surge implies a high wave height, which can be assumed to be around 50% of the water level.

(b) Define the costs of mangrove restoration and levee costs. The rule of thumb described above gives a first indication of whether mangroves are an economically effective measure in flood risk reduction.

(c) Assess the problem in more detail, including wave attenuation rate and levee design parameters ϕ and $\tan(\alpha)$.

2. *Which approaches are applicable to assess the economic effectiveness of levee-mangrove systems?*

   Two distinctive problem definitions can be distinguished when assessing the economic effectiveness of mangroves: (1) a levee-mangroves system in which mangroves have to be restored, and (2) a levee-mangroves system in which mangroves already exist.

   The trade-off in the first problem is whether to decrease the flood risk by increasing the levee or by increasing the mangrove forest width. The second problem assesses the trade-off between using the area where mangroves grow for agriculture versus using it for mangroves, which would provide ecosystem services and decreases the flood risk.

   To assess the flood risk problem, two models have been developed: an analytical model and a probabilistic model. The analytical model has two configurations: (1) a model aiming specifically to minimize the investment costs of flood risk reduction measures, and (2) a model aiming to reduce the total costs of flood risk, including levee and mangrove investment costs and flood risk.

Both configurations give a similar optimal mangrove forest width as a result, described under sub-question 1. The second configuration involves a failure probability approximated by an exponential distribution. The storm surge is also considered as an exponential distribution.

To assess the flood risk problem in a probabilistic manner, rather than a deterministic manner, FORM and SWAN can be used. The wave attenuation can be modelled in SWAN. The variables defining the wave attenuation in the SWAN model are the following:

- Height of the mangroves [m]
- Stem diameter [m]
- Density [stems/m2]
- Drag coefficient [-]
- Wave period [s]
- Wave height [m]

By considering distributions of these variables - rather than their deterministic values - in a FORM analysis, uncertainty in wave attenuation is incorporated into the model results. Furthermore, other uncertainties such as storm surge, the critical wave overtopping discharge and levee shape can be included in a FORM analysis.

The analytical model is useful for first estimates of whether mangroves are economically effective as a flood risk reduction measure. The probabilistic model is suitable for designing a levee-mangroves system, with the optimal levee height, mangrove forest width and failure probability.

3. *What is the optimal combination of mangroves and levee for flood risk reduction?*

   Although the variables vary for each case, common values for each variable have been derived based on the literature, presented in Section 6.3. Considering these common values, the estimated range for each variable shows which variable has an uncertainty which significantly affects the optimal mangrove forest width. Generally, the optimal mangrove forest width is around 900 to 1000 m. This optimal forest width changes if costs or the hydraulic conditions change. In particular, the high estimates of the variable mangrove costs or a low wave height eliminates this optimal mangrove forest width.

   Estimates of the costs for the mangroves vary from 0.12 USD/m/m to 5 USD/m/m, equivalent to 1,200 USD/ha and 50,000 USD/ha, respectively. At the lower end, mangroves become highly effective in economic terms for flood risk reduction. At the higher end, however, this economic effectiveness disappears. Restoration measures such as planting and a permeable structure are relatively inexpensive measures (Aerts, 2018; Bayraktarov et al., 2016; Indonesia and Hakim, 2016; Thao et al., 2014; Van Cuong et al., 2015). Filling or excavating a large area of soil is an expensive restoration measure (Aerts, 2018).

Estimates of the variable costs of raising a levee vary from 448 to 1344 USD/m/m, equivalent to 1 and 3 million USD/km/m of total costs. These estimates apply to levees in developing countries, where most mangroves grow. This range is not as wide as the range for mangrove restoration cost; and for all ranges, mangroves remain an economically effective measure, given the common values of the other variables.

Wave attenuation rate for a mature forest ranged from $c = 1.26 \cdot 10^{-3} m^{-1}$ and $c = 1.67 \cdot 10^{-3} m^{-1}$, equivalent to a wave attenuation of 12% to 15% for the first 100 m, or 71% to 81% for a 1000 m wide forest. For a rather low wave attenuation rate of $c = 1.1 \cdot 10^{-3} m^{-1}$ (equivalent to a wave attenuation of 10% for a 100 meter wide forest), the optimal mangrove forest width is maximum, given the common values for the other variables. Below this wave attenuation rate, the optimal width decreases rapidly; above this wave attenuation rate, the optimal width decreases gradually. This implies that wave attenuation rates are generally sufficient and do not form an obstacle to effectively apply mangroves as a flood risk reduction measure.

The estimates for ecosystem services range from 0.3 to 8 USD/m/m/year, equivalent to 300 and 8,000 USD/ha/year (Costanza et al., 1997; De Groot et al., 2012; Karanja and Saito, 2018). In determining the economic effectiveness of mangroves, the ecosystem services can be deducted from the mangrove costs. When the ecosystem services become similar in magnitude to the variable mangrove costs, the optimal mangrove forest width increases exponentially.

Although potential damage plays a role in determining the height of the levee, it does not directly influence the optimal mangrove forest width; this is because the optimal mangrove forest width is a trade-off between increasing the levee and mangroves, rather than reducing the failure probability. Higher potential damage, however, may increase the height of the levee, such that a higher wave height would be required to make the levee fail. This higher wave height then makes mangroves economically more effective.

4. *What is the optimal combination of mangroves and levee for land use?*

   In cases where mangroves are already existing in the area, the approach focuses on how much mangrove forest width should remain in order to maximize annual total gain. The relevant indicators for this problem are the following:

   - Area where mangroves can grow
   - Ecosystem services [USD/km/m]
   - Agricultural yield [USD/km/m]
   - Wave attenuation [m^{-1}]
   - Failure probability [$year^{-1}$]
   - Storm surge [m]

The failure probability is calculated by using a FORM analysis, with the storm surge and wave attenuation considered as distributions.

Fewer mangroves enable exploiting the land for agriculture, but this also increases the risk of flooding due to less protection by mangroves. This higher failure probability increases the annual expected damage. The optimal mangrove forest width is found where the marginal gain in ecosystem services is equal to the marginal gain of the agricultural yield minus annual expected damage.

For the distribution of the storm surge (exponential distribution with $\lambda = 1$ and $\gamma = 0$) and levee height of 1 meter, and for an ecosystem services value of 50% of the agricultural yield the optimal mangrove forest width at the expense of agriculture is 40% of the maximum mangrove forest width. For an ecosystem services value of 75% of the agricultural yield, the optimal mangrove forest is around 85% of the maximum mangrove forest width.

To maintain the original mangrove forest width, ecosystem services should be above 85% of the agricultural yield. Below this percentage, it becomes feasible to give up some of the mangroves in favor of agriculture. A lower and higher estimate for ecosystem services are 300 USD/ha (Karanja and Saito, 2018) and 8,000 (Costanza et al., 1997), respectively. Estimates of agricultural yield are around 270 USD/ha and 1600 USD/ha. This implies that only for a relatively high yield in combination with a relatively valuation of ecosystem services does it become feasible to (partly) convert a mangrove area to an agricultural area.

5. *What is the optimal levee-mangroves combination in Kaback, Guinea, and what is the optimal location of a levee?*

   The optimal mangrove forest width in Kaback is 900 m, the maximum width physically possible between MSL and high tide. This forest is combined with a levee of 1.1 m in height, placed just behind the mangroves. Placing the levee more inland would make it more resilient to SLR but involves the loss of agricultural land in front of the levee.

   This conclusion is based mainly on the natural restoration of mangroves in the area, due to which the variable costs of mangrove restoration are zero. The deviation in wave attenuation rate or storm surge determines the failure probability. For a levee of 1.1 m and a mangrove forest width of 900 m, it is the deviation in storm surge that is most critical.

10

Recommendations

10.1. Further Research

10.1.1. Recommendations on the Socio-Economic Requirements for Successful Restoration

Mangroves grow in a complex ecosystem and require several physical requirements to develop, such as low wave energy, lack of seedlings, and hydrologic circumstances such as the presence of a freshwater river (Alongi, 2002). Apart from the physical circumstances, there are human or economic influences. The commercial, unsustainable harvesting of timber or other exhaustive use of the mangrove forest threaten their existence (Alongi, 2002). If a harvest is lost and no reserves are kept aside, the local community must look for other sources of income, such as selling mangrove timber. Creating a more resilient economic system could be a requirement for mangroves to contribute to flood risk reduction in a sustainable manner. These physical and economic circumstances limit possibilities and should be assessed before investigating whether to apply mangroves in flood risk reduction. Further research could develop a general framework on these boundaries to provide insights into decision-making entities, such as the World Bank and governments, whether mangroves are a viable choice for flood-risk reduction.

10.1.2. Recommendations on Flood Risk Reduction by Mangroves

Besides reducing wave run-up, mangroves reduce the wave impact on levees, which may reduce maintenance costs of the levee or prevent the levee from failing due to wave impact. Studying the impact of mangroves on this failure mechanism could provide an extra incentive to apply mangroves in flood risk reduction. Another reason to apply mangroves as a flood risk reduction measure is that actual damage after storms was lower when mangroves protected the coast (Brown et al., 2006).

In both the analytical and numerical approaches, the levee height is assumed to be equal to the storm surge and wave run-up height, a simplified form of the build-up of a levee. Sea-level rise and land subsidence are not considered, while these might significantly impact the height of the levee. A more thorough effect of the design of the levee and the allowable wave overtopping discharge would improve the model. For now, this has been implicitly considered by ϕ and $\tan(\alpha)$ in the model representing the strength and shape of the levee.

An advantage of using mangroves is the ability to adapt naturally to changing circumstances such as sea-level rise (McIvor et al., 2013). A levee cannot adapt naturally and, thus, requires intervention at some point. Research so far points to the likelihood of mangroves to keep up with sea-level rise, given sufficient sediment input (McIvor et al., 2013). Sea-level rise rates ($mm/year$) might increase to such heights, however, such that this adaptive behavior is no longer applicable. Considering these issues in the levee-mangroves models would improve the model. Further research on mangroves should shed more light on how this behavior limits and impact the effectiveness of mangroves in flood risk reduction.

At eroding locations, mangrove restoration relies on stabilizing the coastline. In such cases, restoring mangroves is a matter of retaining the coast, even more so than reducing flood risk. This study did not consider these questions but they should be assessed before deciding whether to restore mangroves for flood risk reduction purposes.

10.1.3. Recommendations on uncertainty in failure probabilities

In this research, a model has been developed to assess levee-mangroves systems in flood risk reduction, and what variables contribute to the effectiveness of mangroves. For these variables, it has been assessed how the range in estimates influence the effectiveness of mangroves. Uncertainty concerning vegetation become more important for levees with low strength, while for low levees, system characteristics are more important for low dikes (Vuik et al., 2018). Since mangroves grow mainly in areas where developing countries are located, a levee with a relatively low strength is likely. In contrast to salt marshes, assessed by Vuik et al. (2018), mangroves do not face uncertainty due to seasonality, and stem breaking is only an issue for mangroves in case of extreme conditions such a tsunami (Alongi, 2008). This may decrease the uncertainty of mangroves as a flood risk reduction measure. Further research can focus more on what variables contribute most to uncertainty of failure in levee-mangroves systems.

10.1.4. Recommendations on Cost Estimates

In the calculations, important but still uncertain variables are the costs of the levee and mangroves. This uncertainty is a logical consequence of the complexity and multiple local variables of building a levee or restoring mangroves. However, it would be helpful to gain knowledge on the most probable values for different countries or regions. For levees, this would specifically be the ratio of variable and fixed costs. Moreover, the linear increase of levee and mangrove costs with height and width respectively, might be a too simplified assumption. If the costs are increasing exponentially or asymptotically, the results can differ considerably. Considering revetments when calculating levee costs can contribute to a better perspective on levee costs.

Apart from its flood risk reduction capabilities, an incentive to restore mangroves are the ecosystem services they provide. Research on valuating these services in monetary terms vary due to differences in purchasing power parity between countries (Costanza et al., 1997). That is, one dollar in a developed country is valued differently from one dollar in a developing country. A variety of research techniques for ecosystem services diffuses the outcomes (Costanza et al., 1997; De Groot et al., 2012). These ecosystem services, however, can be segmented into direct and indirect economic benefits. Direct economic benefits can be expressed in monetary terms. For example, an increase in fishery due to ecology in mangrove forests can be translated into fish production and, thus, economic value (Costanza et al., 1997; Karanja and Saito, 2018). It is more difficult to translate indirect economic benefits into monetary terms. Water purification or recreation, for example, provide benefit to the local community but they are not so easily translated into a monetary value (Costanza et al., 1997; De Groot et al., 2012).

It is recommended to create a framework separating the direct economic benefits from the indirect economic benefits. This framework should include methods to assess these direct and indirect economic benefits and indicate values, possibly segmented for developed and developing countries. Segmenting direct and indirect economic benefits enables the World Bank or local governments to discuss the value of benefits separately and, thus, to come to a substantiated value of ecosystem services instead of an overall approach.

10.1.5. Limitations on Mangrove Schematization

This study assumes a mangrove forest to be mature and homogeneous. This implies that the mangroves' characteristics, such as height and stem diameter, are equal throughout the forest. In reality, several species with their own characteristics may grow within one forest. A younger forest might be less dense, which affects wave attenuation. The effect of varying wave period or wave steepness on wave attenuation could also be assessed in more detail. Finally, the bathymetry of the foreshore could affect incoming waves. Local assessments should include detailed bathymetries when studying the potential flood risk reduction by a mangrove forest.

Levee and mangroves have complementary life-cycle properties. The levee must be built such that after some deterioration, it is still sufficiently strong to withstand the load to sustain a certain protection level using a levee. Therefore, levees are more robust than necessary at the beginning of their lifetime. In contrast, mangroves might still need to mature at the beginning of the flood protection measure, eventually gaining strength (forest density, diameter of stems, height). In further studies, a full assessment of the failure probability in a probabilistic manner should be considered. Thorough knowledge of mangrove cultivation would offer valuable insights for this assessment.

10.2. Applications of the Research

10.2.1. Systematic Implementation by Managers

Mangaers from governments or organizations such as the World Bank can use the study to gain insight into the effectiveness of applying mangroves in flood risk reduction for their projects. The analytical model may provide an indication how effective mangroves are in flood risk reduction, and may enable managers to decide whether to continue with evaluating the option of restoring mangroves in an early stage. In a later stage, when a design needs to be made, the probabilistic model may be used by engineers to find the optimal mangrove forest width.

Organizations aimed at encouraging the use of “Building with Nature could use the results of this study to clarify the business case of mangroves or other “Building with Nature” measures. They can also see this study as an example of how ecosystem services can be calculated and include in a cost-effectiveness calculation.

Note, however, that the question whether to restore mangroves for flood risk reduction comes after other, more stringent issues such as whether mangroves prevent erosion or are sustainable. As long as vegetation leads to wave attenuation and a levee is within the range of options, the model can also be used for vegetation other than mangroves.

10.2.2. Mangrove Opportunity Map

Another application of the study can be to make a mangrove opportunity map. This map can indicate how favorable the physical and financial conditions are. For the physical conditions, the significant wave height is most relevant. Also the wave attenuation can be included based on the mangrove species. The financial conditions are mangrove and levee costs. These should be differentiated for developed and developing countries. The estimated costs might be linked to economic indicators like GDP per capita, since the costs (of labor) will be lower in countries with a lower GDP per capita. Costs to restore mangroves are obviously lower where mangroves are still intact. Areas with abundant mangroves should get a reduction factor on restoration costs. Challenges include the broad range of restoration possibilities and corresponding costs for mangroves. An option is to create three different maps - one for each restoration measure.

10.2.3. Mangrove Advice Tool

Based on the work done in this thesis, a mangrove advice tool can be developed. Such a tool would provide the effectiveness of mangroves in flood risk reduction and consists of the following elements:

- Threat of flooding
- Hydraulic conditions
- Costs of mangroves restoration and levee
- Ecosystem services provided by mangroves

First, the threat of flooding needs to be determined. The Global Flood Hazard Model by Sampson et al. (2015) may provide this insight.

If flooding is indeed a risk, the hydraulic conditions should be identified, namely the storm surge and wave height, of which the wave height can be assumed to be around 50% of the water level. With the Global Tide and Surge Reanalysis database (Muis, 2018) the storm surge data can be derived globally.

The costs for mangroves restoration are location-specific. Defining the potential to restore mangroves may indicate which locations qualify for restoration (Worthington and Spalding, 2018). The resulting restoration potential score might also give an indication on the costs of restoring.

Ecosystem services can be included in a mangrove advice tool by subtracting them from the mangroves restoration costs. These ecosystem services are hard to define and prone to subjectivity. Therefore, these should be defined separately from the restoration costs. The mangrove restoration potential mapping tool (Worthington and Spalding, 2018) provides estimates per location.

Combining this flood hazard model and mangrove restoration tool with the model developed in this thesis, a mangroves advice tool can be developed.

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A

Appendix A: Analytical Approach

In Chapter 4, the formulas for the global optima of levee height h_D and mangrove forest width W are derived.

A.1. Additional Derivations of the Analytical Approach

The relations defining which solutions fit best is summarized in the table below. In practice, it could be the case that there already is an existing levee or mangrove forest at the location of interest. If this existing situation exceeds the optimal levee height or mangrove forest width, the optimization turns into defining the levee height given an existing mangrove forest width, or vice versa. In this chapter, the derivations for these situations are given.

By differentiating the total costs relative to the levee height once and separately to the mangrove forest width W, the following equations are obtained:

$$\frac{\partial TC}{\partial W} = I_M - \frac{D}{r}\frac{\phi H_{s,0}\tan(\alpha)ce^{-cW}}{B}e^{-\frac{1}{B}\left(E_0+h_D-\phi H_{s,0}\tan(\alpha)e^{-cW}-A\right)} = 0 \tag{A.1}$$

$$\frac{\partial TC}{\partial h_D} = I_D - \frac{D}{rB}e^{-\frac{1}{B}\left(E_0+h_D-\phi H_{s,0}\tan(\alpha)e^{-cW}-A\right)} = 0 \tag{A.2}$$

The minimum costs are given by setting both equations to zero and then setting both equations equal to each other, the following relation is obtained:

$$\frac{\partial TC}{\partial W} = I_M - \frac{D}{r}\frac{\phi H_{s,0}\tan(\alpha)ce^{-cW}}{B}e^{-\frac{1}{B}\left(E_0+h_D-\phi H_{s,0}\tan(\alpha)e^{-cW}-A\right)} = \frac{\partial TC}{\partial h_D} = I_D - \frac{D}{rB}e^{-\frac{1}{B}\left(E_0+h_D-\phi H_{s,0}\tan(\alpha)e^{-cW}-A\right)} \tag{A.3}$$

Solving this equation leads to the optimal levee height where total costs are minimum, given a mangrove forest width:

$$h_{D,opt} = -E_0 + \phi H_{s,0} \tan(\alpha) e^{-cW} + A + B \ln\left(\frac{D(1 - 8H_{s,0} \tan(\alpha) c e^{-cW})}{rB(I_D - I_M)}\right) \quad \text{(A.4)}$$

The formulas below give an answer to the question whether h_D or W should be increased given the other variable (W or h_D, respectively). Also the optimal failure probability in terms of either h_D or W are given.

To optimize W given h_D, the following equation must hold:

$$\frac{\partial TC}{\partial W} = I_M - \frac{D}{r} \frac{\phi H_{s,0} \tan(\alpha) c e^{-cW}}{B} e^{-\frac{1}{B}(E_0 + h_D - \phi H_{s,0} \tan(\alpha) e^{-cW} - A)} = 0 \quad \text{(A.5)}$$

From this equation the optimal failure probability for mangroves can be defined:

$$P_{f,opt,W} = e^{-\frac{1}{B}(E_0 + h_D - 8H_{s,0} \tan(\alpha) e^{-cW} - A)} \quad \text{(A.6)}$$

This leads to the following formula for the optimal failure probability relative to mangroves:

$$P_{f,opt,W} = \frac{rI_M B}{cD\phi H_{s,0} \tan(\alpha) e^{-cW}} \quad \text{(A.7)}$$

The optimal mangrove forest width can be calculated by solving the equation $\frac{\partial TC}{\partial W} = 0$ for W. This results in the following implicit formula for W_{opt}:

$$W_{opt}|_{h_D} = \frac{-E_0 - h_D + A + B \ln\left(\frac{cD\phi H_{s,0} \tan(\alpha)}{rI_M B}\right) + \phi H_{s,0} \tan(\alpha) e^{-cW_{opt}}}{cB} \quad \text{(A.8)}$$

Both equations above are optimizations given a specific levee height. These are valid in the situation that the levee height is fixed, which does not necessarily represent the global optimum.

Given a certain levee height, if the factor within the natural logarithm is above 1, it indicates that it is attractive to apply more mangroves. The following relation shows that additional mangroves costs less than averted damages by the mangroves:

$$\frac{rI_M B}{D} < c\phi H_{s,0} \tan(\alpha) \quad \text{(A.9)}$$

The same analysis can be done for optimizing the height of the levee h_D given a mangrove forest width W.

$$\frac{\partial TC}{\partial h_D} = I_D - \frac{D}{rB} e^{-\frac{1}{B}(E_0 + h_D - \phi H_{s,0} \tan(\alpha) e^{-cW} - A)} = 0 \quad \text{(A.10)}$$

The optimal failure probability relative to the levee can then be expressed as below:

$$P_{f,opt,h_D} = \frac{rI_D B}{D} \quad \text{(A.11)}$$

$$P_{f,opt,h_D} = e^{-\frac{1}{B}\left(-E_0 + h_D - 8H_{s,0}\tan(\alpha)e^{-cW} - A\right)} \tag{A.12}$$

By solving the equation $\frac{\partial TC}{\partial h_D} = 0$, the following equation expresses the optimum h_D:

$$h_{D,opt}|_W = -E_0 + \phi H_{s,0}\tan(\alpha)e^{-cW} + A + B\ln\left(\frac{D}{rI_D B}\right) \tag{A.13}$$

Both equations above are optimizations given a specific mangrove forest width. These are valid in the situation that the mangrove forest width is fixed. This turns out to be the same as the global optimum formula for h_D.

From this equation, it follows that the levee height should at least be high enough to deal with the storm surge and wave run-up, minus the initial elevation. Increasing the levee above this height depends on how much damage can be prevented and the additional investment that has to be made. The term within the natural logarithm expresses this. In case the factor within the natural logarithm exceeds 1, this logarithm will be positive. Thus, increasing the levee above the level of $-E_0 + S +$ *wave run-up* is valid if the following relation holds:

$$D > rI_D B \tag{A.14}$$

A.2. Results of Analytical Solutions

In case the original bed elevation (E_0), storm surge (S) and wave run-up combined are larger than zero, flooding occurs in case of no flood risk reduction measures (given a failure probability which defines the wave height and storm surge). Since mangroves do not decrease storm surge, a levee is required to reduce flood risk, corresponding to measures 1 and 3 in Table A.1. Since there is an interaction term between the optimal mangrove forest width and the optimal levee height, this levee also needs to be higher than the wave run-up.

The essential balance whether to apply mangroves is between the costs of mangroves relative to costs of a levee, and the wave height. The wave height refers to the wave height at the toe of the levee in case of no mangroves. This balance is expressed in Figure A.1. In this figure, the boundaries of whether to apply mangroves are given for different wave attenuation factors c. Below these lines, mangroves is not an attractive option, while above those lines, mangroves are a feasible option.

Table A.1: Mathematical relations that indicate which flood risk reduction measure is preferable.

	Reduction measure	Investment costs only	Economic optimization (incl. flood risk)
		Here the target failure probability is given, the optimal combination of W and h_D will be analyzed	*Here the optimal failure probability, levee height and mangrove width will be optimized.*
1	**levee**	$\frac{I_M}{I_D} > c8H_{s,0}\tan(\alpha)$	$\frac{I_M}{I_D} > c\phi H_{s,0}\tan(\alpha)$
		$E_0 \leq S + \phi H_{s,0}\tan(\alpha)$	$E_0 \leq \phi H_{s,0}\tan(\alpha) + A + B\ln\left(\frac{D}{I_D rB}\right)$
2	**Mangroves**	$\frac{I_M}{I_D} < c\phi H_{s,0}\tan(\alpha)$	$\frac{I_M}{I_D} < c\phi H_{s,0}\tan(\alpha)$
		$E_0 \geq S + \phi H_{s,0}\tan(\alpha)e^{-cW}$	$E_0 \geq \frac{I_M}{cI_D} + A + B\ln\left(\frac{D}{I_D rB}\right)$
3	**levee + Mangroves**	$\frac{I_M}{I_D} < c\phi H_{s,0}\tan(\alpha)$	$\frac{I_M}{I_D} < c\phi H_{s,0}\tan(\alpha)$
		$E_0 \leq S + \phi H_{s,0}\tan(\alpha)e^{-cW}$	$E_0 \leq \frac{I_M}{cI_D} + A + B\ln\left(\frac{D}{I_D rB}\right)$
4	**Do Nothing**	$E_0 \leq S + \phi H_{s,0}\tan(\alpha)$	$E_0 \geq \phi H_{s,0}\tan(\alpha) + A + B\ln\left(\frac{D}{I_D rB}\right)$

Table A.2: Indicative relations that need to be fulfilled for different solutions in words. This table corresponds to Table A.1.

	Reduction measure	**Investment costs only**	**Economic optimization (incl. flood risk)**
		Here the target failure probability is given, the optimal combination of W and h_D will be analyzed	*Here the optimal failure probability, levee height and mangrove width will be optimized.*
1	**Only levee**	levees only are preferable when the ratio of investment costs of mangroves to levees is larger than the wave run-up. The initial elevation level provides insufficient safety against flooding.	levees only are preferable when the ratio of investment costs of mangroves to levees is larger than the wave run-up. The potential damage in case of flooding gives reason to increase the safety level. The initial elevation level provides insufficient safety against flooding.
2	**Only Mangroves**	Mangroves only are preferable when the ratio of investment costs of mangroves to levees are smaller than the wave run-up. The initial elevation level provides sufficient safety against flooding after the waves are attenuated by mangroves.	Mangroves only are preferable when the ratio of investment costs of mangroves to levees is smaller than the wave run-up. The initial elevation level provides sufficient safety against flooding after mangroves attenuate the waves. The potential damage is low enough such that attenuating waves is sufficient and a levee is not necessary.
3	**Mangroves + levee**	Both mangroves and a levee are preferable when the ratio of investment costs of mangroves to levees are smaller than the wave run-up. At the same time, the initial bed elevation does not provide sufficient protection against storm surge and wave run-up.	Both mangroves and a levee are preferable when the ratio of investment costs of mangroves to levees are smaller than the wave run-up. At the same time, the damage is so high that the initial bed elevation does not provide sufficient protection against storm surge and wave run-up.
4	**Do Nothing**	Do nothing is preferable when the initial elevation level provides sufficient safety against flooding.	Do nothing is preferable when the initial elevation level provides sufficient safety against flooding.

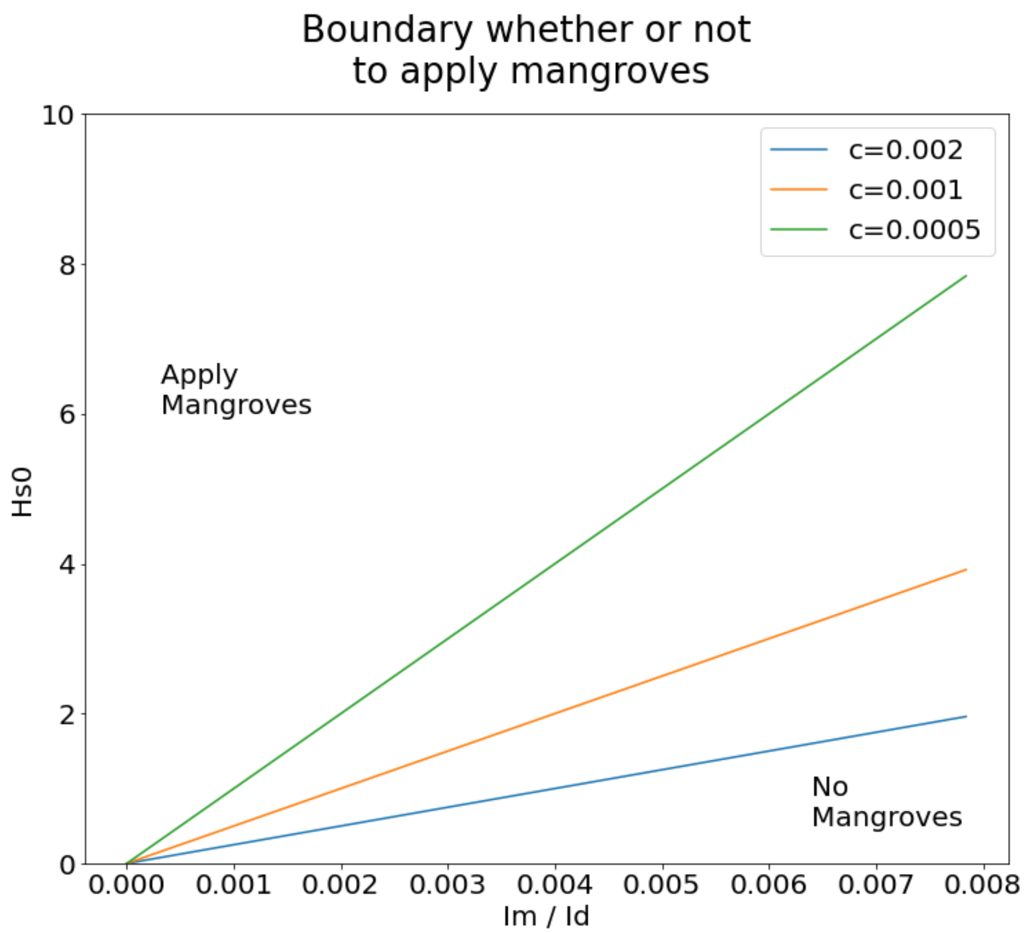

Figure A.1: Whether to apply mangroves depends on a financial relationship and a hydraulic condition. The wave attenuation per meter mangrove width c affects where the boundary lies. The storm surge is important since the wave height is often limited to the water depth. A higher storm surge enables higher waves.

Table A.3: Various numerical examples with the most relevant parameters. Note that these values apply to one meter coast length. The optimal values for h_D and W correspond to the optimal functions in Equation (4.9), Equation (4.20) and Equation (4.21). These scenarios are arbitrarily chosen and do not refer to a specific location. These are given solely to gain insights in how the optimizations work.

Variable	Dimension	Mangroves-favorable	Neutral	levee-favorable	Combination
I_D	$USD/m/m$	300	150	100	150
I_M	$USD/m/m$	0.8	1	1.2	1
c	m^{-1}	0.002	0.001	0.0005	0.002
$H_{S,0}$	m	4	3	2	4
D	USD/m	50	50	50	50
r	-	0.1	0.1	0.1	0.1
E_0	m	-1	0	0.5	0
$\tan(\alpha)$	-	0.25	0.25	0.25	0.25
ϕ	-	8	8	8	8
A	m	0.5	2	4	1
B	m	0.8	0.8	0.8	0.8
Optimal h_D	m	3.42	9.14	8.96	5.48
Optimal W	m	896	0	0	438

A.2.1. Several Numerical Examples

In Table A.3, the parameters and model results are shown for four different numerical examples. For these examples the optimal levee height and mangrove forest width are calculated based on the analytical approach.

In Figure A.2, the derivations of the total costs concerning h_D and W are plotted. Where these lines cross, the optimal combination of levee height and mangrove forest width is found. Below the line formulated by Equation (A.8) is favorable to increase the mangrove forest width, since total costs decrease more than investments costs of the mangroves increase. The same applies to the line formulated by Equation (4.18). Below both lines, increasing either the levee or mangrove forest width is a viable investment. In the blue areas, it is viable to increase the levee and mangrove forest width, in the green areas it is viable to increase the mangrove forest width, and in the grey areas it is viable to increase the levee height. These optimal values for h_D and W correspond with the formulas found in Equation (4.9), Equation (4.20) and Equation (4.21), which shows that these found equations for h_D and W are indeed correct.

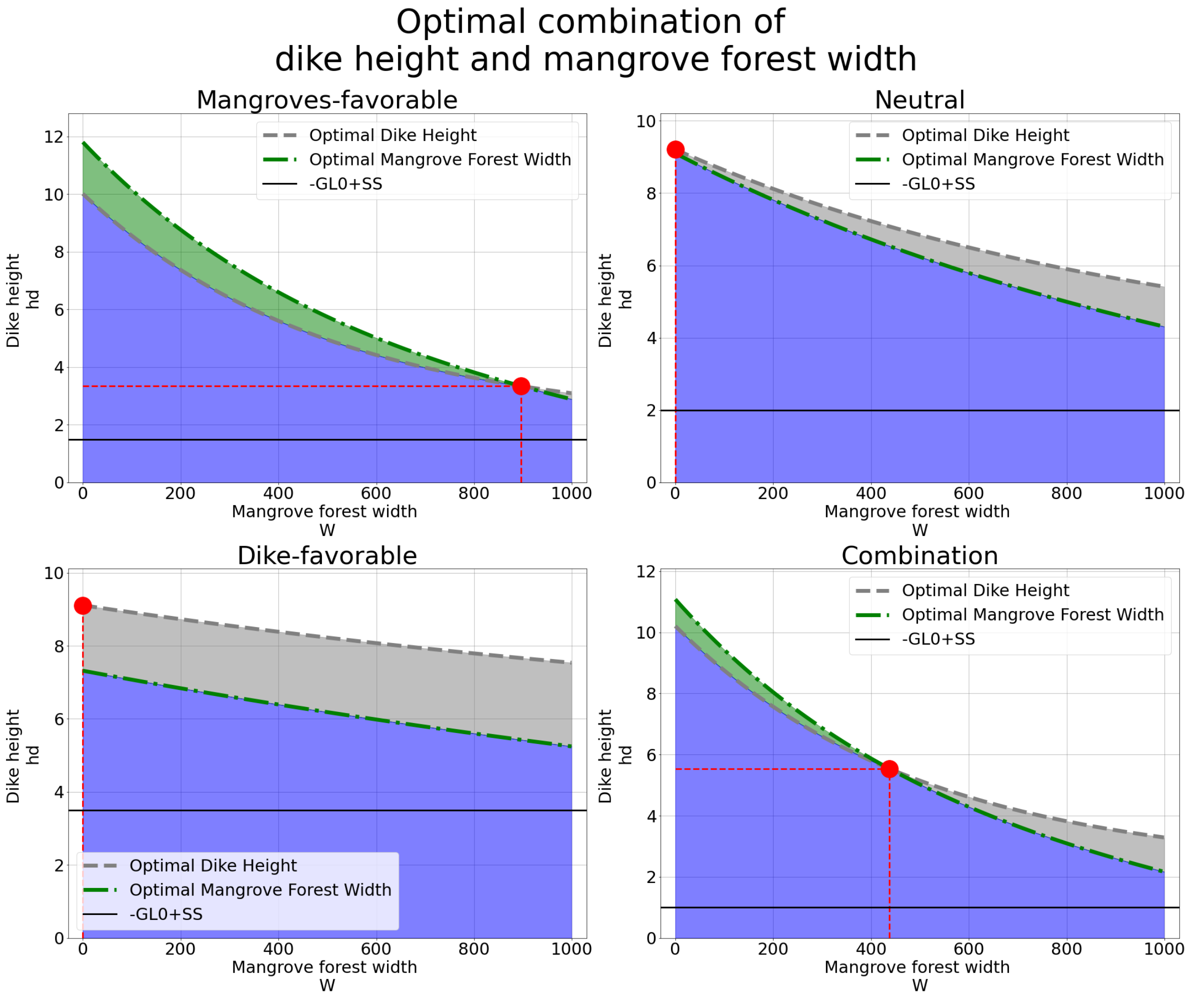

Figure A.2: Four different scenarios with the optimal combination of levee height and mangrove forest width. In the blue areas, it is feasible to increase the levee and mangrove forest width, in the green areas it is only feasible to increase the mangrove forest width, and in the grey areas it is only feasible to increase the levee height. The Combination scenario gives a solution with both a mangrove forest and a levee. For a mangrove-favourable scenario, a levee is still feasible, whereas in a more levee-favourable scenario, mangroves are not feasible at all.

Table A.4: Various scenarios with the most relevant parameters. Note that these values apply to one meter coast length.

Case	Initial mangrove width	Initial levee height
Nothing there	0	0
Existing Mangroves	300	0
Existing levee	0	3
Existing Mangroves+levee	300	3

A.2.2. Different Base Cases

Four different initial cases were defined to assess the most cost-effective solution, see Table A.4. These initial cases are then combined with the numerical examples in Table A.3 to calculate the optimal levee height and mangrove forest width.

By combining the initial cases in Table A.4 with the scenarios in Table A.3, in total, 16 combinations can be distinguished. The combinations differ in how favorable the variable values are for a levee or mangroves and the initial situation before applying (new) flood risk reduction. For each combination, the optimal levee height and mangrove forest width are calculated and shown inFigure A.3. In essence, the initial presence of a levee or mangroves does not change the optimal level of both, except when the initial presence is more than the original optimal heights and widths.

A.2.3. Effect of Changes in Variables

Figure A.4 shows how several variables change the attractiveness of both mangroves and a levee. The triangular shape in the figures represents the optimal combination of levee and mangroves for the reference case. The reference cases correspond to those in Table A.3. For the graphs other than the reference level, a rather high value for the variables are chosen while keeping the other variables as in Table A.3. These values are shown in Table A.5, including the conclusions drawn from the change in optimal levee height and mangrove forest width.

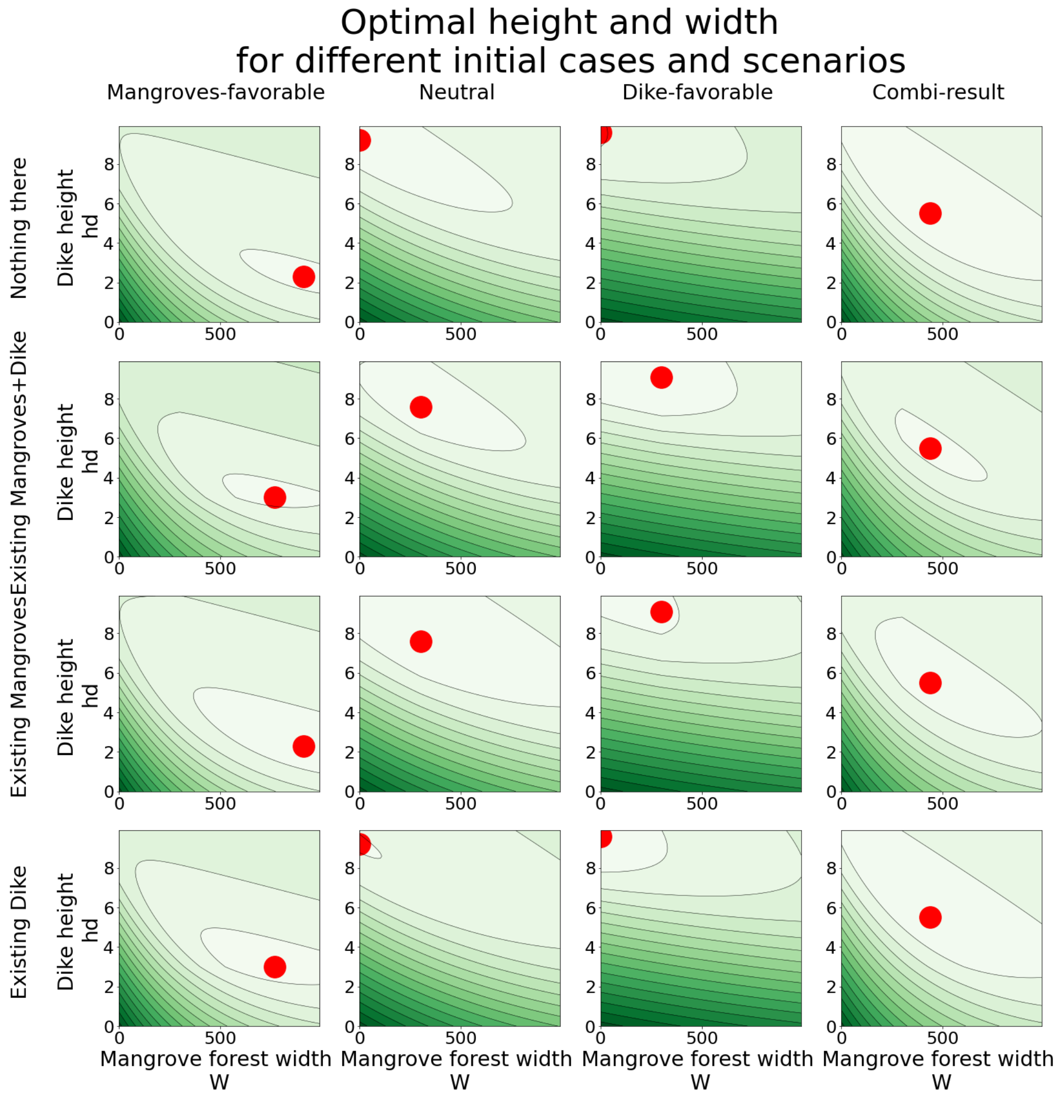

Figure A.3: Optimal mangrove forest width and levee height for each combination of initial case and a numerical example. Dark green represents high costs, while light green represents low costs. The red dots express the optimum combination of levee height and mangroves. If an existing levee is higher than the optimal levee height in case of no existing levee, the optimal mangrove forest width decreases and vice versa.

Table A.5: How variables change the attractiveness of mangroves and a levee. Although the attractiveness of mangroves may disappear entirely, a levee often remains required due to the water level, which mangroves do not reduce.

Variation	Symbol	Value	Conclusion
Reference case			
High ecosystem value		1.2	Makes mangroves a very attractive solution. It does not erase the necessity of a levee due to the water level.
High Damage	D	200	Makes flood risk reduction more effective, either via levees or mangroves. Generally a levee benefits more.
High Id	I_D	500	Makes mangroves more attractive and a levee less attractive. It does not erase the necessity of a levee due to the water level.
High Im	I_M	3	Makes mangroves less attractive relative to a levee. In some cases erases the attractiveness of mangroves.
High Hs0	$H_{s,0}$	8	Makes mangroves more attractive, but also a levee. Attractiveness of mangroves relative to a levee increases.
High Storm Surge	S	4	Makes a levee more attractive, and even necessary. Especially relative to mangroves. Makes more mangroves attractive if the threat by waves is reduced more cheaply by mangroves.
High r	r	0.2	Does not affect the attractiveness of mangroves or a levee too much.

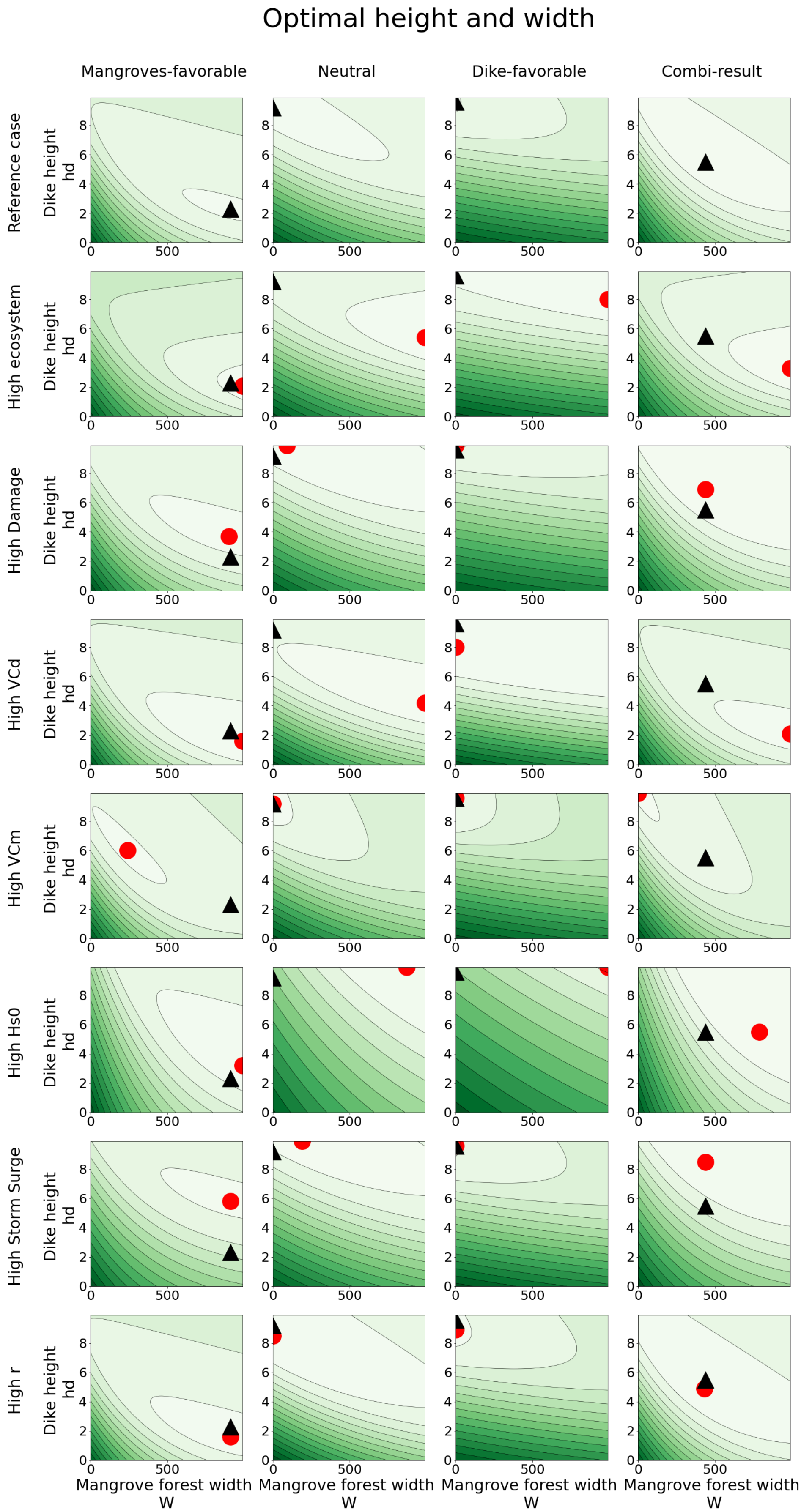

Figure A.4: Effect of changing variables on the attractiveness of using mangroves and a levee. Dark green represents high costs, while light green represents low costs. The black triangles give the optimal combination of levee and mangroves for which costs are minimised in the reference case. The red dots are the optimal combinations in case one variable is changed relative to the reference case (see y-axes).

B

Appendix B: Model Input

B.1. Mangroves Modelling in SWAN

To model mangroves in SWAN, the height, number of stands/m2, the diameter of the stem and drag coefficient must be defined for all layers. Similar to Janssen (2016), seven layers are applied to model mangroves. To reduce the variables when performing the sensitivity analysis, the mangrove characteristics per layer are referenced to one value only. The height of the layers is evenly distributed, the diameter and drag coefficient are relative to the diameter and drag coefficient at the bottom layer. This way, a sensitivity analysis can be performed while limiting the number of variables to maintain clarity over the analysis.

For each run of modelling the wave attenuation using SWAN, a SWAN input file is created, see Figure B.1. Also for each run a vegetation cover file is created, indicating where vegetation is present and where it is not.

Table B.1: SWAN parameters for mangrove characteristics. All parameters are expressed relative to each other, similar to Janssen (2016). This way, a sensitivity analysis can be performed while maintaining clarity on the different mangrove characteristics.

Layer	**1**	**2**	**2**	**2**	**3**	**3**	**3**
Height	0.03	0.29	0.43	0.57	0.72	0.86	1.00
Number of stands/m2	1	1	1	1	1	1	1
Diameter	1.00	0.08	0.33	0.58	0.83	0.56	0.28
Drag coefficient	1	1.00	0.83	0.83	0.83	0.83	0.83

```
PROJ 'input' '01'

SET NAUTICAL
MODE STATIONARY ONEDIMENSIONAL

$ CGRID REGULAR [xpc] [ypc] [alpc] [xlenc] [ylenc] [mxc] [myc]
CGRID REGULAR 0.0 0 0 914 0 914 0 CIRCLE 36 0.14 2.80  31

$ INPGRID BOTTOM REGULAR [xpinp] [ypinp] [alpinp] [mxinp] [myinp] [dxinp] [dyinp]
INPGRID BOTTOM REGULAR 0.0 0 0 914 0 1.0 0
READINP BOTTOM -1 'bathy.txt' 5 0 FREE

INPGRID WLEVEL REGULAR 0.0 0 0 914 0 1.0 0
READINP WLEVEL 1 'wlevl.txt' 5 0 FREE

BOUND SHAPESPEC JONSWAP 3.3 PEAK DSPR POWER
BOUNDSPEC SEGMENT XY 0.0 0 UNIFORM PAR 10 3.04 270 2

GEN3
BREAK CONstant alpha=1.00 gamma=0.77
OFF QUAD
OFF WINDG
OFF WCAP

$ VEGEtation < [height] [diamtr] [nstems] [drag] >
VEGETATION 0.32999999999999996 1.2 1 1.0 &
3.19 0.096 1 1.0 &
4.7299999999999995 0.396 1 0.83 &
6.27 0.696 1 0.83 &
7.92 0.9959999999999999 1 0.83 &
9.459999999999999 0.672 1 0.83 &
11.0 0.336 1 0.83

$ INPGRID NPLANTS REGULAR [xpinp] [ypinp] [alpinp] [mxinp] [myinp] [dxinp] [dyinp]
INPGRID NPLANTS REGULAR 0.0 0 0 914 0 1.0 0
READINP NPLANTS 1 'vegcover.txt' 5 0 FREE

FRICTION MADSEN 0.0

NUMERIC ACCUR 0.01 0.01 0.01 99 STAT 100 0.01

POINTS 'gauge' FILE   'gauges.loc'
$ CURve �sname� [xp1] [yp1] < [int] [xp] [yp] >
$ [int] = nr of locations
CURVE  'curve' 0.0 0 914 914 0
TABLE  'curve' HEAD   'curve.tab' HS TPS $ TMM10 DISSIP DISSURF DISBOT DISVEG
SPEC   'gauge' SPEC1D 'gauges.spc'
TABLE  'gauge' HEAD   'gauges.tab' HS TPS TMM10

COMPUTE
STOP
```

Figure B.1: Example of a SWAN input file. For each run, the input file is replaced with the values applicable to that run, for example the vegetation parameters.