Coastal Erosion in the Progreso Area: A Multidisciplinary Approach

Mapping the technical and social context to work towards a sustainable solution

CEGM3000: Multidisciplinary Project (MDP)

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Project Duration:	September, 2025 - November, 2025
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Cover: Groins in Chelem by G.A. van Grieken

Preface

This report is the result of a multidisciplinary project we conducted at the National Autonomous University of Mexico (UNAM) in Sisal from September to November 2025. We completed this multidisciplinary project (MDP) with six students from five different study backgrounds at the Delft University of Technology. The different studies are Civil Engineering, Strategic Product Design, Offshore & Dredging Engineering, Mechanical Engineering and BioMedical Engineering. We collaborated with UNAM researchers to identify areas where knowledge gaps remain and to develop suggestions that can contribute to improving the situation of the retreating coastline.

We express our gratitude to our daily supervisor at UNAM, Dr A. Torres Freyermuth, for his help and guidance during the project. We would like to specially thank Dr W. Rey and Dr D.E. Castillo Loeza for their feedback on the social analysis. Their expertise and experience, especially about the Progreso area, were essential for conducting this analysis. In addition, we thank Dr L. Vidal for giving us insight into the dynamics of the decision-making process in Yucatán and Mexico. For helping us spread the questionnaire in his class in Chelem, we would like to thank Jesus Lira Castro. For the supervision at the Delft University of Technology, we would like to thank Dr.ing. J.A. Antolínez, for making time to help us and for his feedback during the project. This project is supported by "Fast University Fund" and "Lamminga Fonds".

A special thanks goes to all the community members of the Progreso area for their time for interviews and filling in our questionnaire; this gave us insights into their perspectives regarding coastal erosion. We hope this report contributes to the ongoing efforts to increase coastal resilience.

We are grateful for the opportunity to conduct this MDP with fellow students in Mexico. We have learned a lot from the diverse backgrounds of our team members, both during the project and in our personal lives. We will carry the valuable experiences from this unique period into our professional and personal futures.

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Sisal, November 2025

Summary

Coastal erosion has caused beach loss and threatens first-row beachfront houses and other nearshore structures in Progreso, Yucatán (Mexico). This multidisciplinary project combines shoreline analysis, social research and stakeholder mapping to develop an integrated understanding of coastal erosion, its effects and the socio-environmental context in the study area. The aim is to translate this knowledge into a coordinated and sustainable approach that promotes coastal resilience.

The shoreline analysis that was performed using satellite imagery showed evidence of both accretion and erosion in the study area. A forecast of the coastline retreat showed that in the western part of the Progreso area, the number of properties that lie within 10 meters of the shoreline is expected to double within the next decade. The findings of the social analysis and stakeholder mapping revealed a communication and knowledge gap. The communication gap occurs between neighbours, so among coastal homeowners, but also between them and the governmental institutions. There is a knowledge gap due to the need for knowledge sharing among coastal homeowners.

A solution for the coastal erosion problem in the Progreso area is only possible by first implementing a social strategy; otherwise, no physical measure will be effective. Thus, the coastal community committee (CCC) is proposed to address the identified communication and knowledge gaps, as well as the fragmented responsibilities. The CCC is a group that makes decisions about measures to improve coastal resilience and engages local residents and stakeholders. In order to physically reconstruct a resilient coast, the use of a Sandsaver is proposed for sand accretion. To achieve long-term coastal resilience, dune formation is necessary. The report includes a plan for testing this Sandsaver and also a plan for implementing the CCC.

Contents

1
Introduction

Progreso is a beach town located on the north side of the Yucatán Peninsula in Mexico and is well known for its long pier and the port of Progreso located on this pier. This allows both big container ships and large cruise ships to dock offshore, making the town a popular stop for international travellers. Being the largest port in Yucatán, it serves as a gateway to several historical and cultural attractions and is of great importance to the regional economy via tourism and trade.

Figure 1.1: Study area location in Mexico (The Editors of Encyclopaedia Britannica, 2024)

Alarmingly, the coastline of Progreso is facing a serious problem in the form of coastal erosion. Considerable research has already been carried out to assess this issue along the northern Yucatán coast, including specific studies in the Progreso area that also examine the effects of the pier. Among the institutions conducting research is the Universidad Nacional Autónoma de México (UNAM).

In this chapter, first the study area is defined, after which background information regarding the study area is set out. Next, environmental conditions are described, which sets the basis for a description of the coastal erosion in the area. Using all the information from above, a problem statement is set up, from which the goal of this research is defined.

1.1. Study Area Definition

As the Progreso area is diverse in its characteristics, it is subdivided into three distinct areas to more easily distinguish between the areas.

The total study area extends westward to the village of Chelem and eastward to the pier of Chicxulub, at Calle 40, covering a continuous stretch of coastline that includes the urban centre of Progreso. In this stretch, area 1 covers the whole village of Chelem, area 2 extends from the port of Yucalpetén to the Progreso pier and area 3 extends from the Progreso pier to the pier of Chicxulub. In Figure 1.2, the areas are mapped on a satellite image. The specific coordinates of the areas can be found in Table A.1 in Appendix A.

Figure 1.2: All three areas of the study area (Geojson.io, 2025)

In total, the study area encompasses approximately 18 kilometres of coastline. The study area, therefore, extends beyond the boundaries of Progreso town itself. For clarity, this defined stretch of coast will be referred to as 'the study area' throughout the remainder of this report. This area was chosen because it presents a variety in demographics, while still being comprehensive enough to allow for realistic and detailed research within the scope of this project.

The study area is separated from the inland by a system of back-barrier lagoons, which are shallow waters separated from the ocean by the barrier island upon which the study area lies.

1.2. Socio-Economic Context

The study area is best known as a tourist destination and for its long pier, which accommodates the Progreso port. In this section, these aspects will be further elaborated to provide additional context on the study area.

Development of the Progreso port

The Progreso port is the most significant feature of the study area. The port and town of Progreso were founded in 1871 to serve as the principal port for shipping henequen fibre to foreign markets, as noted by Andrews et al. (2012). To accommodate vessels unable to navigate the shallow waters of the Yucatán coastline, a 1.8 km pier was constructed in 1947, pictured in Figure 1.3. This section of the pier consists of 146 arches, which were designed to facilitate sediment transport along the coast. The adjacent port of Yucalpetén was created west of the Progreso pier in 1968 as a safe harbour for fishermen (Meyer-Arendt, 2001a). This port includes a 500 m long impermeable jetty that stabilises the entrance to a sheltered basin.

To enhance its competitiveness as a major seaport, the pier of Progreso was extended to 6.5 km in 1985, reaching deeper waters offshore. This expansion included the construction of an impermeable structure with a container and cruise ship terminal at its end. By 2023, the port handled 10.1 million tons of goods, (del Sistema Portuario Nacional Progreso, 2024), ranking it as the ninth-largest port in Mexico (México Industry, 2024) and establishing it as a major economic hub in the region. Furthermore, it is equipped with a cruise ship terminal, managed by SSA México. This terminal received 75 ships in 2023 (de Fomento Turístico de Yucatán (SEFOTUR), 2024).

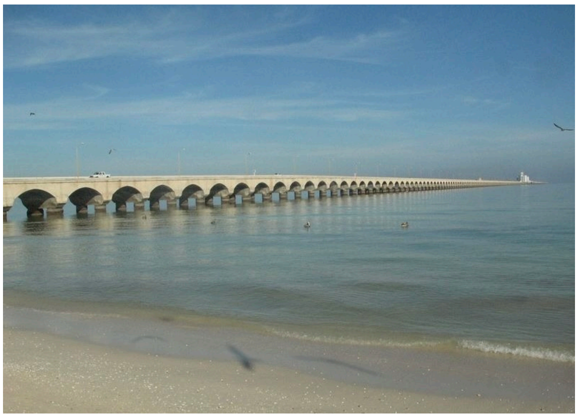


Figure 1.3: Arches of the pier constructed in 1947 (Normal, 2009)

Figure 1.4: Extended pier of Progreso, with the newer section being wider (Allen, 2014)

In 2024, the Mexican government announced an investment of approximately 400 million US dollars to further expand the port (MND Staff, 2024). This project entails deepening and widening the existing artificial channel, as well as constructing two 40-acre platforms to accommodate new terminals (Government of the State of Yucatán, 2025).

Tourism

The study area developed from a small port town into a coastal hub during the 20th century, becoming both a residential community and a destination for leisure and tourism. The construction of the railway in 1881 and later the Mérida–Progreso highway greatly improved accessibility, stimulating the growth of summer residences and tourist facilities (Gutiérrez, 2023). By the mid-20th century, Progreso had established itself as the main vacation destination for Mérida residents, with beachfront development expanding both within the town and westwards towards Chelem, where shoreline retreat was already becoming evident (Meyer-Arendt, 2001a).

Throughout the remainder of the 20th century and into the early 21st century, the study area continued to serve as a prominent hub for vacation homeowners. Between 2015 and 2019, the Progreso town experienced a 36.2% increase in real estate purchases by foreigners (Giraldo, 2022).

Comprehensive data on overall tourism expenditures in the study area is difficult to obtain. However, data from the 2023/2024 cruise season indicate that passenger arrivals exceeded 317,000, generating an estimated 25.8 million USD in expenditures. These expenditures are reported to have supported approximately 555 local jobs and contributed 4.8 million USD in wage income (Association) & Advisors), 2024).

Socio-ecological dimensions

In 2020, the municipality of Progreso, which includes the entire study area, had a population of 66,008 inhabitants, of whom 798 were born outside Mexico. The United States of America was the most common country of origin, accounting for 351 residents, of which 260 (74%) immigrated to Progreso between 2015 and 2020.

Mendoza-Gonzalez et al. (2021) studied the socio-ecological dimensions of the Yucatán coast. Community perceptions of beaches and coastal dunes in three coastal towns were examined, including Chuburná, which lies just west of the present study area. Many inhabitants provide independent tourist services such as renting palm-roofed shelters (palapas), selling food and handicrafts.

Local residents seldom use the beaches for recreation, unlike tourists who primarily value them for leisure (Mendoza-Gonzalez et al., 2021). Further in the report, stakeholders were asked for the main drivers of change in the coastal dunes. In Chuburná, natural phenomena such as hurricanes and 'Nortes' were perceived as the most significant (26%), followed by the presence of the Progreso pier (14%) and other shoreline constructions (9%). These findings echo the historical observations by Meyer-Arendt (2001a), who documented how recreational development and poorly planned coastal defences in the study area intensified beach degradation. The loss of dunes is perceived locally as "catastrophic" or "tragic" because it increases exposure to flooding and erosion, undermines tourism and risks triggering population outmigration in search of alternative livelihoods (Mendoza-Gonzalez et al., 2021).

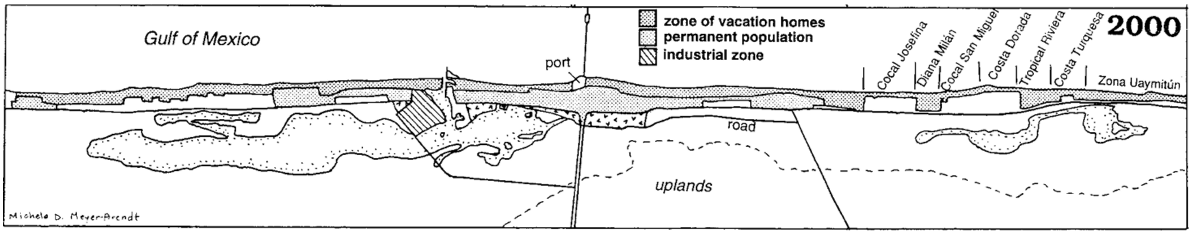


Figure 1.5: Urban land use in the study area in the year 2000 (Meyer-Arendt, 2001a)

1.3. Environmental Context

In this section, information will be given that leads to a better understanding of the climate and the coastal processes in the study area.

1.3.1. Climate conditions

The study area has a tropical sub-humid climate with pronounced wet and dry seasons. This rainfall cycle is mainly caused by the seasonal shifting of the position of a low-pressure band, called the Inter-Tropical Convergence Zone (ITCZ) (Medellín et al., 2018; Cahuich-López et al., 2020). The most important larger-scale processes are the El Niño Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO) (Enfield et al., 2001).

In the winter months, so-called 'Nortes' bring strong north to northeast winds and cooler air. Around 20 to 25 Norte events reach Yucatán each winter (Pérez et al., 2014). Nortes are a defining climatological process for the northern Yucatán coast. The waves they generate stir up coastal waters and drive beach changes (Meyer-Arendt, 1993).

Storm surge and sea-level impacts of Nortes

Rey et al. (2018) conducted a 30-year hindcast modelling study of extreme water levels at a site located 3 km offshore from Progreso. In their analysis, sea levels driven by tropical cyclones were explicitly excluded. For each year, the annual extreme water level was determined, and all extremes coincided with Norte events.

Storm surge alone generated a maximum residual tide of +1.14 m, corresponding to a return period of 67 years. This particular event coincided with a low astronomical tide of –0.35 m, resulting in a total sea level of +0.79 m with a return period of only 3 years. This event corresponded to the so-called "Storm of the Century". The maximum total sea level observed in the model was +1.16 m, associated with a return period of 78 years. This extreme resulted from an astronomical tide of +0.44 m and a residual tide of +0.72 m, the latter having a 7-year return period. Water level extremes are thus highly dependent on the interplay between storm surges and the astronomical tide.

The arrival of hurricanes in the study area is comparatively infrequent, as most landfalls occur along Yucatán's eastern coast (Magaña et al., 1999). Hurricanes that do reach the northern coast typically approach from the east or northeast. Tropical storms and hurricanes mainly occur during the summer and early fall (Cuevas Jiménez et al., 2016).

Historical extreme weather events

Through their cumulative effects, Nortes contribute to coastal erosion and occasionally cause flooding of the back-barrier lagoons (Medellín et al., 2016). Although most events are moderate in intensity, some have produced significant damage. A notable example occurred in March 1993, when the aforementioned "Storm of the Century" brought wind speeds exceeding 20 m/s (Rey et al., 2019).

As mentioned, intense hurricanes are infrequent in the study area. Since an unnamed hurricane in 1944, the most destructive hurricanes in the study area were Hurricane Gilbert in 1988 and Hurricane Isidore in 2002 (Rappaport & Fernández-Partagás, 1995). Gilbert, one of the strongest Atlantic hurricanes on record, made landfall near Cozumel as a Category 5 hurricane and exited the peninsula near Progreso, still a Category 3 hurricane (Lawrence & Gross, 1989). Its waves and surges caused extensive beach erosion and damage to waterfront infrastructure (Meyer-Arendt, 2001b). Isidore made landfall near Progreso as a Category 3 hurricane, reportedly driving a surge of 2–3 meters, causing beach erosion that took years to recover (Enriquez et al., 2010). Recent events with relatively low impact on the study area were Hurricane Wilma in 2005 and Tropical Storm Gamma in 2020 (Pasch et al., 2006 Brown et al., 2021).

Projected climate trends

Under high-emission scenarios, the mean sea level in the study area could be 0.5–1.0 meters higher than today (IPCC, 2021). The low and flat topography means that even moderate sea-level rise will expand the flood-prone area. Recent assessments indicate that although the overall number of Atlantic tropical cyclones may not increase significantly, the intensity of the strongest storms will likely rise. There is medium-to-high confidence that future hurricanes will produce higher peak winds (Knutson et al., 2020). The more extreme surges and erosion caused by these peak winds, in combination with the rising sea level, illustrate the necessity to improve the coastal resilience in the study area.

1.3.2. Coastal processes

To understand the dynamic interplay between sediment accretion and erosion, a general understanding of the coastal processes at play is important. These processes are primarily controlled by wave action on beaches and wind in dunes. The amount of sediment transport by waves is strongly related to the angle of incidence between the incoming waves and the shoreline (Falqués, 2006). The balance between erosion and accretion could be stable, or tip to either net erosion or net accretion when one mechanism is stronger than the other.

Wave regime

Wave conditions were analysed based on ERA5 hourly time-series data, downloaded from Copernicus Climate Data Store (CDS) on October 2, 2025. The ERA5 time-series dataset provides hourly reanalysis data for single points, derived from the full ERA5 reanalysis at a spatial resolution of 0.25° (Hersbach et al., 2020).

The ERA5 time-series data were extracted from the grid point at 21.5° N, 89.5° W, located approximately 21 km north and 20 km east of the study area.

The wave analysis shows a mild wave climate with north east as a dominant wave direction, which corresponds with the findings of Appendini et al. (2012). The statistics of the wave climate are shown in Figure 1.1 and a waverose is shown in Figure 1.6.

	Significant Waveheight H_s [m]	**Peak Period** T_p [s]	**Wave Direction** [°]
Mean	0.69	4.26	47.99
Standard dev.	0.36	1.04	32.71

Table 1.1: Wave statistics

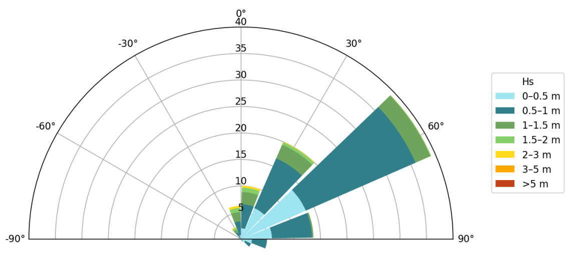


Figure 1.6: Waverose

Wave statistics in storm conditions have also been analysed, these results can be found in Appendix B and are in correspondence with storms described in subsection 1.3.1.

Tidal regime and currents

The northern Yucatán coast is characterised by a mixed tide regime, where diurnal tides predominate and semidiurnal tides occur during neap tides. The tidal range is 0.1 meters for neap tides and 0.8 meters for spring tides (Cuevas-Jiménez & Euán-Avila, 2009). As the normal tidal range is microtidal, storm winds and pressure effects are the main drivers of water level extremes. Similarly, the near-shore circulation (currents) is mainly driven by wind and waves, leading to a net longshore sediment transport (Appendini et al., 2012).

Sediment transport

In 2012, Appendini et al. categorised the coastline here as naturally stable. Sediment is moved along the coast from east to west, driven by waves approaching the shore from the northeast, shown in Figure 1.6. Incoming and outgoing sediment fluxes are balanced, meaning that there is no gradient in potential longshore sediment transport (PLST). They concluded that the net PLST for the study area is 35,700 m^3/y moving westward and that most of the sediment transport occurs within the shoreline and a depth of 3 meters, meaning within 250 meters of the shoreline (Appendini et al., 2012). This is in correspondence with sediment transport rates calculated using a numerical LITDRIFT model by Lira-Pantoja et al., 2012.

Torres-Freyermuth et al. (2019) and Pellón de Pablo et al. (2024) describe the general seasonality of beach erosion and accretion. They note the erosive effect of wind and waves during the winter ('Norte') season due to cross-shore waves with high energy. Accretion occurs in calmer seasons due to the longshore sediment transport described. Under natural conditions, calmer periods regain the beach.

Dune forming

The research Rey et al. (2020) includes a part in the study area where areas 2 and 3 are included, offering valuable insights into the impact of the Nortes and moderate hurricane events named in subsection 1.3.1. Rey et al. indicates that this part presents the higher impact regime experienced during Norte events, which is attributed to the less preserved coastal dunes in that part. This is due to urban expansion in this part of the coast. They conclude that "The implementation of coastal dune protection initiatives is needed to make the Yucatán coast more resilient to Nortes and moderate hurricane events." (Rey et al., 2020).

In the dunes, the wind lifts and moves sediments across the surface. Vegetation plays a critical role in reducing the wind speeds, thereby trapping the sediments and increasing dune formation and stabilisation (Durán & Herrmann, 2006). Coastal dune vegetation increases the dune resistance during extreme water levels (Medellín & Torres-Freyermuth, 2021).

1.4. Coastal Erosion

Man-made structures such as piers, groins and seawalls have a significant effect on the sediment stability described above. This effect is twofold. Perpendicular near-shore structures act as a barrier preventing sediment flow from east to west. Additionally, they induce wave sheltering, dissipating the energy of waves, thus reducing the ability of waves to push sand landward. Together, this leads to gradients in alongshore sediment transport and thus to net erosion.

Appendini et al., 2012 noted that, due to longshore sediment flow, the shoreline near Progreso is extremely sensitive to coastal barriers. Additionally, Lira-Pantoja et al., 2012 concluded that the Progreso pier was responsible for a change in net sediment transport rates west of the pier, inducing alongshore sediment transport gradients. A visualisation of these modelled net sediment transport rates can be found in Appendix C. Similarly, Torres-Freyermuth et al., 2023 found that the Progreso Pier induced erosion along a 10-kilometre stretch, while detached groins negatively impact a downdrift area of approximately 100 meters.

Since the founding of the port of Progreso in the late 19th century, a disruption of sediment transport has been observed, leading to erosion westward of the port. The situation worsened after the construction of the first pier in 1947 (Campos Cabeza, 1990). Between 1948 and 1978, the beach in the Chelem area experienced an average erosion rate of 0.9 m/year (Meyer-Arendt, 1993). It was later confirmed that a similar trend has persisted "in the last 40 years" (Lira-Pantoja et al., 2012).

From 1960 onwards, man-made groins were built on both the western and eastern sides of the pier in an effort to combat erosion. These structures were installed not only by private beach owners but also by local governments (Meyer-Arendt, 2001a). However, the groins generally proved to be ineffective and, due to poor design and lack of coordination, often aggravated erosion effects instead (Tereszkiewicz et al., 2017). Although many recognise that these structures can negatively impact the beach, they are often regarded as a last resort to preserve private property. Officially, permission for groin construction is required from regulatory institutions, yet in practice most are built illegally (Meyer-Arendt, 2001a).

The erosion described above has led to a severely reshaped coastline in the study area. In some sites, these effects are so severe that there is little beach left and properties are practically in the sea. This, together with groins placed as mitigation measures, can be clearly observed in Figure 1.7.

Figure 1.7: Houses in Chelem under threat of the retreating coastline (Photo taken by the author (2025))

1.5. Problem Statement

Over the years, the greater Progreso area has developed into an economic hub, driven by port expansion and tourism growth. While these developments have generated clear economic and social benefits, associated beachfront construction has also disrupted the natural geomorphological processes.

The accelerated erosion of the coast in the study area now threatens first-row beachfront houses and other nearshore structures. This puts the area's future as a residential area and tourist destination at risk. Although cruise ships will continue to call at the port, there is a risk that passengers may avoid visiting Progreso itself if the coast becomes less attractive due to erosion. Similarly, vacation homeowners may choose not to return or may reduce their time spent in the area. This leads to lower local spending and thus less economic growth for the local population.

Thus far, the extent of the threat of the retreating coastline to nearshore structures has not been systematically assessed. Furthermore, the views and experiences about coastal erosion of residents, beach homeowners and other stakeholders are important but not yet investigated.

Past and current strategies to combat coastal erosion have been fragmented, poorly coordinated and often counterproductive. Despite the efforts, erosion continues and may even be aggravated by past and ongoing mitigation strategies adopted by individual home owners.

Thus, the central challenge is the absence of effective, coordinated and sustainable measures to mitigate the negative effects of coastal erosion. To ensure Progreso's future as a tourist destination and a sustainable beach community, it is crucial to work towards a naturally wide and resilient beach.

Therefore, the objective of the project is as follows:

"Develop an integrated understanding of the coastal erosion problem and its socio-environmental context in Progreso, Chelem and Chicxulub, to translate this knowledge into a coordinated and sustainable approach that promotes coastal resilience."

To achieve this objective, the project has been scoped to analyse the shoreline, identify stakeholders, and assess the social context. The report concludes with a solution *proposal*, based on the obtained information.

The shoreline analysis aims to create an understanding of the shoreline patterns in both the past and future. As well as the threat the retreating shoreline poses to near-shore structures. These insights are necessary to determine if and where mitigation measures are required. To do so, the shoreline patterns of the past 10 years will be analysed, and the vicinity of near-shore properties to the current shoreline will be assessed.

The stakeholder analysis aims to create an understanding of the parties involved and affected by coastal erosion and its consequences. These insights are necessary to identify the most important stakeholders and areas of improvement regarding cooperation. This is important for the implementation of possible mitigation measures. To do so, stakeholders involved will be identified and mapped.

The social analysis aims to create an understanding of the perception of the local community regarding all aspects of coastal erosion in the study area. These insights are necessary for an assessment of social dimensions in the study area. It is essential for effectively integrating mitigation measures, shaping demand for interventions and acceptance of solutions. To do so, a questionnaire and interviews will be conducted and analysed.

To work towards the main aim of developing effective and sustainable measures to enhance coastal resilience, concept solutions are developed and an elaborate strategy is proposed. This strategy aims to overcome gaps and problems identified in the research. The proposed strategy is designed to be a first step in working towards an ideal future vision.

2
Methodology

This chapter provides a detailed overview of the methodologies employed in the study. It outlines the approach used for detecting and analysing the shoreline, describing the techniques and programs used. Additionally, the chapter describes the method implemented to identify and map various stakeholders. Following, the social analysis includes a questionnaire and conducting qualitative interviews to gather insights into the perspectives of various stakeholders. Finally, the chapter ends with an explanation of the method used for generating concepts that can help in addressing the coastal erosion problems.

2.1. Shoreline Analysis

To create an understanding of the shoreline patterns in the study area in the past and future, a shoreline analysis was conducted in different steps. First, CoastSat was used to extract shorelines from satellite imagery. Afterwards, the shoreline time series were post-processed in QGIS. Subsequently, a QGIS plugin called QSCAT was used to compute statistics and generate forecasts. Meanwhile, properties were identified in QGIS. A risk analysis was carried out to assess the level of exposure of these properties to shoreline change.

2.1.1. Shoreline detection

To extract shoreline positions in the study area, an open-source software toolkit named CoastSat is used. The toolkit retrieves publicly available satellite imagery from the Google Earth Engine (GEE) (Vos et al., 2019), which will hereafter be referred to as kvos.

To effectively analyse the data in CoastSat, several steps must be undertaken. Initially, the region of interest is defined, which includes the entire municipality stretching from Chelem to the Letras de Chicxulub Puerto. This region of interest has been divided into three specific areas, see section 1.1.

CoastSat configuration

Multiple satellites capture the region of interest. For this research, Sentinel-2 is chosen because it has the best features compared to other satellites. It has a time coverage from 2015 till present, the revisit period is five days, and the pixel size is 10 meters for R, G, B and NIR bands (Vos et al., 2019). The resolution of the pixels is important to reach the highest accuracy and for the interpretation of the results.

To ensure the analysis results are as precise as possible, the longest time period is selected. All the available imagery between 01-01-2015 and 10-09-2025 was used. For detecting the shoreline, all settings of kvos were used, except for the following ones:

- The maximum acceptable cloud cover was set to 0.3 to minimise the manual selection further in the process.
- The buffer around cloud pixels where the shoreline can't be mapped was set to 100 meters.
- The ESPG number of the local coordinate system in Progreso is 32616 (Maptiler, 2025).

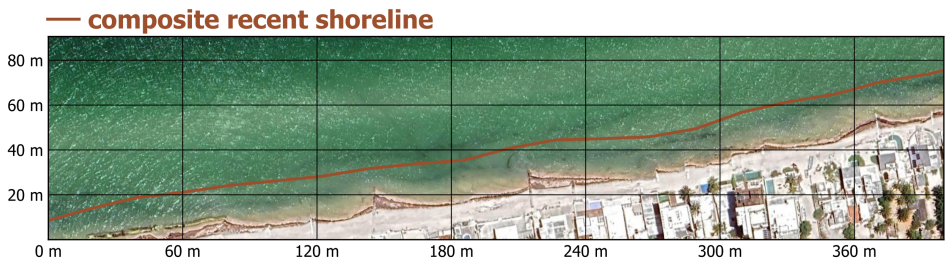
- The minimum area for an object to be labelled as a beach is 1500 m^2, the pixels are 100 m^2, so when 15 pixels are detected as sand, it is defined as a beach.
- The minimum length of shoreline perimeter to be valid is set at 1000 meters, which is to minimise the number of automatically selected images in order to simplify the manual selection.

To improve the mapping of the shorelines, a reference shoreline was manually digitised. After the integrated automated detection of CoastSat, the detections were controlled manually. This resulted in a set of detected shorelines, which was combined in a GeoJSON file.

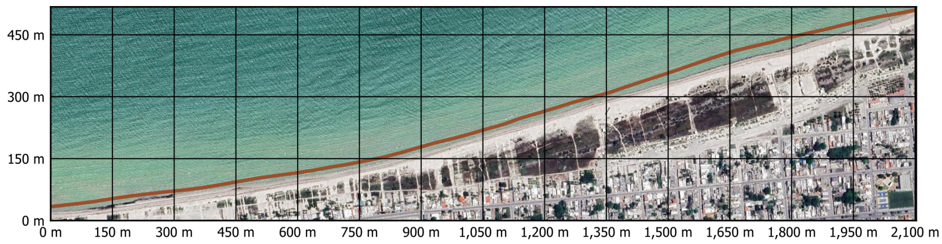
During this analysis in CoastSat, the tides were not taken into account. According to Torres-Freyermuth et al. (2023), there is no significant difference in the results of a sensitivity analysis when including the tidal correction conducted for Sisal. Sisal is a coastal village 40 kilometres away from the study area. This lack of difference is attributed to the low-energy and micro-tidal regime, which is assumed to be similar in Progreso.

Iterations

Shorelines are detected in CoastSat by computing the Modified Normalised Difference Water Index (MNDWI) and using Otsu's thresholding algorithm to find the MNDWI value that maximises inter-class variance between the 'sand' and 'water' distributions (Vos et al., 2019). This methodology is data-driven, and is thus prone to bias due to environmental circumstances like white-foam, near-shore reflectance and shallow waters (Vos et al., 2023). To ensure accurate and viable results, iterations were made in the settings used. For each iteration, validation of the obtained shorelines was done by comparing the composite most recent shoreline (methodology explained in section 2.1.2) to recent satellite images.



(a) Visualisation of shoreline offset in area 3



(b) Visualisation of shoreline offset in area 2

Figure 2.1: Visualisation of shoreline offset in areas 2 and 3

The first run was performed using default settings. This resulted in a seaward offset and is illustrated with a few snapshots of the composite coastline laid over recent satellite images, in Figure 2.1. Two areas with different beach morphologies are shown to illustrate that the offset was independent of local beach features. This seaward offset is a known consequence of shoreline detection in shallow waters, as shallow waters skew the MNDWI histogram, which results in a more negative (seaward) Otsu cut (Reis et al., 2021;Bergsma et al., 2024). A study in 2015 by García-Rubio et al. noted similar results when extracting satellite-derived shoreline in the Progreso area. An average seaward displacement of 5.57 m was noted, which was attributed to shallow waters in combination with an abundance of fine sediments, causing conditions of high turbidity.

A reduction of seaward bias was attempted by first adjusting the minimum area and minimum shoreline perimeter length parameters. This led to an 'over sensitive' shoreline detection, which resulted in a shoreline that was too ruffled compared to reality.

Next, a different threshold computation methodology was attempted by altering the back-end CoastSat code. Instead of a global Otsu cut on MNDWI, a method called 'local minimum histogram thresholding' was adopted. This method has proven to reduce shallow water sea bias (Bergsma et al., 2024). A notable difference in seaward bias was observed when computing the recent composite shoreline. However, the seaward bias was still in the order of 5–10 meters, which is why, eventually, a manual selection was adopted for shoreline detection.

For each image processed, the threshold for shoreline detection was adjusted manually, matching the threshold to the end of the tail of the detected sand distribution. This meant a general shift from negative threshold values to values around 0. The shoreline position was checked in the corresponding image to ensure accuracy of the position.

2.1.2. Geospatial analysis

To convert time series of shorelines obtained using CoastSat into long-term change metrics, the QGIS Shoreline Change Analysis Tool (QSCAT version 0.4.1) plugin was used. QSCAT follows the general methodology of the USGS Digital Shoreline Analysis System (DSAS). It works by constructing a baseline parallel to the coast and casting perpendicular transects, along which dated shoreline positions are intersected. DSAS then applies statistical techniques to estimate shoreline change rates, while incorporating positional uncertainties to provide confidence intervals (Himmelstoss et al., 2018).

Post-processing Coastsat data

To ensure reliable outputs, the obtained shoreline time series were post-processed to improve trend stability. Outliers were removed by excluding abnormally long or short shorelines. The data set was further post-processed by manually excluding shorelines that highly deviated in shape from other shorelines. Using a landward baseline layer, evenly spaced transects with a 25-meter spacing were cast perpendicular to the shore.

The Sentinel-2 resolution of 10 meters was used as input for the uncertainty parameter in QSCAT. Using the transects, QSCAT computed a dataset of transect-shoreline intersects at given dates, from which statistical trend metrics are computed.

Shoreline change statistics

QSCAT allows for the calculation of different shoreline change statistics. The most commonly used statistic to identify coastal erosion is the linear regression rate (LRR) (Gunarathna and Pussella, 2022; Zhang et al., 2024; Quang et al., 2021). The LRR is determined from the slope of a least-squares regression line fitted to all shoreline intersection points for each transect.

To evaluate the statistical relevance of the LRR, the linear regression standard error (LRE) and linear regression confidence interval (LCI) are also calculated. The LRE quantifies the vertical scatter of points around the regression line in meters, whereas the LCI quantifies the half-width of the confidence interval around the slope in m/yr. The LCI is dependent on the confidence interval chosen. For this study, a 95% confidence interval was adopted because it is common practice when applying DSAS methodology (Himmelstoss et al., 2018).

The full formulas for the LRR, LRE and LCI can be found in Appendix D.

Definition current shoreline

To quantify the distance between properties and the current shoreline, a coherent definition of the current shoreline is necessary. As set out in subsection 1.3.2, seasonal wave regimes and storms lead to seasonal shoreline cycles in the study area. Furthermore, other noise attributed to tidal differences and waves may result in inaccurate shoreline measurements. To account for seasonality effects, noise, and the resolution of satellite images used, a composite recent shoreline is constructed, a combination of a range of recent shorelines.

The period chosen for the composite shoreline is 12 months to fully account for seasonal effects. From all shorelines in this timespan, the median shoreline is constructed to account for potential outliers.

Shoreline forecasting

Furthermore, when analysing critical areas in the study area, it is interesting to extrapolate current shoreline trends to forecast future shoreline positions. The forecasting is based on a methodology developed by Long and Plant, 2012, commonly used for forecasting shoreline movement. The model applies a Kalman Filter, initialised with the Linear Regression Rate (LRR), to estimate shoreline positions through time. At each new time step, the filter updates the predicted rate and position by optimally weighing the previous trend and newly observed shoreline data. Doing so, the model accounts for both model uncertainty and observational noise (Himmelstoss et al., 2018).

Property identification

To quantify the risk the current shoreline position poses to houses being lost to the sea, the properties in the areas of interest are identified, using high-resolution Google Satellite imagery (ESRI Wayback archive, accessed 23 September 2025). Each property boundary was delineated manually based on set criteria. To account for uncertainty in delineation, every property was assigned a confidence score (high, medium, or low) according to the clarity of the boundary and shoreline-facing structures. A full description of the identification criteria and decision rules is provided in Appendix E.

Property vicinity to forecasted shorelines

To quantify the threat the retreating shoreline poses to properties in the area, the distance of forecasted shoreline positions to properties is calculated. The forecasted shoreline contains substantial uncertainties, which need to be propagated into the distance calculations.

To do so, for each property, the distance to the forecasted shoreline is treated as a Bernoulli random variable with a normal distribution: $D_i \sim \mathcal{N}(d_i, \sigma_i^2)$, with d_i the calculated distance in m and σ_i the uncertainty of the forecasted shoreline in m. The probability that a property lies within a certain distance threshold T can thus be computed as:

$$p_i = \Phi\left(\frac{T - d_i}{\sigma_i}\right)$$

The expected percentage of properties μ within a certain distance threshold T is calculated by summing all the individual probabilities per property and dividing by the total N. A 95% confidence band of this mean is computed using the variance (Var), as: $S = [\mu \pm 1.96\sqrt{Var}]$

Calculations were performed with python, using property–shoreline distances and uncertainties exported from QGIS.

2.2. Stakeholder Analysis

In order to strengthen cooperation in implementation of mitigation methods, it is essential to gain an understanding of all parties that are involved in decision-making and those that are impacted by coastal erosion. Stakeholders were identified through literature research and subsequently evaluated using a stakeholder network map and a power–interest diagram to assess their influence, engagement and relevance for further investigation.

2.2.1. Identification of stakeholders

The key actors involved in coastal erosion in the study area were identified through three complementary approaches. First, existing literature such as Meyer-Arendt (2001a) and Mendoza-Gonzalez et al. (2021) was reviewed to form the initial basis for identifying key stakeholders involved in coastal erosion. The stakeholders identified were then categorised to establish a clear structure for analysis. Secondly, a first iteration of this stakeholder set was developed during a visit to the study area, which included preliminary conversations with several local actors. These discussions provided valuable context on who is directly affected and who plays a role in responding to coastal erosion. Lastly, the stakeholder set and their interrelationships were continuously evaluated and refined throughout the project, as insights from interviews and other findings led to new understanding and additions.

2.2.2. Relation between stakeholders

A stakeholder network map was designed to visually and intuitively position the identified actors on a map of the study area, illustrating both the relationships and their strengths. This structure allows the map to capture both the influence of individual stakeholders and the intensity of their interactions with one another.

By making visible how power and relationships are distributed, the map highlights key decision-makers, reveals gaps or weak links in cooperation and shows which groups act as bridging actors within the system. These insights are essential for shaping potential solutions, as they ensure that proposed strategies take into account the existing social dynamics and stand a greater chance of gaining acceptance and support.

2.2.3. Stakeholder influence & engagement

After identification, the actors were further evaluated to determine their level of influence and engagement with the issue. This was done using a Power–Interest Diagram, which categorises stakeholders according to their degree of power (influence over decision-making) and interest (level of concern and engagement with the issue).

The diagram contains four quadrants, each representing a different engagement strategy for the stakeholders in that particular quadrant (ProjectManagement.com, 2023; Reed et al., 2009):

- *High Power, High Interest* → *Manage closely*: These stakeholders require active collaboration and participation in decision-making.
- *High Power, Low Interest* → *Keep satisfied*: These stakeholders hold authority and resources but are less involved in daily management.
- *Low Power, High Interest* → *Keep informed*: These are directly affected stakeholders who should be informed through transparent communication and consultation.
- *Low Power, Low Interest* → *Monitor*: Limited engagement is required for these stakeholders, but their roles should still be monitored in case their power or interest changes over time.

In the context of coastal erosion in the study area, the diagram was used to structure the positions of stakeholders in relation to the retreating coastline. It highlights which stakeholders are essential for solution development and which require further engagement to ensure both effectiveness and support for a potential solution.

2.3. Social Analysis

The social analysis is crucial to gain insight into the perception of the local community. These insights are needed for creating a possible solution and acceptance of it. The social analysis is twofold and consists of a questionnaire and qualitative interviews.

2.3.1. Questionnaire

To gather quantifiable data, a questionnaire in Google Forms was drawn up and distributed through the study area. To be able to analyse the data retrieved from the questionnaire, a list of hypotheses was created. The hypotheses were based on previous literature and assumptions from previous field visits.

To capture both qualitative insights and quantitative data, the questionnaire combined open-ended and structured questions. The questionnaire aimed to explore the perceptions and experiences of various stakeholder groups regarding coastal erosion. The questionnaire distinguishes between owners of holiday homes on the coast and permanent residents on the beach, to be able to identify possible differences between those specific groups.

The questionnaire covered four main themes:

1. **General background information** of respondents.
2. **Perceptions of coastal erosion**, such as the perceived severity of the issue, identified causes and expectations for the (ideal) future.

3. **Experiences with mitigation measures**, including both government-led actions and privately implemented solutions such as groins or seawalls.
4. **Group-specific impacts**, for example, property damage and protective measures among coastal homeowners, potential changes in income for tourism service providers, or regulatory perspectives of government officials.

The format of the questionnaire was intentionally chosen to address the language barrier between the research team and local respondents by translating the questionnaire into simple Spanish and using structured questions, the method ensured that participants could respond in their own words. The questionnaire was carried out across the study area both on paper and through an online form via QR-codes, spread physically and online.

The collected data were analysed quantitatively and qualitatively, using both SPSS (Statistical Package for the Social Sciences) and Atlas.ti, respectively. In order to be able to take into account the qualitative data, labels (codes) were assigned to open questions. After the first round of coding, labels were categorised into different themes to structure the qualitative data. The goal of this coding process was to identify patterns, organise and eventually interpret all the data retrieved from the questionnaire.

2.3.2. Qualitative interviews

To collect qualitative data, six qualitative interviews were conducted. These interviews were both semi-structured and unstructured. For the semi-structured interviews, an interview guide was created. All interviews were recorded and later transcribed using Transcribe.ai.

The objectives of the interviews was determined to create an interview guide for this research. Two main purposes for the interviews were defined:

1. Map stakeholder priorities to identify which concerns, risks and responses are most important to the different stakeholders in relation to the retreating coastline. This will help reveal what stakeholders perceive as the most urgent issues or opportunities to address in a further phase of the project.
2. Gain deeper insights into stakeholders' contexts and their relationship to the problem of coastal erosion. The detailed descriptions of experiences, feelings and perspectives can be used to design, test or improve systems and products (Bhandari, 2022).

The interviews were conducted with three focus groups, for which different interview structures are used. The main focus group consisted of *coastal homeowners*. Their perspective is considered highly relevant as they experience coastal erosion in their daily lives and often take measures themselves to mitigate the effect. This focus group is split into two:

- **Coastal homeowners, within the study area**, to gain deeper insights into their perspective and possibilities for the design phase of this project.
- **Coastal homeowners, outside of the study area**, who have a beach in front of their house that is resilient against coastal erosion. This subgroup was included to gain insights from areas where the situation regarding coastal erosion is comparatively stable, providing a useful point of reference.

A semi-structured interview guide was created for the *Coastal homeowner* group (Appendix H). This type of interview allows the interviewer to ensure consistency across the interview while being flexible. This way, the interviewer can adapt to specific individual contexts, experiences and backgrounds of different stakeholders (Ruslin et al., 2022). According to Kircher and Zipp (2022), results of semi-structured interviews can be used as a basis for further investigation.

The third focus group involved **the governmental perspective** on coastal erosion. Due to limited background information regarding the government's stance on coastal erosion, unstructured interviews were chosen for this group. Flexibility was necessary since the specific backgrounds of the interviewees were unclear beforehand. Unstructured interviews are a useful exploratory research tool, characterised by the informal and flexible nature of data retrieval (George, 2025). Therefore, no interview guide was created for these interviews.

All interviews were recorded with the permission of the interviewees and transcribed using Turboscribe. Turboscribe is a transcription tool that automatically converts spoken language from audio into accurate, editable text (TurboScribe, n.d.).

2.4. Concept Generation

To come up with different concepts for creating a resilient beach, various concepts were generated. As stated in subsection 1.3.2, looking at the current stage of the beach in the study area, sand accretion and dune forming are crucial measures to establish a resilient coast. Numerous diverse technical solutions can be proposed to reach this. Through brainstorming and desk research, an extensive list of possible solutions for sand accretion was set up, without yet taking into account their feasibility. To ensure creative input and a variety in solutions, pairs of two were formed and given the instruction that solutions can be unconventional.

2.4.1. PMI-method

The obtained list of solutions was subsequently assessed using the PMI-method (Plus, Minus, Interesting) described in the Delft Design Guide (van Boeijen et al., 2013). This is a quick technique to capture advantages, disadvantages and noteworthy aspects of each proposed solution (de Bono, 1985). This allowed an initial overview of the strengths and weaknesses of the different options without the need for detailed analysis.

The resulting PMI diagram was then used as the basis for an elimination round, during which concepts were screened for practicality of research and feasibility of implementation in the study area. Concepts that were lacking sufficient available data and resources or that were deemed unfeasible in the study area were excluded. A reason for the latter could also be that the technique has already been (unsuccessfully) implemented. This process ensured that only viable and well-supported solutions were carried forward for further development.

2.4.2. Multi-criteria analysis

A preliminary selection of six contenders was made based on the PMI-method, which was then assessed using a multi-criteria analysis (MCA). The MCA was used to systematically compare several design concepts based on a structured set of evaluation criteria. Each criterion received a weight from 1 to 5 based on its importance for the assessment. Weights were established through pairwise comparisons for clear trade-off discussions. The criteria and weights were organised in a matrix, with criteria as rows and design concepts as columns. Each concept was evaluated against every criterion and scored from 1 to 3, instead of the original 1 to 10. This was done to limit the differences between the concepts. The final score was calculated by multiplying individual scores by their weights and summing the results (Roozenburg & Eekels, 1995). The results were interpreted, and a final solution concept was selected.

3 Results

This chapter provides a comprehensive overview of the findings from all the analyses conducted. It presents the historical and future trends of the shoreline analysis, along with the stakeholder network map and the power-interest matrix from the stakeholder analysis. Additionally, the results of the social analysis, including both the questionnaire and the interviews, are explained in detail. The generated concepts are illustrated using the results from the PMI-method and the multi-criteria analysis. Finally, all the findings from the various analyses are integrated.

3.1. Shoreline Analysis

In this section, the results of the shoreline analysis are presented. First, the shoreline change analysis results are displayed. Next, the risks for property loss due to the retreating shoreline are identified.

3.1.1. Shoreline change analysis

Historic trends

As set out in section 2.1.2, the linear regression rate (LRR) gives a good indication of overall shoreline changes in the years examined. The LRR is calculated for all areas, and visualised in Figure 3.1. Negative LRR values (red) indicate net erosion, whereas positive LRR values (blue) indicate net accretion in the observed timeframe of 9 years.

From Figure 3.1, a significant difference in change rates can be observed between and within the three areas. Area 1 generally has a bit more accretion than erosion, with a small LRR for both accretion and erosion. In area 2, in general, accretion occurs, with the highest rates of all areas. Area 3 has a high variance in rates, with high accretion and erosion rates to the west side of the area, close to the pier. For statistical insights, the LRR statistics are reported in Table 3.1. An LRR statistic for a transect is considered statistically relevant if the 95% confidence interval of the LRR does not include zero. Otherwise, accretion or erosion cannot be determined with enough certainty for a set transect.

Area	Mean LRR [m/yr]	Range LRR [m/yr]	Median LRR [m/yr]	Mean LSE [m]	Mean LCI [m/y]	Percentage Statistically Relevant
Area 1	0.43	-2.22 – 2.61	0.44	6.91	0.69	37.6 %
Area 2	3.25	-1.23 – 7.31	2.65	7.77	0.67	97.1 %
Area 3	-0.38	-5.15 – 3.02	-0.28	6.88	0.61	56.4 %

Table 3.1: Summary statistics of shoreline change rates per area

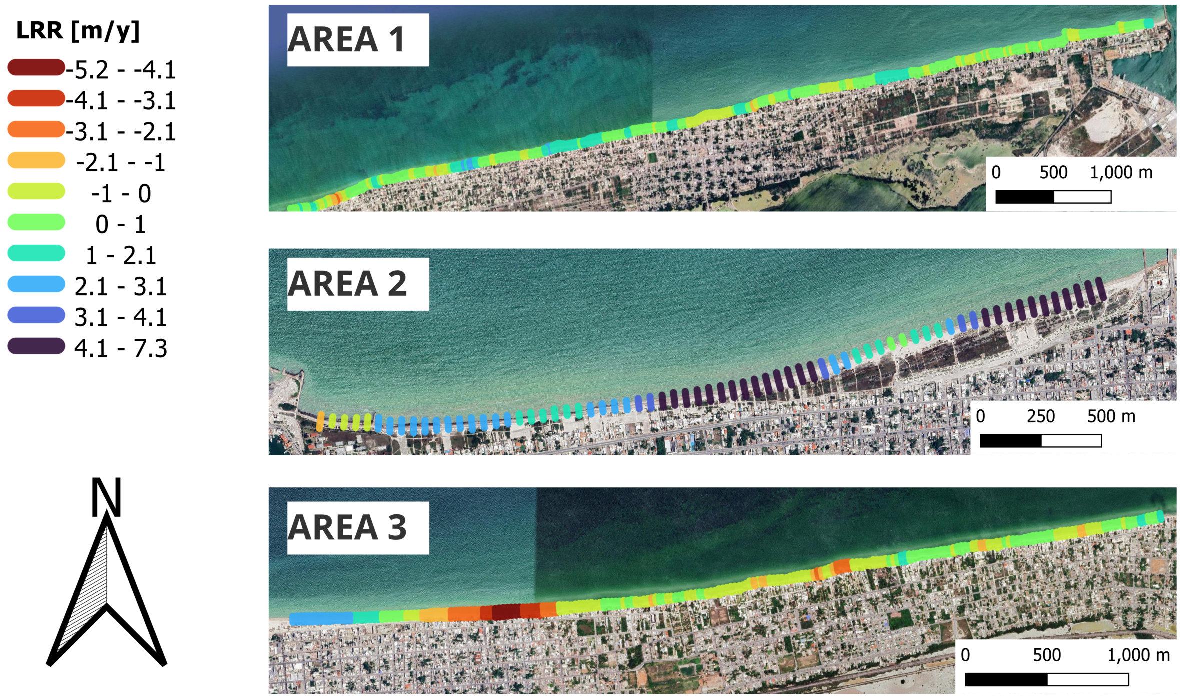


Figure 3.1: Summary of LRR results for all areas

The differences in change rates between and within areas visualised in Figure 3.1 are substantiated by the statistics in Table 3.1. When looking at the mean LRR and median LRR, one can see that for areas 1 and 2, the general trend is accretion, whereas in area 3, this is erosion. For all three areas, the range in LRR is quite high, indicating a high inter-area variance in LRR. Small rates in areas 1 and 3, combined with an LCI in the ranges of 0.61 and 0.69, respectively, lead to a 37.6% of LRR being statistically relevant in area 1 and 56.4% being statistically relevant in area 3. Area 2 has a significantly higher statistical relevance of LRR of 97%, which can be attributed to the general high accretion rates combined with an LCI of 0.67. The notion is made that a statistically insignificant LRR might also indicate a stable coastline. This would mean that the coastline within areas 1 and 3 could be mostly stable.

The high variance in LRR values within and between the three areas exemplifies the sensitivity of the shoreline in the study area to coastal barriers, as discussed in section 1.4. No general trend can be observed in the study area. These differences could thus be due to the influences of both small and larger coastal barriers on the longshore sediment transport.

Next, insignificant change rates are omitted, as no conclusion regarding erosion or accretion can be drawn from them. With insignificant values omitted, the percentage of transects eroding or accreting per area can be reported. The statistics for only statistically relevant shoreline change rates are shown in Table 3.2.

Area	Mean LRR [m/yr]	Range LRR [m/yr]	Median LRR [m/yr]	Mean LSE [m]	Mean LCI [m/yr]	Eroding	Accreting
Area 1	0.90	-2.22 – 2.61	1.06	6.99	0.70	13.6 %	86.4 %
Area 2	3.36	-1.23 – 7.31	2.77	7.76	0.67	4.6 %	95.5 %
Area 3	-0.65	-5.15 – 3.02	-0.80	7.03	0.63	64.2 %	35.8 %

Table 3.2: Summary statistics of statistically relevant shoreline change rates per area

When comparing the statistics from Table 3.1 to Table 3.2, the most notable changes occur for mean and median LRR. These increase or decrease for respective accreting or eroding areas. Areas 1 and 2 can be seen as mostly accreting, with 86.4% and 95.5% of transects accreting, respectively. Area 3 has slightly more eroding transects compared to accreting, with 64.2% vs 35.8%.

Area 1 (Chelem) case study

The finding of a general accreting trend in area 1 is notable, as an eroding trend was expected here. As set out in subsection 1.3.2, earlier studies described high erosion in the Chelem area and the results presented in subsection 3.3.1 suggest people in the study area perceive the Chelem beach as eroding. Therefore, some parts of interest within area 1 are highlighted to explore possible explanations for this discrepancy in results. Figure 3.2 shows two snapshots of ESRI satellite images from the start and end of the dataset used for shoreline identification.

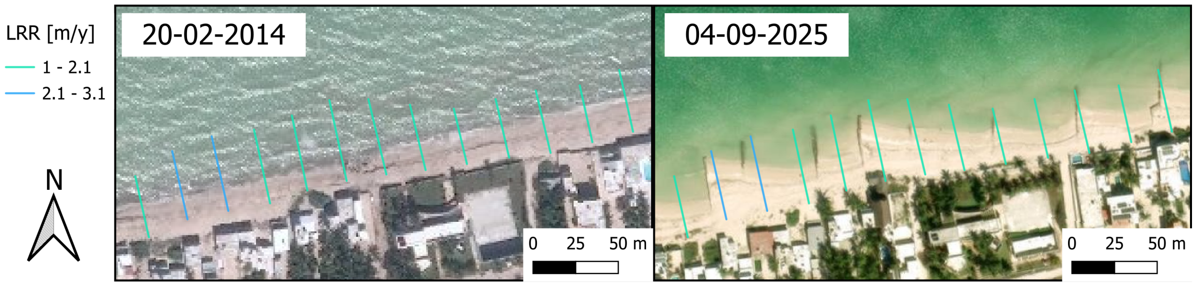


Figure 3.2: Satellite images at two timestamps of an area with general accretion in area 1

Within Figure 3.2, an area in the west of Chelem, with a general accreting trend can be seen. In 2014, a very short beach in front of the properties is observed. In 2025, this beach has increased in size, and one can observe groins and added vegetation. This suggests that some accreting trends in area 1 might be attributed to efforts from local inhabitants to combat erosion. As set out in section 1.4, these efforts are widespread, especially since erosion the Chelem area has been severe.

An area with no identifiable LRR trend is shown in Figure 3.3.

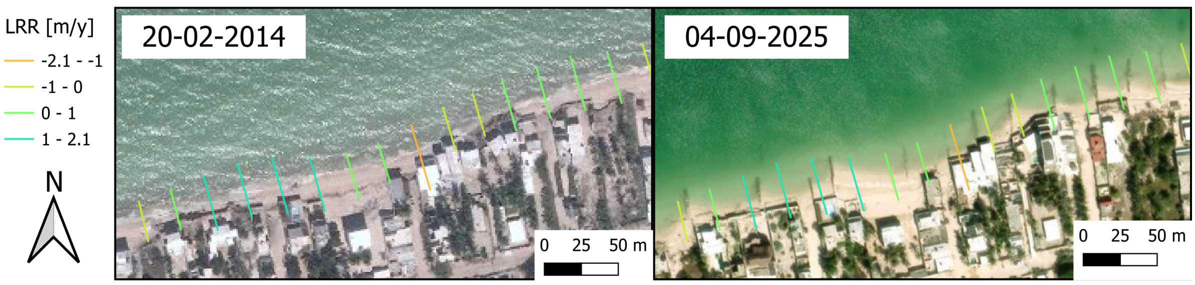


Figure 3.3: Satellite images at two timestamps of an area without a general trend in area 1

Apart from the addition of groins, the shoreline position shows no significant change between the two satellite images presented in Figure 3.3. Furthermore, it is clearly observed that in 2014, in this particular area, the beach size in front of the properties was already minimal. Similarly, observation of satellite images from the beginning of the dataset shows that, for most of the Chelem area, the beach width in front of the properties was already limited at the start of the observation period. This suggests that the shoreline was already so highly eroded at the start of the observed period, that no significant or discernible erosion occurred since.

Shoreline forecast

From historical shoreline data, forecast shoreline positions are calculated on each transect using QSCAT. For each transect, the difference between the forecasted position and the composite recent shoreline is calculated. Landward (eroding) differences are negative and seaward (accreting) differences are positive. The resulting statistics for each area are reported in Table 3.3.

Area	Average shoreline position difference [m]	Average uncertainty [m]	Percentage conclusive
Area 1	-0.52	13.74	7.3 %
Area 2	41.39	13.63	95.5 %
Area 3	-3.64	12.94	29.8 %

Table 3.3: Summary statistics of forecasted shoreline

Apart from the shoreline position difference, each forecasted point contains an uncertainty value resulting from the Kalman Filter model. This uncertainty can be seen as a band around the shoreline position. An average uncertainty for area 1 of 13.74 m thus indicates an uncertainty band for the forecasted position of 27.48 m. If the recent composite shoreline falls within this band, a forecasted shoreline position is deemed too uncertain to take into account, as a conclusion whether that position is increasing or decreasing cannot be drawn. The amount of forecasted points deemed conclusive is also reported in Table 3.3. For areas 1 and 3, this is very low, 7.3 % and 29.8 % respectively. This can be attributed to low shoreline position differences combined with high uncertainties. Within area 2, the forecast is deemed more conclusive (95.5 %). This area is visualised in Figure 3.4

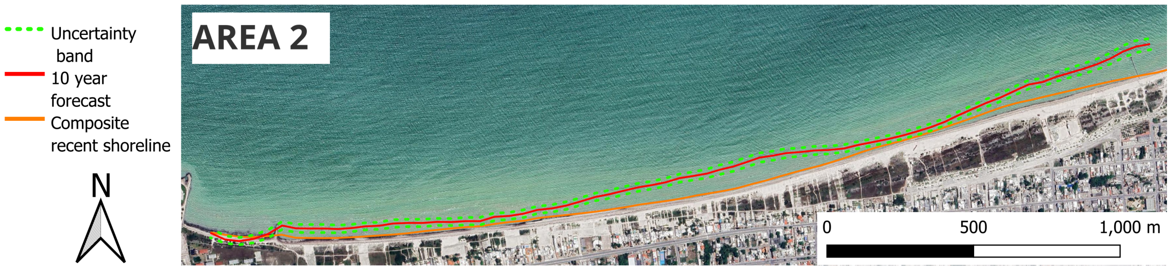


Figure 3.4: Shoreline position forecast in 10 years for area 2

3.1.2. Endangerment of beachfront situated properties

Properties vicinity to current shoreline

Using the geospatial analysis software QGIS, the severity of the erosion problem in terms of the endangerment to the houses has been analysed. This is visualised for all areas in figure Figure 3.5. In this figure, for each property, the vicinity to the most recent composite shoreline is classified from -10 to >50, with positive numbers indicating a landward orientation from the most recent composite shoreline.

Statistics regarding the property distances have been summarised in Table 3.4. Within these statistics, only properties identified with medium and high certainty have been taken into account. For all three areas, the number of properties identified with medium certainty was low compared to high certainty. Consequently, excluding or reweighting properties identified with medium certainty did not significantly affect the results.

Area	N [no. of properties]	Mean dist. [m]	Range dist. [m]	Median dist. [m]	Standard dev dist. [m]
Area 1	488	24.35	0.36 – 72.23	23.19	12.46
Area 2	192	142.52	74.37 – 259.96	121.78	59.48
Area 3	275	27.07	0.30 – 103.86	18.34	25.10

Table 3.4: Summary statistics of the current shoreline distances for the three study areas

A significant difference in property distances to shorelines between areas can be observed. In area 2, properties are generally far from the shoreline, with the lowest distance being 74.37 m and a mean distance to the shoreline of 142.52 m. On the contrary, for areas 1 and 3, the mean distances to the

Figure 3.5: Visualisation of properties distances to the most recent shoreline

shoreline are between 20 and 30 meters, with the lowest distances for both being approximately 0.30 meters. The range of distances for areas 1 and 3 is relatively high. For this research, properties with low to very low distance to the shoreline are of most interest, as these can be seen as critical. It is therefore interesting to look at the general distributions of distances in areas 1 and 3. Area 2 is disregarded, as distances to the shoreline are quite high here. The histograms of property distances for areas 1 and 3 are shown in Figure 3.6.

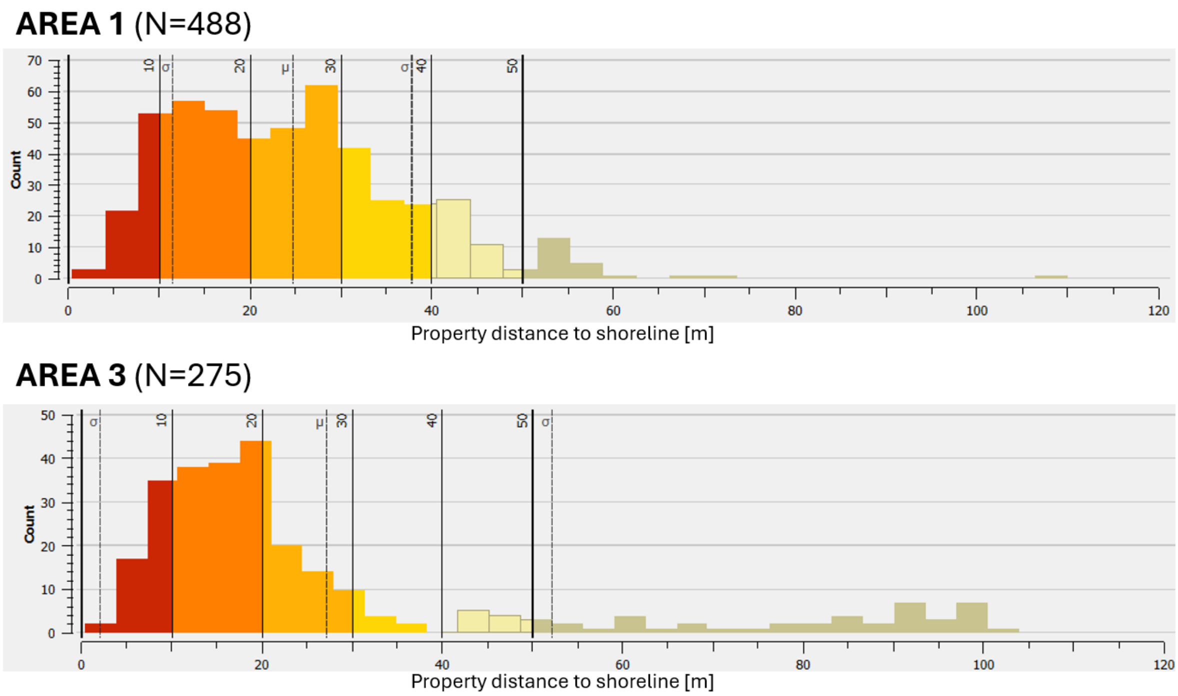


Figure 3.6: Histograms of property distances to shoreline

From Figure 3.6, it can be observed that both distributions exhibited positive skewedness, indicating that the majority of the properties are relatively close to the shoreline. In both histograms, a substantial number of properties that lie less than 10 meters from the shoreline are observed. In comparison to area 1, the histogram for area 3 has a longer tail, which results in a relatively high standard deviation of 25.10 meters and a mean value that does not capture the severity in reality. To better capture reality, the median is a more substantiated figure. For area 3, a median distance to the shoreline of 18.34 meters is reported, compared to the median distance of 23.19 meters for area 1. Percentages of properties within a certain distance of the shoreline are reported in Table 3.6.

Properties vicinity to forecasted shoreline

To get a sense of the risk of future house loss, a similar analysis is done using the forecasted shorelines, as set out in subsection 3.1.1. Statistics regarding the property distances to the forecasted shoreline have been summarised in Table 3.5. Again, only properties identified with medium and high certainty have been taken into account. It is important to note that a negative distance indicates a property situated beyond the (forecasted) shoreline, in the sea.

Area	N [no. of transects]	Mean Dist. [m]	Range Dist. [m]	Median Dist. [m]	STD Dist. [m]
Area 1	488	22.49	-10.81 – 74.68	19.99	15.25
Area 2	192	183.09	64.74 – 311.09	167.66	63.51
Area 3	255	21.47	-40.35 – 138.63	12.04	35.28

Table 3.5: Summary statistics of the forecasted shoreline distances for the three study areas

When comparing Table 3.5 to Table 3.4, a general decrease in mean and median property distance in areas 1 and 3 can be noted. The mean and median property distances increase for area 2. For all 3 areas, the range of distances widens, leading to an increased standard deviation for all.

To better account for the high uncertainty within the forecasted shoreline, amount of properties expected to lie within a certain distance of the shoreline has been calculated, rather than the absolute number of properties. As the properties in area 2 are generally too far from the shoreline to be of interest, only areas 1 and 3 are included in Table 3.6, which compares the forecasted band percentages with those of the current shoreline.

	Area 1		Area 3	
Distance threshold [m]	**Current** [% of properties]	**Forecast** [% of properties]	**Current** [% of properties]	**Forecast** [% of properties]
< 0	0.0	20.3 – 27.4	0.0	27.4 – 37.5
< 10	11.3	31.0 – 38.9	9.8	38.5 – 49.0
< 20	41.2	43.4 – 51.5	33.0	50.0 – 60.1
< 30	70.9	56.0 – 64.0	43.9	60.6 – 69.7

Table 3.6: Comparison between current and forecasted percentages of properties within given distances to the shoreline for Areas 1 and 3. Forecasted values represent 95% confidence bands.

Although the forecasted figures in Table 3.6 are too uncertain to be conclusive, they give an indication that the threat of coastal erosion to properties will increase in the future, as all forecast percentages are higher compared to the current situation.

3.2. Stakeholder analysis

This stakeholder analysis identifies key stakeholders, examines their relationships, and evaluates their relative levels of power and interest in coastal management. Together, the stakeholder network map and the power–interest diagram provide a visual overview of the governance context, revealing which actors hold authority, which are most impacted, and where gaps exist that later inform the social analysis and the proposal to work towards a solution.

Stakeholder Network Map

Figure 3.7 presents the key stakeholders involved in coastal erosion management in the study area and the relationships among them.

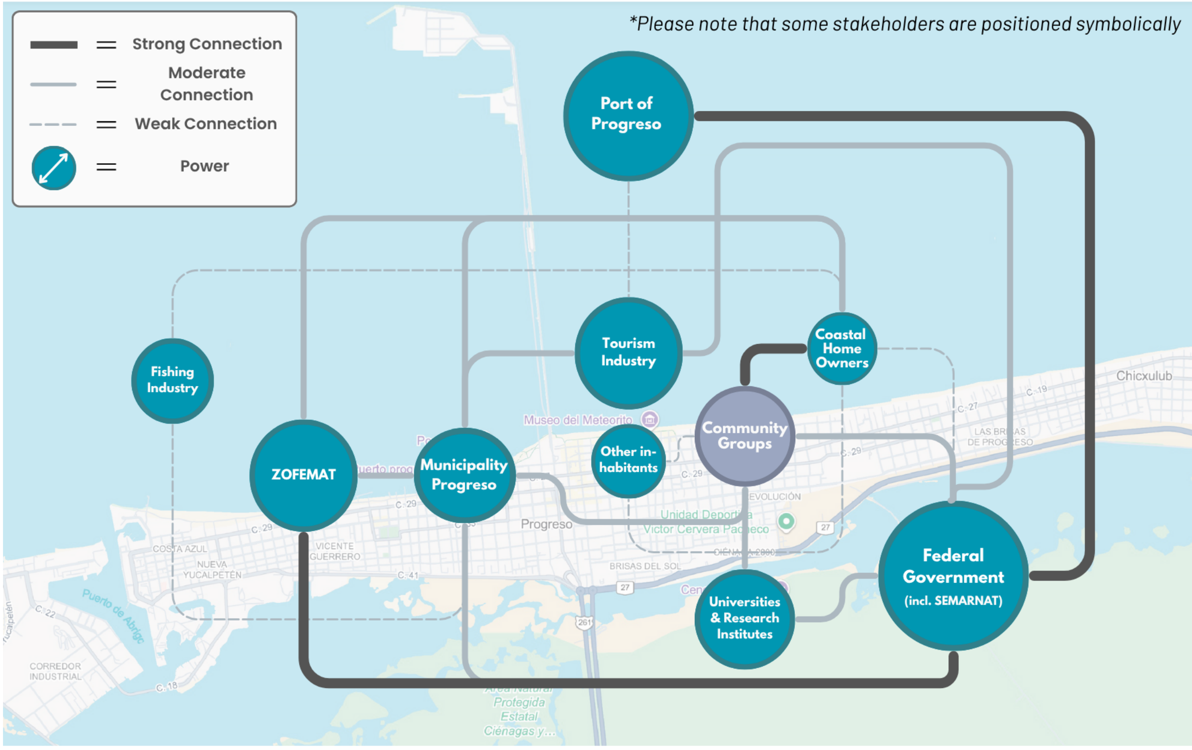


Figure 3.7: Stakeholder network map of coastal erosion in Progreso

Some stakeholders from Figure 3.7 require further elaboration. ZOFEMAT (Zona Federal Marítimo Terrestre) is a federal administrative body responsible for managing the first 20 metres of the coastal zone and collecting coastal-use fees from coastal homeowners and other zone users. ZOFEMAT is considered separately in this analysis as it represents an important actor within the socio-economic network and maintains a local office in the Progreso municipality palace (Palacio Municipal Progreso).

SEMARNAT (Secretaría de Medio Ambiente y Recursos Naturales), the federal environmental authority overseeing national environmental and coastal policies, is included under the Federal Government. The tourism and fishing industries are included as stakeholders because they are both affected by coastal erosion and can influence its severity through their activities along the coast. The state government is not shown in the figure, as coastal management is a federal responsibility divided between SEMARNAT and ZOFEMAT.

The Community Groups node refers to local citizen initiatives that have previously addressed coastal erosion issues or might do so in the future. In the study area, a community group of coastal homeowners once existed to raise awareness and advocate for erosion management, but it gradually faded as members' input did not lead to the desired outcomes (Appendix J). The node is therefore shown in grey to indicate its past or potential future relationships with other stakeholders. Comparable examples of active local environmental initiatives can still be found in the region such as Las Chelemeras, which is a women-led organization in Chelem dedicated to the conservation of mangroves (France24, 2023).

Power interest matrix

The power–interest matrix (Figure 3.8) categorises stakeholders by their relative influence (power) and engagement (interest) regarding coastal erosion in the study area, where power is shown on the y-axis and interest on the x-axis.

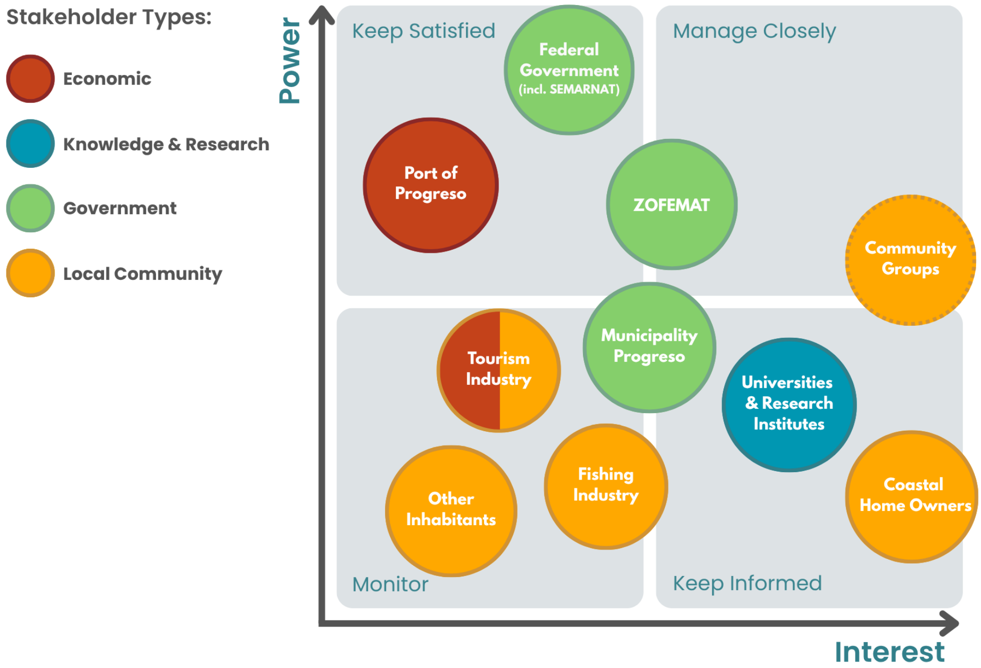


Figure 3.8: Power interest matrix of coastal erosion along the coastal area of Progreso

The diagram above contains four quadrants explained in section 2.2.The reasoning for the stakeholder positions in the diagram is as follows:

- *High Power, High Interest → Manage closely*: Stakeholders with strong influence and direct involvement in erosion management. ZOFEMAT, due to its regulatory role, and community groups, representing those most directly affected by erosion, fall near this quadrant.
- *High Power, Low Interest → Keep satisfied*: The Federal Government and the Port of Progreso hold significant authority and resources to influence coastal management but show limited day-to-day engagement with local erosion issues.
- *Low Power, High Interest → Keep informed*: Municipality Progreso, Universities & Research Institutes, and Coastal Homeowners have a strong interest in addressing erosion but lack the authority to implement large-scale measures. They are crucial for local cooperation, knowledge-sharing, and communication.
- *Low Power, Low Interest → Monitor*: The Tourism Industry, Other Inhabitants, and the Fishing Industry have limited involvement in coastal erosion management but are affected by its impacts.

Each stakeholder's position in the power–interest grid defines how they should be engaged for developing and implementing potential solutions. Stakeholders located across two quadrants represent actors whose power or interest varies depending on context, indicating that multiple engagement strategies may be applied.

Furthermore, the tourism industry is shown half yellow and half red to reflect its dual nature: while most people working in this sector are local residents, their activities are primarily economically driven.

In conclusion, through the development of a stakeholder network map and a power–interest diagram, regulatory workers, tourism industry workers, local inhabitants, and coastal homeowners were identified as the most relevant groups for further investigation through interviews and questionnaires, as discussed in section 3.3. Next to that, the analysis showed that the federal government and its institutions hold the greatest authority in coastal management, while the local community is most directly affected by erosion. This revealed a communication gap between both groups, highlighting the need for stronger coordination and collaboration in future coastal management efforts.

3.3. Social Analysis

In this section, the results of the conducted questionnaire are described using hypotheses, figures and statistics. The qualitative interviews were presented using quotes and the key findings.

3.3.1. Questionnaire

In total, 159 valid responses were collected and used in the data analysis. Four of the questionnaires had to be excluded due to incorrectly completed questionnaires, particularly among the printed ones.

Mentioned in the subsection 2.3.1, a process of coding was used to analyse the qualitative data retrieved from the questionnaire. An overview of the different labels and themes can be found in Appendix F.

General characteristics

To provide context on the demographic characteristics of the respondents of the questionnaire, an overview is presented in Figure 3.9. The results show that the largest share of respondents belongs to the group of 'coastal homeowners' (69.2%). This includes both 'owners of a holiday home on the coast' (49.7%) and 'permanent residents living on the beach' (19.5%).

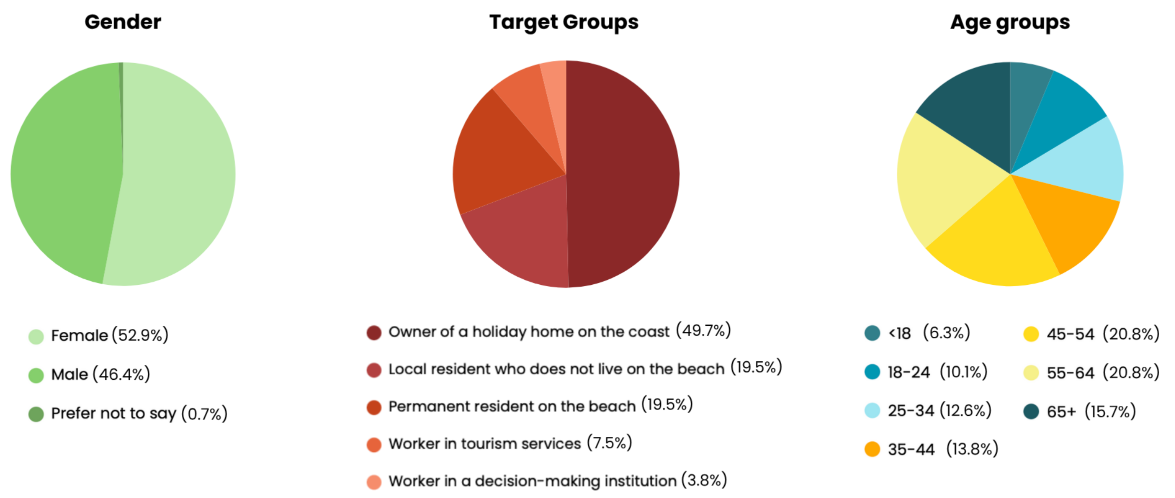


Figure 3.9: Distribution of questionnaire respondents by gender (left), target group (middle) and age group (right). Total of respondents = 159

Hypotheses

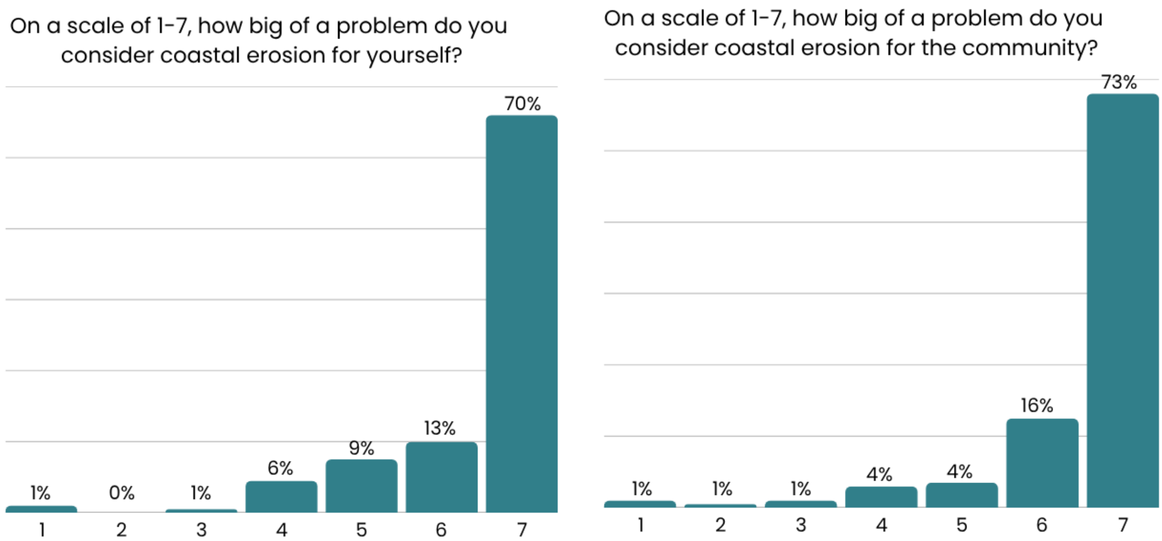
In subsection 2.3.1, a list of eight hypotheses about the study area was set up:

1. The local population perceive coastal erosion as a major problem.
2. The local population perceive the future impacts of coastal erosion pessimistically.
3. The local population is aware of the retreating coastline.
4. The local population most often perceive the pier or its expansion as the main cause of coastal erosion.
5. The local population have low levels of trust in government institutions regarding coastal erosion management.
6. The coastal homeowners do not actively collaborate with their community or neighbours to address coastal erosion.

7. The coastal homeowners see no advantages in community collaboration in tackling coastal erosion.
8. Individual erosion control measures are perceived to cause negative side effects for neighbours.

Relevance of the problem

Hypothesis 1, "The local population of the study area perceive coastal erosion as a major problem.", is tested with two questions in the questionnaire. Figure 3.10 shows how respondents evaluate the severity of coastal erosion as a problem for themselves individually and for the community. The majority identified coastal erosion as a very big problem. According to Greasly (2008), calculating the median is a more reliable measure of central tendency to show the perception of the respondents, since the data is not normally distributed, but skewed to one end of the scale, as can be seen in Figure G.2a and Figure G.1a in Appendix G. The median for both the individual perspective as the community perspective is 7.00, as can be seen in Figure G.2 and Figure G.1 in Appendix G. These results highlight that coastal erosion is widely recognised as a big problem within the study area, both in terms of impact on the wider community and on individuals' personal situations.



(a) Individual perspective

(b) Community perspective

Figure 3.10: Perceptions of coastal erosion as a problem, measured on a 1–7 scale (1=Not a problem, 7=Very big problem), for respondents themselves (Figure 3.10a) and for the community (Figure 3.10b)

Future expectations of respondents

To test hypothesis 2, "Residents perceive the future impacts of coastal erosion pessimistically", two questions were asked in the questionnaire research. Figure 3.11 shows that the majority (N=103) say to expect their living situation to be 'much worse' in ten years from now. Figure 3.12 shows that 78% of the respondents strongly agree with the statement 'Coastal erosion will seriously affect my future in Porgreso/Chicxulub/Chelem/Chuburná'. Next to that, the median is 7.00, see Figure G.3b, so the respondents strongly agree with this statement. Because the data is not normally distributed, see Figure G.3a, the median is used to show the central tendency (Greasly, 2008).

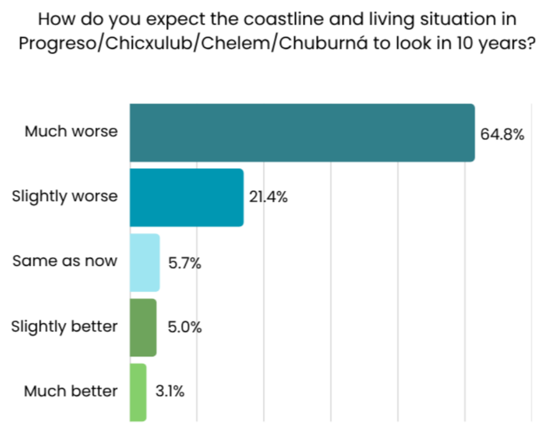


Figure 3.11: Expectations of respondents on the coastline and living situation in the study area in 10 years

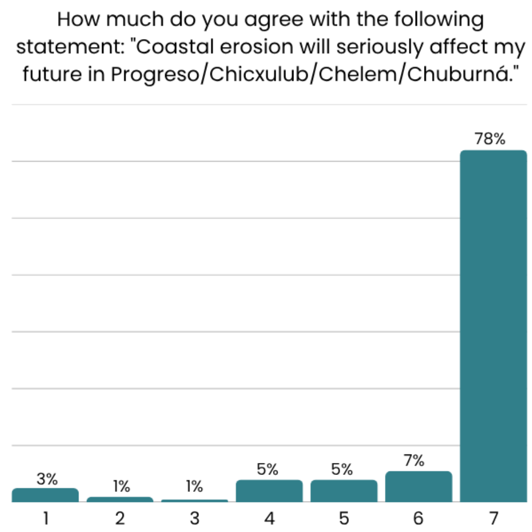


Figure 3.12: Perception on the effect of coastal erosion on people's future in the study area (1=Strongly disagree, 7=Strongly agree).

All the respondents also answered the question "In your view, what would be the most effective solutions for coastal erosion on the coast from Chicxulub to Chuburná?" The different answers are visualised in Figure 3.13. In total, 139 respondents gave a serious answer to this question, and some of them gave multiple possible solutions, which resulted in 188 possible solutions. These answers were labelled and clustered by theme, see Figure F.1.

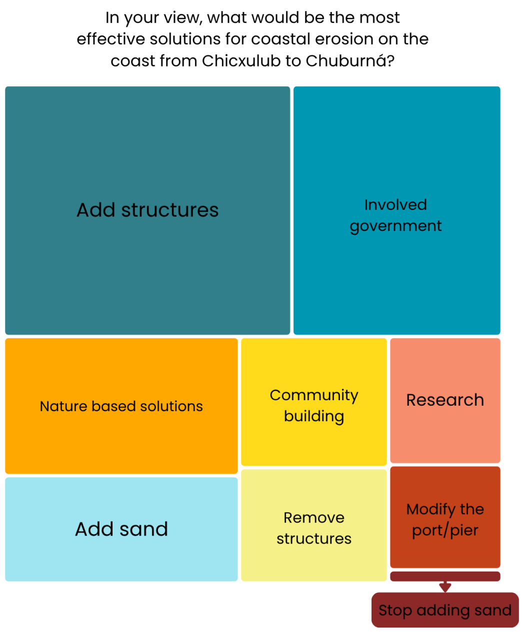


Figure 3.13: Effective solutions for the coastal erosion mentioned by the respondents

Awareness of changes along the coast

The respondents are highly aware of the changes they observe in their living area. Of all the respondents, 89.9% indicate that they have seen changes along the coastline in recent years, see Figure 3.14. These insights can be connected to hypothesis 3, "The local population of the study area is aware of the retreating coastline.". The respondents also got an option to mention which change they had noticed.

To organise all these changes, the answers were labelled and clustered in nine different themes; the labels can be found in Appendix F. The variety of these changes is shown in Figure 3.15.

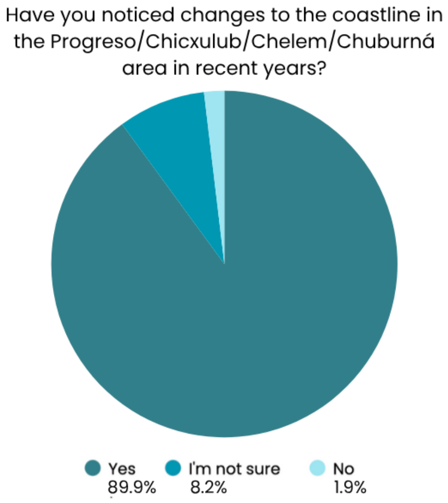


Figure 3.14: Respondents' observations of changes to the coastline in the study area

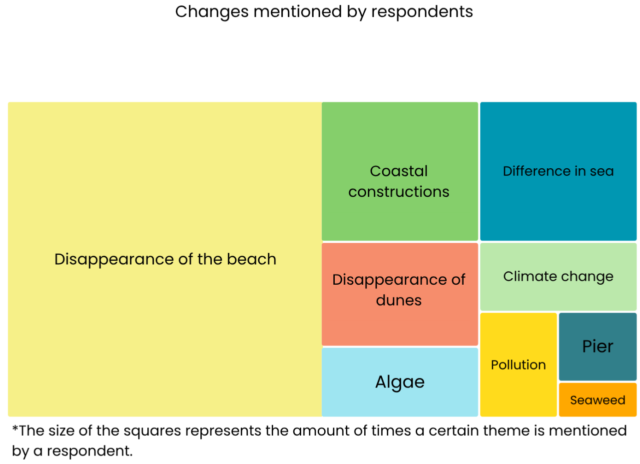


Figure 3.15: Variety in changes, mentioned by respondents. Total of 147 changes mentioned.

When comparing the answers of the respondents between the West (areas 1 and 2) and the East (area 3) from the pier about the changes observed, it is noteworthy that the percentages of beach disappearance are approximately equal in both regions, see Figure 3.16.

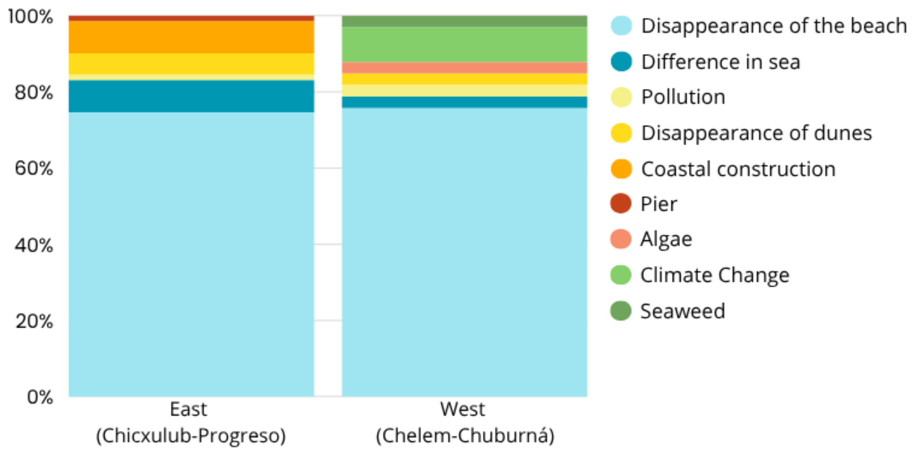


Figure 3.16: Respondents' perspective on coastal erosion, divided in their living areas: East and West of the Pier of Progreso.

Different perspectives on the (main) causes of erosion

Next to the different changes, the respondents also answered what they thought was the main cause of coastal erosion and the answers were labelled and clustered. The fourth hypothesis was that "The local population of the study area most often perceive the pier or its expansion as the main cause of coastal erosion.". As can be seen in Figure 3.18, the pier/port is mostly mentioned as the main cause, which confirms the hypothesis. However, it is remarkable that there is not one clear shared understanding among the respondents about the causes of the problems resulting from erosion.

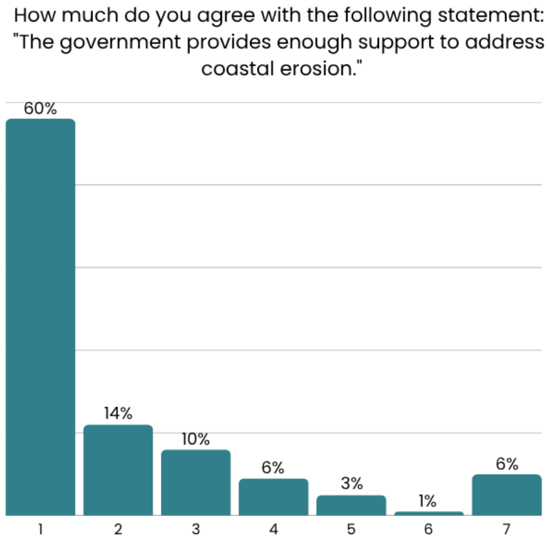


Figure 3.17: Perception of the support of the government, measured on a 1–7 scale (1 = strongly disagree, 7 = strongly agree).

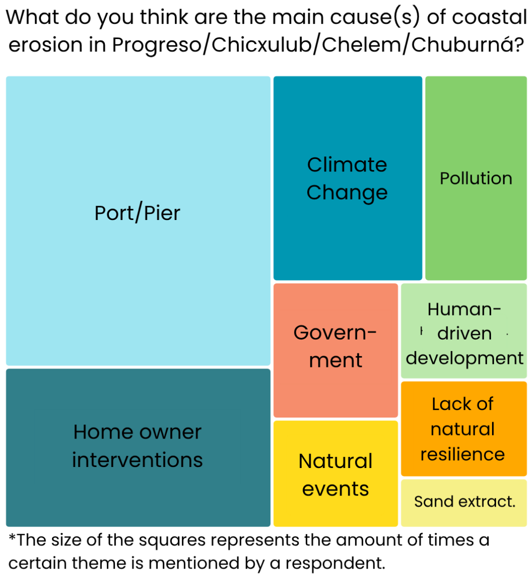


Figure 3.18: Respondents' perceptions of the main causes of coastal erosion in the study area.

Government support

Hypothesis 5 stated: "The local population of the study area have low levels of trust in government institutions regarding coastal erosion management." Figure 3.17 shows the answers of all of the respondents (N=159). As can be seen in Figure G.5, the data is not normally distributed and therefore the median is used to show the central tendency (Greasly, 2008). The median is 1.00, so the respondents strongly disagree with this statement.

Damages and measures

This subsection only includes answers from the coastal homeowners. All these coastal homeowners (N=110) answered the question "Have you experienced any damage(s) due to erosion/storms?". They had to choose between six different options, of which the results can be seen in Figure 3.19.

More than 88% of the homeowner-respondents experienced damage due to the erosion/storms. To protect their property against erosion and/or storms, 74 homeowners took measures, of which 63 respondents mentioned which measures, whereas some homeowners took several measures. The mentioned measures were labelled and sorted. In total, there are seven different measures mentioned and 75 measures have been taken, see Figure 3.20 and for the detailed list see Appendix F.

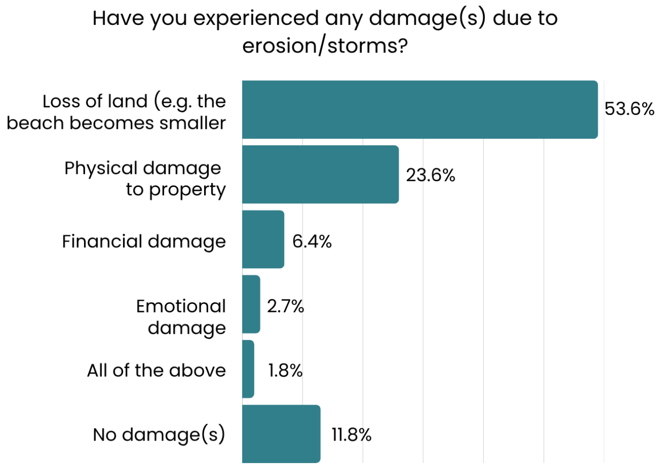


Figure 3.19: Types of damages experienced by homeowners-respondents due to erosion and storms

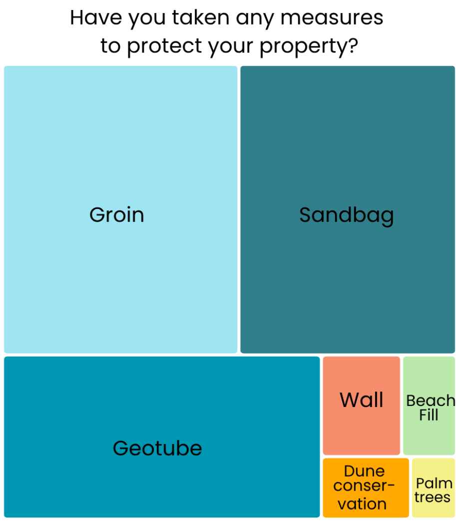


Figure 3.20: The different measures taken by homeowners

Neighbour collaboration

Hypotheses 6, 7 and 8 were about neighbours:

- The coastal homeowners of the study area do not actively collaborate with their community or neighbours to address coastal erosion. (6)
- The coastal homeowners of the study area see no advantages in community collaboration in tackling coastal erosion. (7)
- Individual erosion control measures are perceived to cause negative side effects for neighbours. (8)

It was expected that there would be no neighbour collaboration within the study area, related to the problems of coastal erosion. However, as shown in Figure 3.21, 67.3% of coastal homeowners indicated that they have taken measures to protect their property, and only 5.4% of them reported never collaborating with their neighbours. This indicates that there is indeed neighbour collaboration.

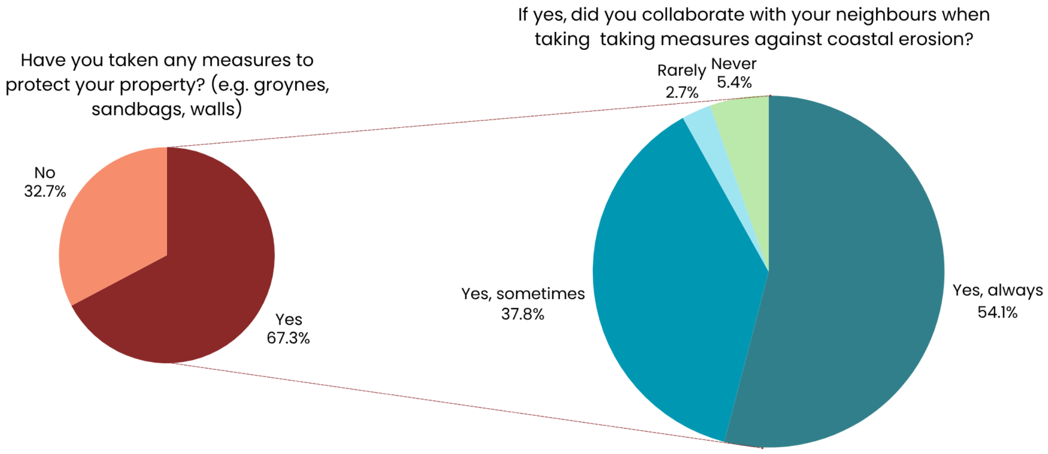


Figure 3.21: Extent of neighbour collaboration among coastal homeowners who took measures against erosion

It was also expected that respondents would not recognise the importance of community collaboration in tackling coastal erosion. However, as can be seen in Figure 3.22, 94 of the 110 coastal homeowners indicate that it is very important to work together with their neighbours for effective coastal protection. With a median of 7.0, see Figure G.3b, since the data is skewed to one end of the scale Figure G.3a (Greasly, 2008)), it can be concluded that the majority of the people in the study area think neighbour collaboration is very important for effective coastal protection.

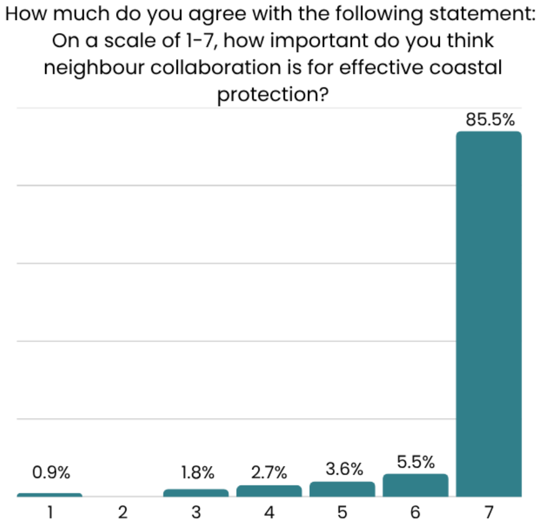


Figure 3.22: Perceived importance of neighbour collaboration for effective coastal protection (1=not important, 7=very important)

Lastly, it was also expected that measures of someone's neighbour were seen as a negative effect. After analysing the answers, it is not possible to give a significant result because only 56 people experienced effects, of which eighteen people responded that they experienced negative effects and 38 experienced positive effects.

Tested hypotheses

In the previous subsections, the hypotheses were tested, leading to the following conclusions:

One of the key findings that the questionnaire revealed was that there is a clear knowledge gap among coastal homeowners regarding the causes, effects and possible solutions to coastal erosion. This highlights the need for information sharing within the local community. In addition, many residents expressed that they do not feel supported by governmental institutions in addressing the erosion problem. Homeowners often take matters into their own hands: they implement uncoordinated measures, such as the placement of groins and sandbags, without fully understanding the broader impacts on the coastal system.

3.3.2. Qualitative interviews

A detailed overview of the collected data using semi-structured interviews can be found in Table 3.8.

Hypotheses	Conclusion
1. The local population of the study area perceive coastal erosion as a major problem.	Confirmed
2. The local population of the study area perceive the future impacts of coastal erosion pessimistically.	Confirmed
3. The local population of the study area is aware of the retreating coastline.	Confirmed
4. The local population of the study area most often perceive the pier or its expansion as the main cause of coastal erosion.	Confirmed
5. The local population of the study area have low levels of trust in government institutions regarding coastal erosion management.	Confirmed
6. The coastal homeowners of the study area do not actively collaborate with their community or neighbours to address coastal erosion.	Rejected
7. The coastal homeowners of the study area see no advantages in community collaboration in tackling coastal erosion.	Rejected
8. Individual erosion control measures are perceived to cause negative side effects for neighbours.	Undetermined

Table 3.7: Hypotheses and conclusions

#	Perspective (Focus group)	Inside/Outside study area	Date	Length	Physical/ Online	Language
1	Coastal homeowner	Inside	23 Sept 2025	∼45 min	Online	English
2	Coastal homeowner	Outside	23 Sept 2025	∼25 min	Online	English
3	Coastal homeowner	Outside	25 Sept 2025	∼30 min	Physical	English
4*	Coastal homeowner	Inside	7 Oct 2025	∼60 min	Online & Physical	Spanish

* Since this interview was conducted in Spanish with the help of a translator and the transcription tool lacked detail, the main insights are based mainly on interview notes; an overview can be found in Appendix J.

Table 3.8: Details of collected data through semi-structured interviews

Two unstructured interviews were conducted to dive deeper into the governmental side of coastal erosion within the study area. A detailed overview of the collected data using unstructured interviews can be found in Table 3.9.

#	Perspective (Focus group)	Institution	Date	Length	Physical/ Online	Language
5*	Government perspective	Civil protection office	25 Sept 2025	∼60 min	Physical	Spanish
6	Government perspective	Researcher at UNAM	8 Oct 2025	∼60 min	Physical	English

* Since this interview was conducted in Spanish with the help of a translator and the transcription tool lacked detail, the main insights are based mainly on interview notes; an overview can be found in Appendix J.

Table 3.9: Details of collected data through unstructured interviews

The interviews were conducted both in person and online, depending on the availability and preferences of the interviewees. When possible, interviews were held in English. When this was not possible, a translator was present in the interviews that were conducted in Spanish. In Appendix J, the transcripts of the interviews conducted in English and the notes from the interviews conducted in Spanish are provided.

To derive insights from the interviews, the transcriptions and interview notes are reviewed. In Appendix I, the main takeaways of the interviews are presented. A summary is given below in which quotes are added to support the results (the quotes are directly taken out of interview transcripts. Some small adjustments have been made for the readability of the quotes. However, to keep the results as realistic as possible, grammar mistakes could have occurred due to the language barrier with interviewees.)

Coastal homeowners, within the study area

Coastal homeowners are very worried about the future of their properties as indicated by interviewee #1:

- *"Since the current state of your house, what is your concern? Is there a risk of the house collapsing? - Interviewer #1. "Totally. Yes, yes, yes. Obviously, any hurricane is going to throw it away. We have remodelled it as it already endured three [hurricanes]." - Interviewee #4"*
- *"Well, although I live in Mérida, of course, it worries me a lot. It's a very, very precious asset. And we go to the beach almost every weekend." - Interviewee #4*

Furthermore, the coastal homeowners reported that they feel unsupported by the government. Interviewee #4 criticises the lack of coordination and understanding from the government, which is also recognised by Interviewee #1:

- *"Unsupported, I feel totally unsupported [by the government]." - Interviewee #1*

Homeowners have taken coastal protection into their own hands, often installing unpermitted rock or wooden groins:

- *"I'm not sure about the regulations, we are not so aware, but we know that if we put the groins, we're illegal, so we were trying to save the beach. We do it [placing groins] because if we don't do it, what are we going to do? We're going to lose our property, so that's why we do it." - Interviewee #1*

Although collaboration with neighbours occurs, organised community structures are currently lacking or have yielded undesired results in the past:

- *"No, there's not an association for that. We are just neighbours and we just get together and do these solutions. We are with about 10 houses from mine." - Interviewee #1*
- *"He recalls a 15 million-peso project intended for beach restoration, which failed because the contractor lacked coastal expertise." - Note of interview with Interviewee #4*

Interviewees recognise the ecological impacts of erosion and highlight the need for coordinated action, research, and technical guidance to develop long-term solutions with residents, experts and governmental institutions. Interviewee #4 pointed out that a substantial investment could be justified because of the economic potential of the area. Revenues from property rentals and tourism could significantly increase.

Coastal homeowners, outside of the study area

Coastal homeowners outside the study area also express distrust in the government and view coastal protection as a personal responsibility. They believe that nature-based solutions, like maintaining dunes and vegetation, are crucial for success:

- *"I think there is more culture around there to preserve the dune and the plants in the dune. And maybe if you ask me for the best solution, maybe it's not to deforest the dune." - Interviewee #2*
- *"I want to keep taking care of the dune. I hope that new dune preserves and thrives. I will keep trying to keep the uvas, which is this tree, which I like very much and helps me in a lot of ways. - Interviewee #3"*

Despite the absence of a formal organisation, they feel that existing community knowledge can enhance coastal resilience, but there is inconsistency in interaction between homeowners:

- *"We are very, very communicative here. So when somebody experiments with something good, they also try to do it with somebody else. And when a bad results happen, it [the measure] also doesn't repeat." - Interviewee #2*
- *"It's like a delicate matter, because I wouldn't be able to go and tell him, don't do that [pruning the vegetation]. Because it's his beach, it's his property." - Interviewee #3*

Governmental focused interviews

Management of coastal erosion is split among federal, state and municipal authorities, leading to fragmented efforts and low political priority:

- *"The federal government is one and the state is the other one. So in my opinion, if I think that they are paying attention to that [coastal erosion], no." - Interviewee #6*

The local community is excluded from the government in the decision-making process. Communication is lacking and there is no transparency about coastal fees that homeowners need to pay, which undermines trust and accountability:

- *"SEMERNAT or the state government or the municipality any of them doesn't have a clear list of people that has paid the fees." - Interviewee #6*

The local people expect the government, in collaboration with academia, to come up with a definitive solution for the coastal erosion problem:

- *"Years ago, I was in one workshop with the people living in front of the literal. And they, for example, asked the academy to say how long it will take for us, the academic sector, to solve the problem. So they believe that this is something like a magical solution that will be solved by hard strategies." - Interviewee #6*

Key findings - qualitative interviews

The interviews highlight a clear communication gap on two levels:

1. Among coastal homeowners themselves
2. Between coastal homeowners and governmental institutions

Among coastal homeowners, communication differs strongly per area: some of the homeowners highlight never speaking with their neighbours on the topic of coastal erosion, while others highlight the open conversations and their valuable outcomes. The inconsistency in interaction between homeowners limits the potential for collective action to address the problems related to coastal erosion.

In addition, a gap exists between governmental institutions and local homeowners. Homeowners report that they do not feel supported by the government, as already mentioned in subsection 3.3.1 and confirmed by the qualitative interviews. Although coastal homeowners pay a fee to the federal government (ZOFEMAT), they report not seeing the money being used for coastal management: the residents feel like coastal erosion is not on the priority list of the institutions.

Besides the communication gaps, the interviews also strengthen the need for information sharing, identified in subsection 3.3.1. Thus, there is a knowledge gap, which results in individual approaches by coastal homeowners in addressing their problems and misaligned expectations on solution-finding.

Lastly, responsibilities within the government and involved institutions are fragmented. There is a division of these responsibilities between federal, state and municipal levels. However, any form of structured approach within these levels is lacking. This results in confusion, conflicting interests and inefficiency in addressing coastal erosion in the study area.

3.4. Concept Generation

In this section, the various steps taken for generating concepts are explained. First, the six remaining concepts after applying the PMI-method are briefly described, followed by the results from the multi-criteria method.

3.4.1. PMI-method

To come up with concepts for accreting sand, different concepts were discussed. The extended result of the brainstorm and the following PMI-method is included in Appendix K. After reviewing all the pluses and minuses, six concepts were eliminated based on the practicality of research and four based on the feasibility of implementation. This resulted in six remaining concepts, which are presented below.

subsubsection*1. Sandsaver The Sandsaver is a modular structure made from durable polyethylene, designed to combat coastal erosion by reducing wave energy and promoting natural sand accumulation. Each unit is contains hollow, tapering channels, with the smaller openings facing landward to encourage sand deposition. Installation is straightforward as the modules are lightweight and can be locally filled with heavier material to ensure stability once in place (“Beach Erosion Solution | SandsaverTM”, n.d.).

Figure 3.23: Sandsaver on a beach in Kenya (Molding, n.d.)

Figure 3.24: Beach nourishment device (Ehardt, 2007)

2. Direct sand suppletion

Direct sand suppletion can be carried out through land-based supply, where sand is transported by trucks, or via water-based supply, in which dredgers pump sand directly onto the shore using floating pipelines. In the study area, supply by boat may be challenging due to the shallow water depth. Nearshore dredging might be viable if enough sediment is present.

3. Traditional groin field

Traditional groins are made of rocks and timber, placed perpendicular to the shore. If incorrectly spaced, they intensify erosion by interrupting alongshore sediment transport (Appendini et al., 2012). Torres-Freyermuth et al. (2020) concluded that low-crested, permeable groins allow partial sediment bypass and overtopping to temper downdrift impact. When properly designed, they can produce net beach accretion. The properties of these permeable groins can be mimicked by selecting local rocks providing similar permeability.

Figure 3.25: Traditional groin field (Photo by author (2025))

Figure 3.26: Large scale groin in Chelem (Google Earth, 2025)

4. Large-scale groin

A large-scale groin is a significant and permanent structure designed to disrupt longshore sediment transport and encourage sand accumulation on its updrift side. An example of this is the two large-scale groins located in Chelem, in the west of the Yucalpetén harbour, see Figure 3.26. The primary objective of a large-scale groin is to accumulate sand over an extended period across a large section of the shoreline.

5. Beach drainage system

Beach drainage is a coastal management technique that uses buried perforated pipes and pumps to lower the groundwater level in the upper part of the beach. By draining excess water from the sand, the beach surface becomes drier and more stable, allowing waves to deposit more sand instead of washing it away. Over time, this can help build up the upper beach and reduce erosion near the dunes (Bain et al., 2016).

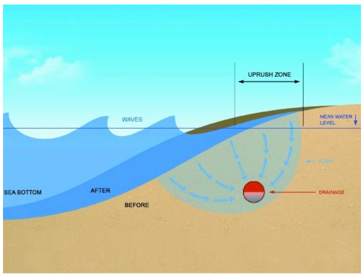


Figure 3.27: Illustration of beach drainage system (Thibout, n.d.)

Figure 3.28: Artificial reef blocks (Yarrow, 2016)

6. Nearshore artificial reef

Artificial reefs are structures made of rock that sit near the shore, often partway down the beach. They can be long, continuous formations or a series of smaller reefs along the coastline. These reefs are usually underwater for part of the tidal cycle, which makes them less noticeable on the beach. They also help increase biodiversity by forming new habitats in the intertidal zone, which can support various types of marine life.

3.4.2. Multi-criteria Analysis

Explanation of criteria

To ensure a clear and systematic evaluation, the criteria were designed to be *mutually exclusive and collectively exhaustive (MECE)*. This means that each criterion captures a distinct aspect of performance, while together they comprehensively represent all relevant dimensions of decision-making. The following criteria were used, their weight ranging from 1 to 5 for each criterion, as shown in brackets:

- *Effectiveness (5)* evaluates how successful the proposed measure could be in achieving sand accumulation over time and in quantity. It was given the highest weight, as effectiveness is the primary condition for any intervention to be considered successful.
- *Implementability (4)* considers the ease with which the measure can be applied under local conditions. This includes the availability of technical expertise, equipment and materials required for installation. It was assigned a high weight, since even the most effective solutions are irrelevant if they cannot be implemented in practice.
- *Downstream effect (4)* takes into account the possible negative effects downstream of taking a measure, for example, loss of land. It was given a high weight because a solution for an erosion problem in one area cannot cause an erosion problem in another.
- *Social acceptance (3)* assesses the support or resistance of the local community and relevant stakeholders based on previous social analysis. It was assigned a moderate weight, as lack of acceptance by the local community may lead to resistance and hinder successful implementation. Moreover, a lack of acceptance would also require increased supervision by the government, which social analysis has shown to be currently lacking.
- *Affordability (2)* assesses the overall cost-effectiveness of the measure. It was assigned a low weight, while cost is important, higher expenses may be justified if the measure ensures long-term stability.
- *Environmental impact (2)* measures the effect of the proposed measure on natural systems and biodiversity. It was assigned a lower weight, as a positive environmental impact is considered an added benefit rather than a primary objective in the current context. Moreover, additional beach creation and dune forming are already a positive ecological development.
- *Maintenance (2)* considers the amount of time and money it takes to keep the measure functional.

It received a lower score, as maintenance challenges are generally considered manageable compared to the initial priorities of effectiveness and implementability.

Weights of the criteria

The completed MCA is shown in Table 3.10. A conclusion based on these results is presented in the text below the table. The motivation behind the assigned scores can be found in Appendix L.

Criterion	Weight	Sandsaver	Direct sand suppletion	Groin field	Beach drainage system	Large-scale groin	Nearshore artificial reef
Effectiveness	5	3	2	3	1	3	1
Implementability	4	3	2	3	1	2	2
Downstream Effect	4	3	3	2	3	1	3
Social Acceptance	3	1	3	2	2	1	2
Affordability	2	2	1	2	1	2	1
Environmental Impact	2	1	1	2	1	2	3
Maintenance	2	3	1	2	1	2	3
	Total	54	45	53	33	42	45

Table 3.10: Multicriteria Analysis for beach accretion

MCA evaluation

The clear 'winners' in the MCA are the *Sandsaver* and the *groin field*, followed by *direct sand suppletion* and the *nearshore artificial reef*, which share third place. The relatively high scores of the first two solutions are mainly driven by their effectiveness and ease of implementation. For this case study, the Sandsaver is selected as the best physical solution. This is because its relatively new and innovative nature makes it a promising technology that may well be worth the risk to explore.

3.5. Integration of Analyses

In this section, the results of different analyses are coupled.

In conformation with previous studies and own observations detailed in section 1.4, the shoreline analysis revealed that erosion in most of the study area has reached a critical point. Area 3 shows a general eroding trend, and Figure 3.2 & Figure 3.3 confirm an already highly eroded shoreline in area 1 at the start of the used data. The current shoreline position poses a major threat to nearshore properties, with over half of the properties lying within 20 meters of the shoreline, as explained in subsection 3.1.2. This critical situation is confirmed by the social analysis, in which it was shown that the community perceive coastal erosion as a major problem, observed in Figure 3.10. 23.6% of homeowners even reported damages due to storms/erosion. Both the social and shoreline analysis foresee a pessimistic future, highlighted by Figure 3.11 and Table 3.5, as the threats and damages resulting from coastal erosion are expected to worsen in the coming years.

The stakeholder analysis and the qualitative interviews revealed fragmented and unclear responsibilities across governmental levels. At the same time, the results of the questionnaire showed that most residents perceive government support as lacking, shown in Figure 3.17. Furthermore the qualitative interviews reveal a communication gap between governmental institutions and local homeowners. Interestingly,Figure 3.22 showed that, according to local residents, neighbour collaboration is highly important for effective coastal protection. These findings reveal an insufficient hollistic approach regarding coastal resilience that combines all stakeholders.

Previous studies, discussed in section 1.4, concluded that the shoreline in the study area is extremely sensitive to littoral barriers, such as groins. This is supported by the high variation in shoreline change rates between and within the area, as set out in (subsection 3.1.1, suggesting a significant influence of small-scale man-made structures. Figure 3.20 however, reveals that groins, sandbags and geotubes are the most common mitigation measures taken by homeowners. Additionally, Figure 3.13 shows a high variety of the most effective mitigation measures proposed by local inhabitants. This reveals a lack of knowledge among local inhabitants about the effectiveness and consequences of implemented mitigation measures.

The three different analyses combine into a clear picture: coastal erosion poses a threat to the people and properties in the study area and current mitigation measures are ineffective and fragmented. Results of the social and stakeholder analysis furthermore highlight an insufficient holistic approach combining all stakeholders, and a lack of knowledge among stakeholders regarding causes and effective measures.

4
Proposal

Previous research showed various challenges in addressing coastal erosion problems within the study area. In section section 3.1, an urgent need for short-term erosion mitigation and sand accretion actions in the majority of the study area is highlighted. From the social analysis (section 3.3), it became clear that there is a need for a holistic view and integrated strategies to bridge the gap between local communities and governmental institutions. In addition, informing and educating local residents seems to be crucial for addressing coastal problems effectively.

Interviews further revealed that physical measures alone are unlikely to succeed without the involvement and support of local stakeholders, highlighting the importance of a social perspective when working towards a potential solution. Social acceptance and inclusion are therefore key to ensuring both the effectiveness and long-term sustainability of any physical measure in this context.

This chapter presents a proposal for both a social strategy and a physical measure, as well as the integration of both. These proposals are based on a future vision that serves as a framework for potential solutions. This future vision was based on field visits and results of the social analysis.

Future vision

In section 3.5 it was shown that to implement any technical matters, social acceptance is critical. Therefore, the defined future vision includes two components: *active community involvement* is essential and *physical measures* need to be taken to move towards the ideal situation. The future vision is defined as follows:

"In 2037, the coastline in Progreso, Chelem and Chicxulub has become a resilient landscape, shaped and cared for by a community where residents and institutions work together in transparency and shared responsibility to protect the coast."

Since physical actions can only be taken while being socially supported, the focus of reaching the ideal situation should first be on implementing a social strategy. This part is elaborated on in section 4.1.

To reach the ideal situation, two different goals need to be addressed, as mentioned in section 2.4, when taking physical measures: first, stimulate sand accretion and second, retain the accumulated sand to enable dune forming. To work towards the future vision, it is important to focus on testing possible physical measures, after which evidence-based decisions can be made on the later implementation.

For both goals (sand accretion & sand retention), a proposal is made in section 4.2.

The pathway towards the ideal situation is therefore divided into 3 different phases, as can be seen in Figure 4.1.

It needs to be highlighted that the proposals suggested in this chapter do not aim to provide a complete solution to the broader coastal erosion problem within the study area, since this is not feasible and realistic in this project. The focus is therefore on the first two phases of the pathway.

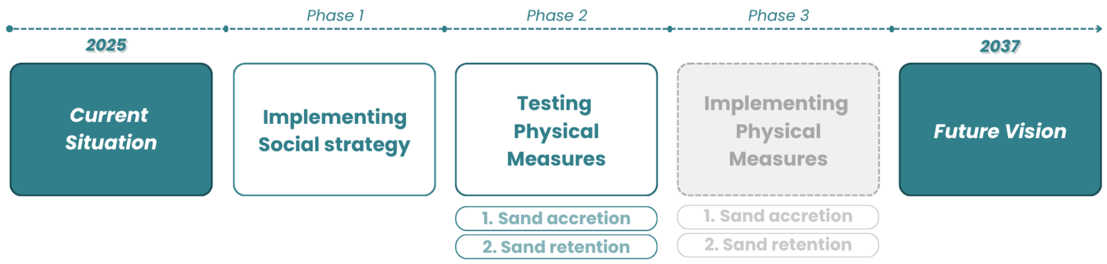


Figure 4.1: Pathway towards the future vision divided in three phases. For this project, the focus is set on the first two phases.

4.1. Proposed Social Strategy

The first step in working towards the future vision is focused on developing a social strategy. In subsection 3.3.1 and subsection 3.3.2, it was shown that two gaps were identified and revealed a fragmentation of responsibilities among governmental institutions. A communication gap exists both among coastal homeowners themselves and between coastal homeowners and governmental institutions. There is a knowledge gap due to the need for knowledge sharing among coastal homeowners.

This social implementation strategy aims to address these challenges by improving communication both among homeowners and between homeowners and government actors and by strengthening knowledge exchange between coastal homeowners, academia, and governmental institutions.

This scope is determined based on priorities and feasibility regarding the time and resources of this project. Internal communication and functioning of governmental institutions to improve the fragmentation of responsibilities, while important, fall outside the scope of this proposal. Nevertheless, recommendations for improving institutional coordination and policy effectiveness are discussed in chapter 6.

Relevant case studies from other coastal areas

The challenges identified in this research are not unique to the study area in Progreso but have been faced and examined in many coastal regions around the world. In these case studies similar coastal management issues were observed.

Olsen (2003) highlights the case of Xcalak in Quintana Roo, Mexico. Rapid tourism expansion and declining marine biodiversity revealed the limitations of existing coastal governance structures. The involvement of an NGO in community-based coastal governance helped raise awareness of ecological risks among governmental institutions. This ultimately led to the creation of a national marine park. This case demonstrates how NGOs can serve as effective bridging actors to encourage governmental engagement in local coastal issues.

Comparable findings are reported in Algoa Bay, South Africa. This case study examined how integrated coastal management can enhance climate resilience in area exposed to erosion. Collaboration between research institutes, NGOs and government agencies strengthened coordination and knowledge exchange across governance levels (Rölfer et al., 2024). It demonstrates how fragmented and uncoordinated institutional responsibility of coastal risks can be addressed through collaboration between multiple actors.

In a case study in Cádiz Bay, Spain where a systematic assessment approach was developed to evaluate stakeholder participation in coastal zone management. Cioffi et al. (2024) showed that key barriers to effective social barriers were limited stakeholder inclusion and unequal power dynamics. Their study reinforces the importance of transparent and participatory processes in decision-making.

Together, these cases demonstrate that bridging organisations can connect local knowledge, scientific expertise and institutional authority, leading to more effective governance processes. Applying such approaches in the study area could similarly help raise awareness among federal authorities and start bridging the earlier identified gaps. These insights form the foundation for the need to develop a coastal management framework that is both effective and durable. Based on this, the establishment of a Coastal Community Committee (CCC - Comité de la Comunidad Costera) in the study area is proposed. This committee would serve as a structured platform where key stakeholders meet regularly to discuss coastal erosion, evaluate its impacts, and develop appropriate solutions.

4.1.1. Coastal Community Committee

The Coastal Community Committee (CCC) is a proposed group that makes decisions regarding coastal resilience. It also informs and involves local residents and relevant stakeholders. In this section, the composition, tasks and implementation of the committee will be described.

Insights of a qualitative interview on governance and coastal erosion (interviewee #6) revealed diverse perspectives among coastal-related sectors, highlighting a key obstacle to effective coastal management. For instance, the tourism sector may seek to remove dune vegetation to facilitate recreational activities, whereas the environmental sector aims to preserve it for protection against natural events.

Therefore, the CCC will follow the principles of Integrated Coastal Management (ICM). This approach promotes coordination across sectors and administrative levels and encourages the inclusion of representatives from all coastal-related sectors, such as tourism, fisheries, and environmental management (Bowen & Riley, 2003; Cicin-Sain, 1993).

Composition of CCC

The CCC brings together those who are most affected by coastal change, those who hold decision-making authority, and those who can bridge the knowledge and communication gaps. Its composition and tasks are described below. An overview of the CCC can be found in Figure 4.2.

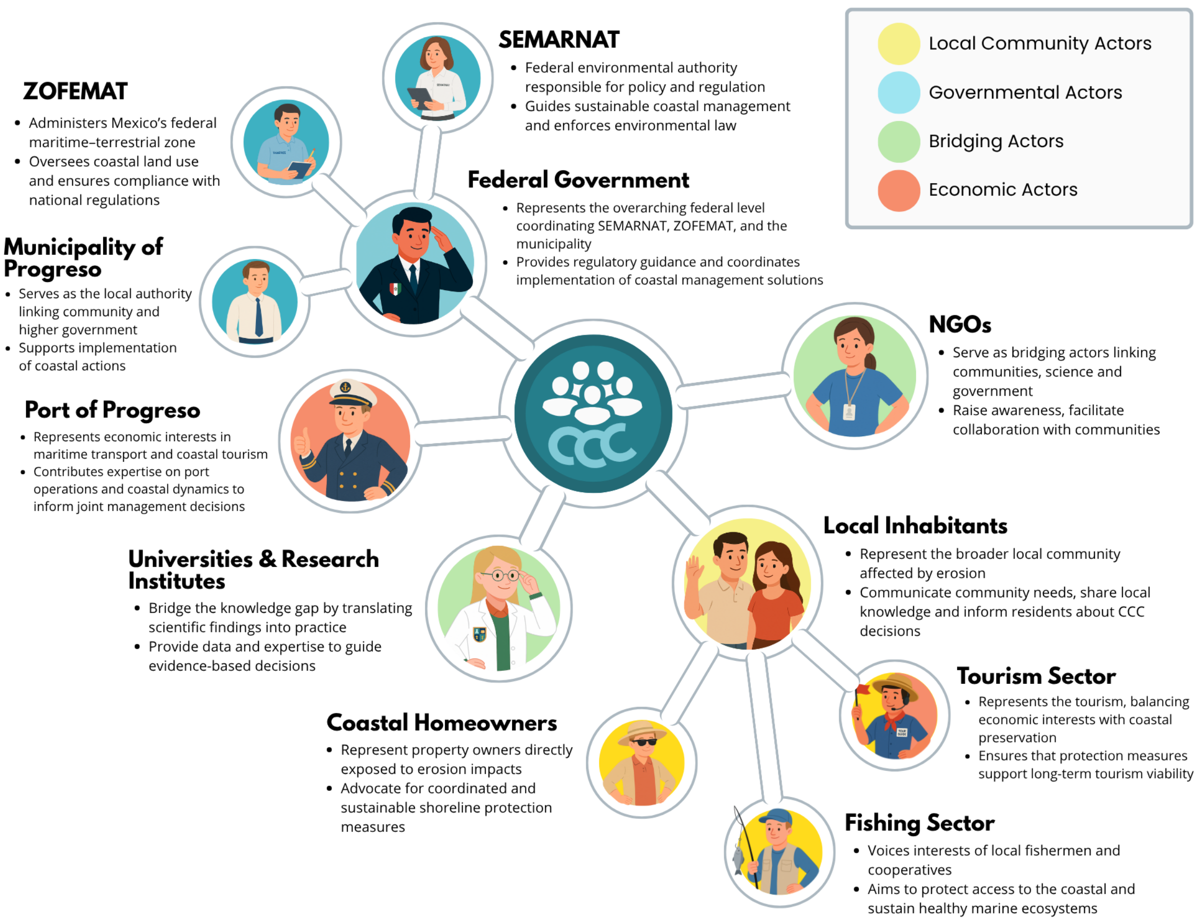


Figure 4.2: Composition and roles of the Coastal Community Committee

Local Community Actors
The local community is most directly affected by coastal erosion. Coastal homeowners face property loss and tourism workers depend on beaches that are steadily disappearing. Including these groups is essential for ensuring social acceptance of coastal management measures and marks the first step toward bridging existing communication and knowledge gaps between residents, institutions, and experts.

Governmental Actors
In this context, the most powerful stakeholders are also the actors most responsible for coastal management. These actors hold the authority and resources needed to coordinate systematic measures and enforce regulations. At the national level, the Federal Government provides the overall structure for coastal governance and coordination between institutions. Within this structure, SEMARNAT oversees environmental policy and ensures that coastal measures follow national environmental rules. ZOFEMAT oversees land use within the federally owned coastal strip and regulates permits for activities or developments in this zone. At the local level, the Municipality of Progreso supports coastal measures and forms the first connection between the local community and the government. The governmental actors should be part of the CCC to ensure that the CCC's actions align with existing laws and can be implemented effectively. Moreover, their involvement helps ensure that coastal erosion remains a recognized priority across governmental policies and decision-making processes.

Economic Actors
The port of Progreso is the main economic stakeholder in the study area, supporting both maritime transport and coastal tourism. Its infrastructure affects local sediment dynamics while also being impacted by erosion through reduced tourism. During a field visit, it was noted that the port plans to expand in the near future. As stated in section 1.4, the earlier expansion of the pier intensified coastal erosion, suggesting that any further extension is likely to aggravate erosion once more. Including the port in the CCC therefore ensures that economic interests are represented while also allowing space for discussion and negotiation to mitigate or counteract the potential negative effects of the expansion. The port's technical expertise can further help develop erosion strategies that balance economic activity and environmental sustainability.

In addition, the tourism sector has a dual role in the composition of the CCC. As shown earlier in the power–interest diagram (Figure 3.8), it is characterised as being partly within the local community and partly economically driven. Most people working in tourism are local residents, but the industry itself is primarily motivated by economic interests. Including this sector in the CCC ensures that tourism activities support, rather than harm, long-term coastal sustainability.

Bridging actors
Universities, research institutes, and NGOs should form part of the CCC as bridging actors that connect local communities, institutions, and decision-makers. Their involvement promotes a more horizontal and shared decision-making structure. This is consistent with the principles of polycentric governance, which are based on the effectiveness of multi-actor decision making by distributing both knowledge and authority among multiple stakeholders (Rölfer et al., 2024). Universities and research institutes act as knowledge-bridging actors, translating scientific findings into practice and providing the data and expertise needed to guide evidence-based decisions. NGOs, on the other hand, function as communication-bridging actors, helping to translate local concerns into policy discussions and vice versa. Furthermore, they can help raise awareness about coastal challenges among communities, industries, and institutions (Olsen, 2003). Through these roles, bridging actors strengthen cooperation, improve knowledge exchange, and enhance the ability of all stakeholders to actively participate in coastal governance (Wang, 2024).

Previous studies by Ariza et al. (2014), Cioffi et al. (2024), Li et al. (2025), Rölfer et al. (2024), and Wang (2024) show that committees with similar structures address the gaps identified before by creating a balanced and representative form that can build trust, improve coordination and efficiency, and strengthen long-term collaboration.

Tasks of CCC

The main functions of the CCC will be to make decisions regarding coastal resilience by acting as an integrated platform that brings together multiple stakeholders and facilitates a holistic and collaborative approach to coastal management. They will facilitate dialogue and establish a clear communication channel between institutions and the community. They should also provide oversight of proposed measures to guarantee that both technical feasibility and social acceptance are taken into account.

In order to achieve this, several tasks have been set up. An overview of these tasks is visible in Figure 4.3

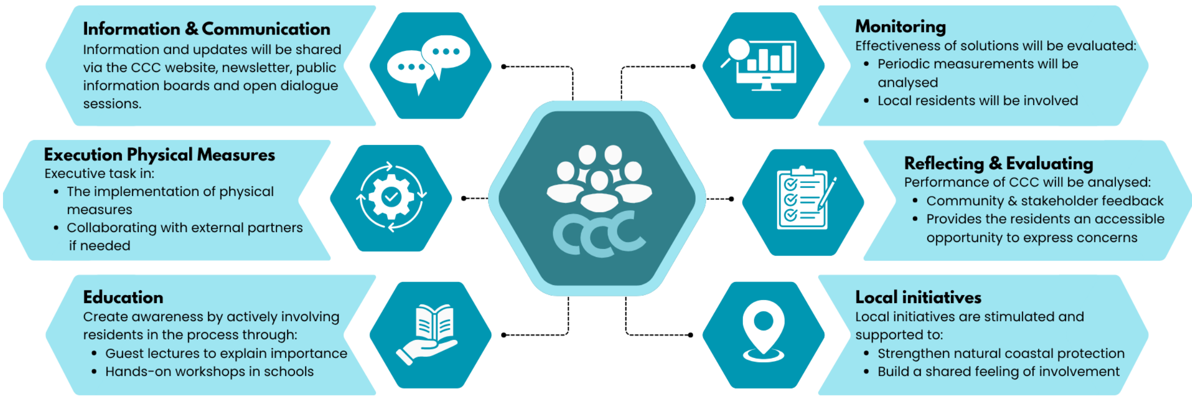


Figure 4.3: Tasks Coastal Community Committee

Information & Communication

The committee functions as a bridge between complex findings from science and decisions in politics and the everyday life of residents. They will have to translate these findings and decisions into accessible and understandable information. Based on subsection 3.3.2 and field research, multiple channels for the provision of communication and information are determined.

Execution Physical Measures

The CCC decides when a new physical measure should be implemented. Within the committee there is sufficient technical expertise in order to assess which measures are feasible. To actually design and produce the measure, an external partner needs to be involved. The CCC is responsible for selecting and supervising the external partner and guaranteeing the deliverable meets the intended objectives.

Education

In schools, guest lectures will be given by the CCC to explain what they do and why the prevention of coastal erosion is important to the students. In addition, hands-on workshops will be organised. For example, conducting small-scale experiments to demonstrate the influence of vegetation on coastal resilience or planting vegetation together. Similar workshops and community events will be organised to educate residents of all ages. Tran (2006) showed that including residents in addressing coastal pollution improved their environmental awareness and the underlying issues. By combining education with active participation, it is ensured that knowledge is created and through education, dialogue and action.

Monitoring

Monitoring the progress, both on a social and on a physical scale, is necessary to evaluate the effectiveness of coastal management. It is important to keep on monitoring the progress. The CCC will be responsible for performing periodic measurements in collaboration with NGO's and Universities. In this monitoring process, the local residents can be involved as well. This not only helps in creating awareness but can also lower the expenses of the CCC. According to Konig (2017), in the long term, the local community gain a better position in participation with government agencies in the decision-making process when the monitoring is done community-based.

Reflecting & Evaluating
The performance of the CCC will be monitored frequently with community and stakeholder feedback. This allows the CCC to reevaluate the functioning of the committee and what aspects can be improved. Moreover, it provides the residents with an accessible opportunity to express their agreement or concerns regarding the committee's actions and the overall direction of coastal management efforts.

Local Initiatives
Finally, the CCC will stimulate and initiate local initiatives. Local residents can set up initiatives, for example, to clean the beaches or plant new vegetation; the CCC will provide guidance.

4.1.2. Roadmap for the formation of the CCC

The composition and tasks described in Figure 4.1.1 and subsection 4.1.1 visualise the fully operating version of the committee as described in the future vision. However, it takes time to form such a structure. Some necessary steps need to be taken.

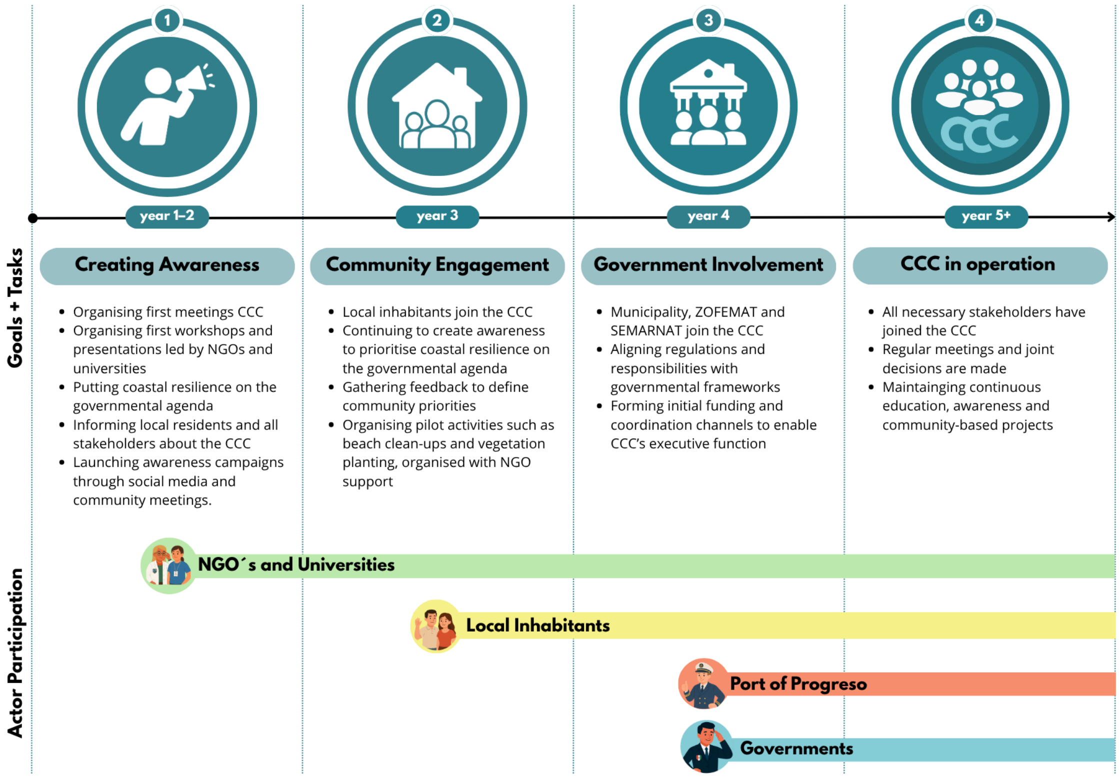


Figure 4.4: Roadmap towards final formation of the CCC divided into four phases

The formation is described in four phases as can be seen in Figure 4.4. In the first phase, the focus will be on creating awareness and putting coastal resilience on the governmental agenda. NGO's and Universities will play an important role in facilitating conversations. Together, they form the foundation of the CCC. At the same time, awareness will be created among local residents and all stakeholders to inform them about the CCC and their potential participation.

In the second phase, local residents will actively join the CCC. Through feedback sessions and pilot activities, the priorities of the community will be defined. This is to create shared ownership and responsibility for addressing the problems. In this phase, it is still important to keep raising awareness for the importance of coastal resilience at governmental institutions.

After creating awareness in the first two phases, the third phase is focused on involving the governmental institutions in the CCC. Roles and regulations are aligned within the committee to be able to work effectively between communities and authorities.

The final phase is reached when all members have joined the CCC and the entire community and all stakeholders know what the working mechanism is. In addition, awareness has been established and will remain current. The CCC will take the responsibility to make decisions.

4.2. Proposed Physical Measures

To achieve the desired dune landscape outlined in the future vision, two crucial steps must be implemented: sand accretion and sand retention. This section explains the proposed physical measures that will be employed, including the use of the Sandsaver and techniques for dune forming.

4.2.1. Sandsaver

As set out in section 3.4, the Sandsaver is a modular structure designed to combat coastal erosion. It works by reducing wave energy and enhancing sand accumulation. The modules are partially hollow, with larger openings on the seaward face compared to the landward face. When waves break upon the modules, water with suspended sand flows through these openings. Due to the difference in opening size, the flow velocity increases when water flows through the holes. As a result of a higher flow velocity, the sand particles remain suspended longer and are carried further op the beach. Additionally, the larger openings on the landward side decrease the sediment carried away in the backwash wave (“Beach Erosion Solution | SandsaverTM”, n.d.).

A detailed analysis of the environmental conditions on a local scale at the site of the case study is necessary for a valid technical design. This detailed analysis is not within the scope of this study; hence, an indication is for the feasibility of the SandSaver and the prerequisites needed for successful implementation are given. These are integrated within an implementation plan along with a monitoring framework.

Sandsaver feasibility

An indication of the feasibility of the Sandsaver solution at the case study site is determined by comparing the area’s environmental condition to the environmental conditions of reference projects with successful implementation of the Sandsaver. The following reference projects are used:

- **Diani Beach (Kenya):** Environmental Impact Assessment and monitoring report of an operational Sandsaver installation along a Swahili Beach Resort frontage (Limited, 2020).
- **Lake Michigan (Camp Arcadia, USA):** Field monitoring report of a SandGrabber (Sandsaver predecessor) installation conducted by local consultants (Land & Water Consulting, 2013). This report provides little information on environmental conditions; the Great Lake Observing System (GLOS) has been used to obtain supplementary information.
- **Wailua Beach (Hawai‘i, USA):** University of Hawai‘i technical study evaluating theoretical Sandsaver performance through numerical modelling (Hataishi, 2022). It is important to note that this is a modelling exercise rather than in-situ observations of Sandsaver effects. This study is regarded as less reliable compared to the other two studies.

Since the Sandsavers’ working principle is based on wave characteristics and sediment transport, these are reported for comparison to the reference projects.

Parameter	Reference projects			Case study site
	Diani Beach	Lake Michigan	Wailua Beach	Chelem (Progreso)
Erosion trend before Sandsaver [m/yr]	-4.4	-0.53	-0.15	-0.9
Length of beach area [m]	103.5	183	640	200
Average significant wave height H_s [m]	1.0	0.5 – 1.0	1.5	0.7
Average Peak period T_p [s]	8–10	3–5	6–8	4.3
Dominant sediment transport	Longshore (N↔S)	Cross-shore	longshore	Longshore (E→W)
Accretion gain	0.065 m^3/day	0.02 m^3/day	9.2%/day	–

Table 4.1: Comparison of key environmental parameters between Sandsaver reference projects and Chelem (Progreso).

When comparing the parameters of reference projects to the study area parameters using Table 4.1, one could say that the Sandsaver would be a viable solution for sand accretion. The wave characteristics are comparable between all projects. For both cross-shore and longshore sediment transport the Sandsaver is a workable solution, with the notion made that this workability is dependent on the orientation of the system with respect to the sediment transport direction and dominant wave direction.

The effect of Sandsaver implementation on the adjacent shoreline is essential in its viability. As highlighted in subsection 1.3.2, the shoreline in the study area is extremely sensitive to erosion protection measures, with currently employed measures often leading to increased erosion downdrift. Only the Lake Michigan reference project reports adjacent impact, drawing the conclusion that the Sandsaver does not induce adjacent negative impacts (Land & Water Consulting, 2013). This is for cross-shore sediment transport conditions. A similar conclusion can thus not be drawn for longshore sediment transport. This is therefore most critical for the viability of Sandsaver as a solution, and is the priority in the implementation/monitoring plan.

Sandsaver prerequisits

For successful implementation, several technical prerequisites are important to adhere to before placement, and to base the technical design on. These are briefly set out below, gathered from communication with Sandsaver, reference projects and own insights.

- Sediment type at site should be predominantly fine to medium sand (D_{50} ≈ 0.2–0.4 mm), non-cohesive
- Beach slope at site should be gentle to moderate (1:20 - 1:40), the installation ground should be even
- Modules should be installed in the surf zone and should always be partially submerged, taking local tidal regime into consideration
- Modules should have optimal orientation with respect to sediment transport direction and dominant wave direction.
- Modules should be connected to a hardened structure or placed up past the high tide line to prevent wave-washing from behind
- Modules should be stable with respect to normative and extreme hydraulic loads
- Placement, and utilisation of the Sandsaver should not disturb local fauna, e.g. turtle nesting

4.2.2. Dune forming

The next step in working towards the future vision is to establish the natural resilience of the coastline through dune forming. In this section, concrete physical solutions are proposed, which should be combined to foster natural dune growth. The combination of these solutions is to be combined with the social measures and should be evaluated in a testing phase before being implemented, as later described in subsection 4.3.3. The solutions proposed follow from a literature review of successful reference projects aimed at stimulating dune growth and maintaining thriving dune landscapes.

Sand stabilisation

A study by Ocaña et al. (2018b), conducted just east of the study area, demonstrated the positive effects of applying *sand stabilisation* techniques, in which natural biopolymers are added to sand to improve its cohesion. Their results showed a significant reduction in sand volume variability in treated areas compared to two control sites. They concluded that PPB (Protein Polysaccharide Biopolymers) technology could be an effective tool to enhance beach resilience, promote dune restoration, and reduce aeolian sediment transport. However, they emphasised the need for site-specific pilot studies prior to large-scale implementation.

Sand trapping fences

In their project, Ocaña et al. (2018b) also made use of sand trapping fences, which serve a dual purpose (Ocaña et al., 2018a) . Firstly, local wind reduction allows for more aeolian sediment deposition. Secondly, they can protect the dune in the early stages of development by limiting human access (Eichmanns et al., 2021). Further detailed literature research should be performed on the type and placement of these fences before implementation.

Planting native species

Plant species that are native to the area have a higher chance of survival when planted in order to promote dune forming. The native dune vegetation in the study area has been investigated by Jesus Lira Castro (personal communication, 2025), who investigated the presence and the function of different plant species in the formation of dunes in the study area. Using systematic field observations along a beach zone in Chelem, Mr Lira Castro used transects and quadrants to allow for consistent sampling of plant cover and the presence of species. The findings were correlated with geomorphological parameters such as dune height, slope and beach width to assess the role of different species in mitigating erosion. He concluded that *Ipomoea pescaprae* has a pioneering role as a sand-fixing species, initiating dune formation through its root system. *Tournefortia gnaphalodes* and *Suriana maritima* reinforce secondary dunes by stabilising deeper layers of sand with their woody and fibrous roots. *Sesuvium portulacastrum* forms a dense mat that prevents surface sand loss.

(a) *Ipomoea pescaprae* (Photo taken by the author (2025)) **(b)** *Tournefortia gnaphalodes* (van Buurt, 2008) **(c)** *Suriana maritima* (Crespo, 2020) **(d)** *Sesuvium portulacastrum* (Msanda, 2010)

Figure 4.5: Important dune vegetation species in the study area

In the back-dune areas, *Calostropis Procera* and *Cascabela gaumeri* provide additional structural stability via their woody stems and tolerance to dry, sandy soils. A complete, translated overview of the findings of the research of Mr. Lira Castro is included in Appendix M.

Of these species described by Mr. Lira Castro, in a reference project by Ocaña et al. just east of the study area, *Sesuvium portulacastrum* was also described. They also reported planting *Sporobulus virginicus*, which was not described by Mr Lira Castro, but is also native to the area (Peterson et al., 2004). This species also plays an important role in stabilising dunes (Balestri & Lardicci, 2013).

4.3. Integration of Proposals

As mentioned, it is essential to integrate social strategies and physical measures to get towards the future vision. Any physical measure will not be viable or sustainable when it is not socially accepted and supported by the local community. For an integrated approach, it is therefore needed that physical measures are developed while actively aligning the social strategy to ensure participation and understanding among local stakeholders.

In this integration, the Coastal Community Committee (CCC), as described in subsection 4.1.1, plays a crucial role. Before focusing on physical measures, it is important that the CCC is fully operating and organised, allowing effective decision making, communication and collaboration.

In this section, the integration of the previously proposed social strategy and physical measures is presented. The aim is not to propose a defined solution for the broader coastal erosion problems in the study area, but to draft a test plan that can be executed in collaboration with the CCC. This test plan should be used firstly to validate the proposed solutions as a viable solution in the study area and secondly to iteratively develop a general implementation plan. The test plan will serve as a small step towards reaching the future vision. Testing is highly valuable before implementing any real measures, since effects and approaches are still undefined.

4.3.1. Proposed location

In order to present the integration of the proposals that is as realistic as possible, a suitable location for testing is chosen. This location should encompass all physical and social issues the proposed solution aims to address.

Based on the results presented in chapter 3, a zone within area 1 (Chelem) will be chosen as the test location. As set out in section 1.4, Chelem was found to be the site most exposed to erosion historically. Currently, beaches in the Chelem area have almost completely disappeared. Many properties are at immediate risk of disappearing into the sea, as found in the shoreline analysis (section 3.1). Furthermore, the social analysis (section 3.3) revealed that (1) local residents in Chelem generally notice coastal erosion and see it as a problem, (2) property owners experience damages due to coastal erosion and (3) there is generally a lot to be achieved in terms of government support and local, social collaboration.

Within Chelem, the specific test location should have somewhat representative conditions for the entire study area, whilst also ideally having severely aggravated local problems. Furthermore, sand accretion should be achievable here. As set out in subsection 1.3.2, net sediment transport rates increase further westward from the pier. The test location should thus be placed eastward in Chelem, where sediment transport rates are generally lower, and erosion rates are generally highest (see Figure 3.1). To stay away from the local influences of the harbour of Yucalpeten, the case study location should not be too far eastward in Chelem. The location chosen can be seen in Figure 4.6. This location adheres to all of the above.

Figure 4.6: Visualisation of case study area location within Chelem with satellite snapshot of recent situation

4.3.2. Sand Accretion: Sandsaver

As mentioned, the first step towards the future vision of the state of the beach is sand accretion. A potential physical measure that can be tested and evaluated is the Sandsaver as described in subsection 4.2.1. To evaluate the effects and potential of the Sandsaver, a test plan has been outlined which can be executed by the CCC. This plan is divided into three phases: preparation, actions while operative and evaluation. In each part, specific actions are required to test the Sandsaver. First, the required actions are presented, along with a short explanation, after which the connection to the CCC will be elaborated.

Preparation

The following actions are required in preparation:

1. **Create support for placement of the Sandsaver within the local community**
   To perform testing with a physical measure, in this case the Sandsaver, it is important for the CCC to create support among the local community. The local community should be informed and educated on what is going to happen and why. This should also create awareness among the local population that tests are being performed, to ensure that local people will not take matters into own hands and disturb testing.
2. **Manage expectations regarding output of testing**
   The goal of the testing needs to be communicated by the CCC to the local community in order to also manage expectations regarding the output. It is important to create the understanding that the Sandsaver testing has the goal of validating this physical measure as a sustainable solution. This is to ensure it is not yet seen as the ideal solution to combat erosion, before its possible negative side effects are evaluated.
3. **Preparation for extensive monitoring while operative**
   To be able to track and monitor the effects of the Sandsaver within the testing period , it is essential for the CCC to find local homeowners willing to help with extensive monitoring. Furthermore, preparations for monitoring should be made in terms of placement of installations and task devision etc.
4. **Determine technical design**
   This technical design must adhere to and be based on the technical prerequisites set out in subsection 4.2.1.

Actions while operative

The following actions are required while operative:

5. **Protect test setup from interference by local residents**
   To be able to test without interruptions, it is highly important that the testing is not interrupted. Therefore, the CCC needs to keep informing and educating local people. This also includes educating local people on how to act if testing is interrupted. The monitoring task of the CCC also includes providing a monitoring system, including cameras, as well as human monitoring provided by the community. Shared responsibility should be encouraged to create a culture where local inhabitants can provide feedback when it seems that someone is interfering with the testing process.
6. **Ensure modules remain stable and functioning**.
   Local homeowners within the testing area should be involved by the CCC to monitor the state and condition of the modules. Their involvement is essential to make sure the modules remain stable and undamaged, so that their function remains optimal. By giving this responsibility to the local inhabitants, community engagement is strengthened and the efficiency of the testing is improved. The following should be specifically ensured:
   - Ensure modules remain (partially) buried and stable
   - Ensure modules remain unclogged from seagrass/other debris
7. **Conduct continuous, quantitative technical monitoring.**
   Performance evaluation is critical for determining the suitability of the Sandsaver as a coastal erosion mitigation measure in the study area. Performance can be evaluated using monitored results on different criteria. The following should (at least) be monitored:
   - Net volumetric change of sand behind modules
   - Type of sediment trapped

- Updrift and downdrift impact of installation

8. **Perform periodical evaluations**
   The performance of the Sandsaver should be assessed periodically, on which further actions can be based and the test protocol can be adjusted if necessary.
9. **Share periodical updates about the project with involved stakeholders**
   The stakeholders involved should be updated periodically, to retain the support established prior to placement.

Evaluation

After testing, a decision should be made on the suitability of the Sandsaver as a solution to regain the beach in the entire study area. This should be done based upon an evaluation of the technical performance of the Sandsaver, an evaluation of the experience of stakeholders affected and an evaluation of the workability of all actions necessary. If necessary, actions should be added or refined in a global implementation plan in the entire study area.

4.3.3. Sand Retention: Dune Forming

The second step towards the future vision is to focus on dune forming. Once extra beach is regained through sand accretion, it is important to retain sand so that dune forming can take place. In subsection 4.2.2, solutions were proposed that promote dune forming. Similar to the Sandsaver, these solutions need to be tested and evaluated before widespread implementation.

Preparation

The following actions are required in preparation:

1. **Create awareness about the importance of dune vegetation**
   Only a small portion of respondents to the questionnaire mentioned *Dune conservation* as a measure that they have taken (Figure 3.20). From the qualitative interviews, it becomes clear that some homeowners actively remove vegetation in the dunes (subsection 3.3.2). This highlights the need for creating awareness about the functioning of dune vegetation to improve social acceptance beforehand.
2. **Prepare for extensive monitoring**
   In preparation for the testing phase, it is important to prepare the extensive monitoring needed. This should include finding local inhabitants willing to take part, and setting up necessary installations.
3. **Plant vegetation**
   Vegetation should be planted prior to the maintenance and protection phase. The right species to be planted should be selected and vegetation should be planted in an optimum stage of the accretion process.
4. **Determine a maintenance and protection plan**
   Including but not limited to:
   - Set up regulatory framework
   - Determine local actors involved

Maintenance and protection

The following actions are required during maintenance and protection:

5. **Protect the dune vegetation from external influences**
   Especially in the earlier stages of dune forming, the testing area is still very sensitive to erosion, as plant roots have not yet fully developed and thus do not provide optimal stability yet. Therefore, it is necessary to protect the dune vegetation from external influences. Sand stabilisation techniques should be applied to improve and cohesion in the early stages. In subsection 4.2.2, the protective function of sand fences was already briefly mentioned. They prevent humans from trampling the vulnerable plants. Combining these fences with the right signage can help raise awareness among passers-by.

6. **Conduct continuous monitoring**
To evaluate the progress of the dune growth, it is important to conduct continuous monitoring. A clear monitoring strategy should be applied to determine which plant species thrive and what their effect is on dune forming. Therefore, the growth and presence of all (planted and naturally occurring) plant species should be tracked. It is advised to divide the testing area into multiple similar areas and plant different species to monitor the effectiveness of different species.
7. **Perform periodic evaluations**
The performance of the dune management plan should be assessed periodically, on which further actions can be based and the test protocol can be adjusted if necessary.
8. **Provide periodical updates about the project**
The stakeholders involved should be updated periodically to retain the support established prior to implementation of the management plan.

Evaluation

Results from the testing phase should be carefully evaluated to assess which plant species and dune forming solutions in general have worked best. Another point of evaluation is the perception of the local inhabitants around the testing area. It is important to evaluate if their perspectives on the testing area have changed, to be able to conclude if the communication and information have been effective.

4.3.4. Visualisation

A visualisation of the actions proposed for sand accretion and sand retention is shown in Figure 4.7. Within this figure, the proposed actions are coupled to the proposed tasks of the CCC as explained in subsection 4.1.1, to showcase the role and importance of the CCC within the proposed plans.

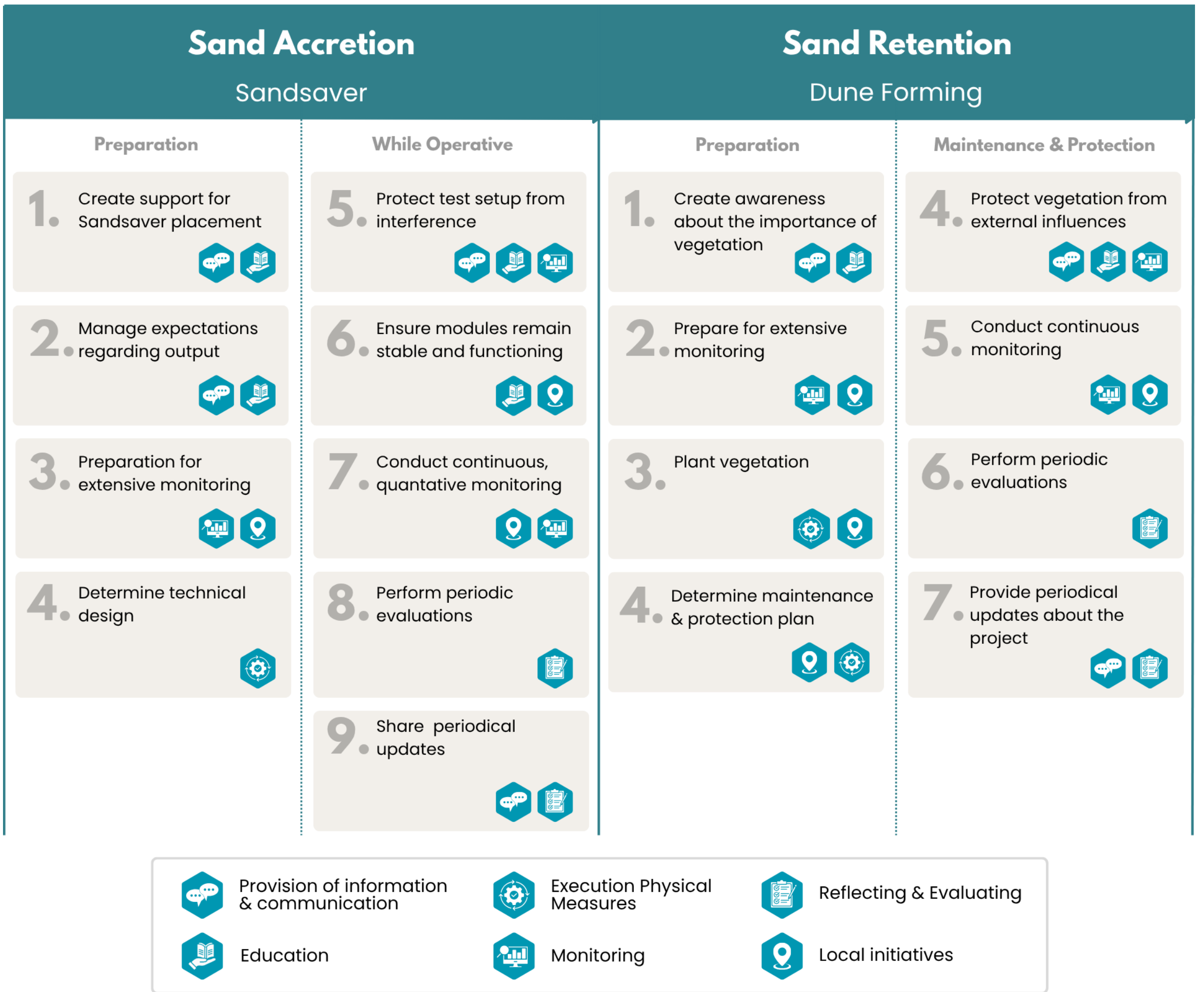


Figure 4.7: Integration of actions in testing and tasks from CCC

5
Discussion

In this chapter the work presented in this report is discussed. First, the analyses are discussed, with a focus on the imitations and reliability, to address how this may have influenced results. Next, the proposed solution is discussed with a focus on the limitations, feasibility and assumptions made

5.1. Analyses

5.1.1. Shoreline analysis

Shoreline identification using satellite images is inherently uncertain due to the low resolution of satellite images and the sensitive identification methodology. Validation of the manually selected shoreline positions was done by comparing them against recent satellite images, which have limitations in accuracy due to the image resolution and seasonal influences. More accurate validation would require in-situ geospatial mapping of the coastline using GPS-based surveying methods. This was beyond the scope of this study and thus not adopted.

Furthermore, a major limitation of the shoreline identification methodology is the inability to accurately detect the shoreline when coastal structures result in small sandy areas. There is an abundance of man-made structures in the area of interest, with some situated very near to the shore, illustrated by Figure 3.3. CoastSat identifies the shoreline based on spectral classification of sandy pixels (Vos et al., 2019), which makes it difficult to accurately detect the shoreline in areas where beach width is very minimal, and man-made structures are in abundance. This is specifically the case for area 1 (Chelem), which may reduce the accuracy of shorelines detected. This limitation should be considered when interpreting the linear regression rate (LRR) results for this area.

The analysis of the endangerment of properties due to the retreating coastline is highly uncertain due to the property identification method and uncertainty in the recent and forecasted shoreline. The shoreline forecast is deemed mostly inconclusive for areas 1 and 3 due to high uncertainty bands attributed to the Kalman Filter model. Furthermore, distances quantify exposure only; true risk also depends on elevation, structural typology and protection presence, which were beyond the scope. The results presented in subsection 3.1.2 should thus be seen as an indication of the problem per area rather than an accurate investigation of individual property endangerment.

5.1.2. Stakeholder analysis

The construction of the stakeholder network map was mainly based on literature and limited field observations, meaning that some informal or less visible connections may not be shown. The method also relies on interpretation, which makes it partly subjective. Because institutional roles and relationships can change over time, the map represents only a moment in time and would regularly need updates to stay accurate.

Likewise, the assessment of stakeholders in the power-interest diagram was also largely based on interpretation and perceptions retrieved from the social research. Furthermore, stakeholders' levels of influence or engagement may change quickly when new projects, funding or policies arise. The diagram also does not reflect how power is used in practice.

5.1.3. Social analysis

Questionnaire

First and foremost, the questionnaires were filled in in Spanish and translated automatically. In this process, important information may have been lost in translation. In the questionnaire, most of the data was collected from coastal homeowners. However, this is not inclusive for understanding the entire study area, as it is not a representative group of the population. Additionally, the use of statements rather than open-ended questions resulted in limited variation in responses, which may introduce bias. Lastly, the use of labels instead of the original answers can exclude some specific and extensive answers; therefore, insightful information might have been missed.

Qualitative interviews

For the qualitative interviews, only six interviews were conducted, representing only three different perspectives. Therefore, their perspectives do not capture the full diversity of stakeholders within the scope of this project. Also, answers can be misinterpreted due to the language barrier between the interviewer and interviewee.

5.1.4. Concept generation

PMI-method

Considering the pluses and minuses encourages decision-making, but it is easy to dismiss ideas too quickly. This means that some concepts may have been unjustly discarded. Next to that, this method can also be based on prejudice and personal experiences and therefore, can be subjective.

Multi-criteria Analysis

The results from an MCA should not be followed without interpretation. Although the weights and scores assigned to the categories are carefully considered, the margins between two choices can be small. Their impact on the final score, however, can be significant. Additionally, it is possible that not all the important criteria are taken into consideration, which could have resulted in a different outcome. Lastly, it is important to note that quantification of certain criteria involves a degree of subjectivity, because there was no thorough calculation for giving the weights to the criteria.

5.2. Proposal

The proposal includes the proposed social strategy, the proposed physical measures and the integration of these. It is important to note that this is a set-up to give an indication of what would be needed to address the main problems found in the assessment. This proposal is a first idea which can be built upon, but should not be used as a direct guideline to take action in addressing the coastal erosion problems.

The proposals for both the CCC and the Sandsaver do not include a financial plan. However, a financial plan is crucial for the successful implementation and long-term operation of the CCC, as well as for the effective implementation of the Sandsaver. Without a financial plan, it will be impossible to request funding, which means that no progress can be made.

The concept of the CCC was created based on a general understanding of all stakeholders involved, their relationships and the division of responsibilities regarding coastal erosion. A more thorough understanding of the social and regulatory dimensions is necessary for a more durable setup of the CCC. This understanding can only be required through extensive, in-depth research, which was not feasible within the timeframe of this project.

The willingness of stakeholders involved in the CCC to collaborate has not been assessed. This is crucial to the viability of the proposed structure of the CCC.

Relevant case studies were used to prove the feasibility and possible effectiveness of both the CCC and the Sandsaver. Although this creates a general understanding of the feasibility of these proposed solutions, this does not guarantee that these solutions are workable in the context of this study area.

The government's assessment was based on two interviews, leading to an incomplete understanding. Therefore, crucial information may have been overlooked.

The proposed physical measures have been selected using selection methods based on general knowledge of the environmental and social conditions and the measures themselves. A more intricate understanding is needed to verify all assumptions made. The proposed physical measures should thus be seen as an example of possible measures, rather than an absolute and verified proposal.

For sand retention, there might have been tunnel vision on dune forming. Due to the limited time and visits to homeowners, limited current solutions for maintaining the beach were seen and therefore researched and explored.

6 Recommendations

This chapter builds on the discussion described in chapter 5 and elaborates on different aspects by proposing recommendations for future research.

To improve the proposed setup of the CCC, further research is needed on the functioning of the governmental institutions in Mexico. This research should aim to gain more insights in the internal operation of, and collaboration between, different governmental institutions. Such knowledge can help pinpoint bureaucratic areas in which operations and the division of responsibility can be improved. Based on this, responsibilities and tasks within the CCC can be specified to ensure the CCC can act as a durable bridge between all actors and their responsibilities.

Also, it is recommended to discuss the CCC proposal with all the stakeholders to improve the viability and long-term functioning of the CCC. With their feedback, an iteration can be made on the proposal. This can help to improve support and willingness to cooperate in this initiative.

Research in this report was focused on identifying the threat coastal erosion poses to near-shore properties. This can be strengthened by evaluating coastal resilience in a broader sense, taking the system's resilience to natural disturbances into account. In this way, vulnerable areas can be identified and prioritised in the proposed mitigation strategies.

To strengthen the foundation for the proposed physical solution, it is recommended to conduct further research on possible solutions to validate assumptions made in the MCA. Working principles and accompanying characteristics of concepts should be assessed in greater depth. Environmental conditions and other characteristics should be evaluated more extensively to be able to validate the feasibility of the proposed solutions more accurately.

For a refinement of the proposed test plan, it is recommended to integrate expert perspectives, such as local contractors and the Sandsaver company itself. Monitoring and measuring location-specific conditions is needed, whereafter a technical design and implementation plan can be made. Afterwards, it is important to elaborate on the described test plan to make it more concrete and actionable.

To improve coastal resilience, it is proposed to focus on dune forming. However, to be able to strengthen the choice for this 'method', it is important to take a step back and explore multiple other (innovative) options to maintain sand and stimulate dune forming. Next to that, it is a natural process that varies from place to place, so it is important to get in touch with experts in this field to assess the local situation.

As mentioned in the discussion, the financial aspects were outside the scope of this project. However, since finances are often a driving factor, it is recommended to develop a financial framework (in collaboration with governmental institutions) accompanying the proposed CCC setup. This should be based on an assessment of current capital flows and possibilities within governmental institutions. Additionally, financial aspects of physical solutions should be taken into account.

7

Conclusion

Coastal erosion has reached a critical point in the Progreso area. Two of the three areas defined in this research showed endangerment of properties. 50% of the properties in these areas lie within 20 metres of the shoreline. Historic trends show this situation will worsen in the future. The community perceives coastal erosion as a significant issue; around 70% of the respondents consider coastal erosion as a very big problem for themselves and the community.

The future is expected to be worse. A forecast of coastal retreat reveals that, in the same two previously mentioned areas, the number of properties located within 10 meters from the shoreline is expected to double over the next decade. This is reflected in the opinions of respondents, with 65% expressing strong concern that the living conditions in the Progreso area will significantly worsen in 10 years. Moreover, 78% believe that these changes will seriously affect their future.

Through stakeholder analysis and social research involving questionnaires and interviews, a knowledge and communication gap was identified concerning coastal erosion, its impacts and the measures taken. There is a knowledge gap due to the need for knowledge sharing among coastal homeowners. The communication gap occurs between neighbours, so among coastal homeowners, but also between them and the governmental institutions. 84% of the respondents think that the government does not provide enough support to address coastal erosion.

A solution for the coastal erosion problem in Progreso, Chelem and Chicxulub is only possible by first implementing a social strategy; otherwise, no physical measure will be effective. The social strategy involves a specially developed committee, named the Coastal Community Committee. For this, an implementation plan is written. For the physical measure, a test plan has been proposed. This physical measure aims to regain and retain a fully resilient beach, using a Sandsaver and stimulating dune growth.

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AI Statement

This report has made limited use of artificial intelligence tools. The following artificial intelligence tools are used:

- ChatGPT (OpenAI, 2025) was used to improve the readability of text and to assist with LaTeX formatting suggestions and BibTeX. Next to that, it was used to generate visuals.
- Grammarly was used to detect typos and shorten parts of the text.
- Turboscribe.ai was used to transcribe the interviews.

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A
Area Definition

Area	Coast length	Coordinates most West	Coordinates most East
Area 1	7.8 km	21°15’52.4”N 89°46’39.0”W & 21°15’45.6”N 89°46’38.0”W	21°16’49.7”N 89°42’14.5”W & 21°16’45.6”N 89°42’13.8”W
Area 2	3.5 km	21°16’57.5”N 89°41’55.4”W & 21°16’49.2”N 89°41’53.6”W	21°17’18.3”N 89°39’59.7”W & 21°17’08.7”N 89°39’57.6”W
Area 3	5.8 km	21°17’22.1”N 89°39’50.2”W & 21°17’11.6”N 89°39’49.0”W	21°17’48.3”N 89°36’29.4”W & 21°17’40.5”N 89°36’28.7”W

Table A.1: Coast length and coordinates of the different areas

B
Storm Wave Analysis

Storms were detected using a storm threshold for the wave height, which was determined using the following formula :

$$H_{treshhold} = \overline{H_{m0}} + 2\sigma \tag{B.1}$$

where $\overline{H_{m0}}$ represent the mean significant waveheight en σ represent its standard deviation.

To make sure that identical storms were monitored, a time step of 48 hours was used. This means that two successive storms are distinct if at least 48 hours of wave height below the threshold are present (Mendoza et al., 2013).

During the period from 2000–2025, 411 storms were identified. A storm threshold of 1.41 meters, determined with Equation B.1. A 48-hour separation interval ensured that consecutive high-wave events were counted as separate storms. This aligns with the findings in subsection 1.3.1. The storms dominate from the northern direction. The waverose for storm conditions is shown below.

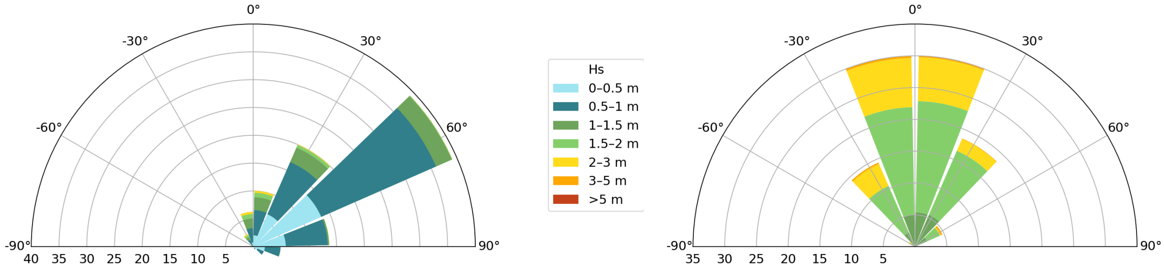


Figure B.1: Waveroses under normal conditions (left) and during storms (right)

C
Sediment Transport Changes

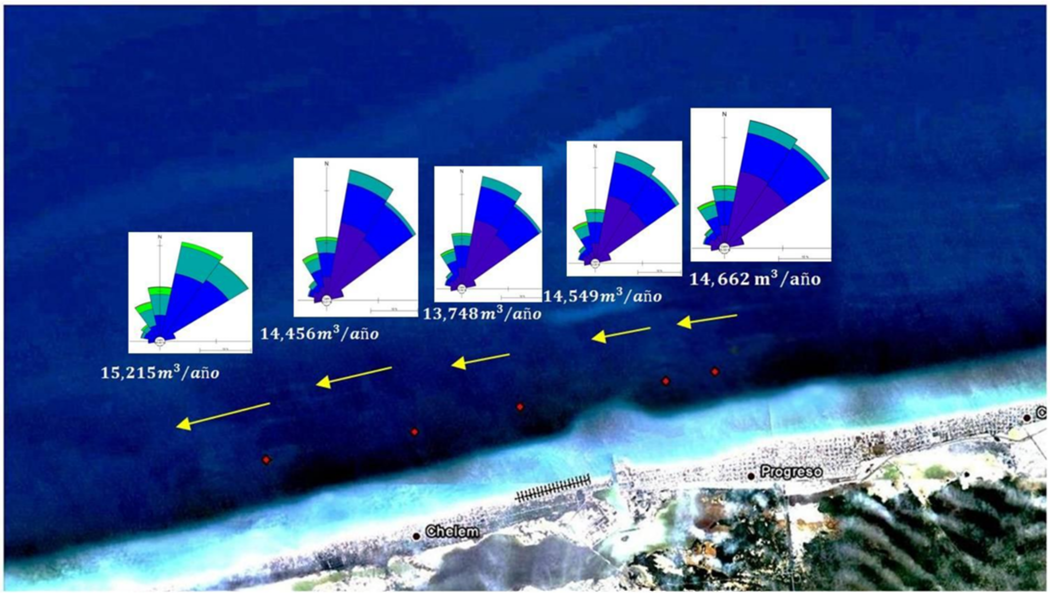


Figure C.1: Sediment transport rates modelled with LITDRIFT model for case without pier (Lira-Pantoja et al., 2012)

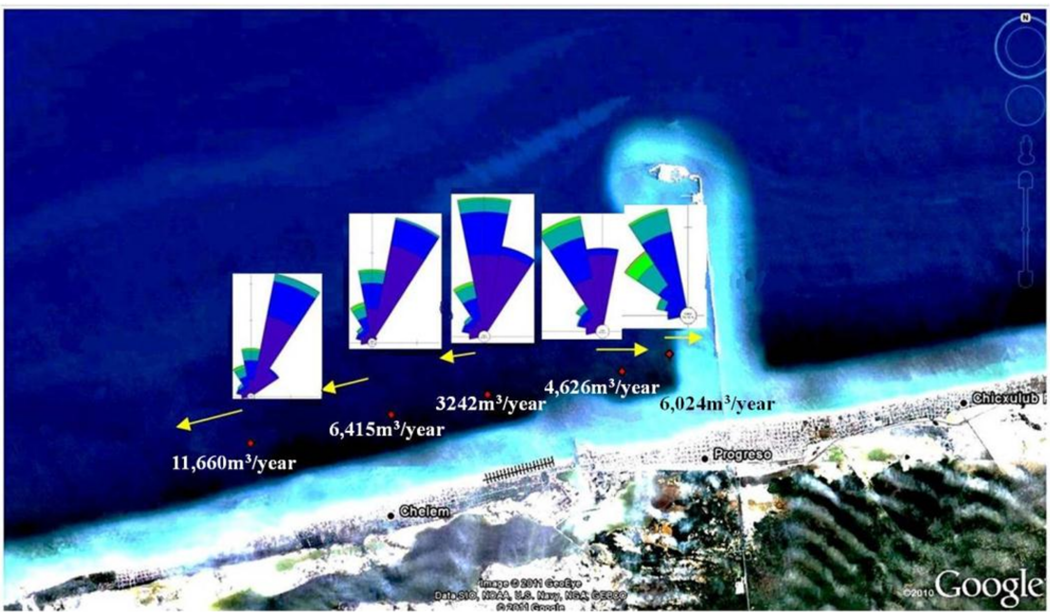


Figure C.2: Sediment transport rates modelled with LITDRIFT model for case with pier (Lira-Pantoja et al., 2012)

D
Shoreline Change Statistic Formulas

LRR

$$LRR = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})(x_i - \bar{x})}$$

where:

- n = length of years and distances
- $\bar{x}$ = mean of years
- $\bar{y}$ = mean of distances
- x_i = i^{th} year
- y_i = i^{th} distance

LRE

$$LRE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n-2}}$$

where:

- n = length of years and distances
- $\hat{y}_i$ = predicted i^{th} distance ($LRR \cdot x_i +$ intercept)
- y_i = actual i^{th} distance

LCI

$$LCI = t_{\text{inv}}(n-2,\, 1-\alpha/2) \cdot \sqrt{\frac{LSE^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2}}$$

where:

- α = significance level, where $\alpha = 1 -$ CI (with CI expressed as a fraction, e.g. 0.95 for 95%)
- $t_{\text{inv}}()$ = Student's t-distribution function
- LSE = standard error of estimate of linear regression
- n = length of years and distances
- $\bar{x}$ = mean of years
- x_i = i^{th} year

E
Property Identification Methodology

To quantify the risk the current shoreline position poses to houses being lost to the sea, the properties in the areas of interest are identified. A *property* is defined as a piece of land with one shoreline edge that appears to be managed as a single lot. High-resolution satellite imagery (Google Satellite accessed at 23-09-2025, ESRI Wayback archive) was used to identify boundaries. The following cues were used in the identification process:

- *Perimeter separation*: continuous walls, fences, substantial hedges or clear gaps that separate the land from neighbouring lots
- *Access*: one primary entrance or driveway
- *Coherence*: buildings and outdoor spaces that function together without internal dividing barriers.
- *Own entrance to the beach*

In special cases, the following decision rules were followed:

- *Multiple buildings within one enclosure:* classify as a single property if they share a perimeter and access.
- *Row houses/condominiums:* if units share a continuous seaward boundary and common access, treat as one property; otherwise, treat each clearly separated unit as a property.
- *Vacant lots:* not marked as a property
- *Ambiguity:* if two or more cues conflict, assign a *medium confidence score*.
- *Hotels/beach clubs:* treat the entire enclosed complex as one property.
- *Industry/offices:* treat separate shore facing buildings as separate properties and select building edge

The *property edge* is what is later used to determine the distance to the shoreline and is considered to be the *permanent constructed element in the lot that is closest to the shoreline.* Elements considered as permanent included:

- foundations, terraces and perimeter walls
- swimming pools and surroundings
- buildings

Removable fences, rope or post barriers or removable furniture are *not* considered permanent.

To reduce misclassification, lots were cross-checked across multiple image dates to avoid temporary features. They were also flagged with a confidence score (high/medium/low). A *medium* score was assigned when the property edge was uncertain. A *low* score was assigned when it was not certain if something could be distinguished as a property.

F
Labels Used in Questionnaire Analysis

The seven different measures of Figure 3.20 and the number of times they are mentioned by respondents:

- **Groin** (N=25)
- **Sandbag** (N=23)
- **Geotube** (N=19)
- **Wall** (N=3)
- **Beach fill** (N=2)
- **Dune conservation** (N=2)
- **Palm tree planting** (N=1)

The nine themes of the different effective solutions for coastal erosion and the amount of times they are mentioned by respondents in Figure F.1:

1. **Add structures** (N=55)
2. **Involved government** (N=40)
3. **Nature based solutions** (N=25)
4. **Add sand** (N=19)
5. **Community builing** (N=15)
6. **Research** (N=11)
7. **Remove structures** (N=13)
8. **Modify the port/pier** (N=9)
9. **Stop adding sand** (N=1)

The nine themes of the different changes at the coast and the amount of times they are mentioned by respondents in Figure F.2:

1. **Disappearance of the beach** (N=110)
2. **Coastal constructions** (N=8)
3. **Difference in sea** (N=8)
4. **Disappearance of dunes** (N=6)
5. **Algae** (N=4)
6. **Climate change** (N=4)
7. **Pollution** (N=3)
8. **Pier** (N=2)
9. **Seaweed** (N=1)

The nine themes of the different main causes of coastal erosion mentioned in Figure F.3 and the amount of times they are mentioned by respondents:

1. **The port and/or pier** (N=62)
2. **Home owner interventions,** such as groins, geotextile tubes and sandbags. (N=34)
3. **Climate change** (N=25)
4. **Pollution** (N=17)
5. **Government** (N=14)
6. **Natural events** (N=11)
7. **Lack of natural resilience** (N=10)
8. **Human-driven development** (N=10)
9. **Sand extraction** (N=5)

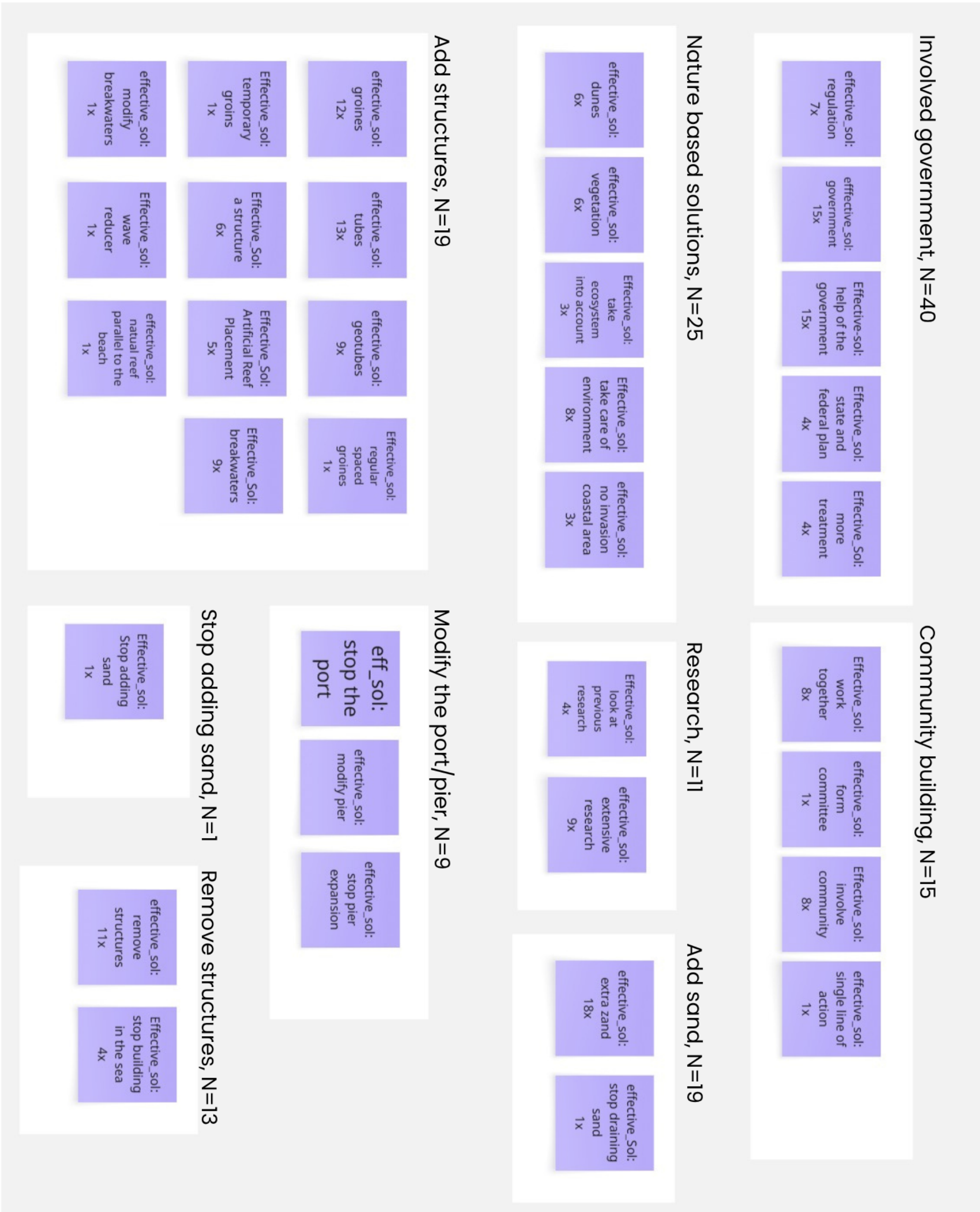


Figure F.1: Themes of the labels of effective solutions

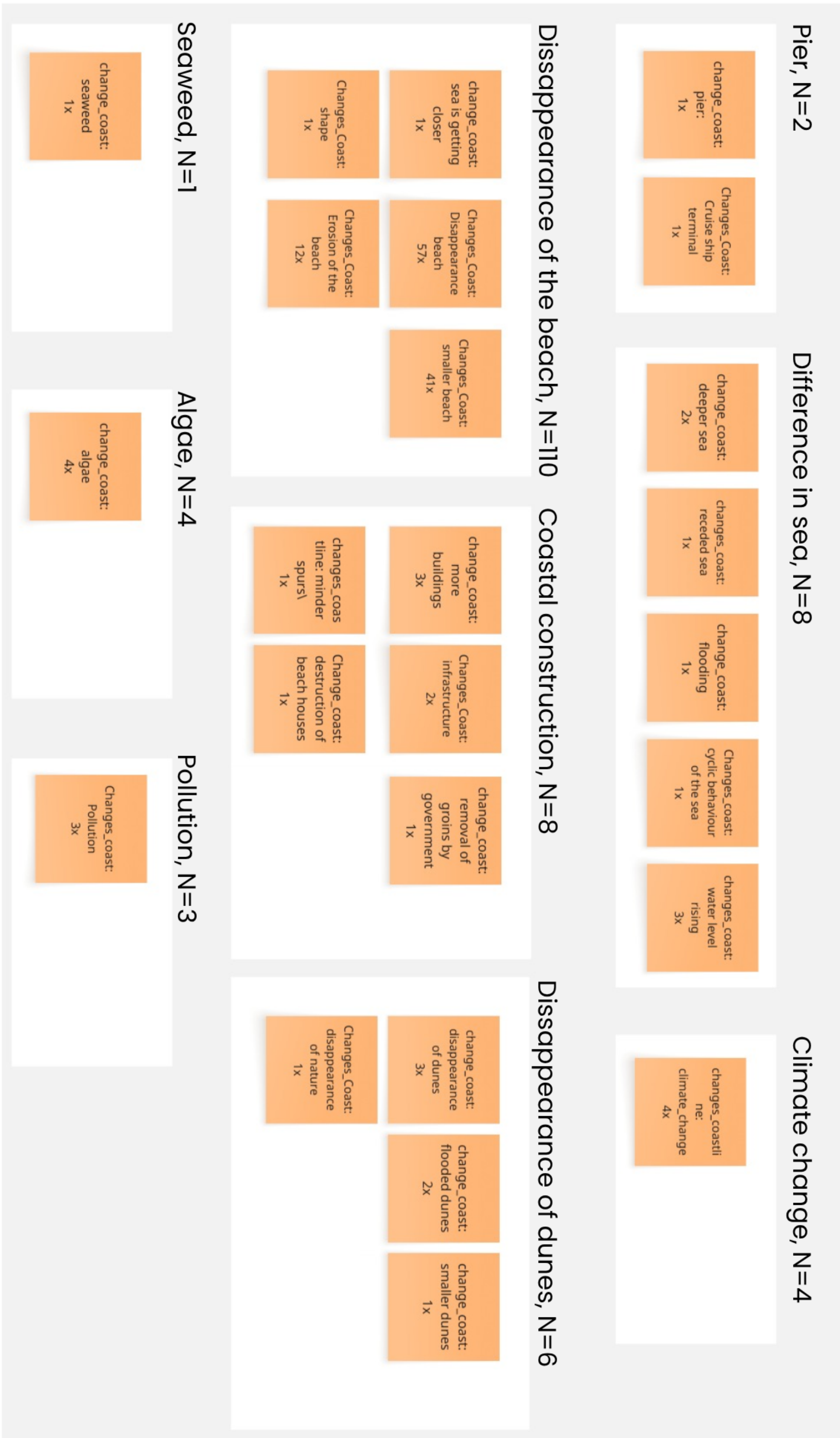


Figure F.2: Themes of the labels of changes coast

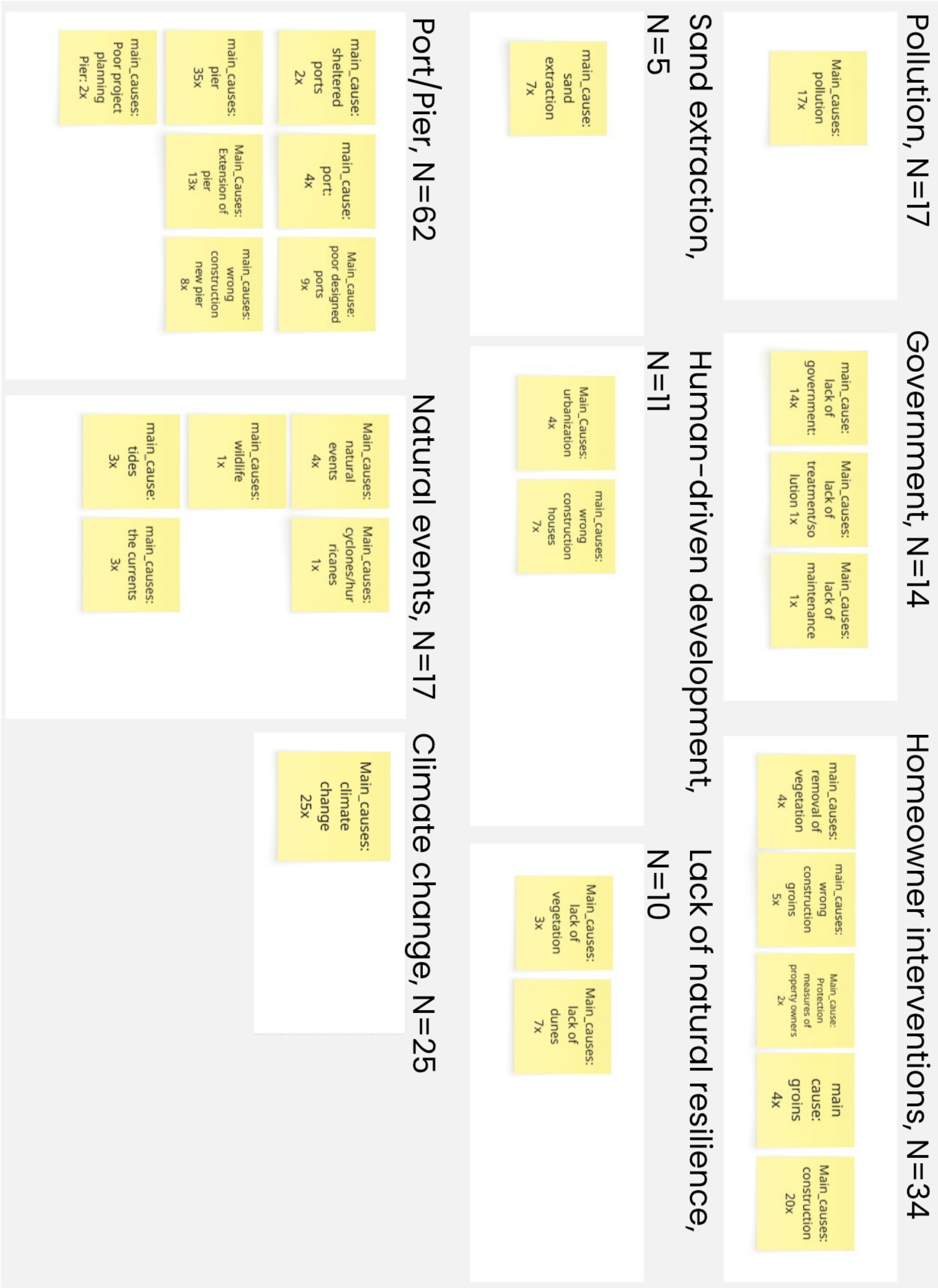
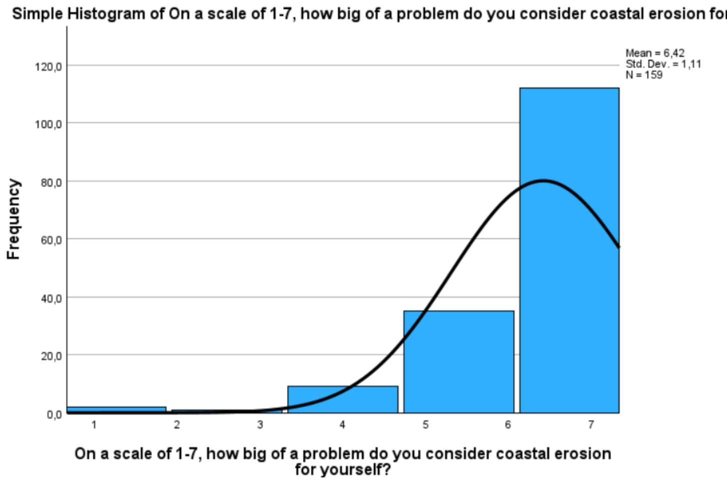


Figure F.3: Themes of the labels of main causes

G
Hypotheses and Statistics of the Social Research

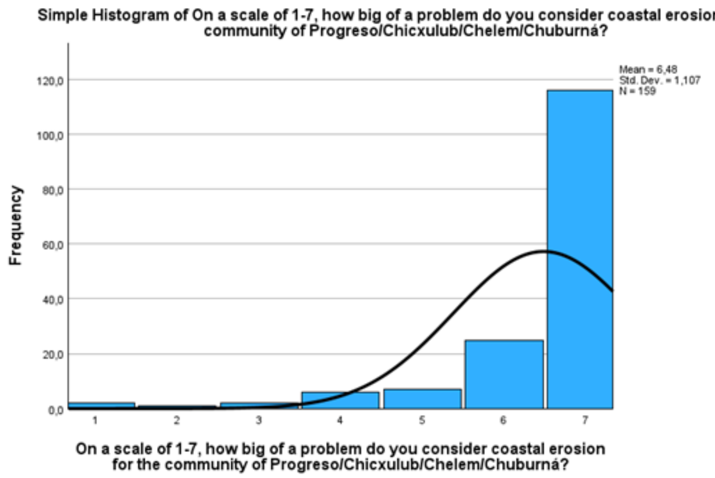


(a) Normal distribution: How big of a problem do you consider coastal erosion for yourself?

N	Valid	159
	Missing	0
Mean		6,42
Median		7,00
Std. Deviation		1,110

(b) Statistics: How big of a problem do you consider coastal erosion for yourself?

Figure G.1: Individual perspective on the coastal erosion problem

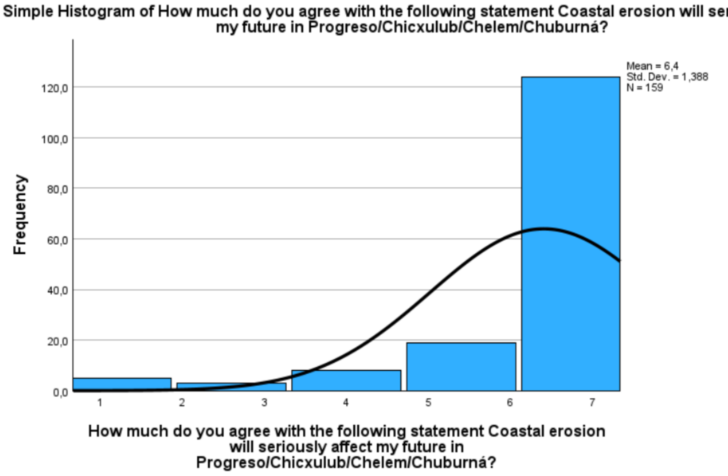


(a) Normal distribution: "How big of a problem do you consider coastal erosion for the community of Progreso/Chicxulub/Chelem/Chuburná?"

N	Valid	159
	Missing	0
Mean		6,48
Median		7,00
Std. Deviation		1,107

(b) Statistics: "How big of a problem do you consider coastal erosion for the community of Progreso/Chicxulub/Chelem/Chuburná?"

Figure G.2: Community perspective on the coastal erosion problem

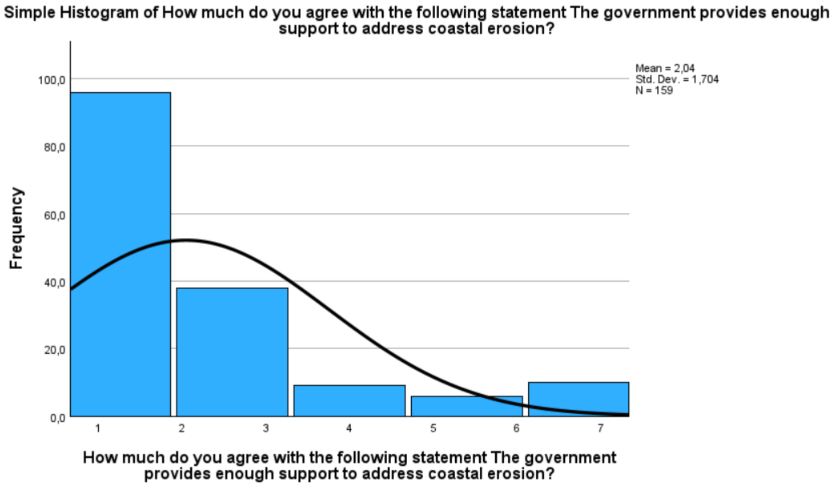


(a) Normal distribution: How much do you agree with the following statement: "Coastal erosion will seriously affect my future in Progreso/Chicxulub/Chelem/Chuburná."

N	Valid	159
	Missing	0
Mean		6,40
Median		7,00
Std. Deviation		1,388

(b) Statistics: How much do you agree with the following statement: "Coastal erosion will seriously affect my future in Progreso/Chicxulub/Chelem/Chuburná."

Figure G.3: Effects of coastal erosion in the future of individuals

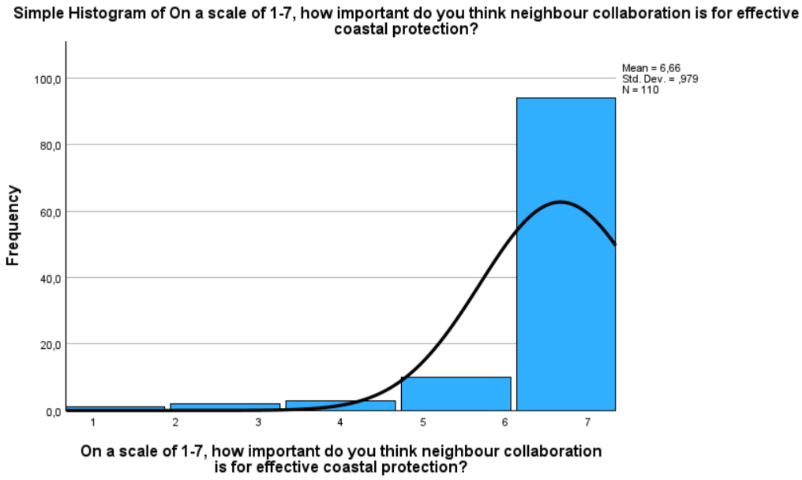


(a) Normal distribution: How much do you agree with the following statement: "The government provides enough support to address coastal erosion"

N	Valid	159
	Missing	0
Mean		2,04
Median		1,00
Std. Deviation		1,704

(b) Statistics: How much do you agree with the following statement: "The government provides enough support to address coastal erosion"

Figure G.4: The perspective of people regarding the government support



(a) Normal distribution: ”How important do you think neighbour collaboration is for effective coastal protection?”

N	Valid	110
	Missing	49
Mean		6,66
Median		7,00
Std. Deviation		,979

(b) Statistics: ”How important do you think neighbour collaboration is for effective coastal protection?”

Figure G.5: Perspective on neighbour collaboration for effective coastal protection

H
Interview Guide for the Coastal Homeowners

Objective of the interviews:

- To gain qualitative insights into homeowners' experiences with the retreating coastline.
- To validate and refine the stakeholder analysis
- Including the identification of potential community groups or representatives involved in the issue.
- To understand local perspectives on possible solutions and future scenarios.
- To uncover latent needs, wishes, and concerns among homeowners (which cannot be retrieved with solely survey research).
- To compare differences in experiences and perspectives between residents east and west of the pier.
- To obtain deeper insights into the technical aspects of self-made solutions designed and implemented by residents.

Introduction

Thank you very much for taking the time to speak with us. We are students from TU Delft in the Netherlands, working on a research project about coastal erosion in Progreso. Coastal Erosion is the retreat of the coastline due to coastal processes or anthropogenic factors and the effects of human-built structures near the coast.

The goal of this interview is to better understand your experiences with the retreating coastline, what solutions people are using, and what this means for the community and the future.

Your answers will remain anonymous and only be used for research purposes. With your permission, we would like to record the conversation, so can process the information as good as possible.

- Do you agree to participate?
- Do you agree to us recording/transcribing this interview?

Section 1 – Background

- Can you tell us a little bit about yourself and your house here?
- Where is your house located? (east or west of the pier)
- Is this your main home or a second home? Since when?
- How would you describe the current situation of the beach in front of your property?

Section 2 – Experiences with Coastal Change

- Have you noticed changes to the beach or coastline since living here?
- When did you first become aware of the retreating coastline?
- What do you think are the main causes of the retreating coastline?
- How important is this issue for you personally?

Section 3 – Actions and Solutions

- Have you or your neighbors taken measures to protect your property? (e.g., sandbags, walls, groynes)
- Did you work together with your neighbors to take measures?
- Why did you choose those measures & how did you built this measure/ what steps did you take?
- How effective have they been?
- For how long do these solutions stay in place on average?
- Can you remember periods in the past 15 years where there was more activity than usual regarding the construction or removal of measures around Progreso in General?

Section 4 – Government and Regulations

- What do you expect from the government regarding this problem?
- Are you aware of any government rules or restrictions about measures taken by people themselves?
- Do you feel the government supports you/residents in this situation?

Section 5 – Community and Collaboration

- Have you heard of any community groups or associations that work on this problem?
- Are you part of such community group?
- Would you be interested in joining such group potentially?

Section 6 – Looking Ahead

- How do you see the future of your property and community in 10 years?
- What would your ideal solution to the retreating coastline look like?

Closing

- Is there anything else you would like to add that we haven't asked?

Thank you very much for your time and valuable input. We will process your answers anonymously.

I

Main Takeaways of the Qualitative Interviews

1. Coastal homeowners, within the study area (N=2)
   (a) **Coastal homeowners underscore to feel not supported by the government.** Interviewees highlight to receive no official communication, support or compensation, despite paying local taxes.
   (b) **Coastal protection has become a private responsibility.** Homeowners install traditional groins or other measures themselves, often without permits, out of necessity to protect their property. One interviewee even pursued legal action to prevent the government from removing their structures.
   (c) **Neighbour collaboration occurs, but community organisation does not exist.** Interviewees work together with their neighbours occasionally, but there are no formal community associations to address the problems.
   (d) **There is a growing awareness of ecological consequences.** Interviewees connect erosion to broader environmental issues such as loss of turtle nests. They therefore think of erosion as a social and ecological problem.
   (e) **Traditional groins of rock and wood are preferred**, because they are locally available, affordable and perceived as 'a part of nature'. This in contrast to government-promoted geotextile tubes, because they are seen as expensive and ineffective.
   (f) **There is a need for coordinated action.** Interviewees express that research and technical guidance are necessary to identify long-term solutions, ideally in collaboration with residents, experts and governments.
2. Coastal homeowners outside of the study area (N=2)
   (a) **Also a lack of trust in the government is highlighted outside of the study area.** Interviewees again emphasize that they see coastal protection as a local or personal responsibility. They have low expectations in governmental support.
   (b) **Preference for nature-based solutions.** These interviewees highlight that the focus lies on maintaining dunes, vegetation and natural elevation, instead of building structures in the sea. Natural adaptation is preferred. Both interviewees highlight that maintaining natural vegetation and dunes is key to protecting their properties. They see these elements as a natural buffer that stabalizes the beach and reduces erosion.
   (c) **Recognition that organized approaches could strengthen coastal resilience.** While there are no formal associations that interviewees are aware of, there is interest in community groups for information sharing and educational purposes concerning the coastal erosion problems. These groups could also raise awareness among governmental parties.
   (d) **Local knowledge spreads through close community building.** Interviewee two highlights that an open culture is positively experienced concerning the coastal erosion problems. Experiences are being shared and spread through word-of-mouth.
   (e) **Coastal homeowners focus on building with more distance from the sea.** In contrast to some parts within the study area, interviewee two and three highlight to intentionally have

built their home as far from the see as possible. Interviewee three even mentions that that is 'the only measure he has taken to address the coastal erosion problems'. By this, they also want to respect natural buffers such as dunes and vegetation.

(f) **Coastal homeowners respect each others mitigation measures.** Interviewee three highlights the importance of preserving nature based solutions such as dune forming and vegetation. However, this is a big difference with his neighbours, who cut out every bit of vegetation. It can be seen that there is way less elevation in the neighbour's area where there is no vegetation left.

3. Governmental focused interviews (N=2)

   (a) **Divided responsibilities across governmental levels.** The management of coastal erosion is divided between federal, state and municipal authorities. However, there is no clarity on responsibilities related to coastal erosion between those levels (among themselves and local residents) .

   (b) **Lack of holistic approach.** Interviewee six explained that there is no integrated management strategy that offers an holistic approach for the problems and that brings together all different perspectives/ stakeholders. There is a lack of coordination and expert guidance in addressing the problems.

   (c) **Reactive, instead of preventive action.** Measures are often taken only after damage has already occurred. This instead of a long-term strategy to address the problems for the entire coastline.

   (d) **Unclear management of coastal fees of ZOFEMAT.** Through ZOFEMAT, fees are collected that residents pay for the use of the coast. However, it is unclear how much money there is collected and how it is spend. There is no transparency about the use of this money.

   (e) **Low political priority.** Compared to other challenges such as tourism and economical developments, coastal erosion has a low priority among the government. This, because most governments are mainly focusing on inland problems, instead of coastal issues.

   (f) **Need for better coordination and (local) participation.** Collaboration between federal, state and municipal levels is crucial for addressing these problems. Local communities and other stakeholders should also be included in the solution finding process, to create shared-responsibility and feasible and sustainable solutions.

   (g) **Lack of communication with residents.** There is to no contact between local residents and governmental institutions. Residents are not informed and involved in the problem, which leads to individual initiatives such as groins, which are no long-term solutions.

J

Transcripts and Notes of the Qualitative Interviews

All transcripts and interview notes used for this research are combined in a zipfile that is attached to the report. An overview is provided in Table J.1

#	**Focus group**	**Transcripts/notes?**	`Filename`
1	Coastal homeowner — inside the study area	Transcript	`Transcript_interview_#1`
2	Coastal homeowner — outside the study area	Transcript	`Transcript_interview_#2`
3	Coastal homeowner — outside the study area	Transcript	`Transcript_interview_#3`
4	Coastal homeowner — inside the study area	Notes	`Interview_Notes_#4`
5	Government perspective — Civil Protection Unit	Notes	`Interview_Notes_#5`
6	Government perspective — School of Science	Transcript	`Transcript_interview_#6`

Table J.1: Overview of interviews and files

K
Results Plus, Minus and Interesting Method

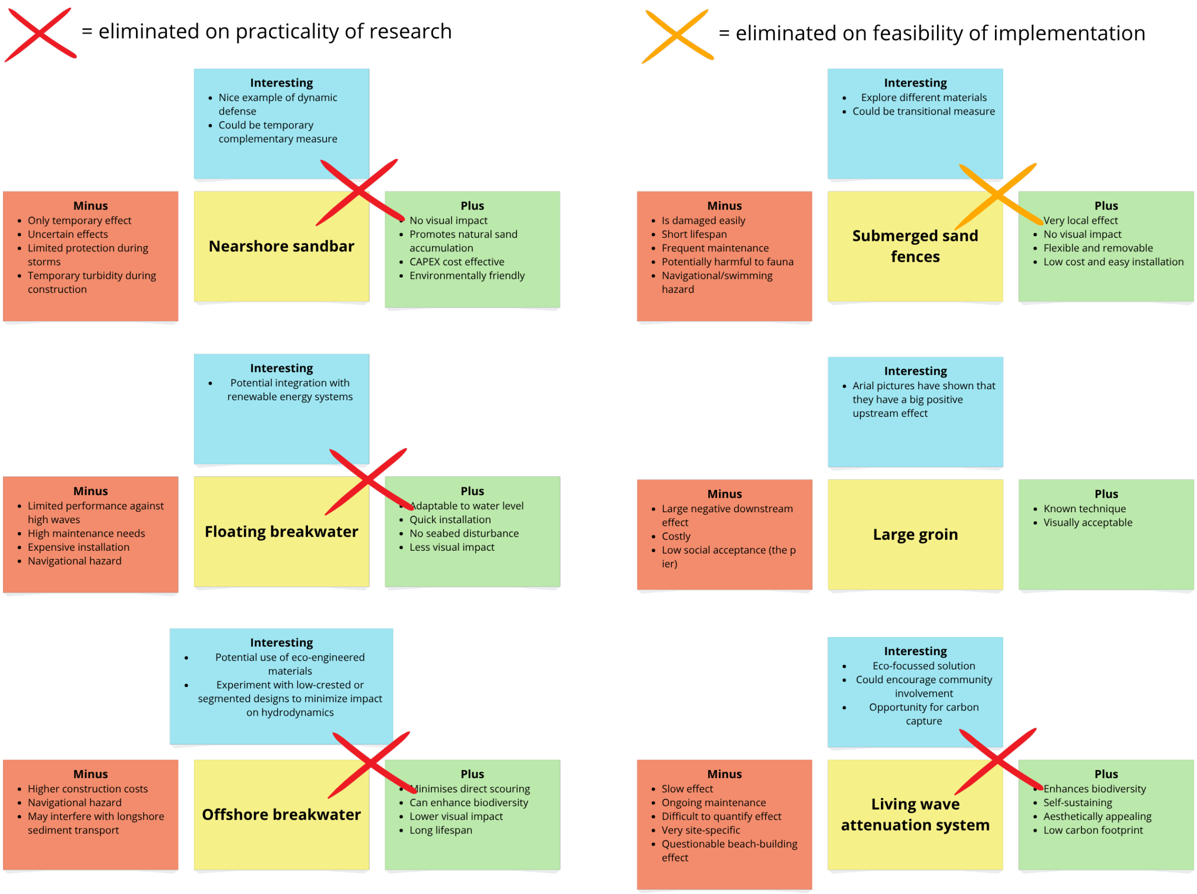


Figure K.1: PMI on Beach Creation, with the coloured crosses indicating eliminations (1 out of 2)

Figure K.2: PMI on Beach Creation, with the coloured crosses indicating eliminations (2 out of 2)

L
Motivation behind Multi-criteria Analysis scores

The considered scores of the Multi-criteria analysis in Table 3.10 are explained in more detail below.

Sandsaver:

- **Effectiveness = 3:** The Sandsaver is considered to be very effective. Hataishi (2022) showed in her case study on Wailua Beach, Kaua'i, Hawai'i, that a sandsaver is useful for beach building under conditions of alongshore sediment transport.
- **Implementability = 3:** The Sandsaver is an off-the-shelf product, and because it needs to be placed close to the shoreline, it is not that difficult to place.
- **Downstream effect = 3:** There is no downstream effect because the construction is not placed perpendicular to the coastline.
- **Social acceptance = 1:** The structure needs to be placed on the waterline. This obstructs direct access to the sea for both local residents and tourists.
- **Affordability = 2:** The Sandsaver is relatively expensive (approximately 40.000 euros per 100 meters), but it can be reused and is made from a strong material.
- **Environmental impact = 1:** The Sandsaver will influence the living environment for fish and other water animals.
- **Maintenance = 3:** The Sandsavers will have to be moved every time the waterline has moved by a few meters.

Direct sand suppletion:

- **Effectiveness = 2:** The beach is immediately replenished once the measure is applied. However, it should be noted that additional measures are required straight away to prevent the deposited sand will eroding again.
- **Implementability = 2:** The sand can be dredged locally due to the sandy soil along the Yucatán coast and brought by trucks or pumped onto shore via floating pipelines. Access to the coastal area can be a restrictive factor, as the majority of the shoreline is occupied by houses.
- **Downstream effect = 3:** There will not be negative downstream effects.
- **Social acceptance = 3:** The impact is direct, and there are no constructions on the beach/in the sea.
- **Affordability = 1:** To dredge sand and move it to the right places will require a lot of working hours and equipment.
- **Environmental impact = 1:** There are no advantages in supplying sand and it might disrupt the ecosystem.
- **Maintenance = 1:** To make sure that the beach will stay intact, the process needs to be repeated.

Groin field:

- **Effectiveness = 3:** A groin field is effective as there will be accretion of sand, especially when done evenly along the shoreline.
- **Implementability = 3:** The technical expertise, equipment and materials are already available in the study area.
- **Downstream effect = 2:** A groin field can partly mitigate downdrift erosion by distributing sediment more evenly along the shoreline (Leont'yev & Akivis, 2020).
- **Social acceptance = 2:** There are already groins placed along the shoreline, which indicates that when doing it with a structured plan, the social acceptance will be increased.
- **Affordability = 2:** There are no special expensive materials needed, but installing will take some working hours.
- **Environmental impact = 2:** It creates more habitat for marine life.
- **Maintenance = 2:** Some maintenance is needed for the wooden structures after a while, and maybe new stones need to be added.

This is why a groin field is considered more effective than placing only one large-scale groin.

Beach drainage system:

- **Effectiveness = 1:** Beach drainage systems are only moderately effective and perform well mainly under low to moderate wave conditions. They offer limited protection during storms, when pipes can become exposed and fail (Bain et al., 2016).
- **Implementability = 1:** Although installation is relatively simple, proper design requires expert input and site-specific adaptation. Implementation is therefore slow and technically demanding.
- **Downstream effect = 3:** The downstream effects are minimal. It does not significantly disturb coastal sediment dynamics beyond the installation area.
- **Social acceptance = 2:** No visual impact but the local inhabitants are unfamiliar with this technique.
- **Affordability = 1:** Initial installation costs are relatively low, but the need for constant pumping, monitoring, and maintenance increases long-term expenses.
- **Environmental impact = 1:** The use of pipes and geotextile beneath the sand negatively impacts the beach ecosystem and increases the risk of microplastics.
- **Maintenance = 1:** Pumping equipment and buried pipes are prone to clogging and exposure, resulting in high maintenance demands.

Large-scale groin:

- **Effectiveness = 3:** When looking at the satellite images of the western part of Sisal and Chuburna, a large-scale groin has a large impact upstream.
- **Implementability = 2:** The technical expertise, equipment and materials are already available in the study area. But requires a lot of planning.
- **Downstream effect = 1:** The downstream effects are big; a lot of land/beach is lost downstream.
- **Social acceptance**: Social research indicates that a significant share of the population holds a negative view of the construction of the Progreso Pier, and would likely have similar concerns regarding the development of a large groyne. As a result, locals may initiate their own construction projects, potentially undermining the coastal management plan.
- **Affordability = 2:** There are no special expensive materials needed, but installing will take some working hours.
- **Environmental impact = 2:** It creates more habitat for marine life.
- **Maintenance = 2:** To maintain the large-scale of the groin, the structures need to be monitored and restored when damaged.

Nearshore artificial reef:

- **Effectiveness = 1:** The primary objective of an artificial reef is not to reduce erosion; rather, it primarily serves to break wave action.
- **Implementability = 2:** In order to place the artificial reef blocks, there is equipment and expertise needed, which is not yet available in the study area.
- **Downstream effect = 3:** There is no downstream effect.
- **Social acceptance = 2:** There can be hindrances for the fishermen during fishing.
- **Affordability = 1:** Both the artificial reef blocks self and placing them are relatively expensive.
- **Environmental impact = 3:** The focus of an artificial reef is on enhancing biodiversity and improving the health of the marine ecosystem.
- **Maintenance = 3:** No maintenance is needed; it should evolve into the ecosystem.

M
Dune and Coastal Vegetation Species

The table below includes the findings of the research of Mr Lira Castro, translated into English.

No.	Scientific Name	Common Name	Morphological and Ecological Characteristics	Function in Stabilization / Erosion Control	Associations or Joint Growth
1	*Ipomoea pes-caprae*	Beach morning glory / Sea batatilla	Creeping plant with long, flexible stems spreading over the sand; fleshy leaves and funnel-shaped flowers. Very tolerant of salinity.	**Very High:** Its stems and fibrous roots fix the sand forming the first dunes. Reduces wind and marine erosion.	Usually grows together with *Sesuvium portulacastrum* and *Tournefortia gnaphalodes* in the coastal zone.
2	*Tournefortia gnaphalodes*	Sea grape / Small beach grape	Woody shrub with thick whitish leaves on the underside, small white flowers; tolerates marine breeze and poor sandy soils.	**Very High:** Deep roots help to fix sand in secondary dunes; they act as a natural wind barrier.	Can coexist with *Ipomoea pes-caprae* and *Suriana maritima*.
3	*Suriana maritima*	Suriana / Saltwood	Compact shrub with small fleshy leaves and yellow flowers; grows in saline and sandy soils.	**High:** Its fibrous roots fix medium and rear dunes and help to stabilise the coastal profile.	Frequently associated with *Tournefortia gnaphalodes*.
4	*Sesuvium portulacastrum*	Sea purslane / Sargabastón	Succulent creeping herb with fleshy leaves and reddish stems; forms dense mats.	**Moderate to High:** Its dense cover protects surface sand and reduces runoff.	Grows with *Ipomoea pes-caprae* in low or humid areas.
5	*Calotropis procera*	Wax flower / Algodonillo	Shrub 1–3 m tall, large succulent leaves and lilac flowers; tolerates dry sandy soils.	**Moderate:** Helps to retain sand in rear dunes; reduces wind erosion.	Can coexist with *Cascabela gaumeri* in high dunes.
6	*Cascabela gaumeri*	Huelem / Mountain oleander	Shrub or small tree with white flowers; drought-tolerant, deep roots.	**Medium:** Its woody structure stabilises high dunes and contributes to soil retention.	Associated with *Calotropis procera*.

Table M.1: Identification guide of dune and coastal vegetation species