Mangrove Habitat Suitability Assessment Framework

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SUMMARY

This report represents the development of an assessment framework for mangrove habitat suitability. The causes of mangrove degradation and the factors influencing the success and failure of mangrove restoration are examined. Through the analysis of these factors and additional research, the key parameters for mangrove habitat suitability such as stressors and optimal conditions for mangrove growth will be identified. The report focuses on four mangrove species: $Sonneratia\ \ alba$, $Avicennia\ \ marina$, $Rhizophora\ mangle$, and $Ceriops\ \ tagal.$

The methodology of the report is a combination of a literature review, expert interviews, and the development of an assessment framework. The assessment framework integrates various parameters identified through a literature review, expert weightings on these parameters, and a scoring system to assess mangrove habitat suitability. The assessment framework can evaluate sites for mangrove survival and growth considering environmental, socio-economic, and institutional factors emphasizing the impact of environmental factors like salinity and temperature on mangrove health, as well as human activities and regulations.

The literature review identified a wide range of parameters critical for mangrove environments, including environmental, socio-economic, and institutional ones. Environmental parameters were categorized into chemical (salinity, pH, nutrients availability), physical (temperature, rainfall, inundation, wave action, sediment, soil type), and ecological (food web, ecosystem connectivity, seedling availability) aspects. Socio-economic factors covered sustainable use, community engagement, and upstream disturbance, while institutional parameters focused on the existence and enforcement of mangrove conservation laws. Additionally, each parameter range gets a score from 0 to 10 based on how favorable they were for the specific mangrove species, with 10 indicating the most favorable conditions.

Furthermore, the weighting system involves input from experts who assign weights to each parameter based on their importance for mangrove survival and growth. In the expert interviews, significant weight was assigned to environmental factors as key determinants of mangrove survival and growth. Experts particularly emphasized on the importance of parameters like inundation duration, wave action, and enforcement of laws due to their substantial impact on mangrove health and conservation. Conversely, the importance of connectivity to other species was regarded as less important in the direct context of mangrove health and development.

The developed assessment framework is designed to assess the suitability of a site for mangrove habitat based on user-provided characteristics of the site. The model has a threshold for critical factors like inundation duration and temperature; if these thresholds are exceeded, indicating potentially harmful conditions, the assessment concludes that the assessment is not possible. Users also have the option to select “No Available Data” for certain parameters. However, if the cumulative weight of parameters without data exceeds a 10% threshold, the model indicates that a reliable assessment is not possible due to significant data gaps

1 INTRODUCTION

1.1 Mangroves ecosystem overview

Mangroves are coastal wetlands found in tropical and subtropical intertidal zones. These plants, known as "roots of the sea", survive in coastal environments tolerating saline seas and waves that many other species cannot (Wildfowl & Wetlands Trust, 2019). Mangroves act as natural barriers, mitigating the impacts of waves and storms on coastlines, reducing erosion, and protecting communities. (Zambonelli, 2022). Their thick root systems stabilize the soil and also slow down the water movement, trapping sediments and thereby decreasing coastal erosion (The Nature Conservancy, 2023). Moreover, mangroves are rich in biodiversity and provide critical habitat for a variety of marine species such as fish, shellfish, birds, and mammals (Zambonelli, 2022). They also help the local economy as they enable activities like fishing and eco-tourism, supporting the neighboring community (The Nature Conservancy, 2023). Additionally, mangroves have an important role in mitigating climate change. They help remove carbon dioxide from the atmosphere by sequestering carbon in the soil, a phenomenon known as "blue carbon" (Spalding et al., 2014).

Despite their advantages, mangroves are under threat globally, Table 1.1 shows the main causes of mangrove degradation. Activities such as deforestation, pollution, and the effects of climate change have resulted in considerable mangrove degradation (UNEP, 2014). Globally, mangroves have suffered significant declines, with around 35% lost in the last two decades alone, mainly due to the expansion of aquaculture and human activities (Verdugo et al., 2015). This decline has a significant impact on biodiversity and communities that rely on mangroves for their day-to-day life and protection from natural disasters.

Table 1.1 Causes of mangrove degradation

Factors	Impact	Reference
Clearance for timber and fuel wood	Direct removal causes habitat fragmentation and ecosystem service loss.	(UNEP, 2014)
Conversion to agriculture/aquaculture	Leads to habitat loss, ecosystem service decline, pollution, and erosion.	(Biswas et al., 2021)
Urban development and harvesting	Resulted in over 25% of mangrove forest loss in the past 50 years.	(Evans, 2020)
Pollution and erosion	Smothers mangrove roots, affecting oxygen uptake, growth, and resilience.	(UNEP, 2014)
Cyclones and floods	Damage mangroves, especially if already degraded or fragmented.	(Biswas et al., 2021)
Climate change	Leads to saltwater intrusion, erosion, and flooding.	(UNEP, 2014)

1.2 Problem statement

Numerous studies have proven the importance of mangroves and their role in coastal ecosystems. However, despite the extensive research available on mangroves, there is a gap in research focusing on the development of assessment frameworks for mangrove restoration and plantation (Jimenez et al., 2010). As a result, a robust and scientifically supported assessment framework is still lacking This assessment framework will be developed in this research. To ensure its accuracy, it should assess specific mangrove species. The selected species are *Sonneratia alba*, *Avicennia marina*, *Rhizophora mangle*, and *Ceriops tagal*. Additionally, this assessment framework should be able to assess the mangrove habitat suitability, guiding plantation or restoration efforts to areas with the best chance of success. As can be seen in Table 1.2 unplanned restoration or plantation and lack of information about the site's conditions can result in poor outcomes and misuse of resources, and they are one of the main causes of restoration failure (Jimenez et al., 2010).

The success of mangrove plantation and restoration projects is crucial, yet these initiatives fail frequently. For instance, in the Philippines, survival rates in some mangrove plantation sites were as low as 13.71% (Pacyao et al., 2018). The low survival rates of planted mangroves are mostly caused by the failure to restore natural hydrological conditions (Matsui et al., 2012). For example, plantations that do not account for the critical inundation by tidal waters experience lower growth and survival rates of mangrove species (Matsui et al., 2012). The failure of these plantations and restoration efforts is also due to the use of immature or young seedlings rather than mature ones and the absence of strict post-planting care, such as regular maintenance and monitoring (Pacyao et al., 2018). These studies emphasized the importance of proper environmental conditions and management practices for the success of mangrove plantations and restoration.

Table 1.2 Causes of mangrove plantation and restoration failure

Causes of failure	Reference
Lack of understanding of the reasons for the loss of mangroves	(Hai, et al., 2020)
Inappropriate hydrologic conditions	(Gauthey et al., 2022)
Inappropriate topography and soil conditions	(Kodikara et al., 2017)
Poor site and species selection	(Hai, et al., 2020)
Lack of local management	(Hai, et al., 2020)

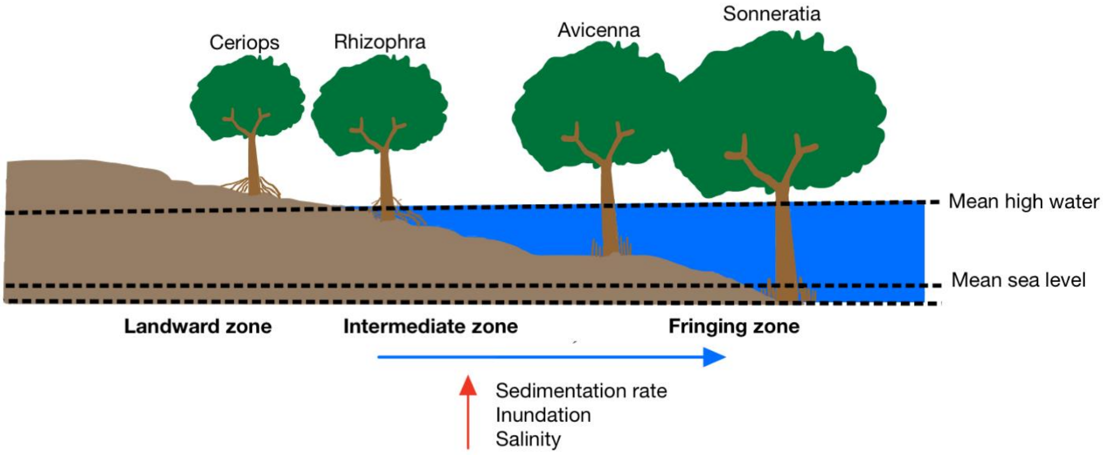
Analysing the causes of these failures provides preliminary insights into the necessary conditions for successful mangrove plantation and restoration. For instance, factors like site selection and community engagement are important parameters in habitat suitability assessments. This analysis helps in the criteria development for mangrove habitat suitability and ensures that future projects have higher chances of success.

1.3 Selected mangrove species

The presence and spread of mangroves are primarily influenced by four key elements: the extent and frequency of inundation, regional climate conditions, the salinity of the water, and the nature of the soil in which they grow (Florida Department of Environmental Protection, 2023). For example, mangroves found at lower tidal elevations, where they are more frequently submerged, have a higher tolerance to regular inundation and elevated salinity levels, compared to those situated in higher intertidal zones (Kathiresan, 2021).

Mangrove forests are home to approximately 80 species of mangroves (Duke, 2017). Each species varies in its adaptability to environmental conditions like inundation and salinity. In this research, four mangrove species were selected to be studied. The species were selected based on criteria such as their distribution across the intertidal zone, ensuring that at least one species represents each specific area, including the landward and intermediate zone, as well as the fringe zone. Additionally, the volume of existing research on each species was also a key factor in their selection. Another reason for selecting these species is their utilization by Witteveen + Bos for plantation and restoration projects. The species studied are $Sonneratia\quad alba$, $Avicennia\quad marina$, $Rhizophora\quad mangle$, and $Ceriops\quad tagal$. Their intertidal distribution of these species is depicted in Figure 1.1.

Figure 1.1 Mangrove species zonation



1.3.1 Sonnaratia alba

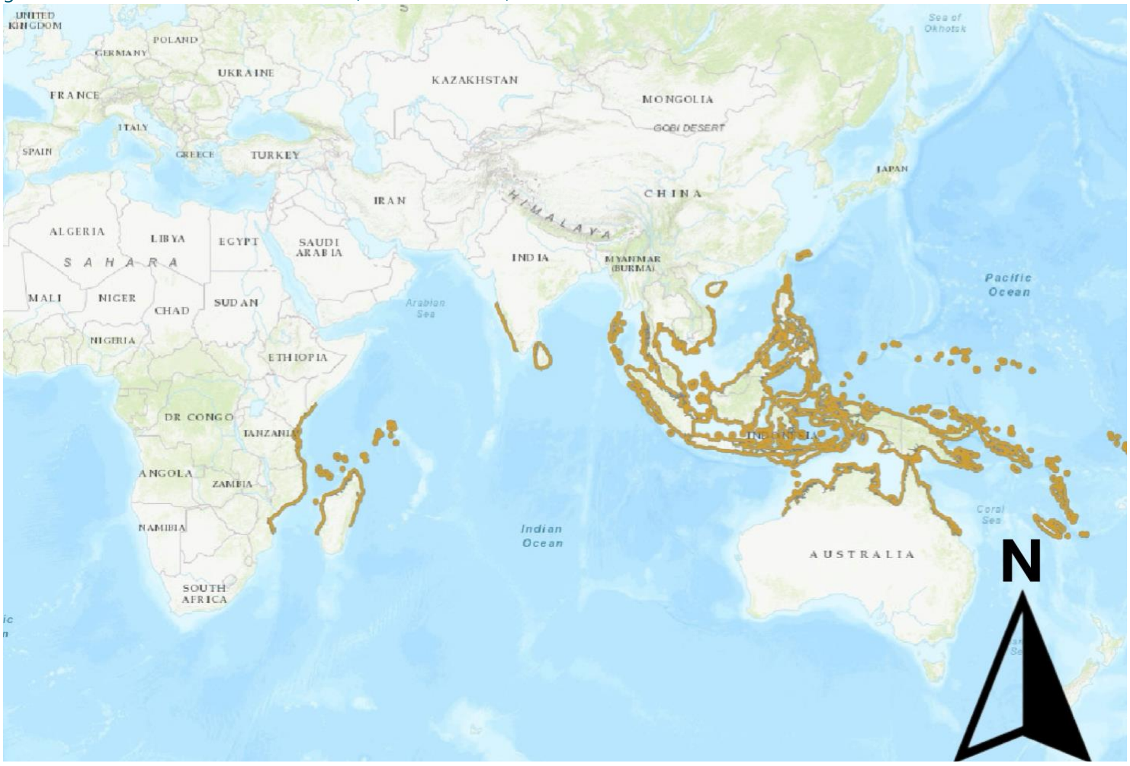
Sonneratia alba (Figure 1.2), commonly known as the white or apple mangrove, is often one of the first species to establish itself in mangrove ecosystems, especially on sandy fringes. Its ability to colonize such areas makes it key in mangrove rehabilitation efforts (Göltenboth et al., 2006). The apple mangrove is also known for its fruit production which is an important part of the ecological food chain (Fern, 2023). Moreover, it has blunt pneumatophores that are crucial for both oxygen uptake and soil stabilization (Fern, 2023) (Figure 1.3). Pneumatophore roots have a slender, pencil-like form which emerges vertically from muddy substrates (Nguyen et al., 2023). Their internal structure is rich in aerenchyma tissue which stores air and facilitates gas exchange (Nguyen et al., 2023). This architecture enables these roots to directly absorb oxygen from the atmosphere which is an essential adaptation for thriving in oxygen-poor, waterlogged conditions (Naturalist, n.d.).

Figure 1.2 Sonneratia alba (Plump, n.d.)

Figure 1.3 Blunt pneumatophores roots (Shutterstock, n.d.)

Sonneratia alba is commonly found across a wide region ranging from the coasts of East Africa, through Southeast Asia, extending to northern Australia, and reaching out to the islands of the western Pacific and the Indian Ocean (Duke et al., 2008). Figure 1.4 provides a view of all the areas where this species can be found (Duke et al., 2008).

Figure 1.4 Sonneratia alba distributution (Duke et al., 2008)



1.3.2 Avicennia marina

Avicennia marina (Figure 1.5), known as the gray mangroves is a pioneer, typically colonizing muddy soils and is mostly found in the intertidal zones of estuarine areas (Naturalist., n.d.). They can grow as shrubs or trees and they have pneumatophores which are essential for gas exchange during submersion (Figure 1.6). Moreover, gray mangroves can tolerate different ranges of salinity from brackish estuaries to complete marine habitats (Queensland Government, 2018).

Figure 1.5 Avicennia marina (Getimages, n.d.)

Figure 1.6 Pneumatophores roots (Getimages, n.d.)

The gray mangrove is found along the eastern coast of Africa, across Asia, and into northern New Zealand and Australia. It also grows in the arid coastal areas of the Arabian Peninsula, including the UAE, Qatar, Bahrain, Oman, and around the Red Sea and Persian Gulf (Duke et al., 2008). Figure 1.7 provides a view of all the areas where this species can be found (Duke et al., 2008).

Figure 1.7 Avicennia marina distribution (Duke et al., 2008)

1.3.3 Rhizophora mangle

Rhizophora mangle (Figure 1.8), also known as the red mangrove can be either a shrub or a tree. It predominantly thrives in moist and estuarine ecosystems in tropical environments (plan of the world., n.d.). This species is recognized for its prop roots that elevate it above water, which play a key role in stabilizing coastal areas by attenuating hydrodynamic energy, thus effectively reducing erosion (Cardenia, n.d.) (Figure 1.9). These roots also help manage shifting sands which aids in protecting coastlines and building up sediment. Moreover, red mangroves are adaptable, thriving in various environments including fresh and saltwater, and often in brackish areas. However, despite all the advantages they offer, red mangroves face threats with a global population decline that is mainly due to coastal development (Takvorian, 2022).

Figure 1.8 Rhizophora mangle (Azgardens, n.d.)

Figure 1.9 Prop roots (Kew, n.d.)

The *Rhizophora mangle* is found in numerous countries and territories, including regions in North, Central, and South America, the Caribbean, and West Africa. Figure 1.10 provides a view of all the areas where this species can be found (Duke et al., 2008).

Figure 1.10 Rhizophora mangle distribution (Duke et al., 2008)

1.3.4 Ceriops tagal

Ceriops tagal (Figure 1.11), also known as the yellow mangrove, is a member of the Rhizophoraceae family (Queensland Government, 2018). It is a shrub or a small tree which is mainly found at the upper tidal limits of mangrove shores (Queensland Government, 2018). It thrives on firm, peaty, and well-drained soil. It has knee roots that are relatively thin, creating loops (Alappatt, 2008) (Figure 1.12). These roots emerge above the soil surface and curve down.

Figure 1.11 Ceriops tagal (Tropical, n.d.)

Figure 1.12 Knee roots (Flickr, n.d.)

The *Ceriops tagal* species are present in a variety of countries across the globe including Australia, Bangladesh, China, India, Indonesia, Malaysia, Myanmar, and Madagascar. Figure 1.13 provides a view of all the areas where this species can be found (Duke et al., 2008).

Figure 1.13 Ceriops tagal distribution (Duke et al., 2008).

1.4 Research questions

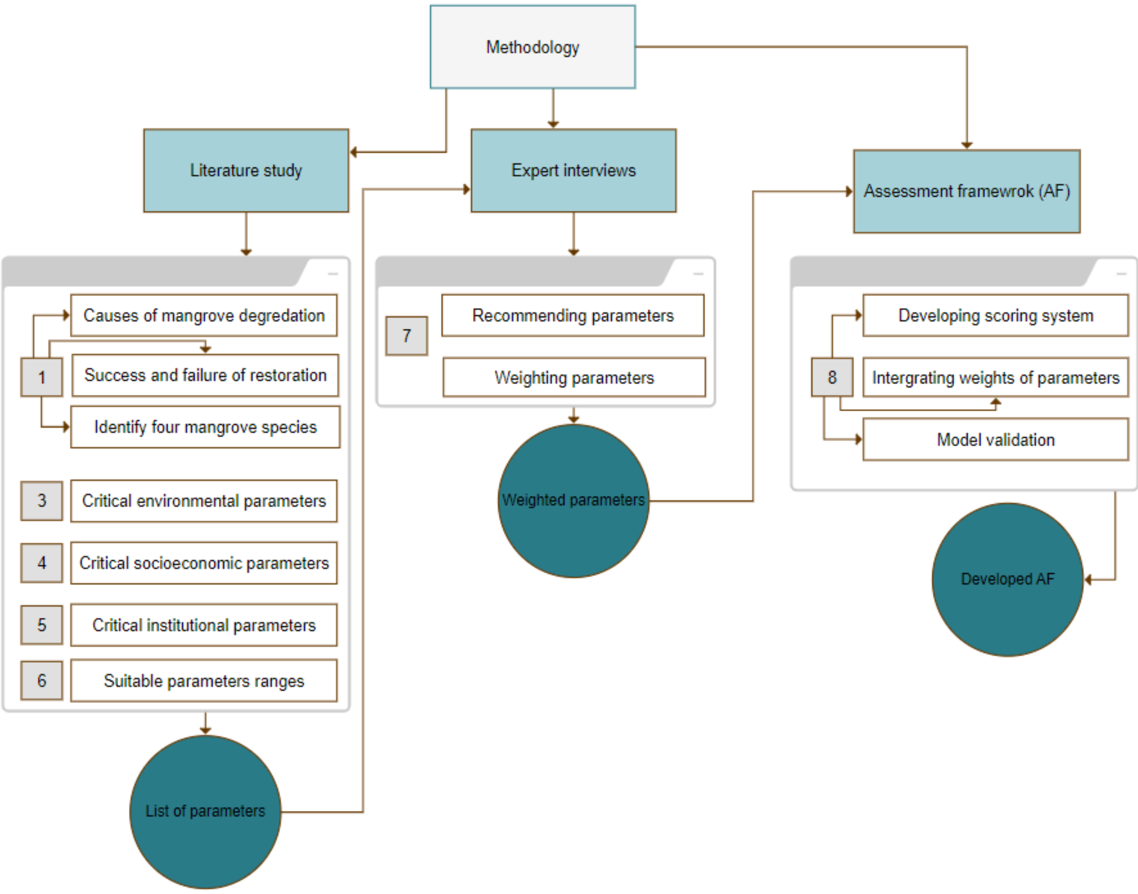
The aim is to develop an assessment framework for mangrove habitat suitability for mangrove restoration and plantation sites.

1. What are the essential parameters influencing mangrove survival and growth?
    1.1. What are the critical environmental parameters including chemical, physical (abiotic), and ecological (biotic) factors that determine the survival and growth of mangroves?
    1.2. How do socioeconomic factors such as community engagement and human activities influence the suitability of locations for the survival and growth of mangroves?
    1.3. How do institutional policies and regulations influence a region's suitability for the survival and growth of mangroves?
2. How can a model for assessing mangrove habitat suitability be developed?
    2.1. How can the identified factors be weighted and prioritized within the assessment framework to reflect their relative importance in mangrove habitat suitability?
    2.2. How can the identified parameters and their respective weights be incorporated into an assessment framework for mangrove habitat suitability?

2 METHODOLOGY

The goal of this research is to develop an assessment framework for determining mangrove habitat suitability, assessing how suitable a location is for mangrove survival and growth. To achieve this, the research will adopt a mixed-methods approach, combining insights from literature reviews and expert interviews. This research starts with a review of the literature to develop a preliminary set of criteria for assessing mangrove habitat suitability. The review will concentrate on identifying essential environmental, socioeconomic, and institutional parameters that are critical for mangrove survival and growth. Building on the insights from the literature review, the second stage involves conducting expert interviews. These interviews aim to refine and prioritize the parameters identified earlier based on expert knowledge. The final phase focuses on developing the assessment framework using the insights gathered from the literature review and expert interviews. Figure 2.1 shows the methodology for the development of the assessment framework, the small squares with numbers indicate in which chapter these steps will be discussed.

Figure 2.1 Research methodology



2.1 Literature review

The first phase in this research is to conduct a literature review, which is the primary source of data for determining critical parameters for mangrove survival and growth. This review covers a wide range of topics including causes of mangrove degradation and the factors that influence the success or failure of plantation and restoration projects.

A total of at least 40 papers over the last two decades were examined, with emphasis on their relevance to mangrove ecosystems and appropriate conditions for their growth. This includes a focus on mangrove plantation and restoration, ecology, habitat suitability, and the influence of socio-economic and institutional factors. Key search terms included "mangrove plantation", "mangrove restoration", "mangrove ecology", "mangrove habitat suitability", "suitable mangroves environment", "socioeconomic impact on mangrove establishment", "policy and mangroves", "salinity ranges for mangrove", "tidal patterns and mangroves", "soil characteristics for mangroves", and "community involvement in mangrove plantation" among others.

The literature review is used to gather information about various mangrove species and to identity the necessary conditions for mangroves to survive and grow. After that literature is used to identify the most suitable environmental conditions for these species. Additionally, it is used to quantify correlations between various parameters which was communicated to experts. For example, examining the correlations between environmental factors such as temperature and salinity or wave action and sediment supply, to determine the extent of their correlation. This is an important step to ensure that when experts assign weights, they do so with a clear understanding of each factor's direct impact on mangroves' health. The analysis of these correlations focuses on determining the appropriate environmental conditions, such as the right salinity levels and temperature ranges for mangroves to survive and grow.

2.2 Expert interviews

Following the literature review, expert interviews were conducted to finalize and prioritize factors for assessing mangrove habitat suitability. Three semi-structured interviews were performed, meaning they had a specific focus while also allowing for flexible discussions. These experts were chosen based on their knowledge and experience in areas directly related to the research, such as mangrove ecosystems and assessment framework development. Additionally, their understanding of socioeconomic and institutional factors was essential in understanding the broader implications of mangrove habitat suitability.

For these interviews, experts were provided with a list of criteria derived from the literature review. They also received a sample of the interview questions in advance, allowing them to base their responses on additional literature research. The experts were asked to select and recommend the essential parameters and finalize the list of criteria. Each expert assigned a weight to the selected parameters on a scale from one to 100, indicating their importance in evaluating mangrove habitat suitability. The weights given by the experts for each parameter were averaged to determine their relative importance in the final assessment framework.

2.3 Model development

The assessment framework incorporates findings from literature reviews and expert interviews, including parameters and their assigned weights and scoring ranges. The model operates by evaluating a range of parameters that are important to the health and sustainability of mangrove ecosystems. For each of these parameters, users input specific conditions relevant to their site. The model then assigns a score to each parameter on a scale from 0 to 10, based on how favorable the conditions are for mangrove survival and growth.

The model multiplies the score of each parameter by its corresponding weight, resulting in a weighted score for that parameter. To determine the final suitability score, the model adds up all the weighted scores achieved and compares this sum to the total possible weighted scores. This comparison is essentially a ratio of the points achieved to the total achievable points. The result is then expressed as a percentage, which represents the overall suitability score for the mangrove habitat at the site being assessed. Finally, the model offers recommendations on which parameters need improvement to enhance the site's suitability for mangrove ecosystems. The recommendations simply consist of the parameters where there is most potential to gain. This potential is the lost out points multiplied by weight. The top five greatest potential loses are shown as recommendation, along with the percentage that could be gained if the parameter had perfect conditions.

3 ENVIRONMENTAL PARAMETERS

This chapter explores all environmental parameters in categories of physical, chemical, and ecological. Each category has its own specific parameters. In the chemical category, for instance, it will focus on parameters like salinity, pH, and nutrients. Each section will discuss the importance of these parameters for mangrove health, examining their direct or indirect effects on these ecosystems and whether these impacts are positive or negative. The goal is to understand the different factors that influence the health of mangrove environments.

The selection of these particular environmental parameters is based on their frequent mention in research papers. These studies covered research on mangrove habitat suitability, factors leading to the success or failure of mangrove plantation and restoration projects, and the reasons for mangrove degradation. Knowing the causes of mangrove degradation for example helped identify some stressors affecting these ecosystems. Additionally, the frequent mention of these parameters in different research papers and the emphasis authors put on their importance was the reason for choosing them as key factors for mangrove suitability. This chapter starts by discussing chemical parameters. These are important for understanding the physical parameters that come next. After that, ecological parameters will be discussed.

3.1 Chemical parameters

Different mangrove species have varied tolerances to chemical parameters such as salinity, pH, and the availability of nutrients (Kathiresan, 2001). These parameters influence the overall ecological balance and functionality of mangrove habitats, on top of the individual plant health. Their direct impact on mangrove health is shown in Figure 3.1.

3.1.1 Salinity

Mangroves are adaptive to salinity grow in saline environments, but they are sensitive to extreme salinity fluctuations (Dittm et al., 2022). High salinity levels can negatively impact mangroves' ability to absorb nutrients and water effectively (Adame et al., 2014). It can also cause water deficit in these plants, resulting in physiological drought (Doganlar et al., 2010). This drought directly leads to various negative impacts, including ionic, osmotic, and oxidative stress, which affect the survival, growth, and stability of mangroves (Doganlar et al., 2010).

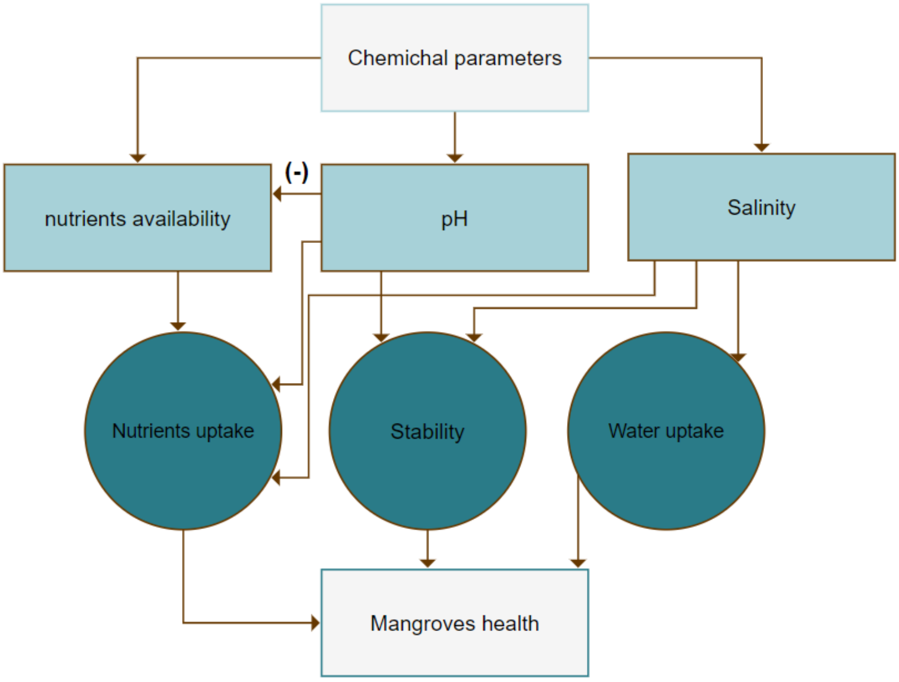
3.1.2 pH

The pH level of the soil is a critical factor influencing mangrove growth (Kathiresan, 2001). Mangroves generally thrive in slightly acidic to neutral pH conditions. This facilitates nutrient absorption and availability (Cooper T., 2009). Extremely high or low pH levels can negatively impact their health and hence, affect its stability (Shahid et al., 2014). High pH can lead to a scarcity of accessible iron, causing iron chlorosis (Cooper T., 2009). Additionally, nutrients like manganese, copper, and zinc become less accessible in conditions of high pH (Cooper T., 2009). There is a clear correlation between sediment pH and the level of ammonium-nitrogen. An increase in sediment pH leads to a decrease in ammonium-nitrogen, showing a negative relationship with a correlation coefficient (R^2) of 0.3 ($p = 0.008$, $n = 22$) (Reddy et al., 2020). This suggests that changes in sediment pH can significantly affect the amount of nitrogen available in mangrove environments.

3.1.3 Nutrients availability

The nutrient availability in the soil is considered one of the most important characteristics affecting mangrove survival and growth (Kumari et al., 2020). In particular, nitrogen and phosphorus are critical for protein creation and energy processes. However, they are frequently limited in low-nutrient soils such as carbonate soils, which is challenging mangrove ecosystems (Campbell et al., 2006).

Figure 3.1 Impact of chemical parameters on mangroves



3.2 Physical parameters

In this section, the key physical (abiotic) parameters that influence mangrove habitats will be discussed. These parameters include climate parameters such as temperature and rainfall patterns, and aspects of hydrodynamic parameters, including inundation duration and wave action. Finally, sediments, such as sediment supply and soil type will be examined for their impact on the resilience and sustainability of mangrove habitats.

3.2.1 Temperature

The distribution of mangroves globally is associated with water temperature ranges, with warmer sea currents enabling their extension into higher latitudes. Different species of mangroves have different tolerance to temperature ranges (Duke et al., 1998). However, extreme temperatures, both high and low, can result in increased stress and mortality in mangrove populations (Ward et al., 2017). The impact of temperature is in Figure 3.2.

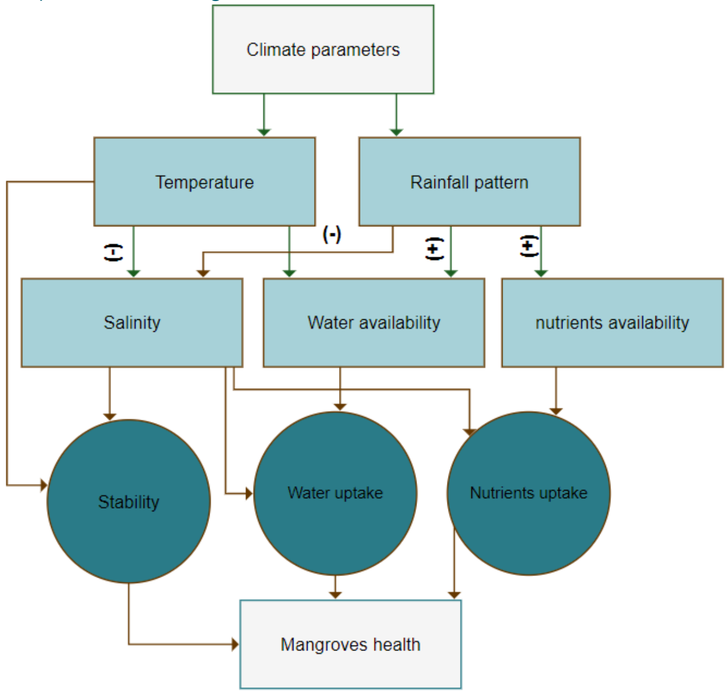
Temperature affects the mangroves' physiological adaptations, distribution, and internal processes. It impacts photosynthesis, salt regulation, and root respiration (Hutchings et al., 1987). High temperatures increase evaporation rates which can result in an increase in salinity. Sea surface temperature (SST) has a negative correlation with sea surface salinity. When SST increases, SSS decreases, with a correlation coefficient (r) of -0.81 ($p < 0.0001$, $n = 377$) (Rato et al., 2022). Additionally, low temperatures cause mangrove mortality and leaf damage, affecting survival, growth, and stability (Ward et al., 2016). An increase in salinity can threaten mangroves in several ways, as explained in the chemical parameters section.

3.2.2 Rainfall pattern

Fluctuating rainfall patterns impact mangrove ecosystems. Reduced precipitation combined with increased evaporation can lead to increased soil salinity, which threatens mangrove seedlings and affects the overall health of these habitats (Makumbura, 2022). Extreme rainfall events can reduce pore water salinity and sulphate concentrations, which significantly influence mangrove health as well (Lacerda et al., 2022). These changes in salinity affect both seedling survival and the growth rates and productivity of the mangroves. Rainfall demonstrates a significant correlation with sea surface salinity (SSS). This relationship is highlighted, with a correlation coefficient (r) of 0.64 ($p = 0$, $n = 348$) indicating that as rainfall increases, sea surface salinity tends to decrease (Wuji et al., 2022).

Furthermore, rainfall is an essential component in the nutrient cycle since it helps in the transfer and cycling of nutrients within the mangrove ecosystems and between the mangroves and surrounding ecosystems (Ward et al., 2017). The impact of rainfall is in Figure 3.2.

Figure 3.2 Impact of climate parameters on mangrove health



3.2.3 Inundation duration

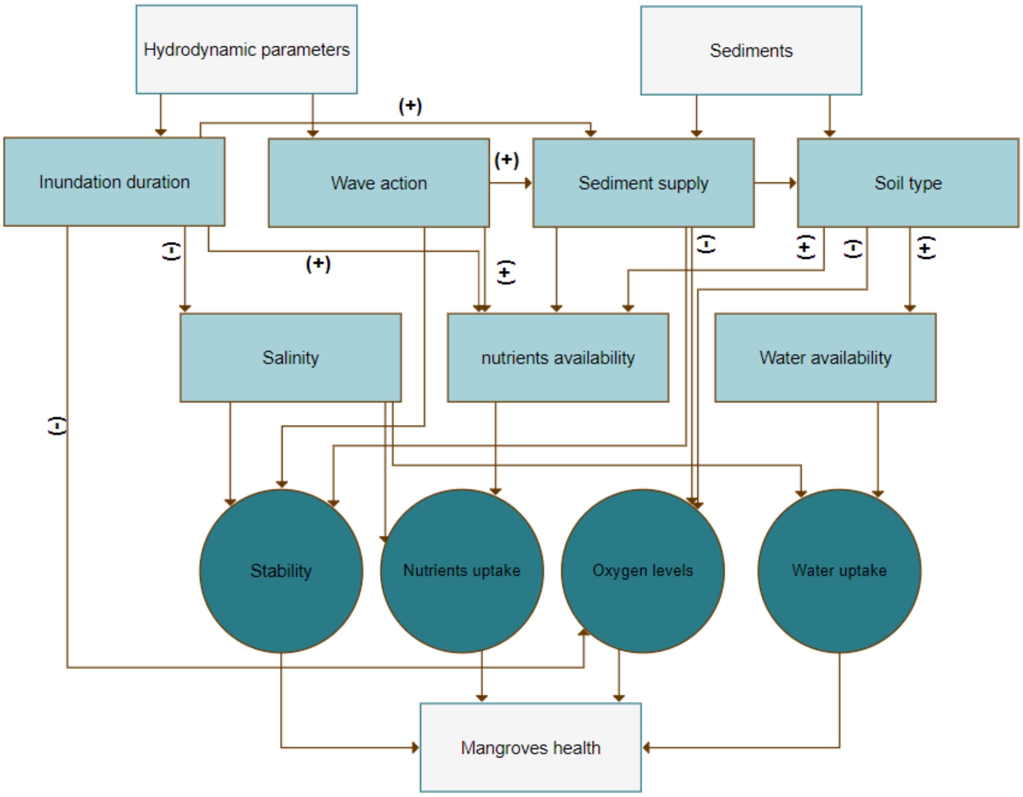
Tides, which are periodic rises and falls of sea level, influence the inundation duration in mangrove ecosystems, impacting their health and resilience (Queensland, 2019). Different mangrove species have different levels of adaptation to these inundation patterns. Prolonged inundation can negatively impact the survival, growth, and stability of mangroves due to decreased gas exchange in their root systems (Jimnez et al., 1985). This effect is particularly important to consider for mangrove seedlings, which are more vulnerable to excess inundation in comparison to adult trees (Jimnez et al., 1985). The impact of inundation duration is in Figure 3.3.

The frequency of inundation determines how often mangroves are submerged, which is a critical factor in their overall health and growth (Balke et al., 2015). Inundation influences a range of chemical properties in both water and sediment, including salinity and oxidation-reduction levels which are all important for the health of mangrove ecosystems (Queensland., 2013). Moreover, inundation ensures a consistent nutrient supply and helps keep soil salinity within safe thresholds for mangroves when inundation occurs with fresh water (Luo et al., 2020). However, during dry seasons, reduced water levels can lead to increased salinity, posing significant stress to mangrove systems (Barr et al., 2014). The impact inundation duration is shown in Figure 3.3.

3.2.4 Wave action

Waves directly affect the health of mangrove ecosystems. Waves that result from the movement of energy across water surfaces driven by wind exhibit variations in height and period depending on weather conditions and geographical location (Méndez et al., 2020). This dynamic process is critical in shaping coastal erosion and sediment deposition, especially in mangrove areas (Spalding et al., 2014). While moderate wave action benefits mangroves by distributing nutrients, intense wave activity can severely limit their distribution (Aung et al., 2011). In extreme cases, high-energy waves can cause significant damage to such forests, and even lead to their mortality (Aung et al., 2011). The impact wave action is shown in Figure 3.3.

Figure 3.3 Impact of hydrodynamic parameters and sediments on mangrove health



3.2.5 Sediment supply

Availability of sediment supply is an essential factor when assessing mangrove habitat suitability. That is because mangroves flourish in areas where there is a continuous supply of mud and nutrients, typically provided by sediment-rich waters (Boughanmi et al., 2020). A steady flow of sediment is essential for maintaining mangrove substrate levels and supporting their role in coastal defense and land formation (Boughanmi et al., 2020). Moreover, sufficient sediment helps mitigate the negative impacts of sea-level rise and land subsidence which can affect mangroves stability (Boughanmi et al., 2020). Lack of sediment can lead to coastal erosion and the failure of mangrove restoration efforts (William et al., 2021). However, if a high supply of sediments deposits in the forest, it can overwhelm mangrove roots, impeding their ability to breathe and access nutrients (William et al., 2021). The impact of sediments supply on mangrove health is in Figure 3.3.

3.2.6 Soil type

The type of soil, determined by its composition of clay, silt, and sand, significantly influences the water and nutrient retention capacities essential for mangrove health (Havlin et al., 2014). Soil particle size directly influences the soil's porosity, influencing its ability to retain water and nutrients (Ashman et al., 2002). Clay soils, for example, have the smallest pores compared to silt and sand and have a higher capacity for water and nutrient retention (Ashman et al., 2002). However, clay soils may restrict oxygen flow to roots, impacting plant health(Ashman et al., 2002). On the other hand, sandy soils have larger soil pores that allow better air circulation but often lack essential nutrients like nitrogen, phosphorus, and potassium, which are crucial for mangrove growth (Ashman et al., 2002). The impact of soil type on mangrove health is in Figure 3.3.

Smaller sized soil such as clay, have a high capacity for retaining nutrients and water compared to larger particles like silt and sand (Reddy et al., 2020). Some studies showed the correlation between the size of sediment particles and the amount of nutrients they can hold. There is a positive correlation between the presence of finer sediment particles, such as silt ($R^2 = 0.33$, $p < 0.0001$, $n = 88$) and clay ($R^2 = 0.66$, $p < 0.0001$, $n = 88$), and the levels of bioavailable nitrogen in the sediment (Reddy et al., 2020). This implies that an increased proportion of smaller particles like clay in the sediment is associated with a higher availability of nutrients, particularly nitrogen (Reddy et al., 2020). Figure 3.3 shows a positive correlation between the type of soil and the availability of water and nutrients and a negative one with oxygen levels. These correlations are primarily based on the assumption that the soil has a small particle size.

3.3 Ecological parameters

This section focuses on discussing the ecological factors that are critical to mangrove ecosystems, such as the food web, the connectivity with other species, and the seedlings availability.

3.3.1 Food web

Mangroves are essential in coastal environments; they function as natural filters for nutrients and sediment, which is crucial for maintaining the area's food chain (Kathiresan, 2021). They are also important habitats for various fish and wildlife, offering food and shelter (Kathiresan, 2021). Mangroves encounter problems with plant-eating insects that can damage these trees. These insects burrow into the tree's bark and wood, leading to leaf loss and jeopardizing the survival of young seedlings (Jenoh et al., 2016). Additionally, crabs are a significant threat as they consume the propagules (Pearce, 2015). This shows how important it is to check the existing species that rely on mangroves. These species might be very harmful for seedlings and hinder their survival and growth. The impact of food web on mangrove health is in Figure 3.4.

3.3.2 Connectivity to other ecosystems

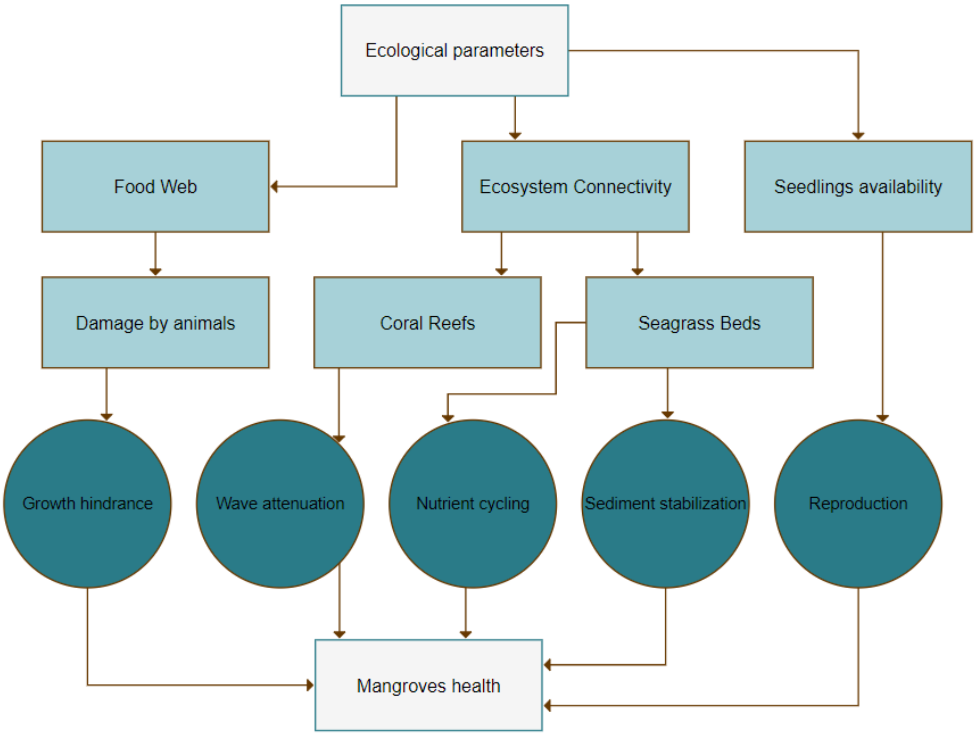
Mangroves together with seagrass beds and coral reefs form a mutually beneficial relationship that is important for their overall health and stability. For instance, coral reefs act as a shield for mangroves against intense waves and storms. This is critical, especially during the growth and establishment of mangrove seedlings (Das et al., 2009). Additionally, seagrass beds contribute to the stabilization of sediments and the cycling of nutrients (Williams et al., 2001). This connection strengthens the health of mangroves and is important for maintaining the ecological balance of these coastal areas.

Mangroves also play an important role in enhancing the diversity and health of these ecosystems. They serve as nurseries and refuges for various marine species, particularly fish that inhabit coral reefs, increasing both the variety of life and the total amount of living matter in these areas (Nagelkerken et al., 2002). Furthermore, mangroves contribute to the stabilization of sediments and the cycling of nutrients, which are beneficial for the growth and productivity of seagrass beds and coral reefs (Orth et al., 2006). The impact of connectivity to other ecosystems on mangrove health is in Figure 3.4.

3.3.3 Seedlings availability

When evaluating the ecological factors that affect the suitability of habitats for mangroves, it is important to consider the area's connectivity to existing mangrove species. This connectivity is key because it allows for the natural dispersal of seedlings, which are essential for the regeneration and sustainability of mangrove forests. Mangrove seed pods germinate while still attached to the tree, a process known as vivipary (Spalding 2010). This early germination prepares the seedlings for immediate growth upon falling. These seedlings, capable of floating, utilize high tides to find suitable grounding or root in tidal mudflats during low tides (Spalding 2010). Therefore, ensuring the connectivity of potential mangrove habitats to existing species is beneficial and ensures seedlings availability. The impact of seedlings availability on mangrove health is in Figure 3.4.

Figure 3.4 Impact of hydrodynamic parameters and sediments on mangrove health



4 SOCIOECONOMIC PARAMETERS

This chapter will discuss the role of socioeconomic factors in the conservation and management of mangrove ecosystems. Socio-economic factors look into understanding how human activities interact with mangroves. The success of mangrove plantations or restoration projects requires an understanding of the needs and culture of locals (Gatt, 2022). This includes assessing the reliance of locals on these ecosystems, upstream disturbance, and locals' awareness and engagement. For instance, areas with a rich cultural history of mangrove utilization might be more accepting of plantation or restoration efforts, ensuring community involvement and support. On the other hand, regions heavily reliant on fisheries might face challenges if plantation or restoration efforts disrupt local fishing activities, even temporarily. The parameters that will be used to assess socioeconomic impact are discussed below.

4.1 Sustainable use

Mangrove ecosystems are essential for the economic stability of coastal communities, especially in the fishing industry. However, they are threatened by unsustainable exploitation, including overfishing and the excessive harvesting of mangrove resources, leading to their degradation and loss worldwide (IUCN, 2021). These forests provide a habitat for many fish species, which is important for the needs and employment of local populations. Some studies indicate that up to 80% of global fish catches are in some way reliant on these mangrove areas (Goodman, 2021). Moreover, wood harvesting in mangrove forests for timber and fuel directly affects these ecosystems. Excessive cutting reduces mangrove coverage, disrupts ecological functions leading to biodiversity loss, and contributes to degradation (Akram et al., 2023).

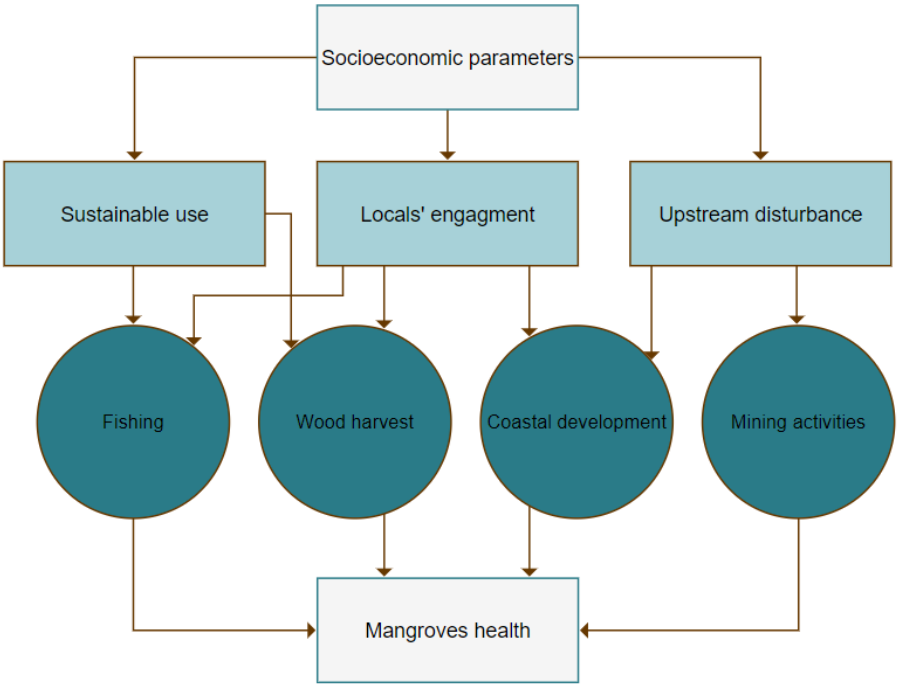
4.2 Locals' engagement

The health and protection of mangrove ecosystems are significantly influenced by the engagement and awareness of local communities. When these communities are properly informed and involved, they gain a deeper understanding of the significance of these ecosystems and the methods for their preservation (Abd Rahman et al., 2015). Unfortunately, the lack of awareness leads to a gap in local understanding, hindering effective community involvement in mangrove conservation efforts (Abd Rahman et al., 2015). Therefore, it is important to enhance local awareness about mangroves' ecological and economic value. This understanding is key to ensuring their protection and preventing their exploitation.

4.3 Upstream disturbance

Human activities such as coastal development, and pollution can significantly impact mangrove habitats. Moreover, these influences often extend beyond local areas, with pollutants originating from upstream sources. Understanding the impact of these activities is critical for the successful plantation and restoration of mangrove ecosystems. Additionally, human activities such as bauxite mining can indirectly harm the environment, altering soil composition, affecting water quality, and increasing sedimentation (Azizah et al., 2023). Such activities may hinder the growth of mangroves and other native flora. Globally, mangroves have suffered significant declines, with around 35% lost in the last two decades alone. This is mainly due to the expansion of aquaculture and other human activities (Verdugo et al., 2015). This decline has a significant impact on biodiversity and also on communities that rely on mangroves for their day-to-day life and protection from natural disasters. The impact of socioeconomic parameters on mangrove health is shown in Figure 4.1.

Figure 4.1 Impact of socioeconomic parameters on mangrove health



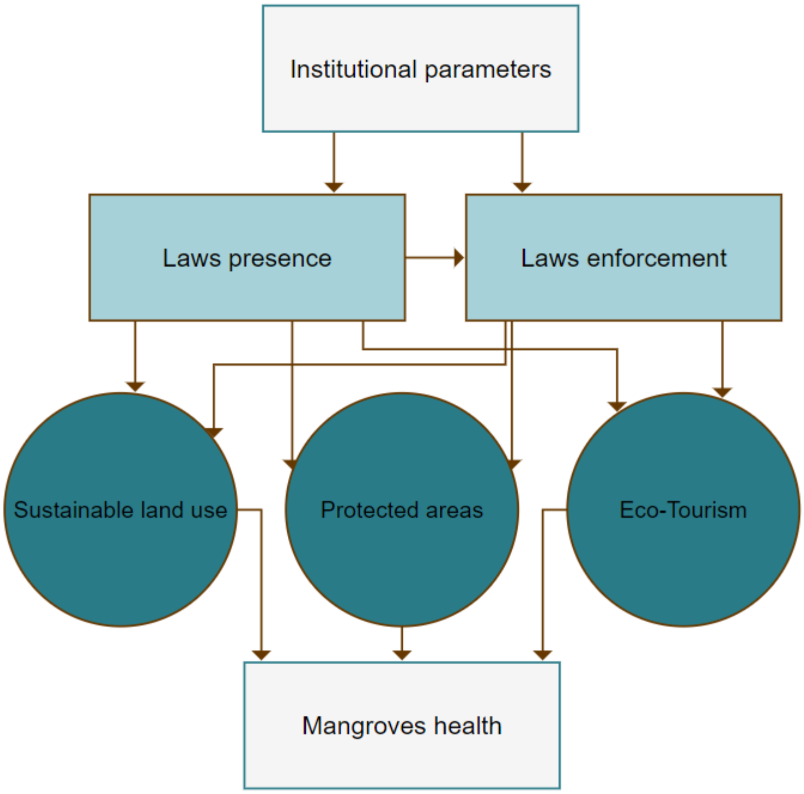
5 INSTITUTIONAL PARAMETERS

This chapter will discuss the institutional parameters which are the presence and enforcement of laws related to mangrove conservation and management.

5.1 Presence and enforcement of laws

Laws and regulations regarding mangrove protection are crucial for its survival and growth, especially in the context of deforestation. Such measures directly address this significant threat, ensuring the protection and sustainability of mangrove environments (Van Lavieren et al., 2012). Moreover, enforcing these laws is crucial for successful mangrove plantation and restoration projects. This includes promoting sustainable fishing and farming practices, creating protected areas for mangroves, and supporting eco-tourism (Fontaine et al., 2022). A sustainable land use is important for maintaining the health of mangroves and offer benefits to the local communities that rely on them. The impact of institutional parameters on mangrove health is shown in Figure 5.1.

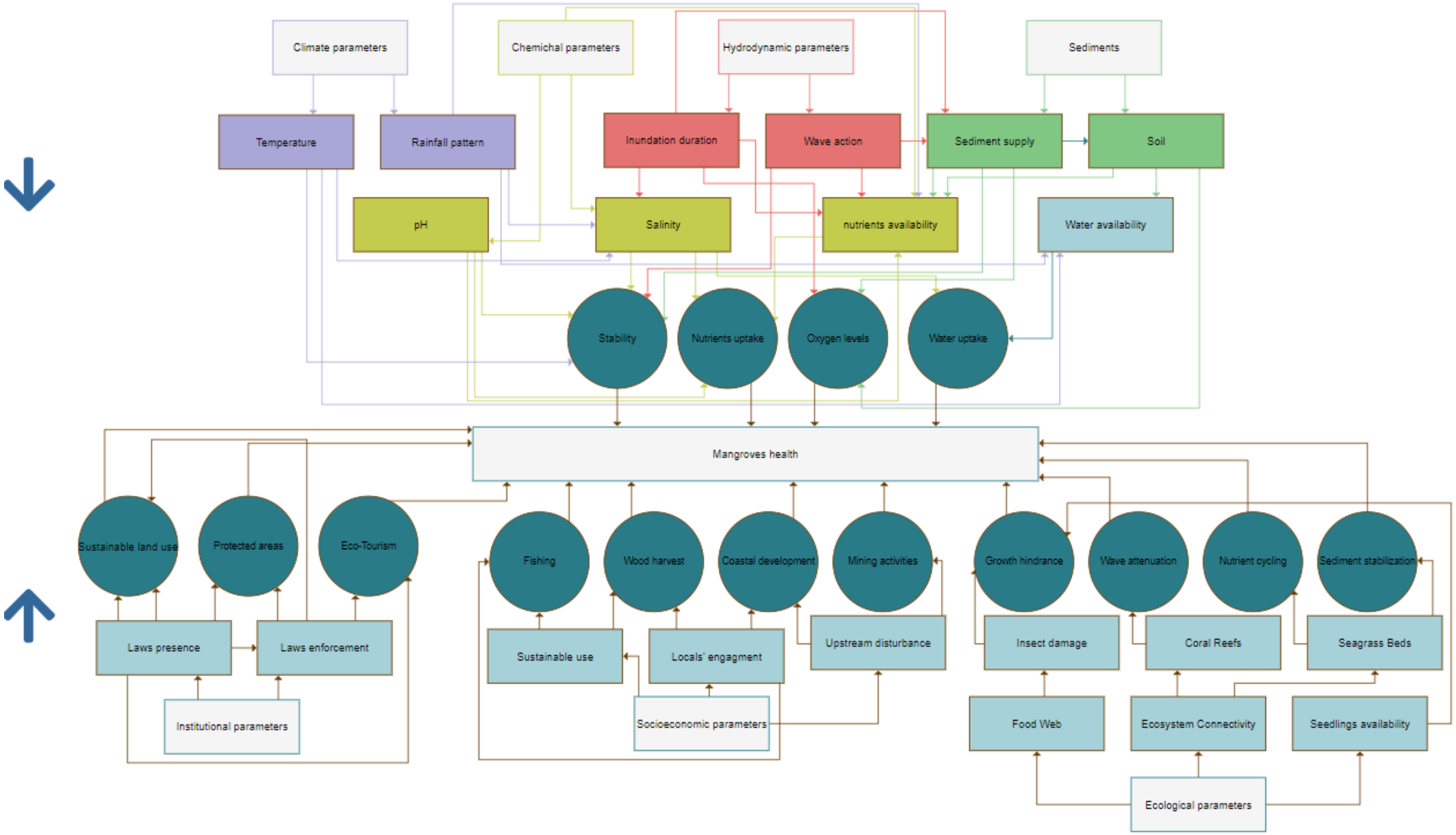
Figure 5.1 Institutional parameters impact on mangroves health



6 PARAMETERS IMPACT ON MANGROVES HEALTH

The relationship between all parameters, including environmental, socioeconomic, and institutional and their impact on mangrove health are demonstrated in Figure 6.1.

Figure 6.1 Relationships between all parameters and their impact on mangroves health



7 SUITABLE PARAMETE RANGES

This chapter provides an overview of the optimal environmental, socioeconomic, and institutional conditions necessary for the survival and growth of the four selected mangrove species: *Sonneratia alba*, *Avicennia marina*, *Rhizophora mangle*, and *Ceriops tagal*.

The right environmental, socioeconomic, and institutional ranges for the four mangrove species have been identified through the literature review and are presented in Table 7.1. Additionally, tables with sources showing optimum ranges for *Sonnaratia alba*, *Avicennia marina*, *Rhizophora mangle*, and *Ceriops tagal* are in Appendix A, Appendix B, Appendix C, and Appendix D respectively.

Table 7.1 Suitable environmental, socioeconomic and institutional conditions for the 4 selected mangrove species

		Sonneratia alba	*Avicennia marina*	*Rhizophora mangle*	*Ceriops tagal*
Chemical parameters	Salinity levels	5-50% ppt (S.A)	5 to 15 ppt (AA)	8- 35 ppt	0-50%
	pH	6.5 - 7.3	5.16 – 7.72 (AA)	5.3-8.5	6-8.5
	Nutrient content	High	Sufficient	High	High
Physical parameters	Temperature (°c)	10-30	15-45	20-30	20-26
	Inundation duration (min per day)	200–400	400-800 (A.S)	100–200	<50
	Waves	Moderate	Moderate	Moderate	Moderate
	Sediment supply	High	High	Hgih	High
	Soil texture	Sandy-clay soil	Sandy soil (AM)	Silty clay (oxygen-poor soils)	well-drained soil
Ecological parameters	Sustainable food web	yes	Yes	yes	yes
	Connectivity to other species	Yes	Yes	yes	yes
	Seedlings availability	Yes	Yes	Yes	Yes
Socioeconomic parameters	Sustainable use	Yes	yes	Yes	Yes
	Locals engagement	yes	yes	Yes	Yes
	Upstream disturbance	No	No	No	No
Institutional parameters	Presence of Laws	yes	yes	yes	yes
	Enforcement of these laws	yes	yes	yes	yes

8 MODEL DEVELOPMENT

This chapter focuses on integrating findings from literature reviews and expert interviews to develop an assessment framework for mangrove habitat suitability. It begins with the development of a scoring system, assigning scores from 0 to 10 to each parameter range, reflecting the favorability of specific conditions for mangrove survival and growth. The assessment framework then incorporates the weighting of parameters as determined by experts, emphasizing their relative importance in the context of mangrove health. This step is followed by verification of the model to ensure it does what it designed to do, and that it gives suitability scores for different sites based on their conditions.

8.1 Scoring system

The scoring system is based on assigning values from 1 to 10 to various parameters conditions, with 10 indicating optimum conditions for a specific mangrove species to thrive. The lower the score, the less suitable the conditions are for that species. *Avicennia marina* will be used as an example to demonstrate how the scoring system was developed. Table 7.1 shows the optimum ranges for *Avicennia Marina*. Suitable parameters ranges with detailed citations of *Sonnaratia alba*, *Avicennia marina*, *Rhizophora mangle*, and *Ceriops tagal* are in Appendix A, Appendix B, Appendix C, and Appendix D, respectively.

The optimum range differs per species, for instance, *Avicennia marina's* optimal conditions might score a 10 for a certain salinity range, whereas another species like Rhizophora mangle might score lower for the same salinity levels. The scoring of different environmental ranges varies by parameter and species. Some species are more tolerant to variations in salinity or pH, but less so to non-porous soils for example. Conversely, others might be adaptable to various soil types but require specific salinity ranges. This variability in tolerance influences the scoring assigned to each parameter, ensuring it accurately reflects the optimal growth conditions for each mangrove species. *Sonnaratia alba*, *Avicennia marina*, *Rhizophora mangle*, and *Ceriops tagal* specific ranges and scores are in Appendix A, Appendix B, Appendix C, and Appendix D respectively.

8.1.1 Chemical parameters

The scoring for chemical parameters in *Avicennia Marina's* habitat suitability analysis is based on their alignment with the species' optimal conditions. This was found using literature sources as shown in Table 7.1. Salinity is optimal for Avicenna marina survival and growth when it is between 5 - 15 ppt (Kai et al., 2012), thus ranges close to this range score the highest. In the scoring system, salinity levels outside the optimal range of 5-15 ppt are given lower scores, reflecting their less favorable conditions for *Avicennia Marina*. Particularly high salinity levels are considered detrimental and thus receive the lowest scores, highlighting their potential threat to the species' survival (Table 8.1).

Similarly, for pH levels, the scoring reflects the species' tolerance and optimal growth conditions. pH values within the ideal range of 5 to 8 receive the highest scores, as this range is most conducive for *Avicennia Marina* (Kai et al., 2012). Deviations from this optimal pH range, particularly those significantly higher or lower, are assigned lower scores to indicate their negative impact on the species' health (Table 8.1). For nutrient content, the scoring system is designed to reflect the nutritional requirements of *Avicennia Marina*. Optimal nutrient levels, neither too low nor excessively high, are given higher scores, emphasizing a balanced environment for the species (Table 8.1). As can be observed, not all scores range from 1 to 10. That is because the scoring system takes into account whether those conditions are detrimental. If that is the case, meaning the conditions are very harmful for the species, the range receives a score of 1 or 0. If the conditions are not favourable but also not detrimental then the lowest score receivable is 3 or 4.

Table 8.1 Salinity, pH scores and nutrients content scores

Salinity (ppt)	Score (1-10)	pH	Score (1-10)	Nutrient Content	Score (1-10)
0 - 5	6	<5.16	4	Very low	1
5 - 15	10	5 - 8	10	Moderate	6
15 - 25	6	8 - 10	4	High	10
>25	1	>10	1	Very High	4

8.1.2 Physical parameters

This section will start with scoring different ranges for temperature, inundation duration, wave intensity, sediment supply, and soil type. The ideal temperature range is 15-40°C (Jacotot et al., 2019) as seen in Table 8.2. Temperatures outside this range, especially extremes like below 0°C or above 40°C, also score very low (Table 8.2). For inundation duration, the optimal range is 400-800 minutes daily, which is why it receives a score of 10 (van Loon et al., 2007). Inundation durations outside this optimal range score very low due to their significant impact on the plant's survival (Table 8.2). The same logic follows for wave energy, moderate waves are favourable for *Avicennia marina* which is why it scores high (Table 8.2).

Table 8.2 Temperature, inundation duration, and wave energy scores

Temperature (°C)	Score (1-10)	Inundation (min per day)	Score (1-10)	Wave energy	Score (1-10)
<0	0	<400	6	Very Low	2
0 - 15	3	400 - 800	10	Low	4
15 - 40	10	800 - 1000	4	Moderate	10
>40	4	>1000	0	very High	4

When it comes to sediment supply, high sediment supply is essential as it provides the necessary stability and nutrients, which is why it receives the highest score (Table 8.3). However, very high sediment can cover seedlings, smothering them which is why it receives a lower score. For soil type, sandy soil scores highest due to its porosity which is essential for proper air and water circulation (Budiadi et al., 2022) . As soil porosity decreases, the scores decrease too, indicating lower suitability for the *Avicennia Marina* (Table 8.3).

Table 8.3 Sediments supply and soil type scores

Sediment Supply	Score (1-10)	Soil Type	Score (1-10)
Low	2	Clay	2
Moderate	6	Silty	6
High	10	Loamy	4
Very high	4	Sandy	10

8.1.3 Ecological parameters

Ecological parameters such as sustainable food web and species connectivity are qualitative rather than quantifiable, the scoring for ecological parameters is the same for the four selected species. Their assessment relies on binary (Yes/No) categorizations, as detailed in Table 8.4. A "sustainable food web" here implies a system where species dependent on mangroves, like crabs, do not overly harm mangrove seedlings. "Yes" means a balanced ecosystem, where such species coexist without causing significant damage to young mangroves, whereas "No" indicates a detrimental impact on seedlings. High scores (10) are given when the ecological condition is optimal, supporting a healthy mangrove ecosystem. These ecological conditions are "Sustainable food web", "connectivity to other ecosystems", and "seedlings availability". Lower scores are assigned when the condition degrades, reflecting the reduced suitability and health of the mangrove habitat.

Table 8.4 Sustainable food web, connectivity to other ecosystems scores and seedlings availability scores

Sustainable food Web	Score (1-10)	Connectivity to other ecosystems	Score (1-10)	Seedlings availability	Score (1-10)
Yes	10	Yes	10	Yes	10
No	1	No	5	No	5

8.1.4 Socioeconomic parameters

When evaluating the impact of socioeconomic factors on mangrove suitability, the highest score is assigned when a parameter is favorable, indicating an environment where mangroves are well-protected and can thrive. Moreover, lower scores are reflective of less favorable conditions, such as a lack of local engagement or the presence of upstream disturbances, which can impact mangrove health and survival. The scoring for socioeconomic parameters is the same for the four selected species Table 8.5 shows the scoring for all socioeconomic parameters.

Table 8.5 Sustainable use, locals' engagement, and Upstream disturbance scores

Sustainable use	Score (1-10)	Local engagement	Score (1-10)	Upstream disturbance	Score (1-10)
Yes	10	Yes	10	Yes	1
No	1	No	3	No	10

8.1.5 Institutional parameters

In the context of institutional parameters for mangrove habitat suitability, high scores are given when laws for mangrove protection are both established and enforced. This suggests strong management and safeguarding of these ecosystems. However, the score is low in scenarios where laws exist without proper enforcement, or where protective laws are absent. The scoring for institutional parameters is the same for the four selected species. Table 8.6 shows the scoring for all institutional parameters.

Table 8.6 Presence of laws and Law enforcement scores

Presence of laws	Score (1-10)	Law enforcement	Score (1-10)
Yes	10	Yes	10
No	1	No	1

8.2 Weighting of parameters

Experts were informed about the correlations between parameters and their mutual influence. The goal was to make sure that the experts considered only the direct effects of each parameter on mangrove health when assigning weights. Experts were asked to assess the most important environmental, socioeconomic, and institutional factors from the developed list in the literature review. The process of determining the weight per parameter involved various approaches, depending on expert preferences. Some experts calculated the weight of each parameter by multiplying different weights they assigned to each (sub-)category. First, they assigned a weight out of 100 to each of the three main categories: environmental, socioeconomic, and institutional. Then, for the environmental category, they gave weights to specific factors like chemical, physical, and ecological parameters. This included giving weights to specific parameters such as salinity, pH, and nutrient availability in the chemical group. The same method was used for the socioeconomic and institutional categories. Each factor within these categories was also weighted based on its importance. Other experts preferred a more straightforward approach. They assigned a weight directly to each (sub-)category, and then the weight for the category as a whole was calculated based on these individual weights. Table 8.7 shows the weight per parameter as determined by different experts, alongside an average weight calculated from all the expert inputs.

Table 8.7 Experts weight per parameter

Parameter	Expert 1	Expert 2	Expert 3	Average
Salinity levels	5.0	7.0	4.0	5.3
pH	5.0	5.0	4.0	4.7
Nutrient content	5.0	5.0	4.0	4.7
Temperature	5.0	3.0	3.6	3.9
Inundation duration	20.0	18.0	14.4	17.5
Wave action	15.0	15.0	10.8	13.6
Sediment supply	5.0	7.0	3.6	5.2
Soil type	5.0	4.0	3.6	4.2
Food web	2.5	3.0	7.2	4.2
Connectivity to other species	2.5	1.0	0.0	1.1
Seedlings availability	5.0	4.0	4.8	4.6
Sustainable use of mangroves	5.0	5.0	8.0	6.0
Local Engagement	5.0	5.0	8.0	6.0
Upstrem disturbance	5.0	5.0	4.0	4.7
Presence of laws	5.0	6.0	8.0	6.3
Enforcement of laws	5.0	7.0	12.0	8.0

In the developed assessment framework, the weightings assigned by experts play an essential role in evaluating mangrove habitat suitability. The most heavily weighted parameters are 'Inundation duration' and "Waves action," with average weightings of 17.5 and 13.6, respectively. These weightings highlight the significance of having the right inundation duration and wave energy in creating an environment favorable to mangrove survival and growth. On the other hand, parameters like "Connectivity to other species" receive lower weightings, averaging at 1.1. While experts recognize its relevance, they consider it less important compared to other parameters.

Furthermore, the table above shows that some parameters were assigned varying weights by different experts. These variations in weightings reflect the different viewpoints of experts, with some prioritizing physical parameters like "Sediment supply" and "Soil type," while others focus on institutional factors such as the "Presence of laws" and "Enforcement of laws." This diversity in expert opinions shows the complexity of evaluating mangrove habitat suitability. It highlights the importance of considering environmental, socioeconomic, and institutional parameters in the assessment process.

8.3 Model application

The mangrove assessment model incorporates a scoring system and a weighting system to determine the suitability of various environments for mangrove habitation. The scoring system considers a range of conditions per parameter, such as salinity levels, soil types, and the presence or absence of laws. Each condition is assigned a score reflecting its favorability for mangrove growth. For instance, sandy soil might receive a higher or lower score compared to clay, depending on what is most suitable for the specific mangrove species. For the weighting system, each parameter is assigned a weight by experts. These weights show the relative importance of each parameter.

The mangrove assessment framework was developed by integrating parameters, each with assigned scoring ranges and weights, all managed through Python, HTML, and CSS. Technically, Python is the core of the model, handling all the necessary calculations. It works out the weighted scores for each parameter and calculates the overall suitability percentage. The interface of the model is built with HTML, which sets up the structure of the web application, allowing users to interact with it by selecting options. CSS is used to style the application, making it look neat and easy to use.

To use the mangrove assessment framework model, users follow a simple, step-by-step process. Initially, they start by selecting the specific type of mangrove they wish to assess (Figure 8.1) The next step is filling in their site's conditions across various parameters. This part of the process involves providing detailed information on aspects like salinity levels and soil type, and other parameters (Figure 8.2). After all necessary data is entered, the model computes the final score, representing the overall suitability of the environment for the chosen mangrove species. In addition to this score, the model identifies key parameters where suitability is low and offers recommendations on which parameters need improvement (Figure 8.3).

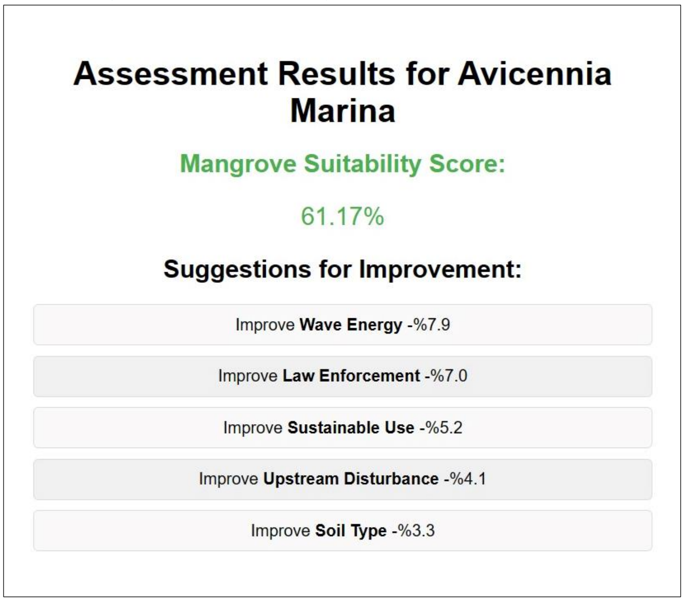
Figure 8.1 Step 1: Selecting the species

Figure 8.2 Step 2: Filling in site's conditions

Assessment for Avicennia Marina

Parameter	Option 1	Option 2	Option 3	Option 4
Salinity (ppt)	0-5	5-15	15-25	>25
pH	<5.16	5-8	8-10	>10
Nutrient Content	Very Low	Moderate	High	Very High
Temperature (°C)	<0	0-15	15-40	>40
Inundation Duration (min per day)	<400	400-800	800-1000	>1000
Wave Energy	Very Low	Low	Moderate	Very High
Sediment Supply	Low	Moderate	High	Very High
Soil Type	Clay	Silty	Loamy	Sandy
Sustainable Food Web	Yes	No		
Connectivity to Other Ecosystems	Yes	No		
Seedlings Availability	Yes	No		
Sustainable Use	Yes	No		

Figure 8.3 Step 3: suitability score and recommendations



8.4 Model features

One notable feature of the model is its capacity to provide recommendations for improving the mangrove habitat suitability score. These recommendations are generated by identifying parameter ranges that have the most significant impact on suitability score reduction.

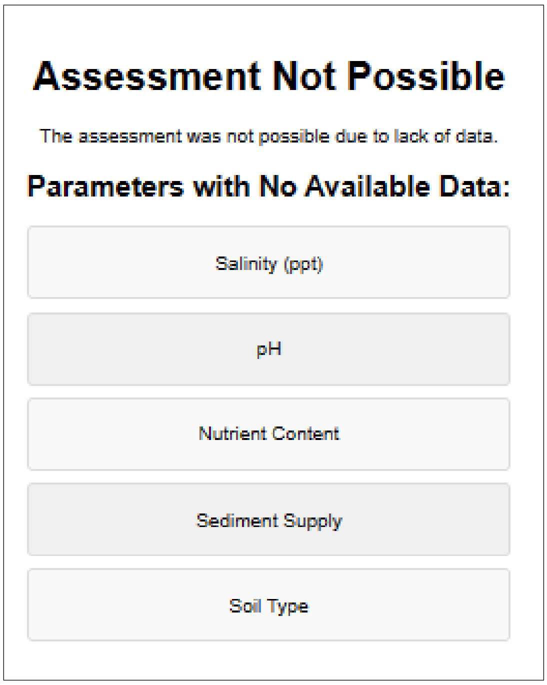
Furthermore, the model is designed to manage situations where data is missing for certain parameters. Users can continue entering data, even if information for specific parameters is unavailable, by simply selecting the "No Available Data" option (Figure 8.4). To maintain the reliability of the model's assessments, a protective measure is implemented: a threshold of 10% is set for the combined weight of parameters with missing data. For instance, if a user chooses "No Available Data" for parameters like "salinity levels" and "sediments supply," which carry weights of 5.3% and 5.2%, respectively, and the combined missing data surpasses 10% of the total weight, the model will not assess the site (Figure 8.5). If the amount of missing data falls below this threshold, the model informs users that the provided score has been calculated without these parameters and redistributes their weight among the remaining parameters.

Figure 8.4 'No Available Data' feature

Assessment for Avicennia Marina

Parameter	Option 1	Option 2	Option 3	Option 4	Option 5
Salinity (ppt)	0-5	5-15	15-25	>25	No Available Data
pH	<5	5-8	8-10	>10	No Available Data
Nutrient Content	Very Low	Moderate	High	Very High	No Available Data
Temperature (°C)	<0	0-15	15-40	>40	
Inundation Duration (min per day)	<400	400-800	800-1000	>1000	
Wave Energy	Very Low	Low	Moderate	Very High	No Available Data
Sediment Supply	Low	Moderate	High	Very High	No Available Data
Soil Type	Clay	Silty	Loamy	Sandy	No Available Data
Sustainable Food Web	Yes	No	No Available Data		
Connectivity to Other Ecosystems	Yes	No	No Available Data		
Seedlings Availability	Yes	No	No Available Data		
Sustainable Use	Yes	No	No Available Data		
Local Engagement	Yes	No	No Available Data		
Upstream Disturbance	Yes	No	No Available Data		
Presence of Laws	Yes	No	No Available Data		
Law Enforcement	Yes	No	No Available Data		

Figure 8.5 Model's results for lack of data



Additionally, the model identifies specific conditions as critical and non-negotiable for the survival of mangroves. Extreme values for temperature and inundation duration are considered detrimental thresholds for mangroves, regardless of other favorable conditions. If the input temperature is below 0°C or the inundation duration exceeds the upper limit for the specific mangrove species (Figure 8.6), the model will conclude that the assessment is not possible (Figure 8.7). This integrated negative threshold reflects the actual limitations of mangrove ecosystems, recognizing that mangroves cannot thrive in environments that exceed their natural tolerance levels.

Figure 8.6 Critical conditions feature

Assessment for Avicennia Marina

Parameter	Option 1	Option 2	Option 3	Option 4	Option 5
Salinity (ppt)	0-5	5-15	15-25	>25	No Available Data
pH	<5	5-8	8-10	>10	No Available Data
Nutrient Content	Very Low	Moderate	High	Very High	No Available Data
Temperature (°C)	<0	0-15	15-40	>40	
Inundation Duration (min per day)	<400	400-800	800-1000	>1000	
Wave Energy	Very Low	Low	Moderate	Very High	No Available Data
Sediment Supply	Low	Moderate	High	Very High	No Available Data
Soil Type	Clay	Silty	Loamy	Sandy	No Available Data
Sustainable Food Web	Yes	No	No Available Data		
Connectivity to Other Ecosystems	Yes	No	No Available Data		
Seedlings Availability	Yes	No	No Available Data		
Sustainable Use	Yes	No	No Available Data		
Local Engagement	Yes	No	No Available Data		
Upstream Disturbance	Yes	No	No Available Data		
Presence of Laws	Yes	No	No Available Data		
Law Enforcement	Yes	No	No Available Data		

Submit

Figure 8.7 Model's results of critical conditions

Assessment Not Possible

The assessment was not possible due to critical conditions regarding Temperature (°C).

8.5 Model validation

For the validation of the model, two sites were selected: Gdansk Bay in Poland, known for conditions that are not suitable for mangroves, and Lac Bay in Bonaire, a site where mangroves are found. The site conditions were not observed directly. Instead, the chemical and physical conditions of each parameter were derived from existing literature specific to each site. Furthermore, valuable insights into the ecological, socioeconomic, and institutional parameters were gathered through expert interviews. Both sites were assessed for $Avicennia\ marina$.

Gdnask Bay

Gdansk Bay, situated in Poland, represents a challenging environment for mangrove growth due to its unique conditions. The model's assessment of the site conditions is detailed in Figure 8.8.

Chemical Parameters:

Salinity ranged from 5 to 15 parts per thousand (ppt), pH levels were between 8 and 10, and nutrient content was high (Naukowa et al., 2020).

Physical Parameters:

The temperature was consistently below 0°C, and the inundation duration ranged from 400 to 800 minutes per day. Wave energy was very high, with a moderate sediment supply, and the soil composition was predominantly sandy (Naukowa et al., 2020; Jakusik et al., 2020).

Ecological Conditions:
Gdansk Bay exhibited an unsustainable Food Web, limited connectivity to other ecosystems, and a lack of available seedlings.

Socioeconomic Parameters:
The site displayed characteristics of Sustainable Use and Local Engagement but suffered from upstream disturbances.

Institutional Parameters:
Positively, there was evidence of the presence and enforcement of laws.

Figure 8.8 Gdansk Bay conditions

Assessment for Avicennia Marina

Parameter	Option 1	Option 2	Option 3	Option 4	Option 5
Salinity (ppt)	0-5	**5-15**	15-25	>25	No Available Data
pH	**<5**	5-8	8-10	>10	No Available Data
Nutrient Content	Very Low	Moderate	**High**	Very High	No Available Data
Temperature (°C)	**<0**	0-15	15-40	>40	
Inundation Duration (min per day)	<400	**400-800**	800-1000	>1000	
Wave Energy	Very Low	Low	**Moderate**	Very High	No Available Data
Sediment Supply	Low	**Moderate**	High	Very High	No Available Data
Soil Type	Clay	Silty	Loamy	**Sandy**	No Available Data
Sustainable Food Web	Yes	**No**	No Available Data		
Connectivity to Other Ecosystems	**Yes**	No	No Available Data		
Seedlings Availability	Yes	**No**	No Available Data		
Sustainable Use	**Yes**	No	No Available Data		
Local Engagement	**Yes**	No	No Available Data		
Upstream Disturbance	**Yes**	No	No Available Data		
Presence of Laws	**Yes**	No	No Available Data		
Law Enforcement	**Yes**	No	No Available Data		

Submit

Figure 8.9 Gdansk Bay suitability score

Assessment Not Possible

The assessment was not possible due to critical conditions regarding Temperature (°C).

Despite positive conditions of most of the parameters, the extremely low temperature led the model to conclude that a mangrove habitat assessment in Gdansk Bay was not possible (Figure 8.9). This demonstrates the model's ability to identify and respond to unfavorable conditions for mangrove habitat.

Lac Bay

Lac Bay, located in Bonaire, is known for its favorable conditions that support mangrove growth. The model's assessment of the site conditions is detailed in Figure 8.10.

Chemical Parameters:
Salinity levels were categorized as exceeding 25 parts per thousand (ppt), which falls within the highest category. The pH level maintained a favorable range between 5 and 8, and the site exhibited a notable high nutrient content (Senger et al., 2021).

Physical Parameters:
Lac Bay presented an environment where the temperature ranged from 15 to 40°C, a suitable range for mangroves. The duration of inundation was consistently between 800 and 1000 minutes per day, and the wave energy was recorded as very high (van Zee, 2022; Senger et al., 2021). Furthermore, the site boasted a high sediment supply and predominantly sandy soil composition (van Zee, 2022; Senger et al., 2021).

Ecological Conditions:
Lac Bay did not host a sustainable Food Web, but it was connected to other ecosystems, facilitating ecological interactions. Additionally, the availability of seedlings was noted.

Socioeconomic Parameters:
The site displayed characteristics of sustainable use and local engagement, reflecting a positive human-environment relationship.

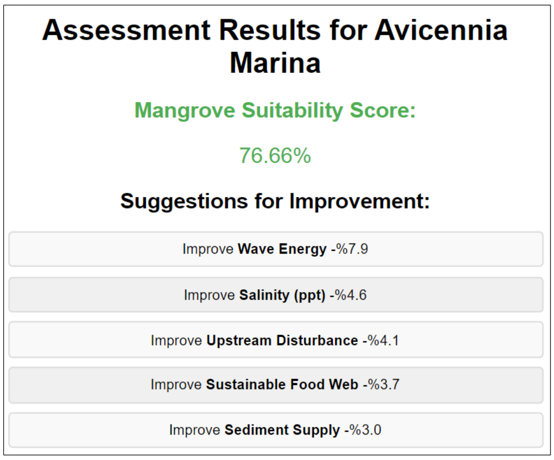
Institutional Parameters:
Lac Bay demonstrated the presence and enforcement of laws, further contributing to its suitability for mangrove habitat.

Figure 8.10 Lac Bay conditions

Assessment for Avicennia Marina

Parameter	Option 1	Option 2	Option 3	Option 4	Option 5
Salinity (ppt)	0-5	5-15	15-25	>25	No Available Data
pH	<5	5-8	8-10	>10	No Available Data
Nutrient Content	Very Low	Moderate	High	Very High	No Available Data
Temperature (°C)	<0	0-15	15-40	>40	
Inundation Duration (min per day)	<400	400-800	800-1000	>1000	
Wave Energy	Very Low	Low	Moderate	Very High	No Available Data
Sediment Supply	Low	Moderate	High	Very High	No Available Data
Soil Type	Clay	Silty	Loamy	Sandy	No Available Data
Sustainable Food Web	Yes	No	No Available Data		
Connectivity to Other Ecosystems	Yes	No	No Available Data		
Seedlings Availability	Yes	No	No Available Data		
Sustainable Use	Yes	No	No Available Data		
Local Engagement	Yes	No	No Available Data		
Upstream Disturbance	Yes	No	No Available Data		
Presence of Laws	Yes	No	No Available Data		
Law Enforcement	Yes	No	No Available Data		

Figure 8.11 Lac Bay suitability score



The suitability assessment for *Avicennia marina* at Lac Bay resulted in a high score of 76.66%, indicating a favorable environment for its survival and growth (Figure 8.11). The model's recommendations for improvement are mitigating excessive wave energy and reducing salinity levels.

The model's validation has confirmed its ability to differentiate between favorable and unfavorable mangrove habitat conditions. The model identified Gdansk Bay as unsuitable due to extremely low temperatures while rating Lac Bay as suitable for *Avicennia marina* with a score of 76.66%.

9 DISCUSSION

The model developed was based on incorporating literature review findings and experts' inputs. Initially, literature was used to develop a list of parameters that are necessary for mangroves' survival and growth. Each condition of these parameters was then given a score based on its favorability for mangrove health. Experts were then involved in assigning a weight for each parameter reflecting their importance in mangrove survival and growth. This resulted in a model capable of assessing the suitability of a site for a specific mangrove species based on its conditions.

Despite the conveniences and accuracy of the model, it has certain limitations. Each parameter condition is scored based on how favorable they are to that specific mangrove species. However, mangrove species exhibit varying levels of tolerance to environmental conditions based on their geographical location. This means that the scores given to some parameter ranges in the research might not be accurate. The research relied mostly on a single source for finding optimum conditions for each parameter, which may not account for regional variations in optimal ranges. Additionally, due to constraints in the research scope, some critical factors were not studied in depth. For example, the specific nutrient needs of different mangrove species, such as the requirement for nitrogen or phosphorus, were not explored. Understanding these unique nutritional requirements could help in making the assessment framework more accurate.

Nevertheless, the model was validated and showed that despite the limitations, the model is still accurate and reliable. Two sites, Gdansk Bay and Lac Bay, were assessed. Gdansk Bay, despite mostly positive parameters conditions, was recognized as unsuitable for mangroves due to its below-zero temperatures. In contrast, Lac Bay received a 76.66% suitability score for $Avicennia\ \ marina$, with recommendations to mitigate wave energy and adjust salinity levels for optimal growth. This validation process highlights the model's ability to accurately evaluate and respond to varying environmental, socioeconomic, and institutional conditions for mangrove habitats.

Comparing the developed model to similar assessment frameworks, such as mangrove restoration suitability maps, shows its strengths. The model stands out for allowing users to evaluate site suitability based on input data. This flexibility encourages users to make local adjustments, ensuring effective restoration or plantation efforts. Additionally, the framework provides critical thresholds for extreme conditions, indicating when mangrove restoration or plantation may not be possible due to inundation and temperature constraints. It also offers recommendations for improving specific parameters, providing guidance to enhance suitability scores. Furthermore, the assessment frameworks model includes a 'No Available Data' option, making it practical for situations with limited or unavailable data. To maintain its reliability, it incorporates a 10% threshold, preventing assessments when the sum of missing data exceeds this limit. This approach ensures robust and trustworthy results.

On the other hand, mangrove restoration suitability maps provide a broader, geographic perspective by visualizing potential mangrove growth areas on maps. These maps identify regions where mangroves can thrive or where restoration efforts may have the most significant impact. While lacking the level of detail found in the assessment framework, they offer valuable insights for regional planning and large-scale conservation initiatives. However, the method used to generate these suitability maps is not clear, as users cannot put data into the model.

The developed model has limitations, the first one is that the assessment does not show when restoring or planting mangroves will be successful, it only shows how close the site conditions are to perfect conditions. It is not known at which score mangrove restoration or plantation is guaranteed to succeed. The other limitations have to do with the quality of the assessment itself. The scores given to ranges are based on educated guesses. The same can be said about what is included in a range. A range can be either too general or not include important divisions. For example, there could be a big difference in the minimum and maximum within a range, such as the range “800 - 1000 minutes per day” for inundation. Furthermore, there can be a big difference between the scores of certain ranges. This is especially seen in parameters where extreme scenarios are detrimental, such as temperature and inundation. For example, when comparing the assessment of a site where the temperature is just below zero degrees and a site where the temperature is just above zero degrees, a dramatic difference will be seen. Even if all conditions are perfect in both sites, the first assessment will not be performed due to “extreme conditions” while the second site will have a high suitability score.

10 CONCLUSIONS

The Mangrove habitat suitability assessment framework presented in this research is a valuable tool for evaluating the suitability of locations for specific mangrove species, including $Sonneratia \quad alba$, $Avicennia \quad marina$, $Rhizophora \quad mangle$, and $Ceriops \quad tagal$. This conclusion summarizes the key findings of this research by answering the two main research questions.

The first main research question asked was "What are the essential parameters influencing mangrove survival and growth?" The key findings in response to this question can be categorized into environmental, socioeconomic, and institutional parameters. Environmental parameters consist of chemical (salinity, pH, nutrient availability), physical (temperature, rainfall, inundation, wave action, sediment, soil type), and ecological (food web, ecosystem connectivity, seedling availability) parameters. Socioeconomic parameters include sustainable use, local engagement, and upstream disturbances, while institutional parameters focus on the existence and enforcement of laws.

The second main research question was "How can a model for assessing mangrove habitat suitability be developed?". The model was developed by combining a scoring system and a weighting system. The scoring system assigns scores from 0 to 10 to different parameter ranges for a specific species, with 10 being the most favorable. Additionally, the weighting system involved experts assigning weights to each parameter based on its importance for mangrove survival and growth. Expert weights showed that environmental parameters, such as inundation duration and wave action, have the most significant impact on mangrove health, justifying their high weights. In contrast, factors like connectivity to other species, while contributing to the broader ecosystem, were seen as less critical for direct mangrove health.

The developed assessment framework is a practical and efficient tool for assessing mangrove habitat suitability. It offers specific recommendations, identifying areas for improvement. Additionally, the model takes into account critical conditions such as extreme temperature and inundation, ensuring that sites are not shown as suitable under these extreme conditions. Furthermore, the model is designed to handle situations where data is missing for certain parameters. Users can continue entering data, even if information for specific parameters is unavailable, by selecting the "No Available Data" option. To maintain the reliability of the model's assessments, a threshold of 10% is set for the combined weight of parameters with missing data.

The model's validation has confirmed its ability to distinguish favorable from unfavorable mangrove habitat conditions. For instance, it identified Gdansk Bay as unsuitable due to extreme temperatures while rating Lac Bay as 76.66% suitable for $Avicennia \quad Marina$. This validation shows the model's effectiveness and potential as a practical tool for decision-makers regarding sites for mangrove plantations or restoration.

Compared to other frameworks, the assessment framework stands out for its user-friendliness and holistic approach, considering environmental, socioeconomic, and institutional factors. It recognizes the importance of community engagement and legal enforcement in mangrove conservation, making it a valuable assessment tool.

11 RECOMMENDATIONS

To enhance the precision and reliability of the assessment framework, further research is needed. Analyzing how geographic location influences mangroves' ability to tolerate different environmental conditions is essential. Incorporating these findings into the scoring system is also needed for more accurate and reliable results. Additionally, involving experts in the field to critically review and validate the scoring system can provide a more accurate scoring of different ranges depending on how favorable or not they are to mangroves' health. Another important step to take is diversifying the sources of information used to determine the optimum ranges for each parameter. Not all sources are equally reliable, and incorporating a broader range of data can help minimize errors and enhance the model's accuracy. Additionally, all the scores and ranges were based on educated guesses, making it essential to be reviewed by an expert.

Moreover, consulting more experts in the process of weighting parameters can lead to a more accurately weighted system. Since experts often have specific knowledge of certain mangrove species but not others, their perspectives help reduce inaccuracies. Additionally, it is recommended that users should find accurate data or collect field data about the site, or involve local experts so that the input data is accurate and the result is a consequence.

Finally, integrating the mangrove habitat suitability model with the Geographic Information System (GIS) could enhance its effectiveness since it will be able to identify suitable sites in entire areas. By merging with GIS, the model can utilize spatial data to accurately identify appropriate sites for mangrove growth within a given area. This combination allows for more precise assessments, as GIS can represent environmental, socioeconomic, and institutional parameters in a geographic context. Such a method would simplify the process of pinpointing potential mangrove habitats and provide recommendations on what to improve in the site for a better environment for mangroves' survival and growth.

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13 APPENDICES

13.1 Appendix A- Conditions for Sonneratia alba

Table 13.1 Environmental, socioeconomic and institutional conditions for Sonneratia alba

Sonneratia alba			
Chemical parameters	Salinity levels (%)	5 - 50	(Ball et al., 1995)
	pH	6.5 - 7.3	(Tropical plans, 2022)
	Nutrient content	High	
Physical parameters	Temperature (°c)	10 - 30	(Jacotot et al., 2019)
	Inundation duration (min per day)	200 - 400	(van Loon et al., 2007)
	Waves	Moderate	
	Sediment supply	High	
	Soil texture	Sandy-clay soil	(Cebu Technological University., 2022)
Ecological parameters	Sustainable food web	Yes	
	Connectivity to other species	Yes	
	Seedlings availability	Yes	
Socioeconomic parameters	Sustainable use	Yes	
	Locals engagement	Yes	
	Upstream disturbance	No	
Institutional parameters	Presence of laws	Yes	
	Enforcement of these laws	Yes	

13.1.1 Chemical parameters

Table 13.2 Salinity, pH and nutrient content scores

Salinity (%)	Score (1-10)	pH	Score (1-10)	Nutrient content	Score (1-10)
<5	7	<6.5	4	Very low	1
5 - 50	10	6.5 - 7.3	10	Moderate	6
50 - 60	5	7.3 - 8	5	High	10
>60	2	>8	2	Very high	4

13.1.2 Physical parameters

Table 13.3 Temperature, inundation duration, and wave energy scores

Temperature (°C)	Score (1-10)	(min per day)	Score (1-10)	Wave energy	Score (1-10)
<0	0	<400	6	Very Low	2
0 - 10	3	400 - 800	10	Low	4
10 - 30	10	800 - 1000	4	Moderate	10
>40	3	>1000	0	very High	4

Table 13.4 Sediments supply and soil type scores

Sediment Supply	Score (1-10)	Soil Type	Score (1-10)
Low	2	Sandy	6
Moderate	6	Loamy	8
High	10	Clay	5
Very high	4	Sandy-Clay	10

13.1.3 Ecological parameters

Table 13.5 Sustainable food web, connectivity to other ecosystems scores and seedlings availability scores

Sustainable Food Web	Score (1-10)	Connectivity to Other ecosystems	Score (1-10)	Seedlings availability	Score (1-10)
Yes	10	Yes	10	Yes	10
No	1	No	5	No	5

13.1.4 Socioeconomic parameters

Table 13.6 sustainable use , locals' engagement, and Upstream disturbance scores

Sustainable use	Score (1-10)	Local engagement	Score (1-10)	Upstream disturbance	Score (1-10)
Yes	10	Yes	10	Yes	1
No	1	No	3	No	10

13.1.5 Institutional parameters

Table 13.7 Presence of laws and Law enforcement scores

Presence of Laws	Score (1-10)	Law enforcement	Score (1-10)
Yes	10	Yes	10
No	1	No	1

13.2 Appendix B - Conditions for Avicennia marina

Table 13.8 Environmental, socioeconomic and institutional conditions for Avicennia marina

Avicennia marina			
Chemical parameters	Salinity levels	5 - 15	(Kai et al., 2012)
	pH	5.16 – 7.72	(Kai et al., 2012)
	Nutrient content	Sufficient	
Physical parameters	Temperature	15 - 45	(Jacotot et al., 2019)
	Inundation duration (min per day)	400 - 800	(van Loon et al., 2007)
	Waves	Moderate	
	Sediment supply	Sufficient	
	Soil texture	Sandy soil	(Budiadi et al., 2022)
Ecological parameters	Sustainable food web	Yes	
	Connectivity to other species	Yes	
	Seedlings availability	Yes	
Socioeconomic parameters	Sustainable use	Yes	
	Locals engagement	Yes	
	Upstream disturbance	No	
Institutional parameters	Presence of laws	Yes	
	Enforcement of these laws	Yes	

13.2.1 Chemical parameters

Table 13.9 Salinity, pH scores and nutrients content scores

Salinity (ppt)	Score (1-10)	pH	Score (1-10)	Nutrient Content	Score (1-10)
0-5	6	<5	4	Very low	1
5-15	10	5 - 8	10	Moderate	6
15-25	6	8 - 10	4	High	10
>25	1	>10	1	Very High	4

13.2.2 Physical parameters

Table 13.10 Temperature, inundation duration, and wave energy scores

Temperature (°C)	Score (1-10)	Inundation (min per day)	Score (1-10)	Wave energy	Score (1-10)
<0	0	<400	6	Very Low	2
0 - 15	3	400 - 800	10	Low	4
15 - 40	10	800 - 1000	4	Moderate	10
>40	4	>1000	0	very High	4

Table 13.11 Sediments supply and soil type scores

Sediment Supply	Score (1-10)	Soil Type	Score (1-10)
Low	2	Clay	2
Moderate	6	Silty	6
High	10	Loamy	4

Sediment Supply	Score (1-10)	Soil Type	Score (1-10)
Very high	4	Sandy	10

13.2.3 Ecological parameters

Table 13.12 Sustainable food web, connectivity to other ecosystems scores and seedlings availability scores

Sustainable Food Web	Score (1-10)	Connectivity to Other ecosystems	Score (1-10)	Seedlings availability	Score (1-10)
Yes	10	Yes	10	Yes	10
No	1	No	5	No	5

13.2.4 Socioeconomic parameters

Table 13.13 sustainable use , locals' engagement, and Upstream disturbance scores

Sustainable use	Score (1-10)	Local engagement	Score (1-10)	Upstream disturbance	Score (1-10)
Yes	10	Yes	10	Yes	1
No	1	No	3	No	10

13.2.5 Institutional parameters

Table 13.14 Presence of laws and Law enforcement scores

Presence of laws	Score (1-10)	Law enforcement	Score (1-10)
Yes	10	Yes	10
No	1	No	1

13.3 Appendix C - Conditions for Rhizophra

Table 13.15 Environmental, socioeconomic and institutional conditions for Rhizophora mangle

Rhizophora mangle			
Chemical parameters	Salinity levels (ppt)	8 - 35	(Pasiec, 2015)
	pH	5.3 - 8.5	(Pasiec, 2015)
	Nutrient content	High	
Physical parameters	Temperature	20 - 30	(Pasiec, 2015)
	Inundation duration (min per day)	100 - 200	(van Loon et al., 2007)
	Waves	Moderate	
	Sediment supply	Sufficient	
	Soil texture	Silty clay (oxygen-poor soils)	
Ecological parameters	Sustainable food web	Yes	
	Connectivity to other species	Yes	
	Seedlings availability	Yes	
Socioeconomic parameters	Sustainable use	yes	
	Locals engagement	yes	
	Upstream disturbance	No	
Institutional parameters	Presence of laws	yes	
	Enforcement of these laws	yes	

13.3.1 Chemical parameters

Table 13.16 Salinity, pH scores and nutrients content scores

Salinity (ppt)	**Score (1-10)**	**pH**	**Score (1-10)**	**Nutrient Content**	**Score (1-10)**
<8	7	<5.3	1	Very low	1
8 - 35	10	5.3 - 8.5	10	Moderate	6
35 - 45	4	8-10	4	High	10
>45	1	>10	1	Very High	4

13.3.2 Physical parameters

Table 13.17 Temperature, inundation duration, and wave energy scores

Temperature (°C)	**Score (1-10)**	**Inundation (min per day)**	**Score (1-10)**	**Wave energy**	**Score (1-10)**
<0	0	<100	4	Very Low	2
0 - 20	5	100 - 200	10	Low	4
20 - 30	10	200 - 250	5	Moderate	10
>30	4	>250	1	very High	4

Table 13.18 Sediments supply and soil type scores

Sediment Supply	**Score (1-10)**	**Soil Type**	**Score (1-10)**
Low	2	Sandy	4
Moderate	6	Loamy	6

Sediment Supply	Score (1-10)	Soil Type	Score (1-10)
High	10	Silty	8
Very high	4	Silty Clay	10

13.3.3 Ecological parameters

Table 13.19 Sustainable food web, connectivity to other ecosystems scores and seedlings availability scores

Sustainable Food Web	Score (1-10)	Connectivity to Other ecosystems	Score (1-10)	Seedlings availability	Score (1-10)
Yes	10	Yes	10	Yes	10
No	1	No	5	No	5

13.3.4 Socioeconomic parameters

Table 13.20 sustainable use , locals' engagement, and Upstream disturbance scores

Sustainable use	Score (1-10)	Local engagement	Score (1-10)	Upstream disturbance	Score (1-10)
Yes	10	Yes	10	Yes	1
No	1	No	3	No	10

13.3.5 Institutional parameters

Table 13.21 Presence of laws and Law enforcement scores

Presence of laws	Score (1-10)	Law enforcement	Score (1-10)
Yes	10	Yes	10
No	1	No	1

13.4 Appendix D - Conditions for Ceriops tagal

Table 13.22 Environmental, socioeconomic and institutional conditions for Ceriops tagal

Ceriops tagal			
Chemical parameters	Salinity levels (%)	0 - 50	(Tropical plans, 2022)
	pH	6 - 8.5	(Tropical plans, 2022)
	Nutrient content	High	
Physical parameters	Temperature (°c)	20 - 26	(Tropical plans, 2023)
	Inundation duration (min per day)	<50	(van Loon et al., 2007) (S.spp
	Waves	Moderate	
	Sediment supply	Sufficient	
	Soil texture	well-drained soil	(SANBI, 2018)
Ecological parameters	Sustainable food web	Yes	
	Connectivity to other species	Yes	
	Seedlings availability	Yes	
Socioeconomic parameters	Sustainable use	yes	
	Locals engagement	yes	
	Upstream disturbance	No	
Institutional parameters	Presence of Laws	yes	
	Enforcement of these laws	yes	

13.4.1 Chemical parameters

Table 13.23 Salinity, pH scores and nutrients content scores

Salinity (%)	Score (1-10)	pH	Score (1-10)	Nutrient Content	Score (1-10)
0 - 25	10	<6	4	Very low	1
25 - 50	8	6 - 8.5	10	Moderate	6
50 - 65	6	8.5 - 9.5	4	High	10
>65	2	>9.5	1	Very High	4

13.4.2 Physical parameters

Table 13.24 Temperature, inundation duration, and wave energy scores

Temperature (°C)	Score (1-10)	Inundation (min per day)	Score (1-10)	Wave energy	Score (1-10)
<0	0	<10	8	Very Low	2
0 - 20	4	10 - 50	10	Low	4
20 - 30	10	50 - 100	3	Moderate	10
>30	4	>100	0	very High	4

Table 13.25 Sediments supply and soil type scores

Sediment Supply	Score (1-10)	Soil Type	Score (1-10)
Low	2	Clay	2
Moderate	6	Silty	6
High	10	Loamy	4
Very high	4	Sandy	10

13.4.3 Ecological parameters

Table 13.26 Sustainable food web, connectivity to other ecosystems scores and seedlings availability scores

Sustainable Food Web	Score (1-10)	Connectivity to Other ecosystems	Score (1-10)	Seedlings availability	Score (1-10)
Yes	10	Yes	10	Yes	10
No	1	No	5	No	5

13.4.4 Socioeconomic parameters

Table 13.27 sustainable use , locals' engagement, and Upstream disturbance scores

Sustainable use	Score (1-10)	Local engagement	Score (1-10)	Upstream disturbance	Score (1-10)
Yes	10	Yes	10	Yes	1
No	1	No	3	No	10

13.4.5 Institutional parameters

Table 13.28 Presence of laws and Law enforcement scores

Presence of laws	Score (1-10)	Law enforcement	Score (1-10)
Yes	10	Yes	10
No	1	No	1