Mapping Resilience in Sisal, Yucatan

Communicating multi-faceted definitions of resilience regarding coastal development

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Delft University of Technology

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Cover: The main road along the natural reserve of El Palmar, westwards of the town of Sisal (Britto, n.d.).

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Preface

This report is the result of a multidisciplinary project conducted at the National Autonomous University of Mexico (UNAM) in Sisal, from September to November 2024. The project emerged from the ongoing collaboration between Delft University of Technology and UNAM. As a team of five master's students, we worked together to assess and map coastal resilience in Sisal, Yucatán.

By combining our diverse academic backgrounds and perspectives, we aimed to provide a comprehensive understanding of the environmental, socio-economic, and human-induced challenges facing the region. This report is intended for anyone interested in sustainable coastal development, environmental conservation, and the socio-economic dynamics affecting coastal communities.

We express our sincere gratitude to our supervisors at UNAM, Dr. A. Torres Freyermuth, Dra. G. Medellín Mayoral, and Dra. G. L. Franklin, for their invaluable guidance and support throughout this project. Their expertise was instrumental in the development of this work. We also extend our thanks to our supervisors at TU Delft, Dr. J. A. Arriaga Garcia and Dr. E. J. Houwing, for their continuous support and insightful advice, which greatly enriched the quality of our project.

A special thanks goes to all stakeholders and community members of Sisal for their time and perspectives, which gave us valuable insights into realities faced by the local community. We hope this report contributes to the ongoing efforts to balance sustainable coastal development with the preservation of natural resources in and around Sisal.

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Abstract

Previous studies show that climate change effects and anthropogenic disturbances are having an increasingly strenuous effect on the performance of the coastal system of Sisal, a rural fishing village in the state of Yucatán, Mexico. Resilience has been a crucial component for these studies, as it presents the system's ability to react and adapt to environmental hazards and human interventions. In recent years, several research initiatives have aimed to assess the resilience of Sisal's coastal system through the use of previously identified resilience index calculations. However, these indices lack the ability to quantify disparities of resilience on a local scale. Furthermore, previous studies focus solely on the technical aspects of resilience, and therefore fall short on defining other relevant aspects of the term.

Consequently, this research project aimed to understand Sisal's coastline by understanding the multi-faceted definitions of resilience by analysing the socio-economic and technical factors impacting the coastal system. The study involved examining both its historical context, as well as potential future trends and developments.

This was done through a thorough evaluation of different aspects of the coast, a storm impact study and a social analysis. The findings of these studies are subsequently incorporated into a comprehensive web-tool, providing experts, policymakers, and community members with clear-cut and valuable information on the current resilience of Sisal's coastline.

The findings of the research present that the coastal resilience of Sisal is highly negatively impacted by human interventions along the coast, predominantly causing inadequate resilience performances on profiles with significant anthropogenic perturbations and generally along the coastline westwards of Sisal's port. Current coastal management policies are considered ineffective to deal with these developments, which is among others caused by exclusive decision-making processes and ambiguous governmental policies. Changes in coastal management strategies are therefore needed to effectively deal with future threats of environmental hazards and human interference. Ultimately, resulting in improved coastal and community resilience.

Key words: *Resilience, Coastal System, Coastal Development, Vulnerability, Indices, Indicators, Stakeholder analysis, Social Research, Communicative Strategies, Web tool, Dashboard, Sisal, Yucatan.*

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
UNAM	Universidad Nacional Autónoma de México
SES	Socio-Ecological System
SNA	Social Network Analysis
P&I	Power and Interest
INSTO	International Network of Sustainable Tourism Observatories
SLR	Sea Level Rise
GEE	Google Earth Engine
NOAA	National Oceanic and Atmospheric Administration
ENSO	El Niño-Southern Oscillation
USGS	United States Geological Survey
CVI	Coastal Vulnerability Index
SRI	Sisal Resilience Index
INEGI	Instituto Nacional de Estadística y Geografía (Mexican National Institute for Statistics
SSA	Secretaría de Salud (Mexican Ministry of Health)
CONAGUA	Comisión Nacional del Agua (Mexican National Water Commission)
CONAFOR	Comisión Nacional Forestal (Mexican National Forestry Commission)
SMN	Servicio Meteorológico Nacional (Mexican National Meteorological Service)
CERC	Coastal Engineering Research Center
LANRESC	El Laboratorio Nacional de Resiliencia Costera

Symbols

Symbol	Definition	Unit
Latin Symbols		
V	Velocity	[m/s]
Y	Shoreline movement rate	[m]
S	Sediment alongshore transport rate	[m^3/year]
s	Relative density of the sediment	
h	Dune or beach height	[m]
A	Area	[m^2]
K	Empirical coefficient for calibration of CERC formula	
H_s	Deep water significant wave height	[m]
c_b	Celerity of the wave at breaking point	[m/s]
p	Porosity	
d	Depth of closure	[m]
Tp	Peak period	[s]
t	Time	[s or year]
Greek Symbols		
ρ	Density	[kg/m^3]
ϕ	Angle wave of approach relative to the shoreline	[degrees]

Symbol	Definition	Unit
η	Sea surface height anomaly	[m]
σ	Standard deviation (used for statistical analysis)	[-]
α	Slope angle of the beach profile	[degrees]

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Introduction

This report presents a detailed account of a multidisciplinary project undertaken as part of the Master's program at Delft University of Technology, conducted in partnership with the National Autonomous University of Mexico (UNAM). The project centres on Sisal, a coastal town situated on the northern coast of the Yucatán Peninsula, Mexico. This project aims to address Sisal's socio-environmental challenges arising from coastal development, climate change, and human impacts on the coastal environment.

Sisal faces a complex interplay of ecological, social, and economic challenges. Coastal erosion, sedimentation alterations, ecosystem degradation, and the rise of tourism threaten the fragile balance between development and sustainability. Designated as a *Pueblo Mágico* in 2020, the rapid increase in tourism and human activities has intensified pressures on Sisal's coastal system. The project aims to map the resilience of this system, capturing technical and social facets that shape its vulnerability and adaptability.

The primary objectives of this project are as follows:

- Analyse coastal resilience, by integrating historical morphological data with coastal indicators and examining erosion and accretion patterns.
- Evaluate community resilience, through social research on stakeholder perspectives, development plans, and tourism impacts.
- Develop a new resilience index, to reflect the capacity of the coastal system to withstand both environmental stressors and human interventions.
- Develop an interactive web tool, that communicates the project's findings to researchers, policymakers, and community members.

The project applies a multidisciplinary approach, blending coastal engineering with socio-environmental insights to build a complete understanding of resilience in Sisal. Technical assessments focus on shoreline position, beach-dune dynamics, and erosion/accretion patterns through drone imagery, CoastSat analysis, and field data collected by UNAM. A 1D coastal model is also developed to predict future scenarios based on historical wave dynamics data. In addition, a storm impact analysis examines the influence of extreme weather events on coastal resilience. On the social side, stakeholder interviews and network analysis are conducted to explore community values, priorities, and the effects of tourism on the social system.

The report is organized as follows:

- Chapter 1: Introduction - Provides the context, objectives, and significance of the project.
- Chapter 2: Problem analysis – Explores the background, study site, and socio-economic dynamics of Sisal.
- Chapter 3: Methods – Details the technical and social research methods used to assess coastal resilience.
- Chapter 4: Coastal analysis results – Presents key findings on coastal dynamics and erosion patterns.

- Chapter 5: Social analysis results – Presents stakeholder perspectives and socio-economic findings.
- Chapter 6: Web tool development – Describes the design and functionality of the web tool.
- Chapter 7: Discussion – Analyses findings from both technical and social research, identifying limitations and areas for improvement in current methodologies.
- Chapter 8: Recommendations – Offers suggestions for future research.
- Chapter 9: Conclusion – Summarizes the project's contributions in understanding and enhancing coastal resilience in Sisal.

Through this interdisciplinary approach, the project aims to help bridge the gap between researchers, local community, and policymakers, contributing to future sustainable coastal development.

2

Problem analysis

2.1. Background

2.1.1. Study Site

Sisal is a village located along the Gulf of Mexico in the northeastern part of the state of Yucatán, Mexico (see figure 2.1). The town has a total of 1,837 inhabitants as of 2010 (INEGI, n.d.-a), and falls under the regulatory jurisdiction of the municipality of Hunucmá and the federal government of Mexico. The town has a direct connection to the city of Hunucmá via one main access road, the Mexican Federal Highway 281.

The town consists of a densely populated central area, including a pier and main square. Infrastructure gradually decreases west and east of the centre, ultimately reaching the protected natural reserves surrounding Sisal. A port, dedicated to the town's fishing industry, separates the urbanized area from the natural reserve of El Palmar to the west of the centre. Finally, Sisal is backed by a significant mangrove system to the south. This study delves into the coastal system of Sisal as a barrier island, specifically analysing the coastal characteristics and developments of the area two kilometres to both the east and west of the port.

Figure 2.1: The location of Sisal in the state of Yucatan, Mexico.

2.1.2. Historical context

Sisal played an essential role in the coastal trade networks of the Maya civilization during the Late Postclassic period (1250–1517). The region's coastal areas were hubs for fishing and salt production and traded with larger inland ceremonial centers. Archaeological studies of Maya trade routes provide evidence of these activities, particularly in the Yucatán Peninsula (Torales Ayala, 2019). In 1811, the Spanish colonial authorities established Sisal as a port to capitalize on its strategic location for maritime trade during the 19th century. This was highly intertwined with the nearby henequen plantation, with the maritime export of the fibre giving it the name Sisal (Paré & Fraga, 1994).

However, by 1871, the newly developed port of Progreso replaced Sisal as the primary trading hub, marking the start of its economic decline (Torales Ayala, 2019). As Progreso became the main port, Sisal's population and significance gradually diminished. In the 20th century, the area experienced a resurgence, driven by communal land grants and the growth of commercial fishing. Currently, the area is known for its historical legacy, still relying primarily on revenue from the local fishing industry, which remains a key economic activity.

In recent decades, there has been a significant global growth in the tourism sector, with sun and sand tourism being the main category that has mobilized the largest number of tourists (Mendoza-González et al., 2021). Mexico's tourism sector has also steadily grown during this period, with the country ranking ninth in earnings from international visitors (Mendoza-González et al., 2021). Parts of Mexico have been particularly popular in recent years, with Sisal ranking among one of the areas that has grown its tourism industry significantly.

2.1.3. Socio-economic context

Sisal's economic landscape has mainly been influenced by its strategic location in the Gulf of Mexico. Ever since the construction of the port back in the 19th century, most economic activity has consisted of the fishing industry and the in- and export of goods. However, the impact of the trades business has declined after the construction of the more developed harbour in Progreso. Since then, Sisal's fishing industry has predominantly acted as the main economic income of the community. This dependency on the fishing industry has caused many of its community members to have an occupation within or related to the sector.

In the previous century, a need for a change in fishing infrastructure started to arise, since the boats used by fishermen were increasingly prone to damage caused by storm and natural hazards. This was mainly related to the lack of a dock or a means to keep boats safe, as vessels had to remain on the beach. Therefore, in 1987 a new and improved port was built, giving the fishing industry the possibility to properly safeguard their infrastructure (Mendoza-González et al., 2021).

Interviews with several stakeholders within Sisal's community has revealed that the public opinion on the port varies significantly. Many see the positive impact that it has on the economic development of Sisal, but the construction of this port has caused several negative influences as well. One of these major effects is the impacts on the coastal system, due to significant changes in the sediment transport patterns on the beach, resulting in erosion to west of the port and accretion on the east side. This erosion is specifically harmful for the natural reserve of El Palmar, located westwards of the village. The intricate integration of the ecological and urban area of Sisal, and its community, can therefore be seen as a coastal socio-ecological system (SES) (Rölfer et al., 2024), where changes in the system's composition affects various parts of the area. The transitions within the system has also created opportunities, as the increase in landmass from accretion on the eastern side of the port has provided sufficient area for various developments. Notably, this expansion enabled the construction of the Universidad Nacional Autónoma de México (UNAM) satellite campus in 2005.

The redevelopment of the port of Sisal has also caused changes to the socio-economic environment indirectly. For instance, fishermen moving their boats from the beach to the port left more room for tourism exploitation on Sisal's coast line. The tourism industry, which mainly consists of nature-based tours and activities, hospitality services, and beach exploitation (Mendoza-González et al., 2021), has therefore seen a significant rise in the last few decades, specifically around the summer months.

Additionally, a drastic increase in tourism was noticed after Sisal's denomination as a 'magic town' (Pueblo Mágico) in 2020, and the 'platinum beach certification' that the area received in the same year (Mendoza-González et al., 2021). This magic town status can be seen as one of the largest perturbations of the village in recent years, causing significant changes to Sisal's development. This increase in tourism, as well as other effects, has caused for several community members to believe that the tourism industry is currently exceeding the fishing industry's impact on Sisal's economy, seemingly making it the most important economic sector of the village.

The development of tourism has had a noticeable impact on Sisal, with many community members that previously worked in the fishing industry choosing to shift to tourism-related occupations. Furthermore, the increase in tourism activities has caused stresses on Sisal's infrastructural services. For instance,

due to visitors causing increasing pressure on the available water and electricity supply.

Finally, Sisal's rising exposure in the last decades has caused for much interest of national and foreign developers to invest in real estate projects in Sisal (Mendoza-González et al., 2021). Many federal concessions were granted to outside-state and international developers for the exploitation of Sisal's beaches and the sale of land that was reclaimed from the sea. This has motivated a new social mobilization in 2021 (Mendoza-González et al., 2021), as many housing and hospitality projects have been constructed or are planned within the village and its outskirts since. This has caused in increasing pressure on the local community, with rising prices and proposals by developers to buy-out local inhabitants. One of the effects that is, among others, related to this strain on the community, is the increase in migration of (mainly young) inhabitants of Sisal to other parts of the state. Ultimately, resulting in changes in the social demographic within the area.

To conclude, the social context of Sisal is highly complex and will likely be subjected to significant transformations in the near future. This is predominantly caused by Sisal's economic dependency on its natural qualities, making the socio-economic and natural processes within the area significantly connected to each other. These relationships are encapsulated in figure 2.2, illustrating the complex nature of the feedback loops related to various aspects of the community.

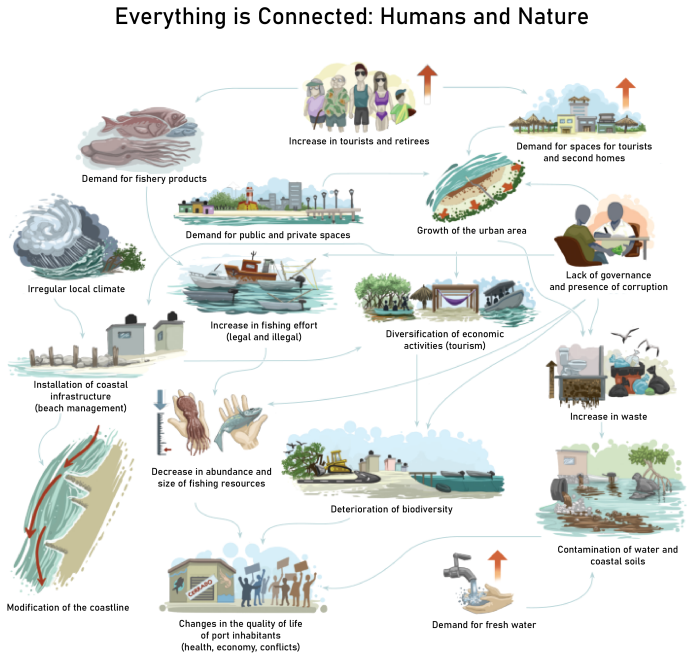


Figure 2.2: Illustration describing the socio-economic web of Sisal, highlighting how natural and socio-economic processes influence each other through feedback loops.

Pueblo Mágico

The Mexican government has implemented various strategies to promote and diversify both domestic and international tourism across a range of destinations in the country (Mendoza-González et al., 2021). The Pueblos Mágicos program is one of these programs, designed to promote sustainable tourism by enhancing the cultural and historical significance of towns with unique heritage (International Network of Sustainable Tourism Observatories, 2023). Towns like Sisal are part of this effort to create diversified tourism opportunities that emphasize authentic experiences (MDPI, 2021).

Towns designated as Pueblos Mágicos benefit from increased visibility, attracting both private and social investments, and boosting local economies through the expansion of tourism infrastructure. While federal funding has fluctuated over time, this designation still typically results in improvements to public spaces. However, the success of the program can depend on factors such as proper planning,

accessibility, and environmental management. Some Pueblos Mágicos communities, like Sisal, have faced challenges managing the influx of tourists while maintaining sustainability (Magazine, 2023). Recent studies confirm that strategies like the magic town program result in a growing trend of increased tourism flow in these destinations. However, no evidence has been discovered of improved social welfare, participation and sustainable tourism development (Mendoza-González et al., 2021). Furthermore, local residents of Sisal have voiced concerns about environmental degradation, particularly the destruction of mangroves, dunes, and the privatization of coastal areas. As a result, inhabitants are advocating for more sustainable tourism models that safeguard Sisal's natural resources (Alterna, 2023).

2.1.4. Coastal system

Like most of the Yucatan peninsula, the coastline of Sisal is generally characterised as a barrier Island. The beach has a relatively flat slope, 0.1% on average, with extensive mangrove systems in the hinterland (Mendoza et al., 2022). The wave climate of the region is relatively calm, with a mean significant wave height of 0.8m, mean peak period of 4.5s, and mean direction of 54 degrees relative to north. (C. M. Appendini et al., 2012). The region is forced by a micro tidal regime, with a tidal range between 0.15 and 1.15 meters (Medellín et al., 2021).

The contemporary evolution of the coastline has been dictated by the presence of a port with dual jetties perpendicular to the coast. This obviously interrupts the easterly littoral transport, inducing clear regions of accretion and lee-side erosion on the east and west sides of the jetty respectively (Franklin et al., 2021). Various measurements have been undertaken to counteract the significant erosion west of the port. Geotextile groynes, submerged breakwaters and sand bypasses have been attempted, with varying degrees of efficacy. Generally, researchers indicate that a re-orientation of the jetties would be most effective. This would increase the bypassing, solving the sediment deficit west of the port (Franklin et al., 2021).

Figure 2.3: Current satellite image of Sisal, with view of the fishing port and the induced erosion-accretion pattern (Google LLC, 2024)

The coastal system of Sisal exhibits a high degree of spatial variability. The western coastline is characterised by a steep scarp system, with a high level of vegetation on top of the scarp. The eastern coastline instead has a dune system, which is highly dynamic. This variability has large implications for the resilience of the coastline at a local level, with resilience often being defined as: *"the ability of a system to prepare, resist, recover and adapt to achieve functional performance under adverse events such as storms and sea-level changes"* (Committee on Increasing National Resilience to Hazards and Disasters, 2012).

The eastern system exhibits a high degree of spatial variability, with vegetation coverage and the presence of anthropogenic perturbations varying significantly across transects. Particularly the presence of coastal structures such as palapas, the breakwater and the pier influence the profiles along the eastern coastline. These are indicated to have a negative impact on the coastal resilience according to diverse methodologies (Mendoza et al., 2022), (Torres-Freyermuth et al., 2021).

2.1.5. Climate characteristics

Sisal, located along the Gulf of Mexico, faces growing climate challenges, particularly due to sea level rise and intensifying storms. The region experiences a tropical savanna climate with distinct wet and dry seasons (Peel et al., 2007). The wet season, from May to October, brings increased humidity, precipitation, and tropical storms and hurricanes. During the dry season, cooler and more stable conditions occur.

Rising sea levels pose serious threats to Sisal's coastal ecosystem, particularly mangroves, wetlands, and dune systems (Fernández-Díaz et al., 2022; Kidwell et al., 2017). Increased inundation and saltwater intrusion endanger these habitats, reducing their capacity to provide essential services like coastal protection (Martínez et al., 2008; M.L. et al., 2001). The erosion of dune vegetation, a natural barrier against coastal flooding, further rises vulnerability to storm surges and long-term shoreline retreat (Zhang et al., 2004).

The Yucatán Peninsula's vulnerability to tropical storms and hurricanes is exacerbated by climate change, with more intense and frequent storms affecting the region (C. Appendini et al., 2019; Mudd & Bradbury, 2020). Powerful storms can increase erosion, cause habitat destruction, and put local infrastructure, tourism, and fishing at risk (Fernández-Díaz et al., 2022; Weissenberger & Chouinard, 2015). Additionally, the seasonal phenomenon known as *"El Norte"* brings strong winds and cooler air from North America, impacting temperatures and increasing wave action along the coast. For a detailed analysis of Sisal's climate and climate change impacts on its environment, see Appendix J .

2.2. Problem statement

As described in the socio-economic, coastal, and climate context, natural and anthropogenic perturbations have caused great changes to Sisal's coastal system. These changes greatly impact the resilience of the coastline, which in turn has significant consequences for the local community. Studies have been conducted using various resilience index formulations to assess the performance of Sisal's coastline in light of shocks and stresses. The well known USACE Coastal Resilience Index utilises beach parameters and water levels, highlighting the negative influence of coastal structures (Torres-Freyermuth et al., 2021). This has also been indicated through aerial photogrammetry data, which has been applied to formulate the Coastal Resilience Index from Remote Sensors (CRIfRS) (Mendoza et al., 2022).

Although these methods provide good indications of resilience, their assessment is only as powerful as their definition. Both indicators only consider the current state of the coast, not taking historical trends or variability of the system into account. Furthermore, as with many coastal indices, there is no consideration for the social aspects of resilience. Due to the inherent connection between a coastal community and its coastline, it is important to assess how a coastal community can "cope successfully with substantial danger" (Al-Manji et al., 2021). Finally, it is important to consider the limitations of resilience indices regarding future predictions. Most indices, including those applied to Sisal, are completely inadequate for future assessments. This is dangerous in light of a changing climate, with rising sea levels and more frequent storms to be expected in the region.

The complexity of the discussion on coastal resilience is exemplified by the number of unique formulations. An overview study conducted by Masselink et al. (2019) identified numerous definitions. They highlighted that depending on the scholar, resilience is considered to contain morphological, ecological, socio-economical, engineering, community and even psychological components. Considering these overlapping definitions, they proposed resilience as *"the capacity of the socioeconomic and natural systems in the coastal environment to cope with disturbances, induced by factors such as sea level rise, extreme events, and human impacts, by adapting whilst maintaining their essential functions"* (Masselink & Hughes, 2003).

This vast collection of varying definitions and methodologies makes it increasingly difficult to communicate the resilience of a coastal system between stakeholders. The ambiguous nature of the term leads to issues when striving to improve performance through collaborative projects or strategies. This confirms the necessity for effective communication strategies regarding coastal resilience, and the acknowledgement of its multi-faceted nature.

2.3. Objectives

This research project aims to address the knowledge gap described in the problem statement by conducting a study on multi-faceted performance characteristics of resilience, regarding both Sisal's coastal system and its community. The project aims to reach this objective by conducting a multidisciplinary study that assesses resilience according to technical conditions, stakeholder perspectives and future projections. This study therefore aims to answer the following main research question:

How can the multi-faceted nature of resilience be understood in the context of Sisal's coastline?

The technical analysis will focus on a stretch of the Sisal coastline according to the available data. Coastal state indicators such as beach width and dune height will be combined with rates of coastline movement to describe the physical profiles of the beach systems over time. These parameters will be extracted from both measured transects as well as satellite images.

A 1D model for future coastline changes is developed, utilizing historical data for model calibration and validation. This model aims to analyze observed shoreline trends and behaviour from a hydrodynamic perspective, allowing an understanding of the physical processes driving these patterns for the future, while at the same time validating the capacity of the trends obtained. Additionally, the model will enable exploration of alternative scenarios to assess potential variations in coastal behavior.

As for this project, focus will be placed upon the coastline position and the characteristics of the coastal profiles to assess the vulnerability and resilience of the coastal system of Sisal. The study aims to assess the vulnerability of the coastal area to sea-level rise and other coastal hazards, by utilizing the USGS Coastal Vulnerability Index. However, a shortcoming of this method is its lack of capacity to assess coastal quality differences over a relatively short distance, such as the scope of this study. Therefore, this research project aims to define a new resilience index that accurately measures the capacity of the coastline to withstand and adapt to coastal hazards between short distance intervals. The index combines the aforementioned coastal state indicators and value parameters into a single resilience index for Sisal's coastline.

Additionally, as the definition of resilience is multi-faceted, research on social, economic, and infrastructural impacts is performed to acquire an understanding on the perspectives of stakeholders in Sisal. This social research intents to study Sisal's history of environmental decline, current coastal management strategies and future development plans to gain an insight on the effect of human interventions and policy decisions on the coastal system. Ultimately, aiming to comprehend the influence that this has on community and coastal resilience.

The insights on the multi-dimensional aspects of resilience will subsequently be integrated into a list of recommendations for future studies. Consequently, this list is intended to provide relevant information for researchers of the coastal engineering department of UNAM to enable them to advance this research and potentially address any identified issues.

Finally, the study aspires to build a robust online web tool that effectively presents the multi-dimensional definitions of resilience in a clear manner. The dashboard should present various definitions of resilience and vulnerability, taking into account both technical and social observations. This online dashboard can subsequently be used by coastal engineers of UNAM in the future. The tool can aid the observation of coastal resilience in Sisal, and spark discussions about coastal management strategies.

3 Methods

3.1. Available Data

The construction of the web tool relied on effective integration of various datasets, maps and stakeholder input. Many of the required datasets were available via UNAM, such as the beach transects, drone images and tidal gauge. Satellite images were available through the open source google earth cloud platform. Stakeholder specific data had to be identified during the project through interviews and literature review. Apart from stakeholder data, the project did not require significant new information. Instead, the method has focused on successfully integrating and processing all available data to develop an accurate resilience index.

Due to the presence of the UNAM campus in Sisal, there was significant historical data on the region. The datasets cover a broad spectrum of hydraulic, morphodynamic, and geological parameters. The project team also participated in a number of UNAM's regular field campaigns to gain deeper insight into the natural system and the methodologies used for the data collection.

The following data is of significant importance to the project, and has been used to analyse the coastal behaviour. Table 3.1 provides an overview of all datasets utilised throughout the method, and their specific function.

Data Set	Aquired?	Obtained through	Purpose
Cross-shore elevation profiles	Yes	GPS measurements	Coastal indicators
Drone images	Yes	Drone flights	Palapa construction
Satellite images 1985 - present	No	CoastSat & GEE	Coastline movement
Sea level near Sisal	Yes	ERA 5 Station	Sea level rise
Historical wave data	Yes	ERA 5 Station	1D Model
S-Phi Curve	No	CERC Formula	1D Model
Storms	Yes	NOAA Database	Storm Impact

Table 3.1: Overview of all datasets, indicating how they have been measured, and how they will be utilised

Profile Data

Researchers at UNAM have conducted observations of the coastal cross-shore morphology across transects east and west of the port of Sisal. Using GPS and altitude measurements, coastal profiles were determined for 20 transects in the 2km west domain and 20 transects in the 2km east domain. The measurements have been conducted with a spatial resolution of 100 meters between transects. Figure 3.1 shows the exact measurement locations.

The measurements are carried out by walking with a GPS differential antenna. The measurements are corrected using a local reference point which remains stationary at a fixed point on the beach. The field

campaign is performed every two weeks, and started in 2015 and 2019 for the east and west domains respectively.

The profile data has been used to extract coastal profile indicators for the east and west domains. These provide valuable insights regarding the evolution of the coastline, specifically indicating changes in the cross-shore profile.

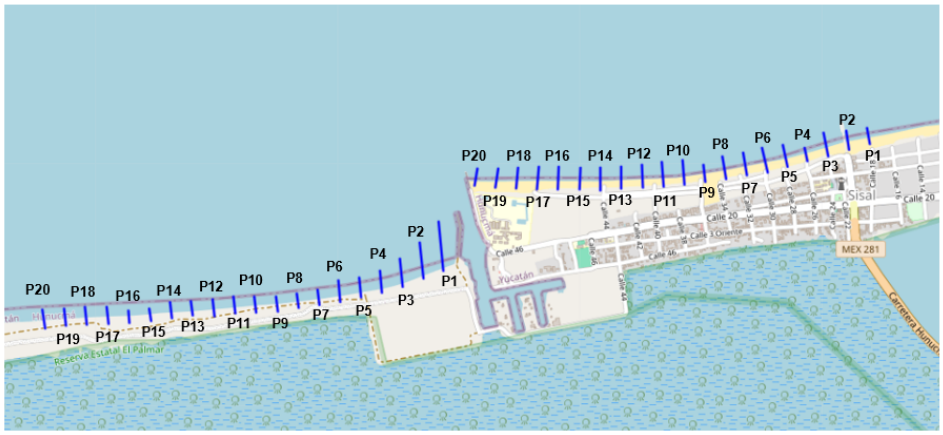


Figure 3.1: Locations of cross shore transects along the east and west domains of Sisal.

Drone data
Since 2020, UNAM has been performing drone flights which can obtain high resolution images and elevation data. In the context of this project, the drone images have been analysed to obtain information on coastal developments, specifically the construction of palapas. By analysing these images, it is possible to determine where and when palapas are built, with the potential to assess their impact on coastal change.

Satellite Images
Historical satellite images are available through the CoastSat toolbox and the open source Google Earth Engine (GEE) cloud platform. These provide a visual indication of changes to Sisal and its coastline over time. For this research project, the satellite images have been used to analyse the change in coastline position. Satellite images allow for an extension of the domain in space and time, by assessing a larger stretch of coastline for a longer period than via cross-shore transects.

The resolution and frequency of the available satellite images is specific to the operating satellite. During the considered period between 1985 and 2024 (present), images from Landsat 5, 7, 8, 9 and Sentinel 2 satellites were available for analysis. Generally the most recent satellite missions (Landsat 9 and Sentinel 2) have the highest resolution and imaging frequency. However for the purpose of this research, images from all available missions were extracted.

Historical wave data
The ERA5 analysis station near Sisal provided critical wave data, capturing significant wave height, peak period, and wave direction every hour over a comprehensive 40-year period from 1984 to 2024. This data set offers high-resolution insights into the wave climate in the region, allowing for detailed analysis of long-term patterns and trends. This facilitated building the S-phi curve and understanding the hydrodynamics of the area.

3.2. CoastSat Analysis

To extend the spatial and temporal domain of the coastal analysis, satellite images of the Sisal coast can be processed using CoastSat, which is a python based open source shoreline mapping toolbox (Vos et al., 2019). Using the CoastSat toolbox, shoreline positions have been extracted from Google Earth Engine (GEE) satellite images, thus allowing for the change of shoreline position to be computed over a larger domain. According to (Vos et al., 2019), shorelines can be extracted with an accuracy of

10 meters, yet the obtained rates can be validated by comparing to those obtained from the transect measurements. Figure 3.2 provides an overview of the image processing workflow in CoastSat.

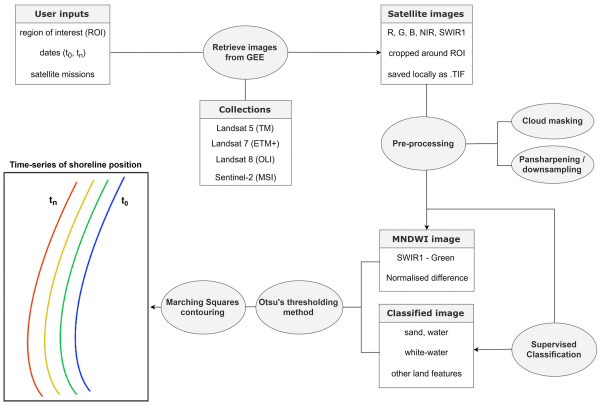


Figure 3.2: Flow chart outlining the data processing in CoastSat (Vos et al., 2019).

Considered Domain and Shoreline Detection:
The enlarged domain consists of a 4.5 km stretch of coastline west from the port of Sisal, as well as an eastward stretch extending 5.5 km from the port. This extended domain covers the entire urban region of Sisal, as well as portions of the El Palmar and Estatal natural reserves. The domain is visualised in figure 3.3.

Satellite images have been extracted over both domains, running from 1985-09-01 till 2024-09-01. This was done using the local epsg: 32615, a bright sand colour, a minimum beach area of 1000 m^2 and a minimum beach length of 2000 meters. All other settings were kept standard. After filtering for duplicates, bad georeferencing, cloud cover and other errors, 743 shorelines have been detected for the west domain and 613 for the east domain. Due to the incorrect detection of the mangroves, many images had to be removed manually. Table 3.2 provides an overview of the filtering process, meanwhile figures 3.4 and 3.5 visualize the filtered coastlines over time.

Figure 3.3: CoastSat West and East Domain

	West Sisal	East Sisal
Domain Length	4.5 km	5.5 km
Dates Considered	1985/09/01 - 2024/09/01	1985/09/01 - 2024/09/01
Satellites Considered	L5, L7, L8, L9, S2	L5, L7, L8, L9, S2
Total Images Available	3144 (Landsat Tier 1 & S2)	3644 (Landsat Tier 1 & S2)
Initial Filter	694 duplicates, 14 bad geo ref	714 duplicates, 15 bad geo ref
Manual Filter	Kept: 748	Kept: 670
Identified Shorelines	743	613
Created Transects	49	56

Table 3.2: Overview of satellite image processing, shoreline detection and transect creation for extended west and east domains.

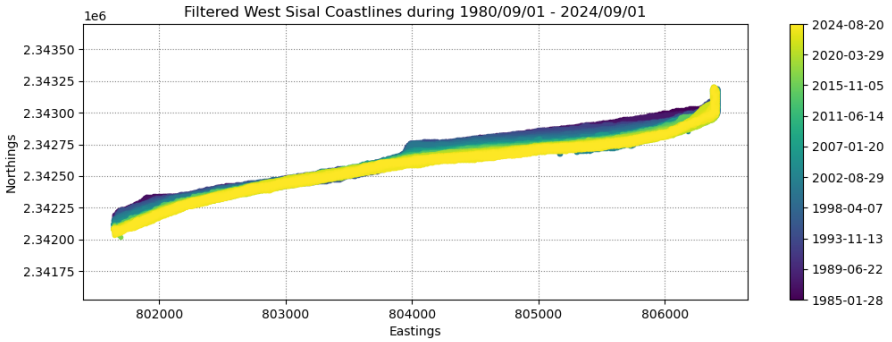


Figure 3.4: Filtered CoastsSat West coastlines from 01-09-1985 till 01-09-2024

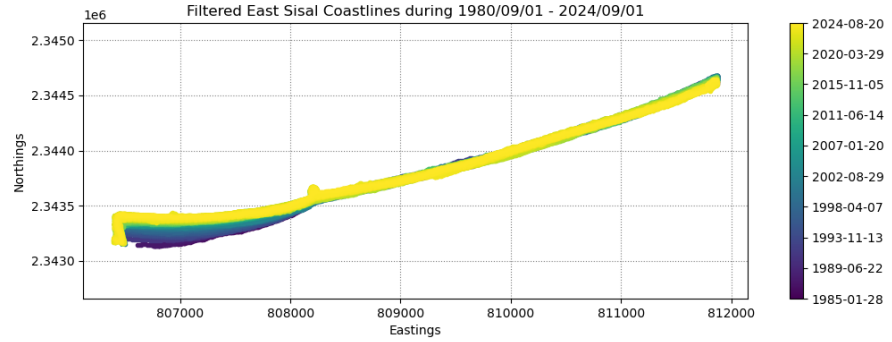


Figure 3.5: Filtered CoastSat east coastlines from 01-09-1985 till 01-09-2024

Transect Generation

To assess the movement of the shoreline over time, transects must be defined. Artificial transects have been generated with a resolution of 100 meters relative to a predefined reference coastline. This gives a total of 49 transects for the west domain, and 56 for the east. The plotted transects are shown in figures A.2 and A.1 in Appendix A. With the the transects defined, it is possible to extract the shoreline movement. This has been done by determining the intersection between the identified shorelines relative to the generated transects. Then, a linear interpolation can be performed through the data giving a rate of shoreline change in meters per year. The final rates are presented in chapter 4.

Satellite Co-registration through Arosics

The utilised set of images is gathered from a range of satellite missions. Constructing a signal from different (satellite) sensors can lead to geospatial misregistrations, significantly distorting the time series. To avoid this, it is vital to align all images with a reference point, using a co-registration process (Scheffler et al., 2017). The arosics python package automates this process, allowing for large databases to be shifted automatically.

Despite this, the arosics algorithm generated incorrect shifts for the given collection of satellite images. The step has therefore been omitted from the method. This effect is illustrated in figure 3.6, which shows the time series of coastline position for a transect in the east domain. As shown in the figure, numerous data points in the shifted signal are significantly displaced relative to the original. Although the shifts are intended to align the images stemming from different satellites, the inverse appears to happen. Different satellites are shifted away from each other, particularly in the most recent decade of images. The reason for this incorrect shift may be due to the lack of constant reference points within the domain. Arosics relies on these points to shift all images in the time signal.

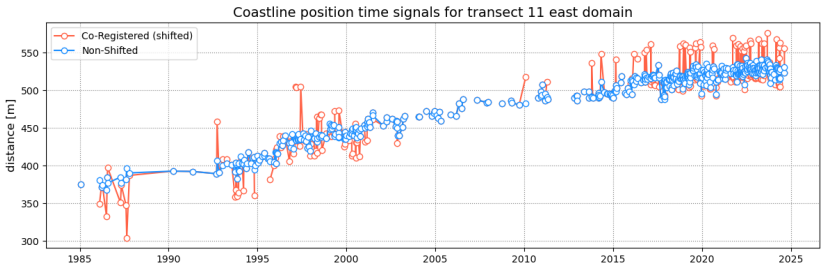


Figure 3.6: Coastline position time signals for transect 11 in the east domain, comparing the effect of the Arosics co-registration shifts.

Tidal Correction

Performing a tidal correction is another required post-processing step. Due to the oscillating waterline, the tide influences the detected shoreline position. To ensure the actual shoreline position is detected, it must be corrected by removing the apparent changes from tidal fluctuations. This is done using:

- 1.) The ERA5 tidal time-signal for Sisal from 1985 till present.
- 2.) An average beach slope of 0.1% (Mendoza et al., 2022).

An example of the tidal correction is shown for the west domain in figure A.3 in appendix A.

3.3. Coastal indicators

In order to visualize the coastal behaviour of Sisal in a comprehensive manner, the actual behaviour of the system must be understood first. One of the goals of this project is to visualize the coastal vulnerability and resilience of the region. This is done using the USGS coastal vulnerability index and by analysing different coastal indicators. The indicators are investigated separately, but are also combined to formulate a coastal resilience index, specific for the eastern coastal stretch. This is further explained in section 3.5. Defining clear and insightful coastal indicators is crucial to construct a robust framework for a resilience index.

3.3.1. Separation of East- and West-side

It is chosen to treat the east and the west side of the port of Sisal separately due to two main reasons. First, there is a distinct difference in dune-beach system between the two sides. On the east side, average beach profiles show a small dune, protecting the hinterland. On the west-side however, it is a steep scarp that protects the hinterland against high water levels and storm surges. Contradictory to the eastern dunes, the maximum elevation of this scarp is often high enough to protect against high water levels. However, the scarp toe can be exposed to storm surges, leading to a collapse of the scarp and a retreat further land inwards of the coastal profile.

The second reason is incomplete data for the west side of Sisal's port. Due to the scarps steep slope, it is often impossible to measure along the entire length of the profile, leading to gaps in the data. Often, the measured profile starts on the sea-facing slope of the scarp, resulting in incomplete profile and missing key indicators, such as maximum dune/scarp elevation.

The beach on the west side is considered to extend from the scarp toe to the waterline. For the eastern profiles, the beach is defined as the area from the first measured point up to the waterline, capturing the entire measured profile. This approach is chosen due to the high cross-shore variability of the eastern profiles. Because of this high variability and the presence of berms, foredunes and other features, the written algorithm to define the dune/scarp toe is not as effective for the eastern domain as it is on the west side. Therefore, it is not possible to define the beach width form the dune toe to the waterline.

This also applies to the dune (or crest) height. Due to the the profiles' variability and sensitivity to disturbances, foredunes or berms can be formed within days (or even hours), often with a higher maximum elevation of the primary dune. Defining beach width from the point of maximum elevation to the water line would lead to abrupt changes in this indicator, as the point of maximum elevation can move drastically. Because the first point of measurement on the East side is fixed, defining the beach width from this point to the waterline provides a more stable basis for comparing the indicators over time and avoids large variations due to algorithmic errors.

3.3.2. Key parameters

Before the coastal indicators can be extracted from the profile data, two key parameters must be determined. These are the water line point (for both east and west) and the scarp toe (for the west domain).

The waterline point

The waterline points is the point where the elevation is 0 meters compared to Mean Sea Level. This location needs to be obtained for every profile in order to compute coastal indicators such as shoreline retreat/advance and beach width. The waterline point is obtained using a python script that interpolates between the smallest positive and the smallest negative value of elevation, returning the exact point where the elevation is 0 meters. Figure 3.7 shows the waterline point for a typical beach profile of the east domain.

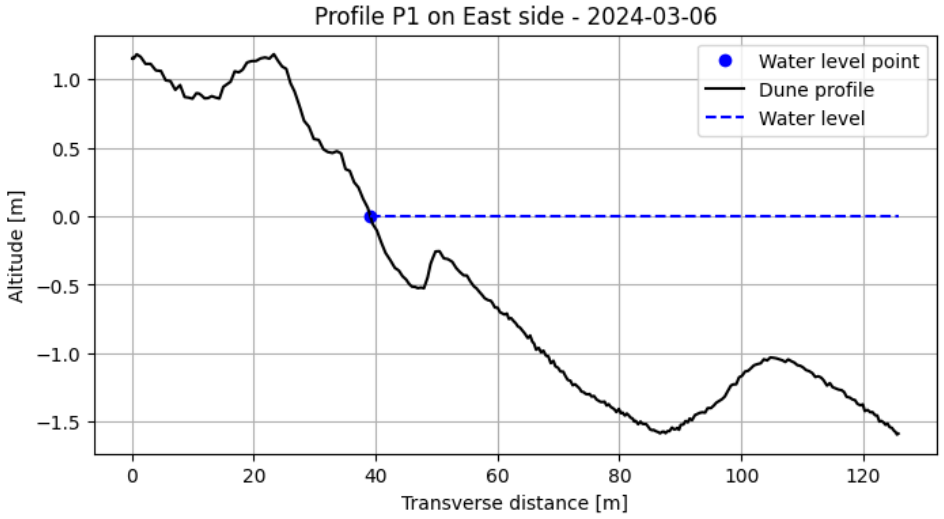


Figure 3.7: Cross-shore profile P1 on east side, with water level point and water level indicated in blue at an elevation of 0 meters.

The waterline point is also used to compute shoreline changes over recent years. Since the construction of Sisal's port, there has been a drastic change in the shoreline east- and westwards of the port (Franklin et al., 2021). The shoreline advance/retreat rates are important variables in order to describe the coastal behaviour and the associated resilience quality.

To quantify the shoreline changes, a linear regression model is fit to the historical data of this waterline point across the available time span. The results are presented in the web-tool and in the next chapter.

Scarp toe (West Sisal)
A lot of research has been performed to automatically define the scarp/dune toe of a dune/beach system. The computation of such an algorithm can be difficult and time consuming. Often, the algorithms contain a large error and can only be used for specific coastal stretches with similar characteristics. (Beuzen, 2019) did an analysis on different methods to compute a dune toe. It was found that an algorithm that uses machine learning performs best. However, due to time constraints and complexity, such an algorithm is out of this research's scope.

The algorithm used to define the scarp toe for the west-side profiles is based on the maximum curvature and similar to the method of maximum curvature used by (Beuzen, 2019), but it has been optimized and calibrated for the considered domain. First, a significant number of interpolation points are added to reduce sharp angles between points of the profile. Secondly, the interpolated profile is smoothed out using a moving average. The value for the moving average window is calibrated, resulting in a value of 150. After smoothing the profile, the 'search window' of the scarp toe is further specified to avoid that the algorithm captures an incorrect point. The scarp toe is then defined as the point with the maximum curvature of the smoothed profile, within the specific search window. The curvature of the line is calculated using the formula:

$$\text{curvature} = \frac{\frac{d^2 z}{dx^2}}{\left(1 + \left(\frac{dz}{dx}\right)^2\right)^{1.5}}$$

Note that this algorithm is not entirely precise and does come along with errors. However, it generally captures the scarp toe accurately, making it a useful addition to this research, especially in estimating trends of the scarp toe.

3.3.3. Coastal Indicators West Sisal

Key coastal indicators defined to analyse the coastal vulnerability of the Sisal's western located coast are:

- Scarp toe elevation
- Scarp toe location
- Beach width
- Mean Beach elevation

Figure 3.8 below shows a typical cross shore profile on the west-side of Sisal's port.

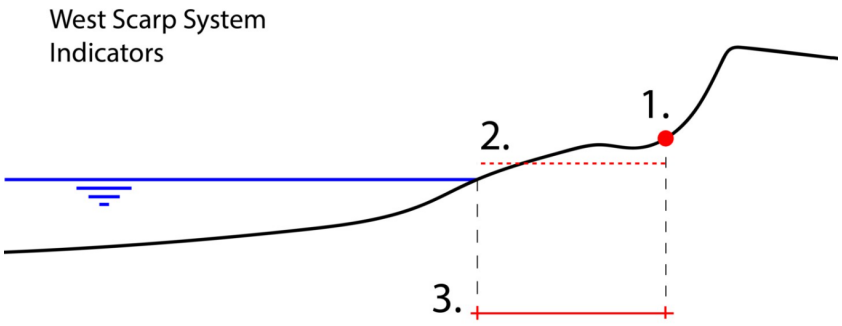


Figure 3.8: Typical west cross-shore profile with identified coastal indicators: 1. Scarp toe 2. Mean elevation 3. Beach width

Scarp toe elevation

The elevation of the scarp toe provides direct information about the vulnerability of the coastal system against high water level and storm surges. A higher elevation of the scarp toe corresponds with a lower probability of it being impacted by storms. When high water levels and wave run up does not reach the scarp toe, the scarp is unlikely to collapse, indicating a low vulnerability. However, relying only on the scarp toe elevation can be misleading. For example, a collapsing scarp can lead to positive trend in the scarp toe elevation. This might suggest a resilient beach, since the elevation of the scarp toe is increasing. Yet, in reality, the scarp toe is moving land inwards, resulting in an irreversible erosion process. Therefore, tracking the location of the scarp toe, and especially the trend of its movement, provides a more valuable indicator of coastal resilience.

Scarp toe location

The trend of the location of the scarp toe gives clear insight in the irreversible erosion process occurring westwards of Sisal's port. The rate at which the scarp toe moves land inwards serves as a strong indicator of the western coast's resilience. The faster the scarp toe moves land inwards, the greater the amount of land loss to the sea, reflecting the reduced ability of the coast to recover. Resulting in a lower resilience for that specific coastal stretch.

Beach width

The beach width for the western profile is defined as the transversal distance from the scarp toe to the water line. This beach width is an important indicator, because it acts as a buffer zone between the ocean and the inland areas. A wider beach generally offers more protection, as it can absorb more energy and can accommodate larger volumes of sand before it reaches critical parts of the dune or structures (Masselink & Hughes, 2003).

Mean beach elevation

This indicator gives direct insight in how much a beach is elevated above water level, as it influences how well the beach can absorb wave energy, especially reducing damage from storm events. A higher mean elevation generally provides more buffer against these external forces. (Dong et al., 2018) have also used this coastal indicator in their research on coastal resilience, although it is referred to as protective elevation. The beach elevation has been estimated using the trapezoidal rule. This is done by computing the subaerial cross-sectional area of the beach, from scarp toe to water line, divided by the beach width.

3.3.4. Coastal Indicators East Sisal

Key coastal indicators defined to analyse the coastal resilience of the Sisal's eastern located coast are:

- Maximum elevation
- Mean Beach elevation
- Beach width

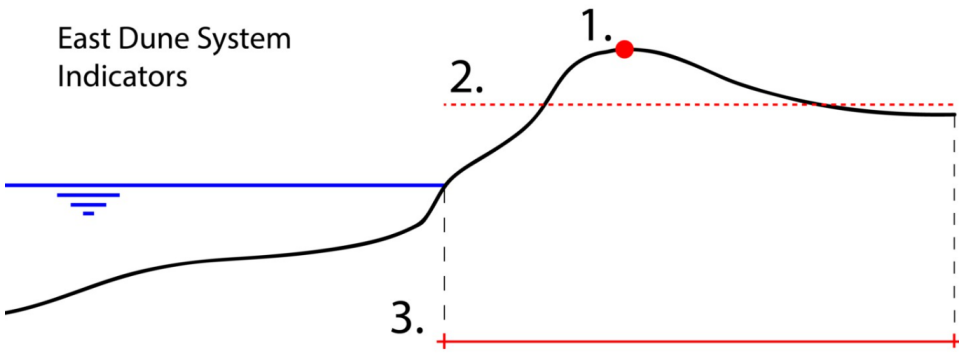


Figure 3.9: Typical east cross-shore profile with identified coastal indicators: 1. Max (dune) elevation 2. Mean elevation 3. Beach width

Maximum beach elevation The maximum elevation is simply defined as the maximum elevation of the profile. This is an important indicator because the maximum elevation acts directly as a barrier against external forces, such as high water levels, storm surges and wave impacts. The maximum elevation also influences the amount of overrash events, potentially resulting in erosion of the protective dune. Therefore a high maximum elevation typically suggests a higher resilience (U.S. Army Corps of Engineers, 2013).

Beach width For the east side, the beach width is considered from the first point measured up to the waterline. See Figure 3.9. The explanation can be found in the previous subsection.

Mean beach elevation

As for the west side of Sisal, the beach elevation is an important coastal indicator. For the east side, the mean elevation is computed by deciding the subaerial cross-sectional area of the beach, from the first point to the water line, by the beach width (See figure 3.9).

3.3.5. Implementation of indicators in web tool

In the web-tool the indicators can be visualized in their current state. In other words, the absolute dune height, beach width and other parameters are presented at the date of the most recent measurement. Secondly, it is chosen to visualize the historical behaviour with a simple linear trend line. This method may not give the best fit, but it is an intuitive indicator that can be communicated with other parties. The trend of the indicators also plays an important role in defining a coastal resilience index. This is explained in chapter 3.5.

3.4. USGS Index

The USGS Coastal Vulnerability Index is used to asses the potential coastal vulnerability against the effect of sea-level rise, storm surge and other coastal disturbances. The index has been constructed by USGS (1999), and is similar to that used by (Gornitz et al., 1994), as well as to the sensitivity index employed by (Shaw et al., 1998).

The index allows the six physical variables to be interpreted in a quantifiable manner:

a. Shoreline erosion/accretion rates [m/yr]

b. Geomorphology [-]

c. Coastal slope [%]

d. Relative Sea-level rise [mm/yr]

e. Mean Tidal range [m]

f. Mean Wave height [m]

For each section of coastline, each variable (a-f) receives a risk index depending on its value, where a value of one indicates low vulnerability and five high vulnerability. The total vulnerability index is then formed by taking the square root of the product of the ranked variables divided by the total number of variables:

$$\text{CVI} = \sqrt{\frac{a \cdot b \cdot c \cdot d \cdot e \cdot f}{6}}$$

Considering the beach-dune system of Sisal, the spatial domain of the system is smaller than the domain over which many parameters in the USGS index vary. The geomorphology, mean sea level rise, mean wave height and mean tidal range can all be considered constant for both the 4 km domain (measured profiles) and the 10 km domain (CoastSat analysis). Coastal slope does tend to vary spatially and temporally, however, for ease of analysis this is also assumed to be constant. The exact values for these parameters are the following:

a. Shoreline erosion/accretion rates: **varies per coastal stretch**

b. Geomorphology: **Barrier Beaches** (Mendoza et al., 2022)

c. Coastal slope Varies between 0.05% and 0.15%, here an average of **0.1%** is taken (Mendoza et al., 2022)

d. Relative Sea-level rise: A sea-level rise analysis using the UNAM Tidal Gauge is performed. This resulted in a sea-level rise of **4.51 mm/year**. The SLR-analysis is presented in Appendix G.

e. Mean Tidal range: Ranges from **0.15m to 1.15m** for neap and spring tides respectively (Medellín et al., 2021)

f. Mean Significant Wave height: The mean significant wave height for this region is estimated by analysing ERA5 measurements data. This data contains values for significant wave heights measured from 1985 up to 2024. This resulted in a mean significant wave height of **0.78 meters**

Figure 3.10 shows the ranking of coastal vulnerability per index variable. Homogeneous variables are indicated in bold for the Sisal domain.

Ranking of USGS Coastal Vulnerability Index					
VARIABLE	**Very Low**	**Low**	**Moderate**	**High**	**Very High**
	1	**2**	**3**	**4**	**5**
Heterogenous variables:					
Shoreline erosion/accretion [m/yr]	> 2.0 (Accretion)	1.0 – 2.0	-1.0 – +1.0 (Stable)	-1.1 – -2.0	< -2.0 (Erosion)
Homogenous variables:					
Geomorphology	Rocky, cliffed coasts	Medium cliffs	Low cliffs	Cobble beaches	**Barrier beaches**
Coastal Slope [%]	> 0.2	.2 – .07	.07 – .04	.04 – .025	**< .025**
Relative sea-level change [mm/yr]	< 1.8	1.8 – 2.5	2.5 – 2.95	2.95 – 3.16	**> 3.16**
Mean tide range [m]	> 6.0	4.1 – 6.0	2.0 – 4.0	1.0 – 1.9	**< 1.0**
Mean wave height [m]	< .55	**.55 – .85**	.85 – 1.05	1.05 – 1.25	> 1.25

Figure 3.10: Ranking used to define the USGS Coastal Vulnerability Index, adapted from(USGS, n.d.).

Despite the erosion/accretion rates being the only variable parameter in this area, the USGS remains a powerful index to use. With satellite data, the domain can be expanded relatively easily, allowing access to locations with different geomorphological variables. Additionally, this index is used in more studies, making it possible to compare values with other coastlines.

3.5. East Sisal Resilience Index

The east Sisal Resilience Index (SRI) has been developed to consider the high spatial variability of the coastal system due to anthropogenic perturbations. It follows the definition by (Committee on Increasing National Resilience to Hazards and Disasters, 2012), quantifying Resilience as *"the ability of a system to prepare, resist, recover and adapt to achieve functional performance under adverse events such as storms and sea-level changes."*. This is done by assessing the coastal profile indicators, considering the mean state of their time signal, as well as their trend and variability.

Formulation

The formulation is given below, where the mean value of an indicator is defined as the 'ability to prepare', referring to the level of protection which the profile gives on average. The variability of the time signal quantifies the 'ability to resist', indicating how the cross-section responds to perturbations. This is computed by taking the standard deviation of the de-trended time signal. Finally, the (linear) rate of the

indicator describes the 'ability to recover' for a specific profile. Positive rates describe growing profiles, suggesting that the profile has capacity to recover after a system shock. Meanwhile negative rates suggest a low recovery capacity. The total formulation is therefore defined as:

$$\text{Resilience} = \text{Ability to Prepare} + \text{Ability to Recover} + \text{Ability to Resist} \tag{3.1}$$

To apply this method using the aforementioned coastal indicators, it is required to sum the values into a single weighted index. This is first done for each individual indicator, as shown in equation 3.2. The weights have been calibrated such that the mean state of the indicator ('ability to prepare') has a relatively high impact on the profile's resilience. Second comes the rate ('ability to recover'), and finally the lowest weight is given to the variability of the signal ('ability to resist'). This has been done to ensure that profiles with poor mean profile characteristics are always given a low level of resilience.

$$RI_{Indicator,x} = 0.5 * Index_{\text{mean, x}} + 0.3 * Index_{\text{rate, x}} + 0.2 * Index_{\text{std, x}} \tag{3.2}$$

To scale the relative 'performance' of the mean, rate and variability indices, a rating is given from one (not resilient) to five (very resilient). Here a high mean state or large rate is considered resilient. For variability this is inverse, as low levels of variability indicate resilience. To determine the boundaries for these ratings from one to five, the 10th, 30th, 70th and 90th percentiles are computed for each index using the values of all 20 east transects. Table 3.3, provides an overview of this process.

Class	**Not Res.** **1**	**Slightly Res.** **2**	**Average** **3**	**Resilient** **4**	**Very Res.** **5**
Mean	X < 10th	10th < X < 30th	30th < X < 70th	70th < X < 90th	X > 90th
Trend	X < 10th	10th < X < 30th	30th < X < 70th	70th < X < 90th	X > 90th
Variability	X > 90th	70th < X < 90th	30th < X < 70th	10th < X < 30th	X < 10th

Table 3.3: Overview of relative percentages used for determining the index given to the mean, trend and variability of coastal indicators

The above process has been performed for all indicators for the east domain in Sisal. This assesses the relative performance of time signals of the maximum dune height, mean elevation and beach width for all 20 transects. The change in shoreline position has been considered indirectly, due to this being captured in the rate of the beach width indicator. With the relative performance of each indicator being quantified, it is possible to construct a total resilience indicator that considers the performance of all indicators per transect. This has been done by computing a weighted sum of each indicator from equation 3.2, dividing by the total number of indicators. Equation 3.3 presents this formula. The weights have been chosen to favour maximum (dune) and mean elevation, with beach width receiving less influence. Elevation generally has a larger impact on resilience, as wide beaches are still easily inundated by high water levels.

$$SRI_{transect,x} = 0.45 * RI_{\text{max dune height, x}} + 0.35 * RI_{\text{mean elevation, x}} + 0.2 * RI_{\text{beach width, x}} \tag{3.3}$$

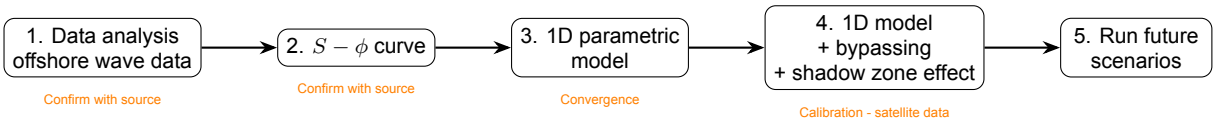
3.5.1. Comment on west side

The Sisal resilience Index (SRI) has been constructed using the available indicators and data for the beach dune system east of the port. During the development an attempt was made to apply the method to the west domain, however this was not possible due to two reasons:

1. The west domain is characterised by a scarp system. This obstructs the measuring of the entire profile, as researchers cannot easily reach the top. This leads to a lack of (maximum) elevation data.
2. The scarp toe is a critical parameter for assessing the resilience of the system. Furthermore, all indicators (beach width, mean elevation) have been defined relative to this parameter. Despite this, the detection algorithm is not always able to correctly identify this feature from the measured profiles. Therefore, the analysis would not yet be deemed accurate for assessing the west system's resilience.

3.6. 1D Model

To be able to assess the future behaviour of the shoreline a 1D model is proposed. The process for building this model requires several steps that were followed. These steps are shown on the following flow chart and explained later on this section.



3.6.1. Wave Data Analysis

Wave data was obtained from an offshore monitoring station operated by UNAM, covering a 40-year timeframe from 1984 to 2024. This dataset was utilized to analyze the long-term wave climate of the location.

Validation of the data was achieved by cross-referencing the findings with historical wave roses from earlier studies conducted in the area. The significant wave height averaged approximately 0.7 meters, with the predominant wave direction falling between 50 and 60 degrees from north and a mean wave period of 4 seconds. Comparisons with the results of (C. M. Appendini et al., 2012) indicated a similar pattern. The alignment between the current dataset and historical records, affirmed its reliability as a representative source of wave conditions for the study region.

In figure 3.11, the results of the wave data analysis is presented:

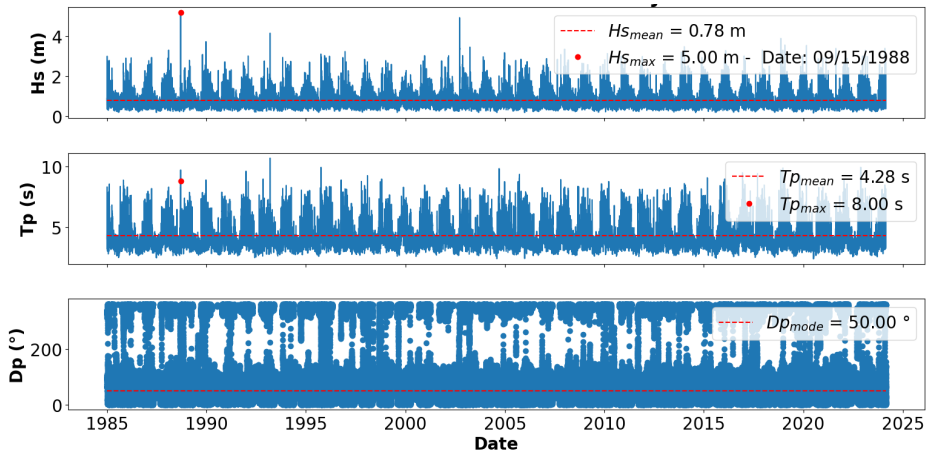


Figure 3.11: Wave data behaviour

3.6.2. Building the $S-\phi$ Curve

To characterize the relationship between sediment transport rate, S, and wave incidence angle, ϕ, a $S-\phi$ curve was constructed. This curve is fundamental for assessing how wave direction impacts sediment transport along the coastline. The $S-\phi$ behaviour observed in this study was compared to the $S-\phi$ curve from a previous study conducted in Progreso, where a similar wave climate and beach

orientation were present (C. M. Appendini et al., 2012). The orientation and order of magnitude in this study were similar to those in the Progreso study. However, the constructed curve in this research, showed a rightward displacement, indicating that equilibrium transport (where $S = 0$) occurs at an incidence angle closer to 20 degrees. This shift is reasonable, as the dominant wave direction in this case was approximately 50 degrees, rather than 0 degrees as seen in the Progreso study. In terms of magnitude the calibration comes later with the 1D model and satellite images, but it ends in an order of magnitude coherent with literature as well.

The estimation of sediment transport was based on the Coastal Engineering Research Center (CERC) formula as explained on (Bosboom & Stive, 2023):

$$S = \frac{K}{32(s-1)(1-p)} H_s^2 c_b \sin(2\phi) \tag{3.4}$$

where:

- S is the sediment alongshore transport rate,[m3/yr]
- K is an empirical coefficient,
- H_s is the deep water wave height,[m]
- ϕ is the angle of wave approach relative to the shore-normal.
- c_b is the celerity of the wave at breaking point,[m/s]
- s is the relative density of the sediment ,
- p is porosity,

It is important to note that the $S - \phi$ curve represents an annual mean behaviour, assuming constant wave action along the coast and over the bathymetry. While this assumption does not fully capture the variability present in natural conditions, it has proven effective as a first approximation. Initial values for the sediment transport coefficient K were derived from existing literature, with calibration adjustments made based on field data to improve accuracy.

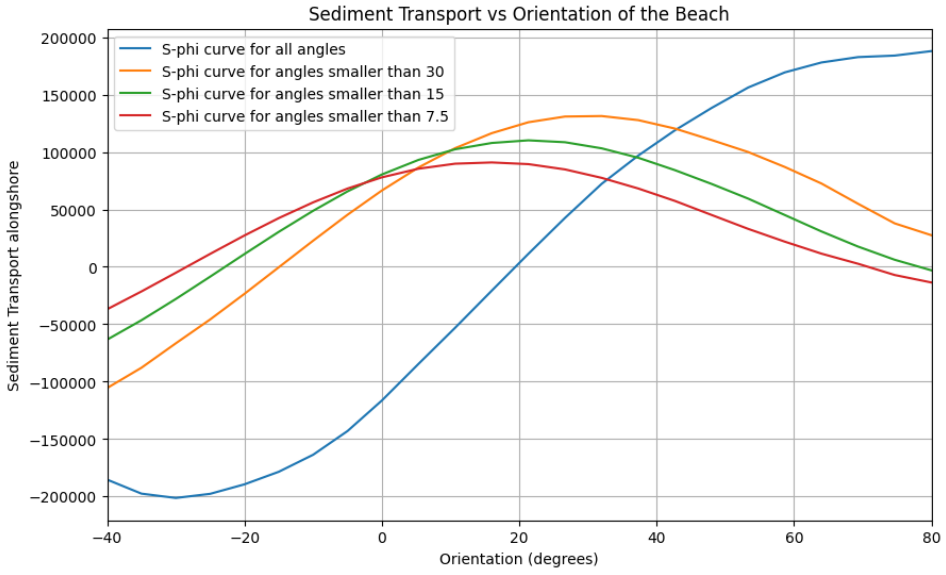


Figure 3.12: S-phi curve including for all the angles and shadow zone iterations

3.6.3. Development of the 1D Model

The 1D model was developed using single-line theory as described in the (Bosboom & Stive, 2023) book by TU Delft. This approach simplifies the coastline morphology to a single line representing the average shoreline position over time. The single-line theory equation is expressed as:

$$\frac{\partial y}{\partial t} = -\frac{\partial S}{\partial x}\frac{1}{d} \tag{3.5}$$

where:

- y is the shoreline position,
- t is time,
- S is the alongshore sediment transport rate,
- x is the alongshore distance,
- d is the closure depth, [m]

This theory provided a simplified, yet realistic representation of shoreline changes due to the rate of change of alongshore sediment transport and the depth of closure. The main assumptions of this model is that the alongshore transport is dominant, or that the cross-shore transport is neglected and the the closure depth is two times the maximum wave height(Hallermeier, 1978).

To ensure convergence, an explicit method was used to discretize the differential equation governing sediment transport. While explicit methods are computationally simpler, they are also more prone to instability, which posed challenges when implementing conditions such as bypassing and shadow zone effects. To mitigate these instabilities, a grid resolution of 25 meters was selected in the x-direction. This finer grid spacing allows for more accurate computation of smaller angles and helps prevent oscillations or instabilities that could arise from abrupt changes in the sediment transport rate.

3.6.4. Shadow Zone Effect

A shadow zone effect was incorporated to account for the reduction in sediment transport rates in areas shielded by the breakwater. For this purpose, separate $S - \phi$ curves were developed to represent the expected sediment transport within the shadow zone, where wave energy is lower and sediment transport rates are reduced. The effect of the shadow zone can be observed on 3.13. This adjustment captured the complex sediment dynamics in areas affected by the breakwater's shadow, generating lee side accretion next to the breakwater that was not observed before the shadow zone effect and present a realistic behaviour of the erosion.

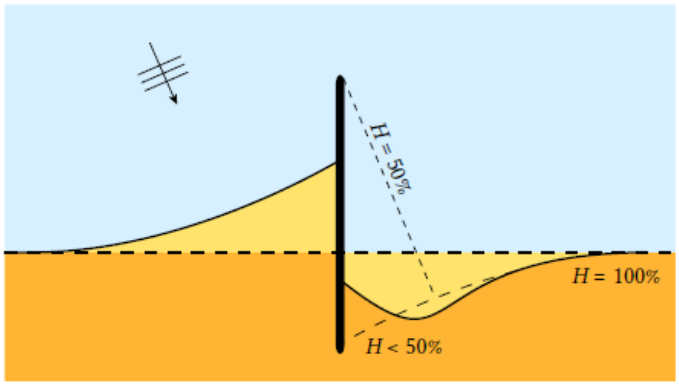


Figure 3.13: Shadow zone effect caused by a vertical breakwater

This is a dynamic process due to the erosion rates that is present throughout the years, the more erosion the bigger the shadow zone effect. Nevertheless, in this case the shadow zone effect was

accounted for the initial grid and then maintained static in the same position through the effect in time. The curves built for the shadow zone are shown in figure 3.12.

3.6.5. Bypassing

It was required that the model represents bypassing for better results over time due to the fast accretion of the breakwater and the physical observation of the constant blocking of the access channel due to bypassing. This can also be observed on the following figure 3.14, where the model without bypassing continues to accrete and erode even after the breakwater is full, simulating a non real behaviour.

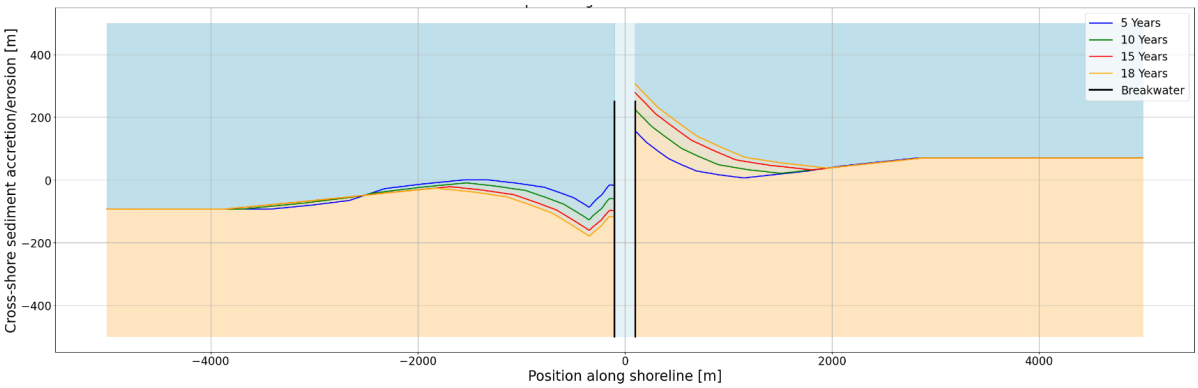


Figure 3.14: 1D model results without bypassing

Therefore, now the model accounted for the potential bypassing of sediment around the breakwater as the coastline accreted seaward over time. Initially, it was assumed that the breakwater would entirely block sediment transport, preventing any bypassing. However, as the coastline advanced towards the breakwater, an increasing amount of bypassing was anticipated. Specifically, the model set bypassing to 0 when the coastline reached a position halfway along the length of the breakwater. As accretion continued and the coastline extended to the end of the breakwater, the model projected that bypassing would increase to a complete bypassing with a linear rate. This approach allowed for a gradual and realistic transition in sediment movement around the breakwater, reflecting the progressive impact of coastal accretion on sediment transport.

$$Bypassing factor = \frac{Yposition - L/2}{L/2} \tag{3.6}$$

where:

- Y: Shoreline position at the breakwater,
- L: Length of the breakwater,

This progressive bypassing factor allowed the model to dynamically represent bypassing as the shoreline advanced seaward. This factor will allow to the Sediment transport to communicate and then let Alongshore transport pass from one side of the model to the other.

3.6.6. Calibration with Satellite Images

Calibration was conducted using satellite images covering an 18-year period since the construction of the port in Sisal. The span of time for the calibration is from 1984 to 2003. These images provided data on historical shoreline changes, which were essential for refining model parameters. The empirical coefficient K in the CERC formula was adjusted to match observed shoreline changes, ensuring that the model accurately reflected real-world sediment transport and shoreline evolution. The value used for K was 0.4.

In the figures 3.15 and 3.16, the coastlines resulting from the model are presented in comparison to the actual value of the shoreline 18 years after the port was built.

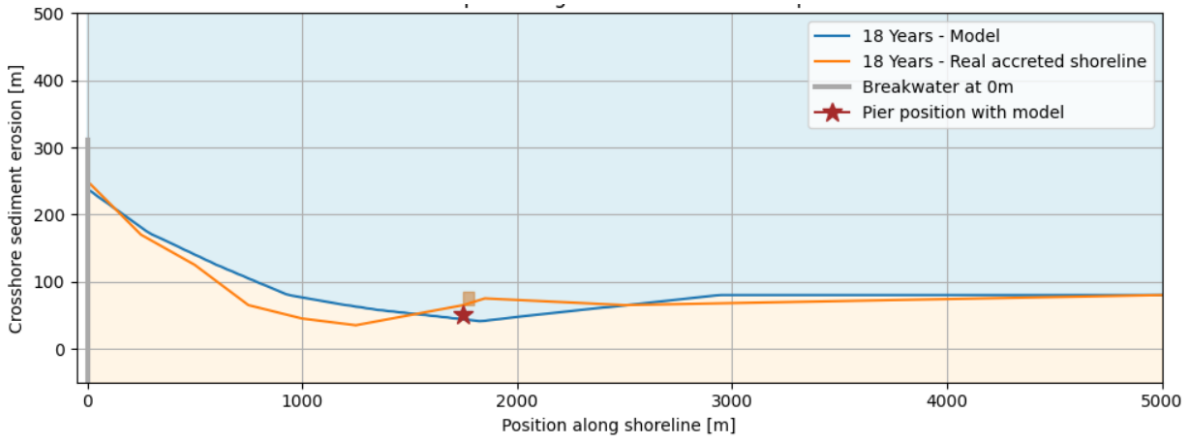


Figure 3.15: Calibration results for the shoreline - Accretion side

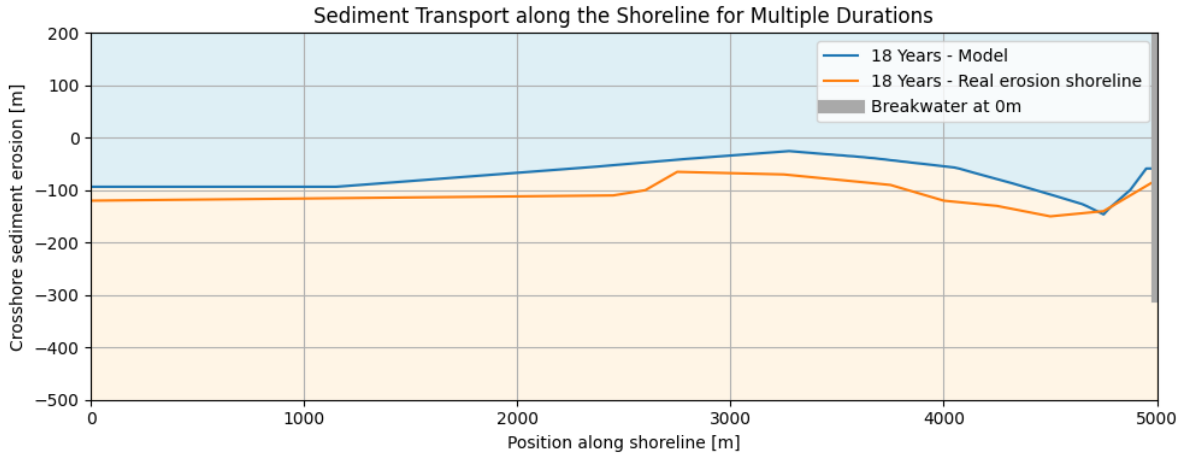


Figure 3.16: Calibration results for the shoreline - Accretion side

For the calibration, three main characteristics were examined: the shoreline position adjacent to the breakwater, the peak values of accretion and erosion, and the spatial extent of shoreline change. This metrics are chosen after observing the behaviour of the model and what information can give us.

In Figure 3.15, a close fit is achieved for all three characteristics on the accretion side. However, there is a notable difference in shape near the pier: the real accreted shoreline shows less erosion at this location, likely due to sediment nourishment and reduced sediment transport caused by the structure. This discrepancy aligns with expectations and does not indicate anomalous behaviour in the model.

On the erosion side, as shown in Figure 3.16, the model demonstrates a less precise fit. While the maximum erosion and the length of the shoreline affected are well-represented, the modelled shoreline shape diverges to some extend from observed data. Despite these differences, the model still provides a reliable approximation for this region.

3.6.7. Future Scenarios

Following calibration, the model was used to simulate two future scenarios over a 20-year period:

1. **Current Breakwater Configuration:** Projected shoreline evolution with the existing breakwater configuration, length of brekwater of 300 m.
2. **Extended Breakwater Configuration:** Projected shoreline evolution with a breakwater of 600 m, double the current length.

These projections provide insights into the potential long-term effects of different breakwater configurations on sediment transport and shoreline morphology. The time horizon was chosen because it is a similar timeline as the calibration, and the starting point is the shoreline from 2024.

3.7. Storms Analysis

The impact of tropical storms on the coastal morphology of Sisal are assessed by analysing changes in five key indicators: maximum altitude, mean elevation, dune toe position, waterline position, and subaerial volume. Transect data were collected before and after each storm event to capture storm-induced morphological changes.

Relevant tropical storms were identified using the NOAA Historical Hurricane Tracks Database, focusing on events within a 100-mile radius of Sisal to ensure local relevance. Key storms include Delta, Gamma, Zeta, Grace, Harvey, Franklin, and Milton. Six storms events were analysed for the east side and four for the west side.

For each storm, the closest transect measurements taken before and after the storm event were used to assess changes in the coastal indicators. This approach ensures that the observed changes are primarily due to the storm's impact. Both individual transect results and averages for each side were computed and analysed to detect localized responses and broader patterns.

3.8. Social Research

The governance of a socio-economic system (SES), like Sisal, is an important aspect for coastal management, as effective coordination between organizations in coastal governance is required to enhance climate resilience Rölfer et al., 2024. Governance can be viewed as "the complex system of regulation involving the interactions of a wide variety of actors, institutions, the environment and all types of socio-institutional arrangements at different territorial levels" (Heslinga et al., 2019), where collaboration and information exchange are crucial for successful and effective decision-making and management (Rölfer et al., 2024).

Thus, gaining an understanding on the norms, values and relationships of relevant stakeholders within the governance system of the project's scope serves as valuable information to communicate the results of the technical research in an effective manner. Stakeholder analysis is a useful method to enhance the understanding of governance arrangements, as it results in this valuable information (Heslinga et al., 2019). Furthermore, collaborating with or engaging stakeholders within the process has many benefits, as it enables discussion, promotes learning and increases the credibility of the project's outcome (Awah et al., 2024).

The following section delves into the various methods of social research that have been performed to gain a better understanding on the actors involved in the project's scope. The results of the social research are presented in section 5.

3.8.1. Interviews

Acquiring an insight in the norms, values and relationship of all stakeholders involved in the coastal management of Sisal can not solely be done via a literature review. Opinions within a community often vary and information on individuals with a lesser presence in the system's network is regularly difficult to find or validate online, especially in a small, rural area, like Sisal.

Conducting interviews with various members of the community with different background and relations to the research is an effective method to gather this information, as interviews offer the opportunity to look beyond policy assumptions or top-down decisions, to examine how these play out in the lives of those affected by the policies and whose experiences might otherwise be overlooked or ignored (Knott et al., 2022).

Interviews can be structured, semi-structured and unstructured, ranging from short to long. In this research, the semi-structured interview was chosen, as it is more intimate, flexible and open than a fully-structured interview (Mendoza-González et al., 2021), while still providing the basis to make interview results comparable.

During the interview, interviewees were asked about their connection to Sisal, their knowledge on Sisal's recent economic and coastal development, their relationships with other identified stakeholders, their opinion on the importance of specific components of Sisal's (coastal) system, and their thoughts on the future. Interviews were conducted in English and Spanish, both in-person and online. Interviews were carried out in a semi-structured manner, with the use of a predetermined template of nine questions.

3.8.2. Identifying relevant stakeholders

It is necessary to identify relevant stakeholders that are able to provide a valuable contribution to the research, before any results can be obtained to address social characteristics related to this project. Stakeholders can be seen as individual and group representatives with values, beliefs, norms and capacities, (potentially) with different connections to the project scope (Lyon et al., 2020). Thus, stakeholders have a varying capability to contribute effectively to the project's outcome. It is therefore important to draw boundaries for which stakeholders are identified, but to also understand that these boundaries can have a significant impact on the result (Lyon et al., 2020).

Stakeholders can be selected based on their norms, values, connection to the project, and their level of agency. Agency is described as 'the capacity of individual and collective actors to change the course of events or the outcome of processes' (Rölfer et al., 2024). Stakeholders with a high level of agency are therefore important actors, as their influence can lead to the transformation to effective and sustainable coastal management.

Key actors were identified using the non-probabilistic sampling method known as snowball Mendoza-González et al., 2021, where talks are held with initially contacted stakeholders related to the project. Brainstorming and discussion with these stakeholders subsequently lead to identifying additional individuals and organizations, who in term provide other connections. The initial stakeholders mainly consisted of individuals closely related to the coastal engineering department of UNAM, Sisal. Other initial stakeholders have been identified via literature study.

3.8.3. Stakeholder classification

A subsequent step in the analysis of stakeholders is the categorization of identified actors. A method to achieve this is to distinguish the conceptual role of a stakeholder within a (complex) system, as this allows for a more thorough understanding and description of the organization or individual (Lyon et al., 2020). Stakeholders have an objective role, but in addition to that, also perform distinct functions or influences on the system. Evaluating and understanding the role and agency of stakeholders within networks can facilitate effective governance, thereby enhancing the resilience of a socio-economical system (Rölfer et al., 2024).

Furthermore, analysing the roles of relevant actors against key system roles identified by literature can provide valuable insight into a system's characteristics. For instance, realizing that a system lacks a fundamental role, or has several in abundance, can lead to strategies to develop better system management (Lyon et al., 2020).

(Lyon et al., 2020) describe a total of eight key stakeholder roles in a complex system. These roles, and their definition, are presented in table 3.4. After all interviews were conducted, the identified stakeholders (see section 3.8.2) were categorized into these eight roles to gain a better understanding of their function within the coastal management system of Sisal.

Power and Interest grid

The classification of identified stakeholders into the aforementioned key roles give an understanding of the level of power and influence of an organization or actor within the system. Yet, it does not provide insights into a stakeholder's relative system influences in comparison to other identified actors. This data can be assessed by developing a power and interest grid.

A power and interest (P&I) grid is a helpful method to understand the relationship between the stakeholder and the system in which it resides, particularly in terms of how their relative influences come into practice (Lyon et al., 2020). The grid shows how relevant stakeholders within the scope act on matters within the system. This enables a different method to classify identified stakeholders into various categories of interest and power, giving valuable context on how to manage them.

System role	Definitions
Regulator	Makes the rules and sets the standard for how they are managed.
Decision-maker	Holds a key visible or hidden, formal or informal decision-making ability that influences different parts of the system.
Guardian	Performs monitoring, evaluation, and enforcement functions to maintain system functioning with sufficient authority and trustworthiness.
Owner	Performs control functions but may not directly decide or guard the system.
Advocate	Promotes certain functions or potential functions in the system.
Catalyser/Blocker	A catalyser instigates or stimulates actions, while a blocker inhibits.
Winner/Loser	Winners benefit from the system, losers are disadvantaged without adaptation.
Seller/Buyer	Engages in financial or market-based exchanges within the value chain.

Table 3.4: Stakeholder roles within a complex system, as described by (Lyon et al., 2020).

The P&I-grid elaborates on a stakeholder's relative influence in comparison to other identified actors on the x-axis. The y-axis presents a stakeholder's level of power. Subsequently, the axes are categorized into four quadrants, each representing a stakeholder management strategy. This was first done by Freeman in 1984, categorizing the four quadrants into Monitor (bottom left), Keep informed (bottom right), Keep satisfied (top left) and Manage closely (top right) (Chigona et al., 2010), as presented in figure 3.17. Several variations of the four categories have been developed since, however, Freeman's original categorization is used in this report.

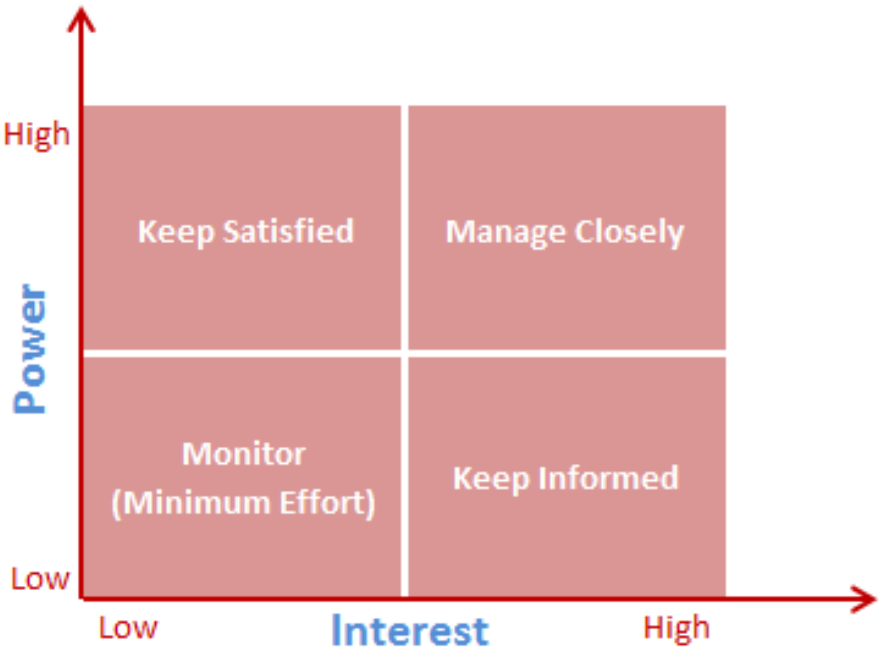


Figure 3.17: Example of P&I-grid, developed by Freeman in 1984 (Thamma, 2023)

3.8.4. Communication network

It is important to examine the communication patterns and relationships between identified stakeholders within a network, as it helps to better understand governance arrangements (Heslinga et al., 2019). Knowledge exchange and relationships between stakeholders are an important part within a social network to achieve goals, as relationships between stakeholders can enable or constrain the sharing of benefits. Furthermore, communication is a crucial component to achieve effective stakeholder inclusion (Heslinga et al., 2019). However, even though communication between organizations involved in coastal governance is crucial to enhance climate resilience, the understanding of the level of information exchange between stakeholders within coastal governance issues is still poor Rölfer et al., 2024.

Information on the effectiveness of communication and the level of coordination between stakeholders is valuable, since these are crucial preconditions for the development of improved collaborative interactions. These interactions are an important factor to develop effective coastal governance (Heslinga et al., 2019). Thus, gaining an understanding on the relationships and communication between relevant stakeholders within Sisal's community serves as an important analysis.

A method to acquire such information is a social network analysis (SNA), as it can reveal potential hidden vulnerabilities within the network, facilitates strategy development (Rölfer et al., 2024) and helps in understanding the dependencies and relationships between actors. Ultimately, this method allows for the analysis of stakeholder's behaviors and their impact on the network as a whole over time (Tabassum et al., 2018).

The data needed for the SNA has been gathered via a literature review and semi-structured interviews (as described in section 3.8.1). Interviewees were asked about the existence of information exchange with other identified stakeholders, how frequent these interactions were, and how effective they deem the communication to be. The social network was subsequently visualized in Gephi, as this software allows for various modeling methods and provides a broad arrange of parameters to present results.

3.8.5. Stakeholder priorities

Research on the relationships between actors gives valuable information on the information exchange between organizations and individuals within a community. This information is valuable to investigate communication patterns and potential vulnerabilities, as it could lead to strategies to build synergetic interactions of high potential. However, it is important to understand that managing these relationships in complex (coastal) environments can be difficult. An important factor that contributes to this complexity is the diverse and sometimes conflicting values, interests and attitudes of stakeholders within the network (Heslinga et al., 2019). In other words, conflicts can emerge within the governance of interactions in the network, because each organization or individual will likely pursue their own preferred outcomes (Heslinga et al., 2019). Identifying these preferences can therefore lead to a valuable insight for strategies or actions to improve the communication and relationships within the network.

However, it is often difficult to compare preferences, as they are likely specific and non-quantifiable. A method to compare preferences in a quantifiable manner can therefore give a valuable insight in the priorities of a large number of identified stakeholders.

Nevertheless, quantitative methods for network analysis to analyze coastal governance are still new and rare (Rölfer et al., 2024). Therefore, the interviews (as described in section 3.8.1) were used to gather quantifiable data on the preferences of identified stakeholders. During the interview, stakeholders were asked to rank several categories related to Sisal from 'most important' to 'least important', resulting in a numerical ranking. The results of these priority lists can subsequently be compared and categorized into various parameters, like occupation or background.

3.8.6. Stakeholder perspectives

A stakeholder network analysis and the identification of preferences of stakeholders give an important insight into the history, current state and short-term future of Sisal. However, the coming decade(s) will likely serve as an important point for the development of Sisal and its community, as the increase in tourism activities will expectantly have an effect on the (urban) development of the area.

The conversations during the interviews delved into the short-term future of Sisal, as the limited time

span served to be more tangible for interviewees. Nevertheless, interviewees' thoughts on the long-term future of Sisal can give an important insight into the values and attitudes of relevant actors. An approach that allows for the capturing of actors' long term perception in an unfiltered manner is the method of 'mental mapping' (Mittermüller et al., 2021). This method is a valuable tool to understand how interviewees view a specific subject, as it reveals an individual's mental reflection without the need to provide a lot of context (Frantál et al., 2017). The unfiltered approach of the method is important, as it can justify certain perceptions and preferences of people, that might not be disclosed otherwise. Thus, the method is potentially helpful for future planning and decision-making processes (Frantál et al., 2017).

Therefore, an additional question was added to conclude the semi-structured interviews. Interviewees were given a blank piece of paper and had to draw their vision of Sisal in 2070. The only requirement was that it had to be a two-dimensional map of Sisal, accurately reflecting the participant's realistic expectations. Apart from that, no context was given in order to promote the gathering of unbiased results. Whenever an interviewee seemed stuck in the process, slight nudges were given to inspire the drawer to think of specific components to add to their vision.

Elements of the mental maps were subsequently analyzed, as components of the mental map give an understanding on what a stakeholder considers to be important in a context, potentially providing data on a participant's reasoning to have a specific attitude towards the subject of the map (Frantál et al., 2017). Several aspects of the map can provide this insight, like the structure, inclusion or exclusion of elements, interrelation of features, content, style, and level of detail (Frantál et al., 2017). The analyzed mental maps were then categorized into various attributes of the interviewees and consequently compared to other mental maps.

3.9. Web-tool Interface

The web-tool has been built using Streamlit, an open-source Python library. Streamlit is designed to facilitate data visualization in an interactive way, including representations on maps, making at an ideal choice for this application. The python library enables developers to create interactive web applications with minimal coding, making it accessible for developers that have basic python experience. Interactive elements like buttons, sliders, text input and selection boxers, allow the user to control how data is visualized and analysed (Streamlit, Inc., 2024). Because Python is open source, and a relatively easy coding language, the code used to determine key indicators and analyses the raw data, can be easily modified for further or different analyses.

Code Management and Version Control

A GitHub repository has been created for this project, containing all the required code. The repository contains two branches; a development branch and a main branch. The first is used to construct and test the web-tool, allowing for iterative changes and new additions without affecting the 'working' version. The main branch is used to store a working version of the application.

The code for data analysis and web visualization has been separated as much as possible. This is done by organizing different processes into different notebooks and .py files. Additionally, the code has been written in such a way that the tool can be updated when new data is available. This allows the researchers at UNAM to easily upload new data, such as the measured transects or satellite data. Subsequently, incorporating new information within the tool.

Data Analysis

The algorithms used to define and analyse the key indicators have been designed to allow for future optimization and adjustment. In Python, a profile class is created to specifically handle the profile data. This profile class contains methods to define and return specific parameters and indicators present in a profile. Details of this class can be found in appendix I.

Web-tool Structure and Presentation

The main body of this web-tool shows an interactive map on which the user can visualize different data layers, such as shoreline advance/retreat rates, vulnerability/resilience indices and all the discussed coastal indicators. The user can select these layers using a selection menu on the left side of the

web-page. Additionally, the web-tool also contains a stakeholder and infrastructure map, showing the locations of critical stakeholders and infrastructure. Qualitative results from the social research are also presented on a dedicated page in the web-tool, making the tool valuable for a multi-disciplinary analysis.

Data exploration and Easy communication

The interactive nature of the tool will allow users to explore the data thoroughly, whilst also visualising indicators and indices in an intuitive way. The web-tool gives users a powerful dashboard to understand the coastal processes along the coast of Sisal, whilst directly observing their impact on vulnerability and resilience. It is important to mention that the tool can visualise a much wider range of results than presented in chapter 4, allowing users to make use of it for their own research.

4

Results - Coastal Analysis

4.1. Shoreline Position

Both the CoastSat and profile rates have been determined using transects taken with a resolution of 100 meters. This identical spacing allows the rates of each method to be compared per transect. Figure 4.1 and 4.2 show the shoreline advance/retreat rates for the west and the east sides of Sisal, respectively.

To properly compare the two methodologies, the CoastSat data has been resampled to match the range of dates for each profile campaign. The rates on the west side are calculated using the profile date beginning in 2019, while data for the east side is available from 2015 onwards. Comparing the results, it is clear that the CoastSat rates closely match the profile measurements. Significant erosion is observed on the west side, with retreat rates up to 5.7 meters a year. On the east side, the beach is accreting with rates up to 4.2 meters per year.

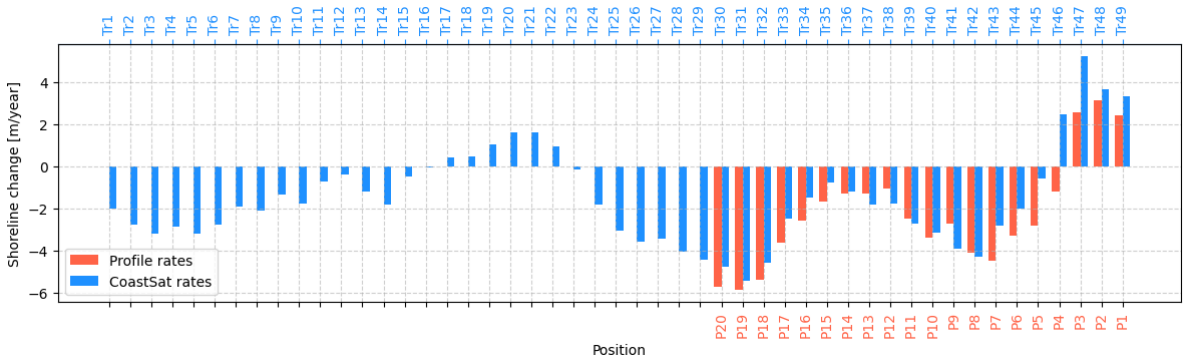


Figure 4.1: Rates of shoreline change in meters per year along the west domain, visualised per transect for both profile measurements (red) and CoastSat analysis (blue). Both methods indicate shoreline retreat west of the port.

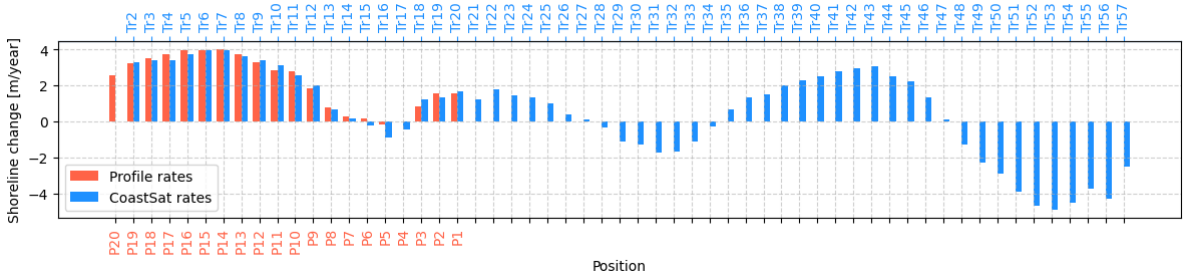


Figure 4.2: Rates of shoreline change in meters per year along the east domain, visualised per transect for both profile measurements (red) and CoastSat analysis (blue). Both methods indicate shoreline advance east of the port.

Figure 4.3: Shoreline advance/retreat from profile data vs satellite data

4.2. USGS Coastal Vulnerability Index (CVI)

Figure 4.4 shows the computed USGS coastal vulnerability index, using the shoreline rates computed from the measured transects. The result is as expected, and directly related to the shoreline retreat/advance rates presented in chapter 4.1. The results generally give the east domain a low vulnerability to the shoreline advance, meanwhile the west domain is considered more vulnerable due to the retreating shoreline. The considered domain can easily be expanded using the results from the CoastSat analysis. The web-tool facilitates the visualisation of both domains. Here it is also possible to visualize the indicator, taking a range of data for a specific time window. This procedure is elaborated more thoroughly in chapter 6.

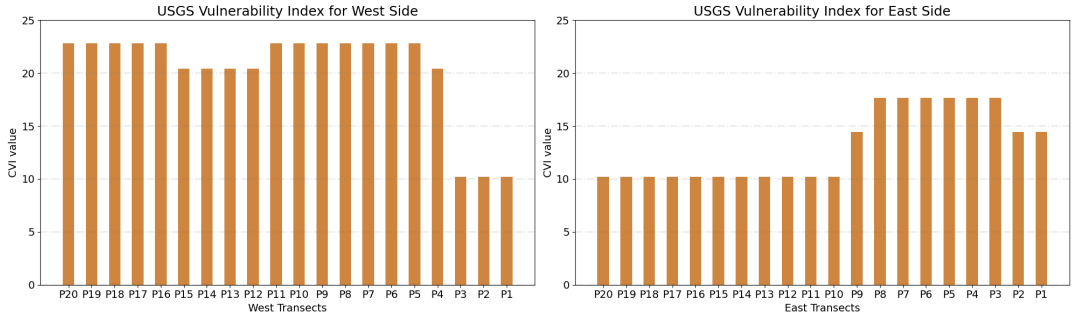


Figure 4.4: USGS Coastal Vulnerability Index computed per transect for the west and east domains, using the measured changes in shoreline position.

4.3. East Sisal Resilience Index (SRI)

The results from the Sisal resilience index are presented in figure 4.5. As explained in the method, first a resilience index is computed for each coastal indicator, taking into account its mean state, trend and variability. Then, the SRI is computed per transect, taking a weighted sum of the resilience values per coastal indicator. To gain a full understanding of the coastal performance, figure 4.6 presents the relative scores for all indicators along the east domain. The figure shows the performance per indicator for each aspect of the time signal, highlighting the individual performance of the mean state, linear trend and variability.

Summing the values from figure 4.6, the resilience index can be determined per coastal indicator. This has been done using the weights as specified in the method, giving the results as shown in the left of figure 4.5. The SRI can then finally be constructed for each transect along the east domain, illustrating the relative resilience of each transect in a single index. This final result is shown on the right of figure 4.5. The SRI values show that transects P20, P09, P04 and P01 are relatively least resilient. Meanwhile transects P14, P08 and P05 are most resilient.

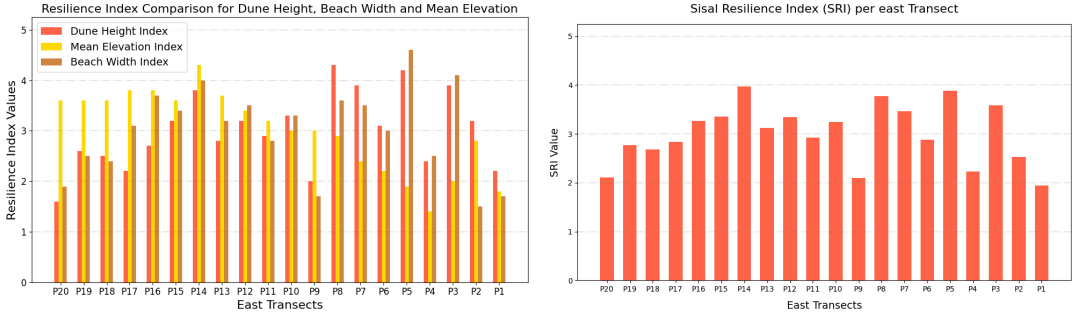


Figure 4.5: Left: Resilience index for each coastal indicator per transect. Right: Sisal Resilience Index (SRI) per east transect.

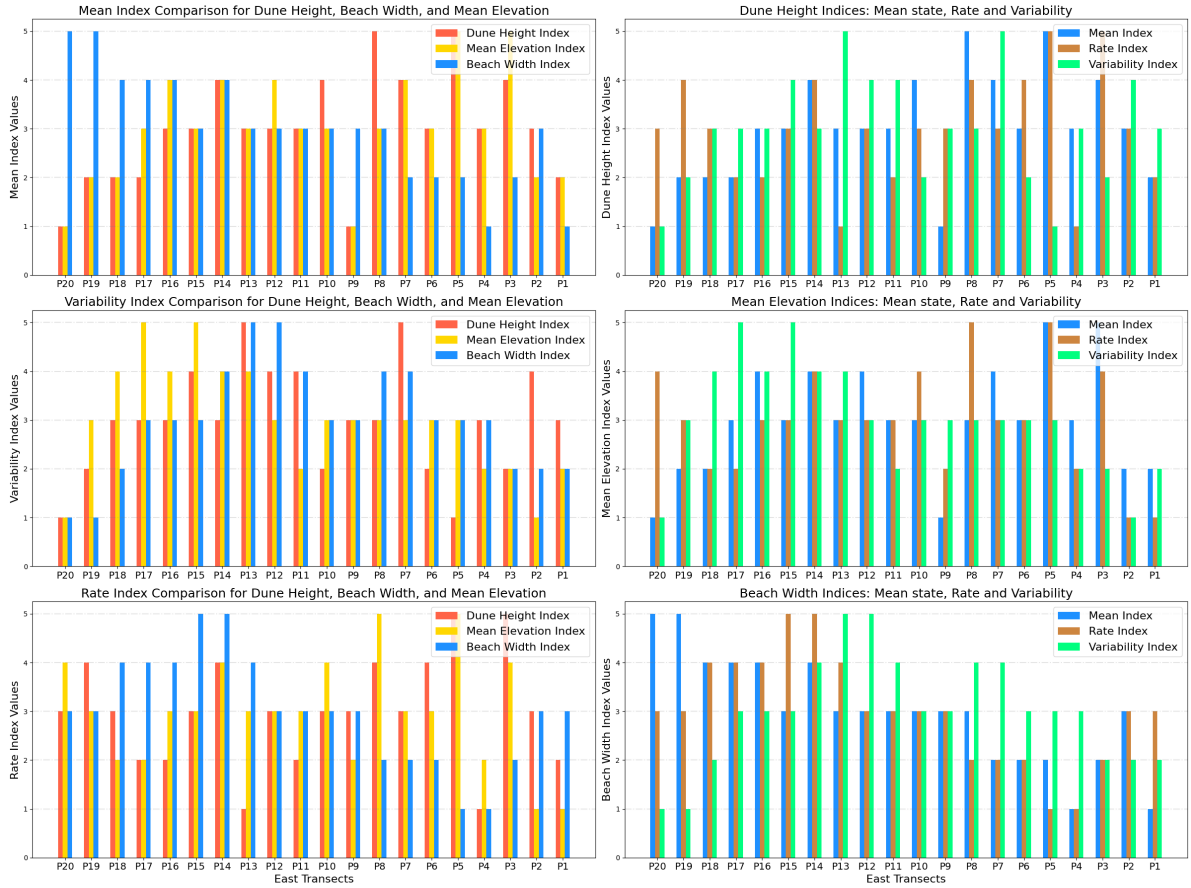


Figure 4.6: Overview of the relative performance per coastal indicator. Left column: Relative performance of the mean values (top), rates (centre) and variability (bottom). Right column: performance per coastal indicator, with the maximum elevation (top), mean elevation (centre) and beach width (bottom).

4.4. Coastal Behaviour of West Side

The behaviour of the coast westwards of Sisal's port is determined by analysing the defined coastal indicators separately, as it was not possible to obtain the SRI values for this part of the system.

The west side of the coastal system is marked by significant erosion, which has been present since the construction of the port in 1985. This erosion causes the entire profile to shift landward over time, without significantly altering the shape or characteristics of the profile. This is evident, for example, from the analysis of the linear trend lines of the scarp toe location in comparison to the shoreline advance/retreat rates, visualized in figure 4.7. These values closely align with each other. The difference between these two parameters corresponds to the trend in beach width change, as beach width is defined as the distance between the waterline and the scarp toe. Except from the profiles near the port (P02 - P04) and P12, the beach width shows no significant changes. The results will further be discussed in chapter 7.

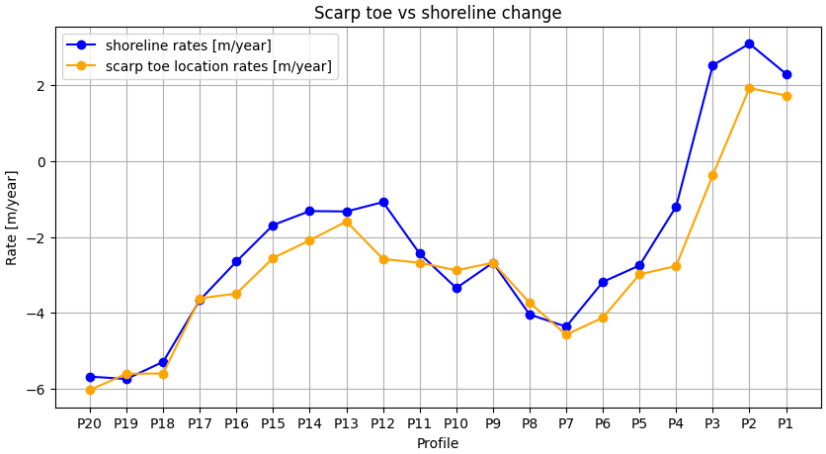


Figure 4.7: The scarp toe change compared to the shoreline change for the west side

Figure 4.8 shows the observed trend of the scarp toe elevation over the last five years. The scarp toe elevation shows a small increase across most profiles, with a more noticeable rate in a few specific cases. Most rates however, are relatively small, especially considering the error associated with the algorithm used to define the scarp toe.

Figure 4.9, shows the typical behaviour of a western cross-shore profile over time. It can be observed that the profile, including the scarp toe, moves land inwards. Also, the elevation of the scarp toe is visible in this figure.

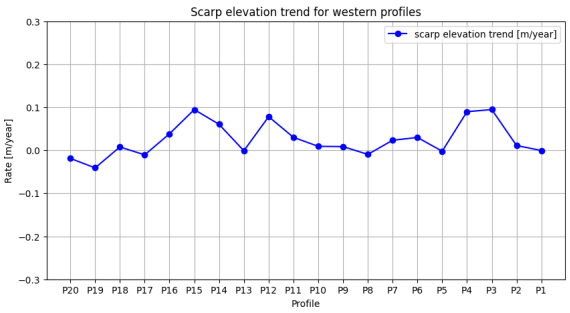


Figure 4.8: Scarp toe elevation results

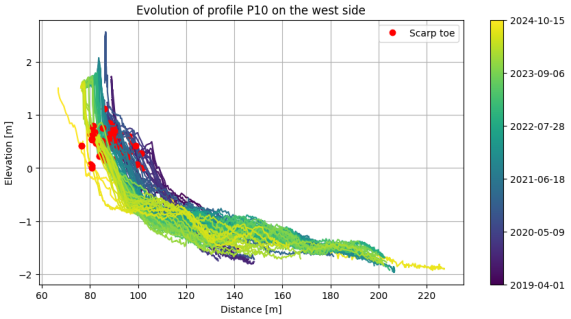


Figure 4.9: Typical scarp toe behaviour west side

Figure 4.10: Scarp toe behaviour

4.5. 1D Model Results

As mentioned before, there are two modelled scenarios. The variable that is going to be changed is the length of the breakwater. The first scenario (A) it is going to be the current length of the breakwater and the second one (B) the breakwater will have a double length.

4.5.1. Scenario A

This scenario has a breakwater length of 300m and the starting coastline is from 2024, extracted from satellite data.

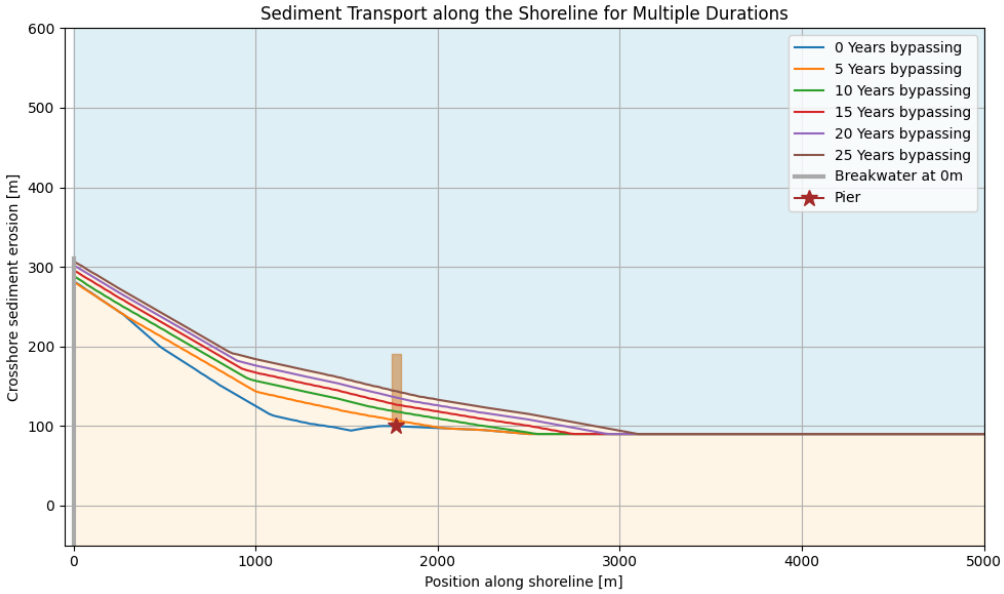


Figure 4.11: Scenario A - Accretion side

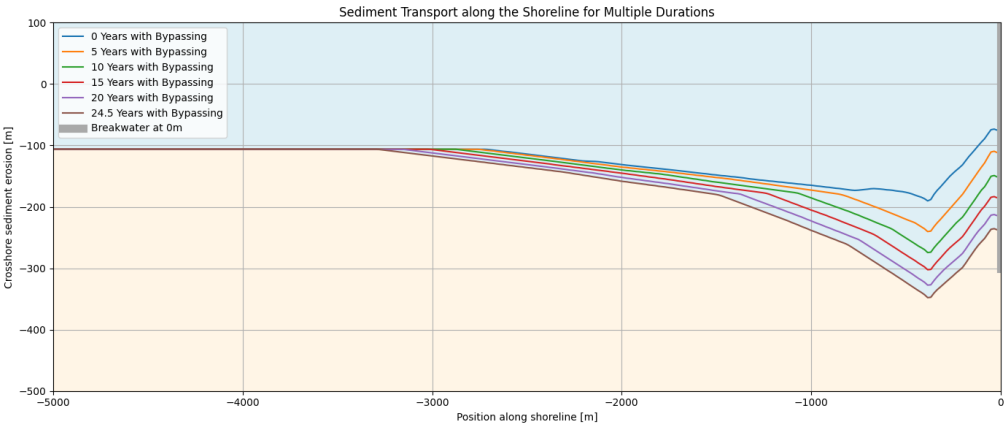


Figure 4.12: Scenario A - Erosion side

In figure 4.11., it can be observed that the breakwater is entirely accreted up to the tip, with no significant changes, as it is currently nearly filled. The effect of accretion extends progressively eastward, reaching from 2 km at 5 years to 3 km at 25 years. This pattern resembles a wave of sediment, where accretion increases the farther it is from the breakwater. It is also noteworthy that the pier becomes almost half-covered (45 m of accretion) after 25 years, this also fits the behaviour of the last years where a clear accretion can be observed next to the pier. The model does not account for the influence of the pier on sediment transport; however, based on the calibration, it is evident that it is slightly underestimated.

In figure 4.12, erosion is observed both next to the breakwater and at the erosion peak, with approximately 125 meters eroded over 25 years, corresponding to an average erosion rate of 5 meters per year—similar to the rate observed in recent years. Regarding the longitudinal effect, the erosion ”wave” extends around 300 meters. The highest erosion rates occur close to the breakwater, decreasing gradually with distance away from the breakwater and the peak of erosion happens before 500 m from the breakwater due to the shadow zone effect.

4.5.2. Scenario B

This scenario has a breakwater length of 600 m and the starting coastline is from 2024, extracted from satellite data.

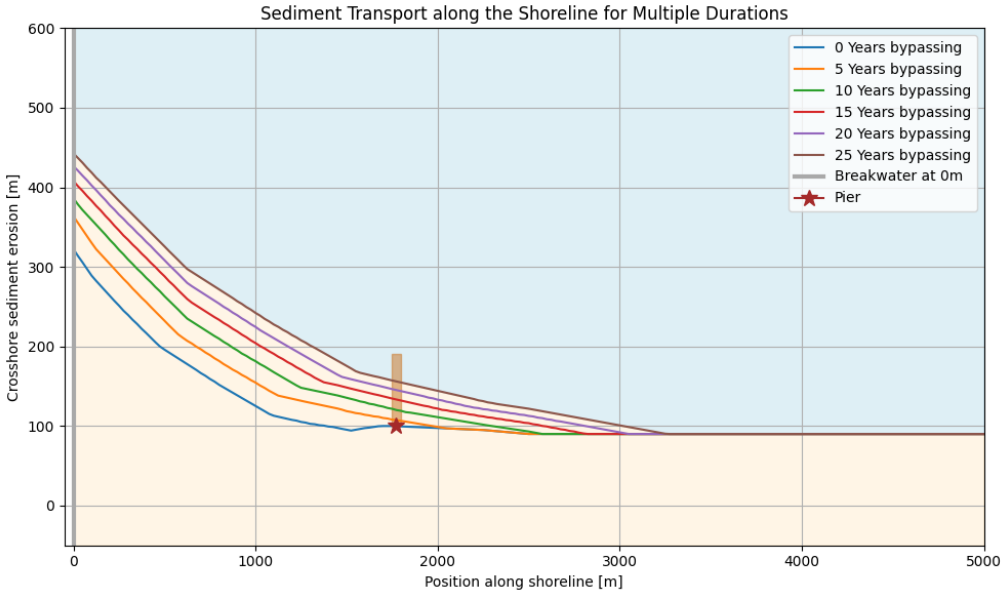


Figure 4.13: Scenario B - Accretion side

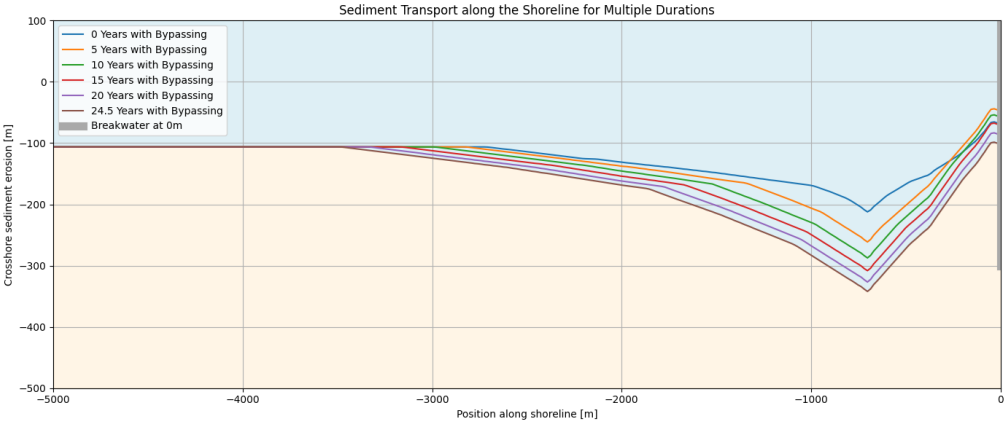


Figure 4.14: Scenario B - Erosion side

In figure 4.13, accretion near the breakwater is significantly higher due to the extended length, with accretion rates around 5 m/year. Maximum accretion occurs centrally, consistent with the calibration results. The accretion effect extends progressively eastward, reaching from 2 km at 5 years to 3.25 km at 25 years—250 m further than in scenario A. Notably, after 25 years, more than half of the pier is covered by sediment, with an accretion rate around 65 m, nearly 20 m more than in scenario A. While the model does not include the pier's influence on sediment transport, the calibration suggests that the model slightly underestimates this effect.

In figure 4.14, erosion occurs adjacent to the breakwater and at the erosion peak, showing rates nearly identical to those in scenario A. The longitudinal effect, however, is more pronounced, with the erosion "wave" extending roughly 600 meters—double the extent observed in scenario A. The highest erosion rates follow a similar pattern, tapering off with distance from the breakwater, but the erosion peak is shifted approximately 750 meters from the breakwater. This shift aligns with expectations, as a longer

breakwater creates a more extensive shadow zone, resulting in a displaced erosion peak further down the shoreline.

4.5.3. Comparison of scenarios

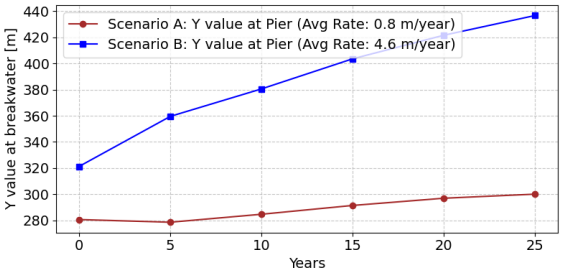


Figure 4.15: Accretion at the breakwater for both scenarios

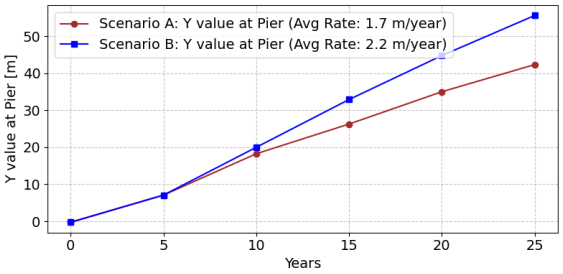


Figure 4.16: Accretion at the pier for both scenarios

The behaviour of the accreting side near both the breakwater and the pier is illustrated in figures 4.15 and 4.16. Notably, both accretion rates are higher for Scenario B, as expected, since the additional space facilitates greater sediment accumulation. A significant difference between the scenarios is evident near the breakwater, where Scenario B experiences much higher accretion rates, while near the pier, both scenarios show similar accretion magnitudes, averaging around 2 m/year. This is likely due to the observed dynamics illustrated in figure 4.11. Additionally, it's worth noting that the rates near the pier might be underestimated, as piers typically trap sediment, a tendency that was evident during model calibration.

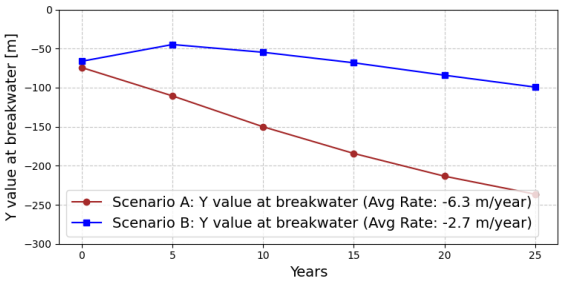


Figure 4.17: Erosion at the breakwater for both scenarios

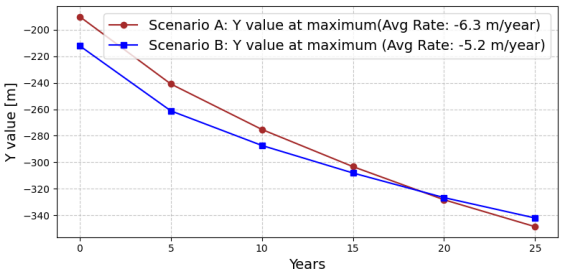


Figure 4.18: Erosion at the maximum point for both scenarios

Figures 4.18 and 4.17 show the evolution of erosion near the breakwater and at the peak erosion point on each side, respectively. Surprisingly, Scenario A exhibits a higher erosion rate in both areas. Similar to the accretion trends, there is a notable difference between scenarios near the breakwater, while at the peak erosion points, rates are comparable, averaging around 5–6 m/year. It's important to note that for the peak erosion values, measurements were taken only at the point of maximum erosion, without a fixed x-position.

An almost linear trend is observed in all plots, except for Scenario B at the breakwater, where a deviation from linearity is evident.

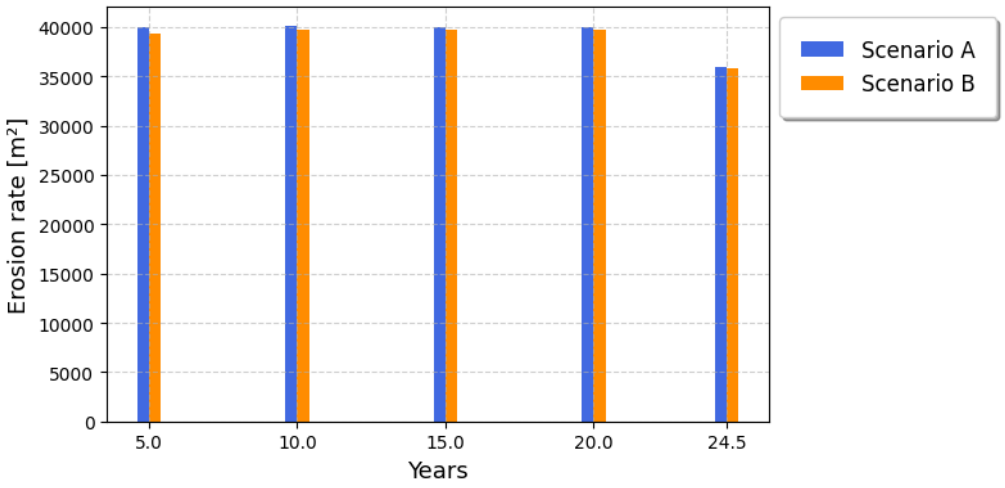


Figure 4.19: Area of erosion for both scenarios

Another key metric assessed by the model is the area eroded over time. Figure 4.19 illustrates the area eroded every 5 years for both scenarios. The magnitudes are comparable, averaging around 40,000 square meters, which aligns with the near-linear trend observed in erosion patterns. This consistent erosion rate suggests a steady progression in sediment loss over time.

4.6. Storm analysis

The analysis of individual coastal indicators, including max altitude, mean elevation, dune toe position, subaerial volume, and waterline position, revealed a high degree of variability across transects and storm events (appendix F). Each indicator exhibited a different response pattern, with frequent shifts between positive and negative coastal indicator responses over short spatial scales, even for consecutive transects. This spatial variability was evident in both east and west of the port, with no clear consistent pattern emerging across the indicators. Subaerial volume change showed the most coherent response among the indicators, presenting a relatively distinct pattern of erosion and accretion across storm events, particularly in areas further from the port (figure 4.20).

The cumulative subaerial volume change across all four storm events, shown in figure 4.21, further emphasizes the spatial patterns discussed above. The west side, particularly transects P15(W) to P20(W), consistently experienced higher accretion, contributing to a net gain across storm events. In contrast, the east side showed a more variable pattern, with generally lower magnitudes of change and a slight trend toward stability or mild accretion in the central transects.

The proximity of the transects to the jetty appears to play a significant role in shaping these responses, with transects on both sides of the port showing erosion. This suggests that the jetty may act as a partial barrier, moderating sediment transport in its immediate proximity while allowing for greater accumulation further away.

Only the most relevant resulting graphs are included in this section, while detailed indicator response per transect comparisons per storm event are provided in figure F.1. Full profile comparisons for each storm are also provided in figure F.3 to figure F.9. These profiles capture ”pre- and post-storm event” profile measurements for each transect, illustrating localized sediment movement and morphological changes.

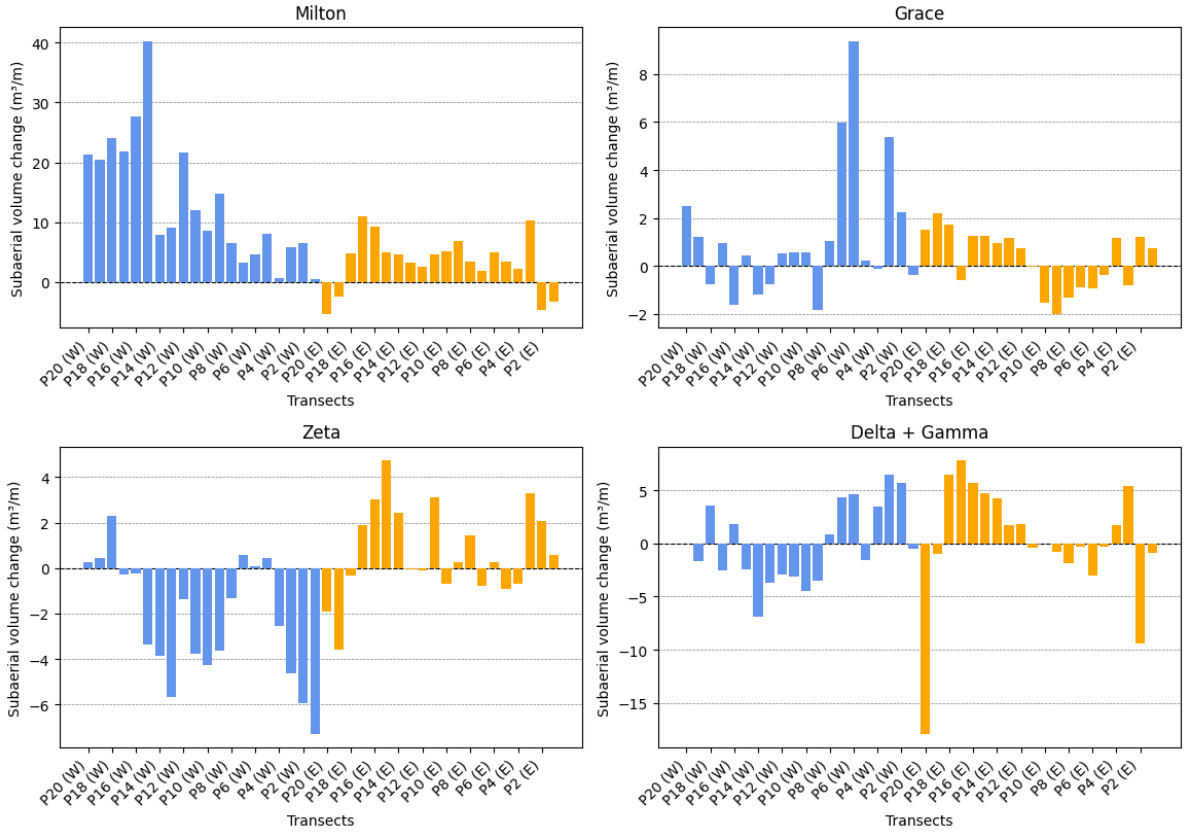


Figure 4.20: Subaerial volume change comparison per storm event.

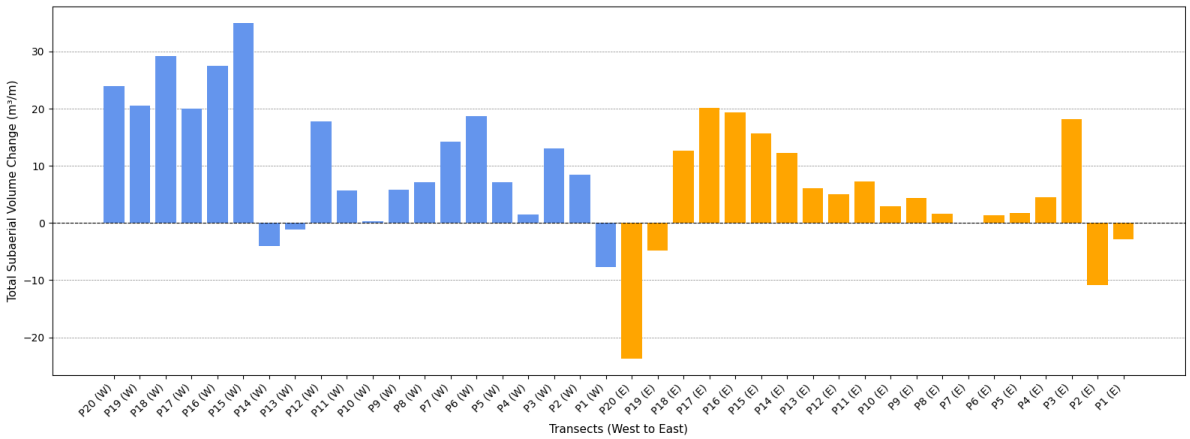


Figure 4.21: Total Subaerial Volume Change across storm events

5

Results - Social analysis

The following chapter presents the results of the social research methods, as described in section 3.8. First, the process of stakeholder identification and interviews are further elaborated upon. Subsequently, the results of the interviews and literature review are discussed, both in identified social challenges, as well as the methods to acquire an understanding on specific social characteristics, as described in section 3.8. The latter includes findings regarding stakeholder classification, Sisal's communication network, an analysis on stakeholder priorities, and finally an evaluation of interviewees' perspectives on Sisal's future.

5.1. Identified stakeholders

Initial stakeholders were identified in collaboration with several researchers from the UNAM institute in Sisal. Their knowledge on the community, and other stakeholders and organizations related to the coastal system, proved very useful and resulted in an extensive starting list of actors to potentially interview or study. Using the snowball method, initial talks with stakeholders lead to more identified actors. All distinguished stakeholders were subsequently added to a Miro board, categorizing them into various groups according to their connection to Sisal's coastal system. A total of thirteen relevant stakeholder groups were recognized, as presented in figure 5.1.

Subsequently, if needed, the list was updated with new information that was gathered during interviews. Ultimately, 48 individuals and organizations were identified, leading to an extensive and broad list of actors. The complete list of identified stakeholders is presented in figure 5.1.

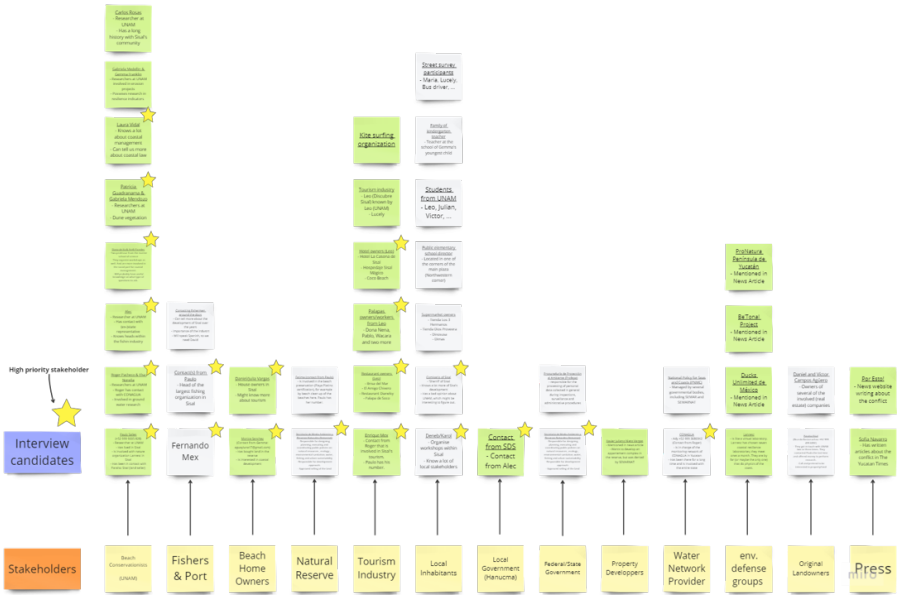


Figure 5.1: List of identified stakeholders categorised into various backgrounds related to Sisal.

5.2. Interviews

The stakeholder identification process yielded a significant number of individuals and organizations to approach for interviews. All identified stakeholders were carefully analyzed to select a broad number of actors and organizations that represent all relevant components of Sisal's coastal system, as presented in figure 5.1. Ultimately, 22 identified stakeholders were selected to approach for an interview. This goal has generally been achieved for most categories. However, stakeholders' willingness to collaborate, the re-evaluations of some categories' relevance to the research, and time constraints have resulted in less total interviews then expected.

In total, 16 full-length interviews have been conducted, with an average length of an hour. The interview templates in English and Spanish are presented in appendix B. All 16 summarized interviews are presented in appendix C.

Alongside the full-length interviews, five short interviews were conducted. These interviews were done in an afternoon with several of Sisal's inhabitants. The objective aimed to engage individuals outside of the knowledge network of previously identified stakeholders, to reduce bias by broadening the sample of participants. For the short interviews, a summarized version of the full-length interview template was used. The template for the short interviews is presented in appendix B.

An analysis of the variety in background, occupation/role, and (in)direct connection to Sisal's community of all 21 interviewed stakeholders is presented in figure 5.2. All circle diagrams are enlarged in appendix D.

(a) Occupational/social background of interviewed stakeholders

(b) Occupation/role of interviewed stakeholders

(c) Ratio of interviewed stakeholder's being in- or outside Sisal's community

Figure 5.2: Variety of interviewed stakeholders according to three subjects: background, role/occupation, and (in)direct connection to Sisal's community.

5.3. Results

The following section delves into the results gathered by the interviews and a literature review. First, a summary of the predominant social tensions and challenges of Sisal's coastal management and economic development is presented. This is followed by several social analyses, including identified organizations' function within the coastal system, stakeholder priorities, communicative relationships, and future perspectives.

5.3.1. Social tensions and challenges

Literature and interviews conducted with relevant stakeholders gave an understanding of the social interactions between stakeholders and the challenges that they, or Sisal, face(s). Most of these socio-environmental conflicts occur due to conflicting interest, actions and economic activities of these different local actors related to Sisal's coastal system (Mendoza-González et al., 2021). The following subsection delves into several social tensions and challenges that have mainly been identified from information gathered by interviews with the aforementioned identified individuals (see section 5.1). All interviews are individually summarized and presented in appendix C.

Economic development versus nature preservation

Interviews with relevant stakeholders reveal that many of Sisal's community members value the development of the village greatly. When prioritizing several of Sisal's characteristics - such as coastal health, tourism, and nature - interviewees, on average, ranked community development as their top

priority. The results of these prioritization lists are presented in 5.3.4. Improving the community's quality of life, by increasing Sisal's available amenities and improving the reliability of its services, is often mentioned as the main reason to prioritize Sisal's development above all else. Ultimately, leading to sustained economic development.

However, improving the quality of life within Sisal might come with a price, as economic development and tourism also creates environmental, social and economic burdens to society (Mendoza-González et al., 2021). Previous years in Sisal, and the history of locations similar to it (like Progreso), have shown that economic development will likely lead to an expansion of the area, including increases in inhabitants and (unwanted) entrepreneurs seeking opportunities for business.

A major concern for developing Sisal economically is the negative effect this can have on the area's ecological system. Interviewees express concerns about future nature degradation, as the increase in tourism activities in previous years has had an effect on Sisal's natural qualities. This is noticeable in the coastal system, where the effects of natural erosion, occurrences of dune and vegetation removal, and climate change are exacerbated by human interventions close to and on the beach. These constructions, like hotels, palapas, self-made breakwaters, and holiday homes, have caused an increased decline in coastal system function (Mendoza-González et al., 2021). Other effects are a noticeable increase in waste and decreases in water quality due to unregulated discharge. Furthermore, occurrences of overfishing are noted by stakeholders, as the fishing industry has to keep up with increased demand and a declining amount of available catch due to changes in fish migration patterns.

A changing climate and ecosystem

Interview participants often mention the changes that they have noticed in Sisal's climate and ecosystem. Inhabitants of Sisal seem to know about these ecological changes on the beaches and the natural reserves, but have various levels of knowledge on the reason why the ecosystem is transforming or what function various aspects of the coastal system have. For example, dune vegetation is often mentioned as an important component for the protection against floods, cold fronts and storms, specifically for the infrastructure directly behind the dunes. However, not all participants seem to be aware of its function, with one stakeholder removing parts of the vegetation in front of their house due to aesthetic reasons. Furthermore, some inhabitants believe that coastal changes are solely caused by objects and decisions outside of Sisal, like the port of Progreso.

In general, it seems that the community is not aware of all ecological developments, which is sometimes caused by a lack of interest or a different view on priorities. As an example, community members understand that the port has a negative influence on the ecological system, but stress its importance for the economy, therefore justifying its effect. Changes in the ecosystem are therefore not necessarily part of everyday concern within the community, as the matter is predominantly put on the agenda by researchers or inhabitants that experience direct negative effects, like land owners in the parts of the reserve with significant sediment transport patterns.

Moreover, when interviewees are asked about their safety against climate change, many state the fact that they are currently not concerned about sea level rise and other potential environmental effects, believing that Sisal is adequately safe for future environmental hazards. This opinion is shared by most interviewed researchers. They mention that, despite the dynamic and complex nature of the coastline, the coast is relatively safe for climate change. This fact, and the decreasing cold front effects, make researchers believe that Sisal's beaches are not likely to be vulnerable to major climate change hazards.

However, researchers do express their concern on recent and future tourism developments. The increase in tourism activity has caused many human interventions on the beach, resulting in new real estate developments, the construction of palapas, the removal of dunes to improve beach accessibility and decreases in dune vegetation, all contributing to coastal degradation. Apart from coastal system changes, researchers believe future issues might arise in waste management and water quality. Previous research by interview participants employed by UNAM has pointed out that the amount of waste is increasing and water quality is decreasing in recent years. Furthermore, the water supply is already pressured, as the lack of available water is already causing environmental problems, like the inability to extinguish wildfires. Interviewees therefore express concern on future water availability, as unregulated water discharge, increased salinization and intensifying demand for water due to a rising tourism

sector will likely put more pressure on Sisal's infrastructure. Ultimately, increasing the cost of basic needs as a consequence.

A difficult political landscape

Interviewees state that the political environmental of Sisal poses considerable challenges. Sisal does not have an official municipality, as they fall under the jurisdiction of the municipality of Hunucmá. The only direct connection between Sisal and other governmental institutions is that of Sisal's Comisaría, who communicate with the municipality of Hunucmá and the state of Yucatán, if necessary.

A problem that arises generally, is the geographical distance between Sisal and Hunucmá, as interview participants mention that it is difficult for the municipality to forward their interest to Sisal. The municipality of Hunucmá has several aspects that require attention, including a high percentage of inhabitants living in poverty (Gobierno de Mexico, 2020), which is most likely higher on their priority list than the current coastal degradation or the pressure on Sisal's infrastructure. This can also be partially explained by the relative little time politicians have to try to get re-elected, as elections are organized every three years. Consequently, the initiation of long-term infrastructure projects is not prioritized, leading to heightened pressure on Sisal's existing infrastructural issues.

Furthermore, interviewees note that the communication by governmental institutions on the planned developments in Sisal is notably lacking transparency. For instance, interview participants mention that environmental impact reports on construction projects are almost never published, and when they are, it is often during times when the public's online access is limited. In some cases, these reports are not published at all, and requests for them go unanswered. Moreover, regulations on construction and nature preservation seem vague, as multiple governmental organizations have a say in various parts of the regulatory framework. Additionally, laws regarding construction seem to be occasionally changed or ignored. For example, interviewees mention that real estate development concessions to build in the natural reserves of Sisal where recently approved by the federal government, even though this was previously not allowed (Mendoza-González et al., 2021). Other interview participants mention cases of the disregard of regulations for the maximum construction height, as development projects of large size are still approved.

Likewise, stakeholders note that inhabitants feel left in the dark, as communication with the government is often last-minute and very one-sided. In general, information on decisions seem rarely communicated, with governmental institutions holding a very passive attitude. For instance, local stakeholders involved in tourism services feel that their input was not taken into account in the decision-making processes regarding tourism strategies (Mendoza-González et al., 2021).

Researchers at UNAM have similar views, with communication with the state being one sided and ineffective in previous years, as policymakers are often difficult to reach. Some researchers mention that the state sporadically initiates contact whenever specific information is needed. During those instances, governmental representatives often want responses and results quickly, regularly at the last second. Interview participants express that this contact appears to be more of a mandatory formality, rather than a genuine expression of concern or a need for assistance.

This inadequate communication and absent participation strategies by the government seems to have caused uncertainty and a lack of confidence in policymakers within Sisal's community. Inhabitants seem to rarely have contact with governmental institutions, primarily reaching out to Sisal's Comisaría only when absolutely necessary. The government's passiveness, and the unwillingness of inhabitants to reach out due to a lack of communicative methods, seems to have caused the community to self-organize and self-regulate (Mendoza-González et al., 2021).

UNAM as a knowledge island

Interviewed researchers employed by UNAM mention that they find it difficult to communicate and collaborate with the community of Sisal. This is seen as an unfortunate circumstance, since UNAM has very valuable knowledge on Sisal's ecological system. Researchers believe that the data and findings from studies conducted by UNAM on the ecosystem in recent decades could be instrumental in mitigating future coastal degradation. However, a historically frictional relationship, time constraints and a distant location have made this difficult as of yet. Therefore, the research institute can both geographically and socially be seen as a 'knowledge island'.

Interview participants mention that the community often seems to have a negative or neutral view towards UNAM, which was reaffirmed by some interviews with inhabitants. This negative opinion is predominantly caused by UNAM's establishment. At the beginning of the 21st century, UNAM was looking to relocate their research institute, with the current location in Sisal being one of the preferred alternatives. Apparently, the State approved the relocation of UNAM's institute to Sisal, without involving the community in this decision. Interviewees state that the local population was not necessarily happy with the establishment, as it was seen as unwanted development by an organization outside of the community. Furthermore, residents expected that UNAM would provide significant employment opportunities, which over time did not materialize. Even though UNAM has provided Sisal with a lot of upsides, like the development of the telecommunication network, this initial negative perspective does not seem to have changed.

Researchers at UNAM have undertaken several initiatives for community participation. They believe that incorporating the view of the community in UNAM's studies, and the distribution of the results of their research, can be valuable for the development strategies of Sisal. Nevertheless, most interviewed community members have never been in contact with UNAM, which can partially be accounted to most research being written in English in a high technical level. Interviewed researchers mention that they would like to dedicate more time for community participation efforts, but are often unable to do so due to time constraints.

Shifts in the economic sector

The fishing industry has played a significant role in Sisal's economic sector ever since the construction of the first port back in the 19th century. This remains the situation, as numerous interview participants highlight the importance of the employment opportunities currently generated by the fishing industry. However, it is most notably the inhabitants that state that Sisal is not as dependent on the fishing industry as it ones was, noting that the community is increasingly relying on tourism. As a result, several interviewees indicate that many residents who previously worked in the fishing industry have chosen to transition to the hospitality and tourism sector.

The decline of the fishing industry is not solely caused by the economic interest towards the tourism sector, as climate change is causing an increasingly difficult environment for fishermen to generate income. Interviewees note that the water temperature is increasing due to climate change, causing changes in fish migration patterns, ultimately leaving a decreasing catch for fishermen. It appears that fishing activity is prohibited in some parts of the year to decrease pressure on the ecosystem, with governmental institutions reimbursing fishermen during these times. However, interviewees state that many cases of overfishing continue to persist.

Yet, stakeholders overstate the importance of the fishing industry and the associated infrastructure for Sisal, given that a substantial portion of the community relies on it for their livelihoods. Currently, external state and international real estate developers are pressuring the local community to sell their land for housing and hotel development projects. Should the fishing industry collapse, this pressure is likely to intensify, potentially leading to cases of gentrification.

Sisal: A magic town

Following its designation as a 'Pueblo Mágico' (Magic Town) (see section 2.1.3) in 2020, Sisal experienced an unexpected surge in tourism activity, specifically from outside-state and international visitors. Interview participants indicate that communication from the State to Sisal regarding the magic town status seems to have been minimal, as the local community was not aware of the decision and its meaning. Consequently, it was mainly Sisal's residents that suffered the implications. Interviewees state that Sisal lacked reliability on basic services, as pressure already existed on the infrastructure, like the available water and electricity supply, before the magic town denomination. Inhabitants note that the rising tourism activity has caused an increased strain on the community's services, with many believing that infrastructure quality should currently be prioritized over tourism development. Additionally, several interview participants mention that it is surprising that Sisal was integrated into the magic town status without notice, as previous magic town locations received state budget to improve the area's qualities as a preparatory method. It is unknown to interviewed stakeholders why Sisal has seemingly not received this state contribution. Finally, inhabitants indicate that the government appeared to lack

a prepared strategy for the effects following the denomination, making the decision even more unexplainable to the local population.

Consequently, many stakeholders believe that Sisal's integration into the government's 'Pueblo Mágico' program was premature, leading to significant dissatisfaction among community members. Interviewees note that the community was afraid of the exposure the program had, as it could result in the attraction of foreign developers and entrepreneurs that would subsequently compete with local businesses. As a result, inhabitants grew concerned of rising prices and a loss of cultural heritage. This fear subsequently materialized, as external investors, unlike local residents, began developing real estate projects to capitalize on the area's natural beauty and attractions. However, rather than improving, local social development deteriorated instead (Mendoza-González et al., 2021).

In 2023, a survey was conducted by the International Network of Sustainable Tourism Observatories (INSTO) in Mexico, asking residents of four magic towns, including Sisal, about their opinion on tourism and the government program. Inhabitants residing in Sisal notably had a more negative view towards the developments after the integration, in comparison to participants from other magic towns. For instance, 84% of respondents agreed that tourism has increased prices and 43% believe that tourism is harming the environment. Other noteworthy responses include that only 23% of respondents believe that tourism is management by their own community, and that the revenue generated from the sector stays within the local population. Finally, 46% of respondents had social concerns regarding tourism development, like uncontrolled urban growth and environmental impacts (International Network of Sustainable Tourism Observatories, 2023).

As stated by INSTO themselves, 'The assessment of the residents of a destination with respect to tourism will be directly related to the benefits, mainly economic, that they perceive from this activity, both individually and as a group' (International Network of Sustainable Tourism Observatories, 2023). Unsurprisingly, there still seems to be an absence of a popular consensus in the designation of Sisal as a magic town (Mendoza-González et al., 2021). Interviewees mention that the status is only viewed positively by selective members of the community, primarily working in the hospitality sector, as only these select view seem to be reaping the rewards that the program provides.

Another observation is the rapid growth of human interventions on the beach after the magic town denomination in 2020. This seems to have been a consequence of the exclusion of the original settlers from the decision-making process, as this induced social mobilizations through the installation of illegal palapas along the beach and coastal dunes, driven by concerns of losing territorial autonomy (Mendoza-González et al., 2021).

However, the developments after the magic town denomination have not solely been negative. Collaboration between actors in Sisal's hospitality sector has notably improved, as stakeholders with occupations in these sectors saw opportunities to provide business to each other. Specifically a strong relationship between palaperos, fishermen and tourism agencies was observed, as they collaborated to provide tourists with a 'complete package'. Furthermore, fishermen state that they are satisfied with the increased opportunities that the tourism sector presents, as it allows them to sustain a livelihood despite the declining fishing industry.

The future of Sisal

Interviews primarily concluded with an individual's thoughts on the future of Sisal. It stands to reason, that many interviewees would like Sisal to have a different future then where they currently think it is headed. There are varying views on Sisal's development, with most expecting that Sisal's expansion will continue. Participants note that these developments will primarily involve additional infrastructure and housing associated with the tourism industry. Many interviewees base their viewpoint on already proposed real estate projects, of which they think it is likely that they will materialize. Furthermore, participants expect further nature degradation, as more infrastructure will likely be built around Sisal's natural reserves. Nevertheless, not all stakeholders view Sisal's future developments negatively. It should be noted, however, that most interviewees that view this positively are also involved in Sisal's hospitality sector, and thus see the development as an opportunity to expand their business.

In brief, participants state that large-scale tourism will have consequences for Sisal, as tourism imposes environmental, social, and economic burdens on society. While it accelerates the growth of supporting

industries – like hotels, transportation, and hospitality-related activities - which generate more employment opportunities, it may also result in social inequalities (Mendoza-González et al., 2021). As a result, gentrification and segregation could become a threat to the Sisal's local population. Furthermore, urbanization may worsen existing coastal degradation and climate risks, such as sea level rise, erosion, flooding, and air pollution, especially affecting members of the most vulnerable populations (Velayo et al., 2024). However, a more natural setting with reduced urbanization may reduce the economic revenues created by the tourism sector (Mendoza-González et al., 2021), making strategies for effective development difficult.

Yet, most stakeholders agree that Sisal's development does not necessarily have to have a negative impact for the community, provided that the decision-making process on expansion strategies are made through a participative process and are regulated adequately after implementation. It is therefore important that community members have access to details regarding development plans, as better access to information could positively influence Sisal's urban growth.

5.3.2. Stakeholder classification

The thirteen identified stakeholder groups, as described in section 5.1, were categorized according to the key system roles presented by (Lyon et al., 2020) (see section 3.8.3). The analysis of the roles of these organizations in the coastal management of Sisal shows how different identified stakeholders act within the system. Ultimately, providing information for insights in the system's functioning, both in comparing the function of organizations against each other, as well as against an 'ideal' coastal system according to the key roles described by (Lyon et al., 2020).

All identified organizations, their predominant role within the system, and their relative level of power and interest, are presented in the power and interest grid of figure 5.3. The following paragraphs delve into the characteristics of each organization.

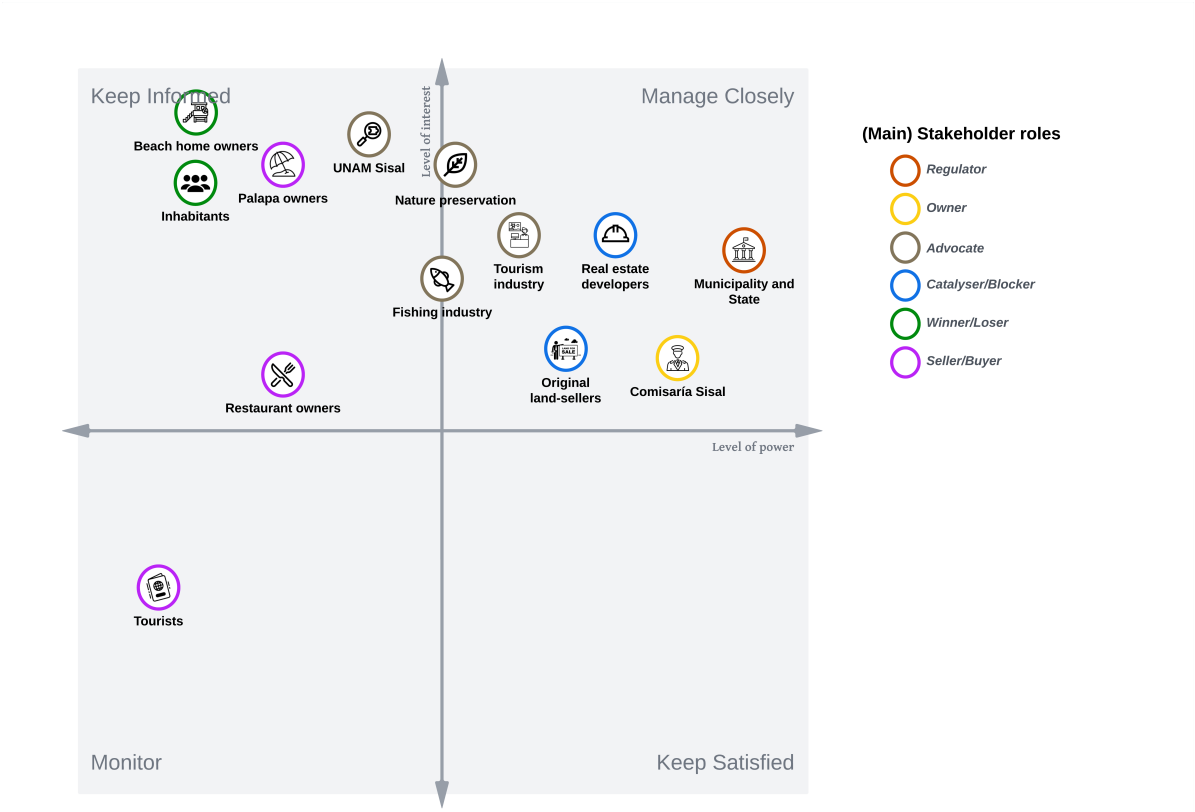


Figure 5.3: A power and interest grid, classifying identified stakeholders on their relative level of power and influence. An organization's role, as described by (Lyon et al., 2020), is presented by the border color of the node.

Municipality & State: The municipality of Hunucmá and the state of Yucatán set the rules within the system by implementing regulations, policies, and laws regarding coastal management and the development of Sisal's infrastructure. Furthermore, they hold the power to make decisions within the scope area. For example, by providing concessions and approvals to change land planning and for the construction of real estate projects. This makes them both a 'Regulator', as well as a 'Decision-maker' within the system. The state should ideally also act as a 'Guardian', evaluating the enforcement of their laws and regulations. However, this enactment does not seem to be sufficiently present. The government's ability to change the system significantly makes them the most powerful organization within the network. However, their interest in Sisal's coastal system is relatively low due to the difficult political landscape, as described in section 5.3.1.

Comisaría Sisal: Sisal's Comisaría has a unique role in the system, as their observed passive attitude towards the coastal system makes them an organization with a relatively high level of power, but little interest. Their high level of power is mainly explained by the community's dependency on their connection to other governmental institutions. The Comisaría has the ability to make decisions within the network, but not necessarily to the coastal system directly. This results in their role as an 'Owner', as they enforce specific components of the rules set by the municipality and state.

Real estate developers: The main function of organizations responsible for the (future) real estate development projects in Sisal is that of a Catalyser/Blocker. Large real estate projects can have a significant influence on changes to Sisal's coastal system and the economic development of the area, both positively and negatively. Real estate developers have the ability to prevent further coastal degradation by advocating for sustainable development. However, their infrastructure projects can also lead to ecological degradation. They also act as an 'Owner', as they hold assets and resources within the system in the form of land and infrastructure. Developers have significant power in the system, as policymakers need their services to increase Sisal's value as a tourism destination. Subsequently, they hold a high level of interest, as the success of their projects is dependent on adequate coastal management.

Original land-sellers: The original land-sellers of plots in Sisal's natural reserves hold similar power as real estate developers, as they still own a large surface area of land that has a direct influence on the coastal system. They hold the same function as developers, as their assets make them both a 'Catalyser/Blocker' and an 'Owner'. Since original land-sellers already own the land, their interest is limited in comparison to developers, as they are less dependent on project success. However, their interest in the coastal system is still present, since the value of their assets are directly related to Sisal's development and coastal quality.

Beach home owners: The interviews shed light on the fact that many of Sisal's beach home owners were unaware of the changes in sediment transport patterns close to the land that they acquired. The erosion to the West of Sisal's port has led to a decrease in land surface area in many cases. Home owners therefore hold high interest in Sisal's coastal development, as it could directly affect their daily lives, if it does not do so already. However, home owners are unable to change the system, as they are dependent on top-down decisions by the government. Ultimately, making them a stakeholder with a low power level, resulting in their predominant function as a 'Winner/Loser'.

Tourists: The development of Sisal's coastal system is of little importance to tourists, as there decision to travel to a tourism destination is dependent on the services that the location can provide. If Sisal is unable to present tourists with what they require, they will likely opt for another destination. Furthermore, tourists do not hold any power to change the coastal system themselves, as their presence can only alter the system indirectly. This makes them a stakeholder with both a low level of power and interest. Their predominant function within the system is that of a 'Buyer'.

Restaurant owners: Most of Sisal's hospitality sector, apart from palaperos, have a relatively low interest, accompanied by little power due to their inability to change the system. Restaurants benefit from the tourism sector within Sisal, which is related to Sisal's coastal management, but interviewees mention that they do not necessarily care about it directly. This makes restaurant owners both a 'Seller', as well as a 'Winner/Loser'.

Palapa owners: Similarly to restaurant owners, palaperos hold the function of a 'Seller' and a 'Winner/Loser', the latter even more so than other stakeholders in the hospitality sector. Palapa owners

provide services on the beach, making the success of their business highly dependent on adequate coastal management. This explains their high interest relative to other organizations.

Nature preservation: Ecosystem preservation initiatives hold a significant interest in the system, as their objectives include that of coastal system conservation. This makes them predominantly act as an 'Advocate' for preservation of parts of the system. They have power within the system, due to their responsibility to maintain the beaches of Sisal, and their efforts towards beach certifications.

Tourism industry: The developing tourism industry has an increasing share in the economic sector of Sisal. Their services are predominantly located on and around the beach, making them an organization with high interest. They hold a significant power within the system, as their activities have a direct effect on the coastal system. Stakeholders within the tourism industry mainly act as an 'Advocate' for their businesses, but their dependency on the coastal system's functioning makes them a 'Winner/Loser' as well.

Fishing industry: Interviewees often mention that the fishing industry seems to have little interest in the functioning of the coastal system. However, their dependency on the fauna within the system explains their interest level, as this is directly related to effective coastal management. The industry's decreasing share in the economic sector results in a neutral power level. Similarly to the tourism industry, the fishing industry acts as an 'Advocate', as well as a 'Winner/Loser'.

Inhabitants of Sisal: As the interviews have pointed out, Sisal's inhabitants are very concerned with the quality of the coastal system. They hold a high interest in the management of the beaches and are often unhappy with current coastal governance strategies. However, they do not have any means to act on their interest, making them unable to change the system. This makes them a stakeholder with a low level of power and a main function as a 'Winner/Loser'.

UNAM Sisal: The objective of UNAM regarding coastal research make the institute a stakeholder with high interest. Their efforts to evaluate the quality of the coastal system is unique within the system. However, as mentioned by many of UNAM's researchers, it is difficult to act on the findings of their research, making them a stakeholder with relatively low power in the system. This is also the main reason why they can not be seen as a 'Guardian', as UNAM does not have the authority to change the system based on their evaluations. The research institute's main function is therefore that of an 'Advocate'.

As presented in the power and interest grid of figure 5.3, stakeholders with equal roles hold a similar level of power and interest. This can be explained by the fact that key system roles often have similar levels of agency and interest, as their function is comparable. Organizations with equal roles holding similar positions in the power and interest grid therefore reaffirms their function within the system.

5.3.3. Communication network

During the interviews, participants were asked about their relationships with other identified stakeholders to gain a better understanding of the communication lines between important organizations that are related to Sisal's coastal system. In total, 17 interviewees were asked about their communicative relationship with organizations connected to the project's scope.

Interviewees were asked if they have had any communication with a specific organization, how frequent that communication has been (weekly, monthly, or yearly), what type of information exchange was present (either sending, receiving, or reciprocal), and finally if they perceived the communication to be effective. A communicative relationship was solely defined as information exchange between two organizations regarding either the coastal system, Sisal's community or its development. The results of the interviews and a literature review were combined into the communication network presented in figure 5.4, using the thirteen identified organizations, as described in section 5.1. The communication network was created to asses the exchange of information and knowledge related to Sisal's coastal governance and economic development.

The communication network has been developed via the network analysis program 'Gephi', as the software provides various methods to analyse important aspects of the network. The network shows both nodes (organizations) and edges (relationships). The centrality of a node represents an organization's relative importance or influence within the network. Nodes that are central in a network can therefore

be seen as important stakeholders, as they play a critical role in bridging different parts of the system. This is often defined as a node's 'betweenness' value (Rölfer et al., 2024).

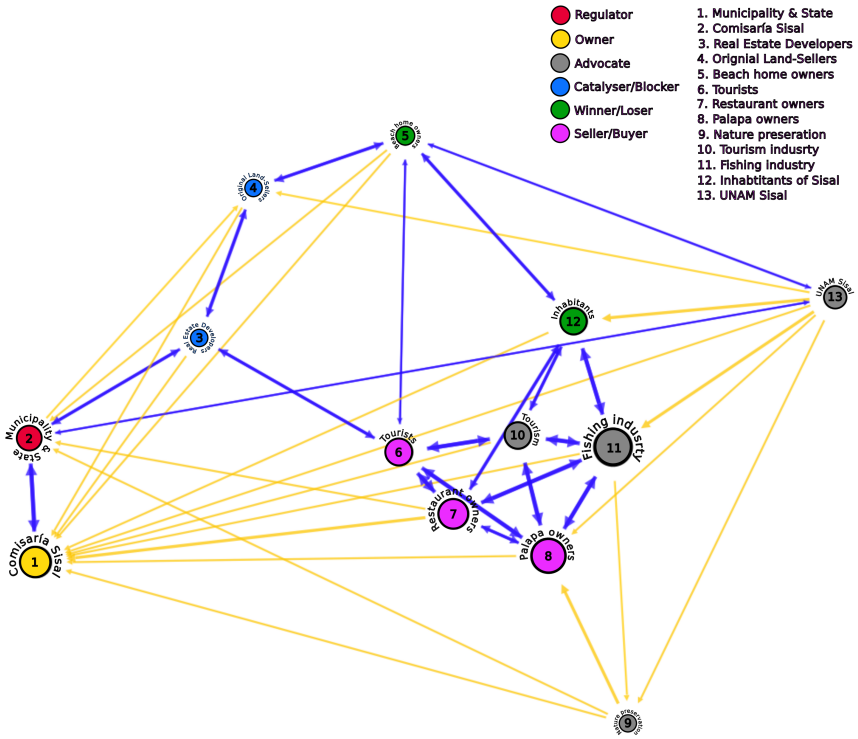


Figure 5.4: The communicative network of organizations involved in Sisal's coastal system.

A node's size is determined by the amount and weight of incoming and outgoing edges. This is defined as a node's 'weighted degree'. Nodes with a higher weighted degree will therefore have a bigger size relative to other nodes in the network, and thus have a higher number (and more frequent) relationships. Finally, the colour of a node represents an organization's role within the coastal system, as described in section 5.3.2.

Edges represent a communicative relationship between two organizations. Edges are either presented in yellow (directed relationship: sender to receiver) or blue (reciprocal). The thickness of an edge represents the frequency of a communicative relationship, which was determined during the interviews between a value of one to three. Weekly communication was established with a value of three, monthly with a value of two, and yearly with a value of one. The complete communication network is presented in figure 5.4.

5.3.4. Stakeholder priority analysis

During the interviews, interviewees were asked to rank a total of six aspects related to Sisal from 'most important' to 'least important'. This resulted in a priority list of the categories from one to six, with one being the category with the highest priority. In total, 22 interviewees were asked to make this priority list. The six categories to prioritize consisted of the following:

- Liveability & development of infrastructure: implying the improvement of Sisal's services and amenities. Ultimately, increasing the quality of life within the community, without causing expansion and gentrification.

- Fishing industry: implying the functionality of the port, the economic revenue created by the fishing industry, and the job security it generates.
- Coastal health: implying the preservation of the coastal system by preventing erosion, dune and vegetation removal, water quality maintenance, and effective waste management.
- Nature: implying the preservation of the natural reserve areas and mangroves around Sisal, preventing further degradation of flora and fauna, and keeping adequate salinization levels.
- Tourism: implying the increasing touristic activities in Sisal, the revenue created by the industry and the development of infrastructure projects by (inter)national developers outside of the state.
- Expanding Sisal: implying the expansion of Sisal's area, creating more densely populated areas and an increase in inhabitants and visitors.

The results of the average value of the six categories are presented into a total of seven figures. Figure 5.5 shows the aggregated total result, figure 5.7 shows results divided by four backgrounds of interviewees, and figure 5.2c presents the results categorised into local and external stakeholder perspectives.

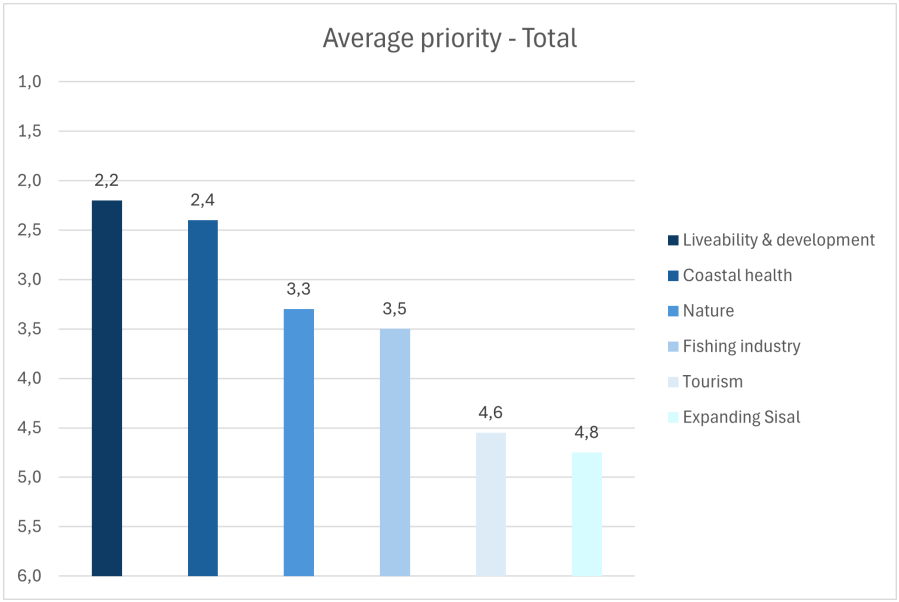
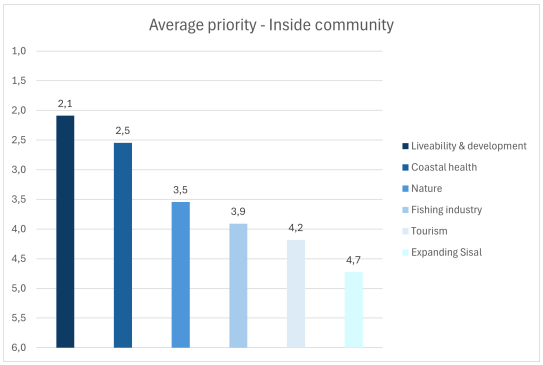
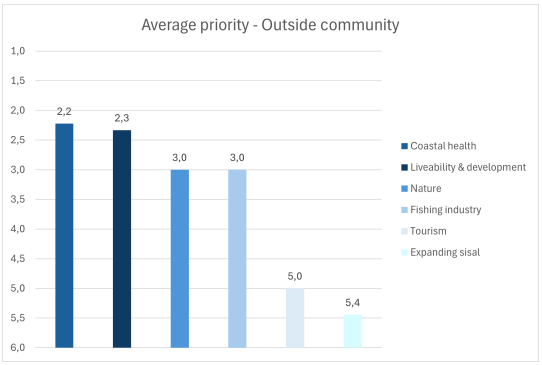


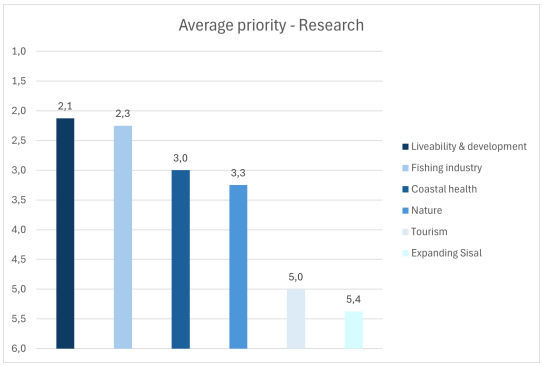
Figure 5.5: Average priority list results following all interviews



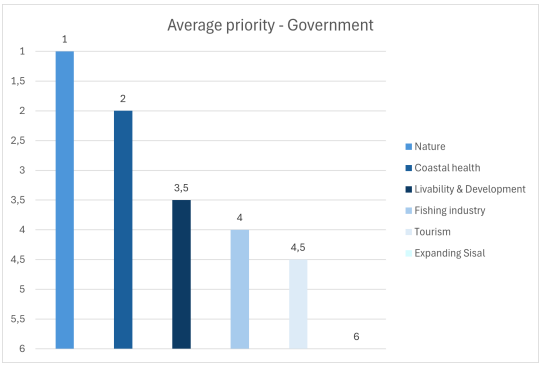
(a) Average priority results for stakeholders with a direct connection to Sisal's community



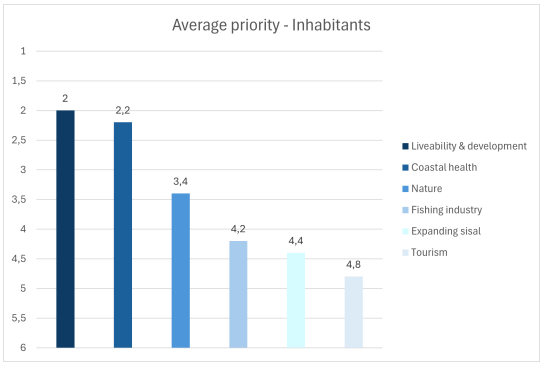
(b) Average priority results for external stakeholders



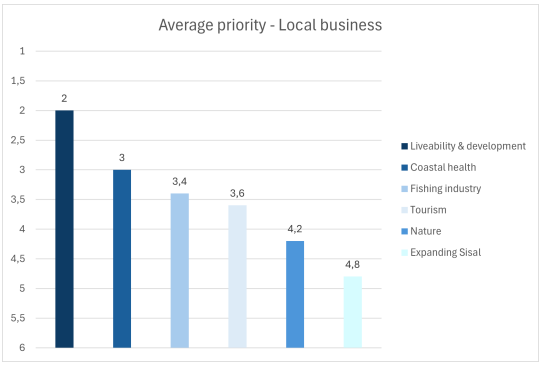
(a) Average priority results for stakeholders with a background in research



(b) Average priority results for stakeholders with a governmental background



(c) Average priority results for inhabitants of Sisal



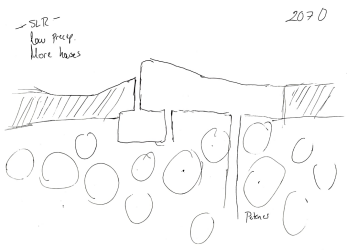
(d) Average priority results for local business owners in Sisal

Figure 5.7: Stakeholders' priority list results categorised into relevant actor backgrounds

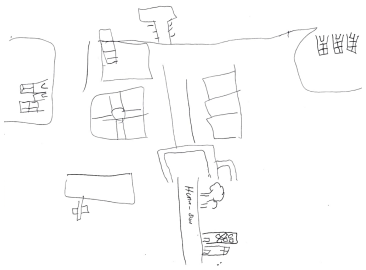
5.3.5. Stakeholder perspectives

Most of the full-length interviews were concluded with mental mapping, a process were interviewees were asked to create a map of Sisal in 2070, according to their view of the prospective development of the area. In this way, stakeholders could provide their unbiased vision on the future of Sisal.

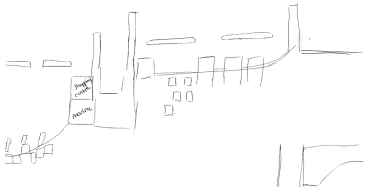
In total, thirteen mental maps were made by interview participants of various backgrounds. The thirteen mental maps were subsequently analyzed on their contents. Three examples of the drawn maps are presented in figure 5.8. These, and all other drawings, have been included in appendix E.



(a) Mental map of a researcher of UNAM involved in ground water studies



(b) Mental map of a restaurant owner in Sisal



(c) Mental map of a researcher of UNAM involved in coastal studies

Figure 5.8: Mental maps of three interviewees with various backgrounds to the coastal system of Sisal

6

Results Web-tool

The results from the coastal analysis are visualised via an interactive manner in the developed web-tool. The web-tool allows the user to visualize the shoreline retreat/advance rates, describe coastal indicates, the USGS vulnerability index, and the constructed coastal resilience index for east Sisal.

Shoreline retreat/advance

The user can visualize both the shoreline retreat/advance obtained from the historical profile data as from the CoastSat analysis. The cross sections of the profiles and the transects used for the CoastSat analysis are displayed on an interactive map of Sisal. By clicking on one of these transacts, the user can visualize a graph showing the measured and determined location of the waterline and it's trend.

Furthermore, the user is able to select a specific time window for which the computation of the advance/retreat is performed. This function allows the user to investigate the behaviour of the shoreline in more detail. It also allows the comparison between the shoreline change rates obtained by the profiles and the ones obtained using satellite data, by selecting a time window for which both historical data sets are available. For example, since the profile data for the west side is available since 2019, the user can select a time window ranging from 2019 - now, resulting in a computation of the shoreline advance/retreat rates, only for this specific period. This allows for comparisons between east, west and the profile data and the satellite data.

Figure 6.1 shows an overview of the visualization of the shoreline change in the web-tool.

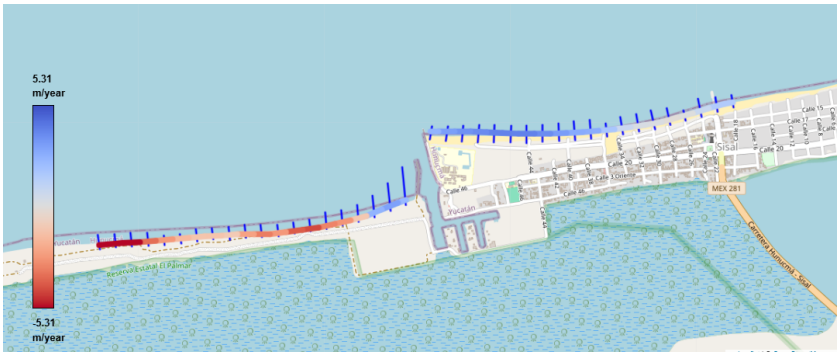


Figure 6.1: Shoreline change visualized on the web-tool interactive map

Vulnerability and Resilience Indices

The results of the USGS index and the Sisal Resilience Index (SRI) are displayed similarly to the shoreline trends. Again, the user can specify a time-window for the computation of the index. Figure 6.2 shows how the coastal resilience index is visualized on the east side. The overview allows users to quickly identify coastal areas that are underperforming in comparison to other sections of the coast.

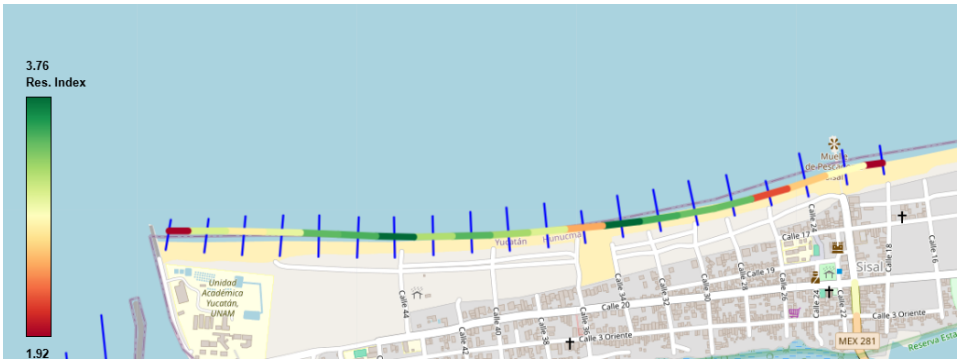


Figure 6.2: Sisal resilience index (East)

Indicators

The user can select one of the coastal indicators to visualize it on the interactive map. Both the performance of the linear trend of the indicator and the the relative performance of the profiles in the current state are available for visualisation. When the current state is selected, the user can visualize a pop-up, showing the cross-shore profile with the selected indicator shown on it. When the linear trend is selected, the historical data and its linear trend are plotted in the pop-up. Figure 6.3 shows the trend of the scarp toe location as an example. Figure 6.4 shows the state of the maximum beach elevation on the east side.

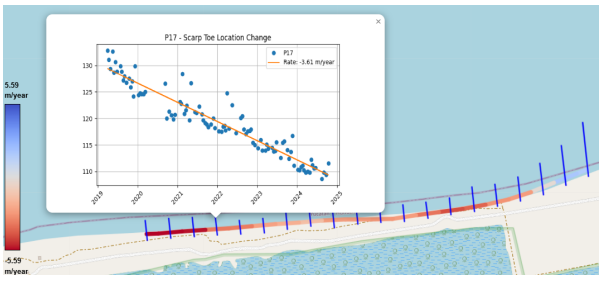


Figure 6.3: Scarp toe change rate (West)

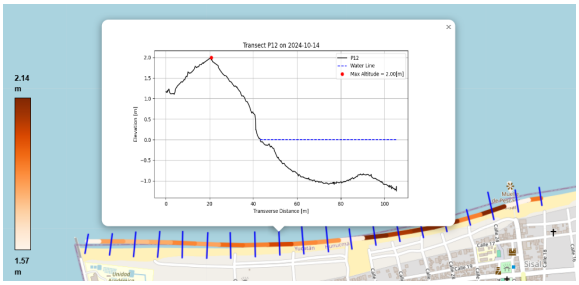


Figure 6.4: Maximum dune elevation (East)

Stakeholder Map

A map of where different stakeholders, critical infrastructure and coastal objects are located, is presented in the web-tool (figure 6.5). This allows the user to quickly overview where certain stakeholders and infrastructure are located. This enables insight in the relation between, for example, coastal infrastructure, and results obtained from the coastal analysis.

Figure 6.5: Stakeholder map in web-tool

Stakeholder Perspectives

The quantitative findings of the social analysis are also summarized on the web-tool. This allows the user to see what different stakeholders of these region consider important.

7
Discussion

7.1. Coastal research

The following sections discuss the findings of the coastal research as presented in chapter 4. The results are discussed separately for the shoreline position data, USGS index, Sisal resilience index and the coastal characteristics of the west domain.

7.1.1. Shoreline retreat/advance

The shoreline change presented in chapter 4 generally aligns with the rates obtained by researchers of UNAM. A study of (Franklin et al., 2021) shows the shoreline advance rates of the eastern domain for 2015-2020. When this time window is selected in the web-tool, the computed shoreline change rates correspond with the values of this research, reaching a maximum of around 7 meters per year at the eastern profiles near the port's breakwater.

It is important to mention that these rates describe observed coastal changes over recent years. While this linear trend is straightforward to communicate to third parties, it is not a suitable method for predicting future shoreline behaviour. Additionally, the shoreline rates presented in chapter 4 are calculated over the entire available time series, which limits insights into any accelerating or decelerating trends. In the web-tool, users can analyse shoreline trends over chosen time windows, allowing for comparisons between, for example, early dataset trends and more recent years. This functionality significantly enhances the method, as it enables visualization the higher erosion rates just after construction of the port compared more moderate trends in recent years. Also, adjusting the time window allows users to observe the effects of artificial sediment bypasses performed periodically along the shoreline.

Another limitation is the 100 meter resolution of the measured profiles. This is a relative coarse resolution, especially considering the anthropogenic perturbations that are present in this system. These perturbations can impact the coastal behaviour very locally, on a spatial scale that is not fully captured with a 100 meter resolution.

Furthermore, the measurements of the profiles are affected by human errors due to the manual process of walking the profile with an ADCP (Acoustic Doppler Current Profiler). Additionally the ADCP signal contains instrumental errors and computational errors in defining the exact location and elevation. However, these error are considered small and will most likely have little impact on the result.

CoastSat Data

As shown in figures 4.2 and 4.1, the CoastSat rates closely match the measured rates determined through walked transects. This is despite the 10 meter error when identifying shorelines (Vos et al., 2019). These errors are usually caused by cloud cover, complex shorelines and aliasing. This significant error is averaged out of the rate due to it being computed using hundreds of shorelines. The analysis could be improved by including a co-registration process with Arosics (Scheffler et al., 2017). As stated in the method, this led to incorrect shifts and should be investigated in further research.

Considering the extended domain, the CoastSat rates usually follow the changes in shoreline orientation. However, this connection does not always hold true. In the east domain, significant shoreline retreat is observed from transects Tr48 eastwards. This is particularly interesting, because the shoreline orientation remains unchanged, and there are no anthropogenic interventions in the area. Previous

studies identified the presence of sand waves along the Yucatan coastline, which travel with celerities of 300 meters per year and can drive 40 meter shoreline oscillations. While these disturbances originate from distant anthropogenic sources, their impact extends across a broad section of the coastline. For these transects, the erosion may have been caused by a sand wave generated by constructions near the Progreso pier (Torres-Freyermuth et al., 2023), further research is needed to confirm this.

Since satellite images were collected from 1985 onwards, the CoastSat data allows for a greater historical analysis. Viewing rates from 1985 till now, significant differences can be observed compared to those computed during the last decade. Capturing the full evolution of the coast due to the construction of the port, the east side rates are relatively more positive, whilst the western rates are more negative. This is to be expected, as the effect of the port is expected to flatten off as time passes. By taking the full signal, its effect will be more present in the rates. This observation confirms the fluctuation of linear rates over time. It is therefore critical to select a time window which is correct for the context of the analysis.

7.1.2. USGS Index

The results presented in chapter 4, figure 4.4 correspond with the shoreline advance/retreat rates shown in figures 4.1 and 4.2. A big limitation of this index on this coastal stretch is the fact that the shoreline change rate is the only variable parameter. This results a reduced range of only five distinct vulnerability scores over approximately 8 km (When the satellite data domain is used). A resolution that is arguably too course for such a small area.

The results presented in the web-tool are rated relative too each other. This could indicate that the coast is very resilient, because of its green colour, while it, compared to a different domain actually is not very resiliency. An advantage is that this method is more widely used, so results can be compared to different locations.

As for the shorelines, can the USGS index also be calculated for a specific time window, adding valuable flexibility and depth to the method.

Another key limitation is that by aggregating multiple parameters into a single index, details specific to each variable are lost. The loss of detail could result in the overlooking of critical aspects of vulnerability. That is why for coastal engineering, such an index should also be used in conjunction with more detailed coastal research that provide more insight in the hydro and morphodynamic factors. This also due to the fact that the USGS index does not take into account direct hydrodynamic forcing, such as (high) water levels, storm surges, wave heights etcetera.

7.1.3. SRI

The results from the Sisal Resilience Index (SRI) are shown in figures 4.5 and 4.6. Viewing the values obtained through the final index, it appears that transects P20, P09 and P01 are relatively least resilient. Meanwhile, transects P14, P08 and P05 are relatively most resilient. These least resilient transects are all located near a specific anthropogenic perturbation of the coastal system. P20 lies next to the breakwater, which has created a highly fluctuating coastline due to bypassing and accretion patterns. The presence of the structure also limits the growth of the dune system, leading to a limit elevation. P09 suffers due to the extensive removal of the dune system, leading to a low elevation. This transect is also highly prone to inundation from storm induced water levels. Finally P01 lies east of the pier, and exhibits poor performance regarding dune growth with relatively high variability due to the presence of the structure.

Observing the full set of SRI values in figure 4.5, it can be seen how coastal structures impact the coastline, reducing its resilience. The SRI values are lowest for transects closest to these structures (P20, P01), and slowly increase with distance removed from the perturbation. This effect is however not always true, exemplified by P09, which is a singular poor performing transect bordered by transects with relatively high SRI scores. This highlights the varying alongshore extent to which a a perturbation impacts the coastal system. Overall, the SRI identifies a similar coastal performance compared to those using the CRI by (Dong et al., 2018), and the CRIfRS by (Mendoza et al., 2022).

The detailed analysis presented by figure 4.6 shows the performance of the individual coastal indicators (dune height, mean elevation, beach width) as well as each individual component of the time signal

(mean, rate, variability). Viewing these results provides a detailed view, indicating specifically what aspect of the coastal profile is responsible for the SRI value. Considering the least resilient transects, it is clear that P20 scores low on variability, meanwhile P09 scores low on mean values. Viewing the components individually, it is possible to identify transect specific issues. This is highly valuable for applying effective coastal management strategies, informing the design of tailored mitigation methods.

Considering the value of an individual analysis, it is important to reflect on the balance between providing accurate information and being able to communicate this effectively. Resilience indices are often designed to aggregate complex sets of information to a single, easy to understand value that can be communicated towards stakeholders. They serve an important purpose for informing stakeholders without expertise in coastal systems and can be seen as a powerful tool for strategising good coastal management. Despite their communicative strengths, resilience indices inherently lose detail by combining multiple forms of data into a single value. This can be dangerous, as transect specific issues may be obscured in the index value. Therefore it is critical to present not only the final SRI values, but also dive into the performance of each indicator and time signal component.

Despite the relatively accurate performance of the SRI, its formulation creates a number of limitations. Firstly, the index depends on a high density of data which is labour intensive for researchers to obtain. This harms the future applicability of the index, as it is reliant on data collected during the biweekly transect campaigns. Secondly, the walked transects have highly varying starting positions due to the presence of structures and vegetation which obstruct the paths. The variation in initial measurement location impacts the values of the coastal indicators, such as the mean elevation. This can artificially skew the performance, impacting the accuracy of the methodology. Finally, the SRI only considers morphological parameters, limiting its assessment to a specific aspect of resilience. Indices such as the CRI by (Dong et al., 2018) often consider hydrodynamic forcing, as this describes the risk of inundation along the coast. This would be an important process to consider as barrier islands like Sisal are often exposed to flood risk. Vegetation data is also not considered in the SRI. The variation of vegetation, as well as other coastal developments such as palapas, can highly impact the resilience of the coastline by influencing morphological processes. This has been indicated using the CRIfRS index, making use of remote sensing imagery (Mendoza et al., 2022).

7.1.4. West Sisal indicators

The method used to asses the coastal behaviour of Sisal's west coast provides valuable insights but has specific limitations that influence how certain indicators, particularly the scarp toe, should be interpreted.

The algorithm used to identify the scarp toe, while effective in most cases, has limitations and errors. These errors arise especially when the cross-shore profile differs from a typical steep scarp profile. In these cases, the scarp toe is less distinctly marked by an abrupt change in the profiles curvature. Such deviations often occur after a scarp collapse, as it drastically impacts the shape of the cross-shore profile. For example, hurricane Milton (2024-10-07) caused significant profile changes (Figure F.7) and led to multiple scarp collapses. After incorporating the post-hurricane data into the web tool, the indicator's inaccuracy was immediately apparent.

Since other indicators for the west side, such as beach width and dune height, are defined using the scarp toe, these indicators are similarly affected by the algorithm's errors, making them less reliable. Despite the large error, the scarp toe algorithm is still a valuable deliverable from this research project. When a linear fit of the historical data is made, these indicators can provide meaningful patterns and support the understanding of the coastal system, despite not being completely free of errors.

As for all indices, indexes and shoreline changes, a linear trend might be useful for detecting general coastal behaviour, however, its extrapolation is not an accurate prediction of future behaviour.

An additional insight from Chapter 4 is the increase in scarp toe elevation across many profiles. As described, this increase is due to collapsing scarps, resulting in a new defined toe more land inwards and with a higher altitude. Although some of this increase may reflect algorithmic error, it could also reflect a real response of the system. Figure 4.9 in Chapter 4 substantiates the increasing behaviour of the scarp toe elevation. Theoretically, as the system moves towards a new equilibrium, erosion deceleration aligns with an exponential decay function, which gradually reduces erosion rates over time. This elevation increase could thus act as a negative feedback mechanism as the possibility of

collapse of the new, higher dune to is smaller than before.

As described in Chapter 4, does the scarp toe retreat align with he shoreline retreat in most cases, resulting an a more or less stable beach width. For the profiles near the port however, this behaviour is not captured. This is because of the sediment aggregation that occurs near the port (See Figure 4.2). Because of this shoreline advance, the beach width does grow nearby the port, resulting in the deviating results for these profiles.

7.2. 1D Model analysis

The results from the 1D coastal model revealed key patterns in sediment accretion and erosion dynamics for two scenarios: one with a 300 m breakwater (Scenario A) and another with a 600 m breakwater (Scenario B). The analysis focused on how factors like bypassing, linear trend approximations and sediment distribution affected both the breakwater and nearby pier.

7.2.1. Influence of bypassing factor

The bypassing factor played a central role in shaping sediment movement around the breakwater. For both scenarios, it strongly influenced the eastward sediment accretion pattern extending from the breakwater. In Scenario B, the extended breakwater length shifted the accretion zone further offshore, suggesting that a longer structure could capture more sediment on the accreting side due to reduced bypassing close to the breakwater. On erosion, Scenario B showed a more gradual rate change but led to higher cumulative erosion over time. This result suggested further study since bypassing was affected by factors like the surf zone location relative to the breakwater and sediment trapped within the access channel.

7.2.2. Linearity of accretion and erosion Rates

The model displayed a near-linear increase in accretion and erosion rates over the initial years for both scenarios, although Scenario A exhibited a plateau, indicating a saturation point where rates began to stabilize. This implied that while linear sediment transport assumptions worked well initially, they became less accurate over time. In Scenario A, accretion near the breakwater saturated, suggesting that beyond a certain point, sediment transport decreased, especially for shorter breakwaters where bypassing limited sediment movement. After a few years, the declining trend suggested that linear approximations might not accurately capture long-term behaviour.

7.2.3. Erosion dominance over accretion

Erosion consistently exceeded accretion over time in both scenarios, with Scenario A showing higher erosion rates near the breakwater compared to Scenario B. This result could have been due to limited sediment replenishment in Scenario A's shadow zone. The saturation of the breakwater may have led to higher erosion rates due to faster sediment transport. Scenario B's extended breakwater shifted the peak erosion zone further along the shoreline, consistent with a longer shadow zone effect that displaced the erosion peak farther from the structure.

7.2.4. Accretion effects on the pier

The pier experienced significant sediment accretion over 25 years, covering nearly half its length in Scenario A and over half in Scenario B. This suggested that accretion rates near the pier were influenced by natural sediment-trapping processes, even though the model did not explicitly include the pier's influence. Observed calibration patterns implied that the pier likely accelerated sediment accumulation by altering local flow patterns, highlighting the need to consider such structures when modelling sediment distribution around coastal infrastructure.

7.2.5. Comparison with measured erosion Rates

A comparison of the model's rates with field measurements provided insight into its performance. Table 7.1 shows erosion rates from Scenario A alongside field-measured rates:

At the breakwater, the model predicted an accretion rate of 0.8 m/year, lower than the measured rate of 2.2 m/year. This discrepancy was notable, as the breakwater tip was fully accreted in recent years, yet field measurements showed higher rates. The model's rate of 0.8 m/year reflected expected behaviour,

even if it was lower than measurements. For the pier, the model prediction of 1.7 m/year aligned closely with the measured rate of 1.8 m/year, suggesting that the model reasonably approximated accretion here, even without explicitly accounting for the pier's hydrodynamic effect.

Location of Rate	Model Rate [m/year]	Measurement Rate [m/year]
Accretion at Breakwater	0.8	2.2
Accretion at Pier	1.7	1.8
Erosion at Breakwater	-6.3	2.0
Erosion at Maximum Curvature	-6.3	-4.1

Table 7.1: Comparison of Model and Measurement Rates for Accretion and Erosion (m/year)

The model's erosion rates showed more marked differences from measurements. At the breakwater, the model predicted -6.3 m/year, while measurements showed accretion at 2 m/year. This discrepancy may have indicated that the model overestimated erosion forces, potentially oversimplifying sediment dynamics. Close to the breakwater, human interventions like dredging and sand nourishment likely contributed to this difference. Similarly, at the maximum curvature point, the model predicted -6.3 m/year, while the measured rate was -4.1 m/year. The model's estimation likely missed the effects of detached breakwaters or groynes that impacted sediment transport in this area.

7.2.6. Model limitations

Several limitations in the model affected the results. The CERC formula, which represented sediment transport, relied on average rates based on wave incidence and frequency, but did not account for storm events, which significantly impacted sediment transport and shoreline morphology. Consequently, storm-induced sediment changes were not reflected in the model, potentially underestimating the variability of sediment transport over time.

Furthermore, the model excluded coastal structures such as detached breakwaters, groynes, and the pier, all of which influenced sediment transport. The pier particularly affected sediment accretion, though it did not significantly impact peak accretion rates. However, it likely influenced erosion rates and sediment distribution. These omissions suggested that while the model captured general sediment transport trends, it may have overlooked site-specific details and variability introduced by coastal structures and extreme events.

In summary, comparing Scenarios A and B demonstrated how structural adjustments to coastal defences impacted sediment dynamics. These findings offered a basis for assessing the long-term effects of breakwater modifications on sediment transport and coastal morphology, while also highlighting the limitations inherent in the model's assumptions and structure.

7.3. Storm analysis

The storm analysis shows that the east and west sides of the port respond differently to extreme storm events. Consecutive transects often have distinct patterns, suggesting that local factors like topography, wave exposure, and proximity to the port's jetty are important in how the coast reacts to each storm. However, the results don't directly indicate that the port structure consistently affects sediment movement during storms. Transects near the jetty behave similarly to those further along the shore, suggesting that the jetty might not be the main factor influencing sediment dynamics during storms.

Subaerial volume change was a reliable indicator for measuring erosion and accretion patterns, while other indicators like dune toe position, mean elevation, and waterline position were more variable and localized. These other indicators often changed significantly between nearby transects and different storms, with no clear pattern across the study area. Because of this variability, subaerial volume change was used as the main indicator in the analysis since it offers a more consistent measure of sediment

transport and deposition patterns. However, subaerial volume change alone does not capture all aspects of coastal vulnerability or the ability to resist, as factors like dune height and waterline position also play a role in how well the coast can withstand storm impacts.

The trends observed are different on the east and west sides of the port. The east side generally loses sediment during most storms. The dune toe has moved back several times, indicating ongoing changes in the land shape, while the highest dunes stayed mostly the same, suggesting that storm surges did not reach them and left them largely untouched. On the other hand, the west side has more mixed responses. Some storms cause sediment to build up and dunes to grow, while others lead to erosion. For example, during the Delta storm, the dune toe moved seaward and the shoreline widened, but the Zeta storm caused erosion in several west transects.

These findings are similar to other studies(Medellín et al., 2024), which also found that storm impacts can vary a lot along coastlines, even over short distances. However, our analysis has some limitations. Background processes like natural erosion, sediment redistribution, or other short term morphological changes may have influenced the observed patterns. Additionally, the two-week gap between transect measurements makes it hard to pinpoint the exact impact of each storm. Some changes might have happened before or after the survey dates, which could affect whether they were caused by storms or background processes.

Furthermore, meteorological and hydrodynamic factors such as wind speed, wave direction, and storm surge height were not included in this analysis, which limits our understanding of the storm dynamics driving these morphological changes. Future research that incorporates these variables would enhance the interpretation of storm impacts and provide a more comprehensive assessment of coastal vulnerability. Lastly, the discrepancy in profile measurement dates between the east and west sides introduces an imbalance.

7.4. Social research

The following section discusses the results of the social research, as presented in chapter 5. First, the observations on the social dynamics are addressed. Subsequently, insights into various social analysis discoveries are explored, including the key system roles, communicative relationships, priority lists and future perspectives.

7.4.1. Implications of social dynamics

The analysis of the social dynamics of Sisal shows how future development plans are threatening the area and the local population. Following the statements from interviewees, the economic development of Sisal, caused predominantly by increasing tourism activities in previous years, can be observed to be negatively correlated with the quality of its ecological system. Furthermore, the underdeveloped capacity of Sisal's infrastructure is currently causing issues, with most community members stating that decreasing this pressure should be prioritised above all else. Nevertheless, interviewees note that it seems that the development, and associated expansion, of Sisal is inevitable. Managing Sisal's growth in a sustainable manner will therefore be an important focus point in the future (Mendoza-González et al., 2021).

However, the lack of initiative by governmental institutions to organize participatory decision-making processes on matters of high local importance has seemingly caused for the local population to lose confidence in policymakers. It appears that this loss of trust has not caused for a call for change, but rather a feeling of responsibility of the community to self-regulate and self-organize. This is not inherently a positive outcome, given that it has lead to occurrences of illegal construction, with associated consequences for the environment. Apart from that, there is a lot of uncertainty about future developments, as interview participants state that previously made regulations and law are not adhered to or changed without communication.

The local population's perception of responsibility, in addition to this aforementioned uncertainty, can become a threat. Previous research shows that as soon as a system gets more uncertain, government institutions become more influential (Maye et al., 2017), which might result in negative consequences for the community. Particularly, as the monitoring and enforcement of regulatory compliance appears to be either insufficient or entirely lacking. An example of this is policymakers' tendency to undervalue the

ecological system of Sisal, resulting in seemingly uncontrolled decisions threatening further ecosystem deterioration. This does not appear to be caused by bad intentions, but rather due to differences in priorities and a potential lack of expertise on the consequences of courses of action.

Organizing participatory decision-making processes to effectively regulate Sisal's development sustainably appears to be key in addressing this issue, as it involves the interests and values of all parties involved. This setting should ideally be coordinated by authorities and has to subsequently encourage bottom-up initiatives, to make sure that the voice of the local population is included. Furthermore, local culture and perception must be respected, and social and economic benefits have to be distributed equally. Ultimately, creating an environment that effectively addresses the threat of gentrification, (further) ecosystem deterioration, and infrastructural pressure.

An important question, however, remains on how to achieve this solution. The government's reluctance to take responsibility of sustainable development appears unlikely to change, as conflicting priorities, limited time and resource constraints form a significant bottleneck. UNAM could play an important role in bridging this gap by combining relevant technical expertise with perspectives of the local population, potentially influencing policymakers to adapt adequate coastal management and development strategies for Sisal. Yet, it is not UNAM's organizational requirement to take this responsibility, making it challenging to address this social issue effectively.

7.4.2. Key system roles

The analysis of the system roles of the thirteen identified organizations shows that the system seems to lack a clear 'Guardian' role, as governmental institutions inadequately control evaluations of the system, whilst stakeholders that do hold this interest do not have the power to do so. This can be a problem, as any complex system must have the capacity to self-organize, and thus needs to contain elements of monitoring, feedback and control (Lyon et al., 2020). These functions are overseen by a system's guardian, and the absence of this key role can result in issues, as no entity is present to ensure that established rules and standards are carried out correctly. This can result in a system's increased vulnerability to potential cases of mismanagement, inefficiencies, or exploitation.

Furthermore, the power and interest grid illustrates that stakeholders with a high interest have no authority to change the coastal system, while organizations with a high power level seem to lack the concern to effectively address issues. This reaffirms the lack of a clear 'guardian' organization. Changing the function of an (or multiple) organization(s) within the system to resolve the absence of an evaluating and controlling stakeholder could lead to positive outcomes in adequate coastal governance. For instance, by giving nature preservation initiatives more authority to set rules or setting-up a governmental program that actively oversees Sisal's coastal preservation.

Finally, interviews have pointed out that decisions and progression related to the development of Sisal currently seem to be predominantly revolved around organizations with a stake in the tourism industry (i.e. tour operators, restaurant owners, etcetera) and within governmental institutions. This is reaffirmed by the power and interest grid, as it presents that these stakeholders are also the ones holding the most power.

7.4.3. Communication network findings

The communication network presented in section 5.3.3 illustrates the quality of the communicative relationships of the thirteen identified organizations. The characteristics of these connections are analysed in the following section, by addressing insights of relevant node sizes, centrality, and colour, as well as findings on edge types.

Node centrality and size

The centrality of the nodes shows that a clear group of organizations form the core of stakeholders within Sisal's community, with all organizations having a direct relationship to Sisal's economic sector. This can be explained by the extensive collaboration between the hospitality industry, as palapa owners, restaurants, tourism companies and the fishing industry work together to create economic opportunities for themselves. Tourists are located most centrally in the network, as they have a connection to the hospitality industry, as well as representatives from the real estate sector.

The relatively distant connection of governmental institutions and UNAM to other nodes is also noteworthy. The high level of power of state and municipal representatives can play an important role in adequate coastal management. However, interviews and literature point out that policymakers hold a relatively passive attitude towards coastal governance, instead prioritizing economic and touristic development. This attitude is reaffirmed by their distant position in the communication network. Furthermore, it should be pointed out that Sisal's Comisaría has a relatively high weighted degree value, accompanied by a low centrality. This too re-emphasizes their passiveness.

Finally, the size and centrality of UNAM shows their lack of connections with other organizations in the community, further acknowledging their difficult position as a 'knowledge island' within the system, as described in section 5.3.1.

Node color

The colors of nodes reaffirm the result of the power and interest grid, presented in section 5.3.2, as organizations with equal or similar roles are located around the same positions within the network. The network shows a close relationship between the Advocate and Buyer/Seller roles, which can be explained by the main objective of most Advocates, which is to convince a Buyer/Seller of their product or information. Again, corroborating the view that the hospitality sector of Sisal acts as the core relationship group.

Lastly, it should be pointed out that both governmental representatives (Sisal's Comisaría and the Municipality and Sate) are closely related, due to their roles being somewhat dependent on each other. In this system, the Municipality and State (Regulator) set the rules, with the Comisaría of Sisal (Owner) ensuring that a specific part of those rules are lived by.

Edge types

The type of communication lines of an organization present an important insight into the effectiveness of a stakeholder to communicate with other organizations, as this is not necessarily determined by the number of relationships that a node has. Variations are made in direct (yellow) and indirect (blue) relationships, with the edge type ratio and edge directions describing the communicative role of an organization within the network. Again, the thorough collaboration with the Sisal's hospitality sector is showcased by the relationships between the related organizations: Communication is frequent and undirected, representing a strong relationship.

Furthermore, the analysis of the communication networks reveals that some organizations act like information senders or receivers, resulting in one-sided communicative relationships. An example of this is UNAM mainly sending information. This is reaffirmed by the interview results, with researchers acknowledging the fact that they find it difficult to reach Sisal's community members, whereas inhabitants often mention to never have been in contact with UNAM at all.

Another example is the almost solely receiving role of the governmental institutions, re-emphasizing the government's passive attitude. In other words, top-down information initiatives do not reach local stakeholders. This acknowledges results from the interviews, as interviewees mention to only reach out to government representatives if absolutely needed, with the institutions themselves rarely supplying information to the community. Especially the role of the Comisaría is interesting in that regard, as most stakeholders mention that they have solely had infrequent contact with the Comisaría, who in turn gets in contact with other state representatives. Therefore, there is next to no contact from Sisal's community members with the municipality of Hunucmá and the state of Yucatán directly. This highlights a gap between strategic planning and the realities faced by policymakers, accompanied by a lack of local control over the implementation of policies. These disconnections are frequently emphasized in coastal management literature (Rölfer et al., 2024). The network therefore suggests that there is a higher need for more two-way communication between key regulators (governmental institutions) and other stakeholders to promote balanced management practices.

Finally, it should be noted that real estate developers could hold an important role in Sisal's development, as they have a central function in connecting Sisal's hospitality sector to the government. Their potential ability to catalyse or block the system's progress should therefore be acknowledged.

7.4.4. Findings on stakeholder priorities

Generally, the results suggest that interviewees predominantly prioritize aspects of Sisal that are related to the connection of their background to the community. Aspects that are directly connected to their occupation therefore seem to rank higher than other characteristics. Overall, the importance of Sisal's development is overstated by stakeholders with various roles and functions, while plans to expand the area are generally viewed negatively. Furthermore, the health of the coastal system is seen as an important factor in all results, amplifying interviewees' suggestion that adequate coastal management will have a positive effect on other important facets of Sisal's community.

Aggregated results

The average values for the priority lists of all interviews is presented in figure 5.5. The results show a clear distinction between stakeholders' priorities, with Sisal's development and the health of its coastal system being prioritized over other aspects, while the tourism industry and Sisal's expansion are viewed to be less important. Developing Sisal by increasing the quality of life within the community was the main reason for individuals to rate the importance of development highly. Interviewees mention that Sisal's availability of basic services should be improved significantly, as the current presence of amenities is lacking. The improvement of the reliability of services in Sisal was therefore often regarded as the first priority. Additionally, the high priority value of coastal health was predominantly caused by interviewees' view that other aspects of the priority list could not be maintained without a healthy coastal system.

Furthermore, it is noteworthy that, even though Sisal is increasingly dependent on the tourism sector, stakeholders do not seem to value its contribution. Interviewees often mention that they do not view tourism as something negative in itself, but are currently unsatisfied with the management of the sector. Therefore, actors often valued the negative social impact of the tourism sector higher than its economic contribution. This also explains the relatively higher priority of the fishing industry, as the industry seems to be more accepted within the community. This may be caused by the long-standing presence of the industry in Sisal and the fact that many interviewees have direct occupational connections to it.

Sisal's expansion was regularly immediately placed at the bottom of an interviewee's priorities. Most, if not all, stakeholders believe that Sisal should not expand according to the current development strategies. Actors are afraid of gentrification and an increased pressure on Sisal's infrastructure. However, the high priority of Sisal's development in comparison to the unwanted expansion is noteworthy, as it is unlikely that one can occur without the other. This is described in more detail in section 5.3.1.

Priority variations based on stakeholder backgrounds

An analysis of the priority list results based on the interviewees' position within Sisal's community is presented in figure 5.2c. A stakeholder was perceived to be directly inside Sisal's community, if that person either lived in Sisal or had direct and daily contact with the local population. All other individuals were categorized as outside of Sisal's community.

Generally, actors within the community ranked the various aspects of Sisal more evenly, whereas actors more distant from Sisal viewed tourism and Sisal's expansion as significantly less important. This could suggest that stakeholders within Sisal's community place greater value on the cohesion of these different aspects. However, the background of the surveyed individuals might have a strong influence on the results, as most of the individuals considered to be outside of the community are involved in coastal or ecological research. This can result in biased results, as these actors may have similar attitudes towards the coastal system and are generally more involved with technical aspects, therefore prioritizing these subjects over other characteristics.

Another noteworthy observation is the outside stakeholders' priority of Sisal's coastal health. This can again be explained by the research-related background of these individuals, as well as the fact that it is generally easier to prioritize the ecological value of a location to its development if one does not reside there.

Finally, it is remarkable that insiders value the fishing industry significantly less than individuals outside the community. This is attributed to inhabitants' opinion on the aforementioned decreasing importance of Sisal's fishing industry. During the interviews, this fact was predominantly mentioned by community members, suggesting that this opinion or knowledge is not (yet) shared with outsiders.

Priority variations based on local and external perspectives

An analysis of the average priorities of participants regarding their occupation or connection within the system is presented in figure 5.7. The four graphs show significant differences compared to the total average and to each other, both in observed values, as well as the rankings of the six aspects.

Participants with a research-related background place the priority of the fishing industry considerably higher than other actors. Interviewees mention that they believe the economic revenue that the fishing industry creates for Sisal is crucial, emphasizing that large parts of the community are dependent on the employment that the industry provides. However, this view does not seem to resonate with community members themselves.

Government representatives clearly value the ecological aspects of Sisal over economic and development characteristics. This could suggest that they prioritize the aspects of Sisal that fall under their responsibility first, as the governmental institutions are predominantly liable for ecological management.

The priority list results of inhabitants are most similar to the aggregated results presented in figure 5.5. It is noteworthy that community members value their quality of life and the ecological characteristics of Sisal over the (development) of their economic sector, as the priority for important revenue sectors are have low average values. Furthermore, their negative view towards tourism is reaffirmed, as this is the only average priority list where Sisal's expansion is *not* considered to have the lowest priority.

Local business owners have a more balanced view on the importance of the six aspects. However, entrepreneurs seem to prioritize components of Sisal that are beneficial for their business, like the fishing industry, tourism sector and health of the coast. This is reaffirmed by the low placement of nature. The high priority of Sisal's development can both be explained by the fact that increased services of Sisal make their business more valuable, as well as the fact that the business owners reside in Sisal themselves.

7.4.5. Stakeholder perspectives

Drawing a scenario of the long-term future of a relatively undeveloped location, like Sisal, proved to be difficult for many participants. Sisal will likely change significantly in the coming decades due to the growing tourism sector, which makes it challenging for interviewees to envision the location in 50 years. This was clearly noticeable, indicating a level of uncertainty about Sisal's future for many.

Due to this challenge, participants drew predominantly from their background or connection to Sisal. For instance, stakeholders with expertise in aspects of the coastal system drew that part significantly more detailed, or decided to focus on that subject entirely. Ultimately, drawing maps with more technical details, especially on the development of the port or changes in Sisal's ecological zones.

Inhabitants of Sisal had a more general view, with a greater focus on the cohesion between the coast and the town's community. Their thoughts on future development was often solely directed towards real estate development in the reserves, with most leaving the development of coastal processes out of their vision. Furthermore, it was noticeable that inhabitants often drew specific landmarks of Sisal, like the yellow arch at the entrance of the town, suggesting the cultural significance of these infrastructure objects to the local population.

Reoccurring mental map content

Specific landmarks of Sisal were drawn often, as they provided the participant with a sense of direction. Even though interviewees were asked to envision Sisal in 2070, relatively little changes were made to existing infrastructure in the area. The following reoccurring aspects were noticed in the mental maps:

- The fishing port and breakwater were drawn in all mental maps, either holding the same function as it currently has, with an added function, or repurposed in some way. This suggests that, even though the fishing industry has a declining share in Sisal's economic sector, the port is still seen as an important landmark in the area.
- The pier at the end of the main access road was often drawn, usually unchanged in comparison to its current form.
- Almost all participants added real estate developments to their map, indicating significant changes in Sisal's size. New infrastructure was most often drawn in the natural reserves to the East and

West of the town, with some individuals also adding housing projects in the centre, within the mangroves, and/or along the main access road.

- UNAM was often added to the mental maps in its current location. This was not only done by researchers there, but most inhabitants drew the institute as well. This is surprising, as most community members do not have a relationship with UNAM at all. However, it can be explained by the fact that participants were aware that the contents of the interview were related to a research project at UNAM, subconsciously influencing their vision.
- The access road to Sisal was often drawn as the only transport component of a participant's vision, sometimes accompanied by the mentioning of its connection to Hunucmá.

Opportunities and threats

The analysis of the mental maps provided several reoccurring opportunities and threats that Sisal could face in the future. Opportunities are mainly related to Sisal's development, providing chances for the tourism sector by adding more housing projects and improving the town's accessibility. Smaller opportunities were noticed in the maturation of Sisal's beach services, like the expansion and increased quality of palapas.

However, the opportunities related to Sisal's infrastructure development were often seen as a potential threat to the system. Interviewees overstate their concern of gentrification, (further) declining ecosystem health, inequality, and segregation. Participant's drawings of real estate developments were predominantly accompanied by a negative view towards these transformations, with many seeing the increase of infrastructure as negative. Other threats were mostly related to future climate change effects, with interviewees expecting increased coastal erosion patterns, sea level rise, lower levels of precipitation and dried-up mangroves.

These opportunities and threats reaffirm the social challenges and dualities described in section 5.3.1. Ultimately, resulting in a complex social system, where decisions in the coming decades can have a significant impact on the quality of life in Sisal and the effectiveness of coastal management strategies.

7.4.6. Shortcomings of the social research

Although the interviews have provided a substantial amount of information on characteristics and stakeholders Sisal's coastal system, several shortcomings of the social research still need to be addressed. This is mainly related to generalization and assumption issues related to the number and variety of interview participants.

Even though many individuals and organizations were identified during the social analysis process, it proved to be difficult to approach and conduct interviews with all relevant stakeholders. This was predominantly caused by the project team's lack of connections within Sisal's coastal system network, time constraints to acquire results, and willingness of approached individuals to participate in the study. Similarly, these challenges have potentially lead to the oversight of other relevant stakeholders.

Accordingly, sixteen full-length interviews do not provide enough results to confidently state that all information provided by the interviews is accurate. Especially, as some organizations have not been (adequately) represented in the research, consequently with misleading or incorrect information as a result due to a potentially biased opinion by other stakeholders. As an example, the authors of this research believe that real estate developers and governmental institutions have not been sufficiently included.

Considering this fact, data used for the qualitative and quantifiable methods to analyse the social characteristics related to identified organizations is, to some extent, based on assumptions and generalization. Similarly, the level of power and interest of individual organizations, along with the frequency and presence of communicative relationships in the social network analysis, is primarily based on the information provided by a relatively small number of interviews. Comparatively, the findings on stakeholder priorities are presented as the result of complete organization, despite the fact that the data is determined from a small percentage of the total population.

Finally, interview participants could have been influenced in the mental mapping process by an interviewer's nudging. Many interviewees had difficulty in drawing characteristics of Sisal regarding its

long-term future, as the high level of uncertainty of the area's development seemed to lead to doubt. As a result, interviewers attempted to encourage participants to think of (future) opportunities and threats, potentially influencing the mental mapping process.

7.5. Defining and Communicating Resilience

Reviewing the obtained results from the coastal and social analyses, it becomes clear that each has a unique perspective of resilience whilst being deeply intertwined. There have been numerous social and physical perturbations in Sisal, which stem from various social developments within the community. The construction of the port, the magic town status, as well as the pier and the palapas all influence the coastal system, impacting its resilience. This often leads to negative effects, such as reduced coastal resistance, recovery and protection. The reduced coastal resilience impacts the local community, making it more vulnerable to storms, as well as taking longer to restore from these events. This flow of events highlights how the resilience of the coast and that of the community influence each other. Therefore, it is critical to assess both coastal, as well as social resilience for a thorough analysis.

Although the coastal and social systems influence each other, they do not always experience identical effects. It is interesting to observe events which have contradictory impacts regarding coastal and social resilience. Tropical storms and hurricanes are a clear example of this phenomenon. As concluded from the storm analysis, the beach profiles in Sisal tend to grow drastically after a tropical storm. Subaerial volumes grow significantly, which has a positive effect on the coastal resilience. This positive effect is clearly not present when considering social resilience, as hurricanes damage critical infrastructure, whilst also inundating large areas of the barrier island. These widespread negative effects deeply harm the community, and threaten its possibility to develop and thrive. Considering this paradoxical situation, it is clear that a resilience assessment is highly field specific and does not hold for the entire system.

Observing the complex and multi-faceted nature of resilience, it is important to question how it can be most effectively communicated. Combining coastal and social observations is highly difficult due to the different forms of data. Many resilience indices attempt this by averaging diverse data into a single value. Social observations are particularly inappropriate for this method, as they cannot easily be quantified. Even if this is attempted, the process of quantifying personal perspectives can introduce unwanted biasses which skew the results. Instead of combining these highly different forms of observation, the web-tool has attempted to communicate the multi-faceted nature of resilience by presenting different observations in a single interactive dashboard.

Although the web-tool communication strategy presents a highly customisable overview of resilience, there are limitations to its analysis. The lack of a single overarching indicator can convolute the message towards stakeholders, reducing the success of its communication. The method is also limited by its scope, as the resilience of Sisal will also be dependent on the state of its ecology, economy and climate. Further analysis of these systems would be required to provide a more comprehensive overview of resilience in Sisal.

8

Recommendations

The following chapter delves into technical and social recommendations that are related to the findings of this study. Additionally, suggestions are provided on potential initiatives for further research. The presented recommendations are intended for researchers within UNAM's coastal engineering department and the wider scientific field. Consequently, they do not include proposed actions for other stakeholders, such as methods to successfully change policies.

8.1. Technical Recommendations

During this research difficulties in comparing the east and the west domain arose. Given the unique characteristics of each system, direct comparisons can be misleading and it may overlook critical aspects. Therefore, it is essential to recognize the difference between the systems and be aware of the limitations when comparing the two, especially regarding their resilience indicators.

Additionally, this research shows that human perturbations are best captured when analysing coastal profile indicators, rather tan the existing vulnerability/resilience indices, such as the USGS index.

Finally, the technical resilience indices should not be the sole basis for coastal management strategies because of its simplicity and the loss of a lot of relevant detail of aspects to the coastal system. The recommendation is to always combine these indices with a further in depth analysis of the coastal system, including studies to the hydrodynamic forces and social impacts.

8.2. Social recommendations

'An area is only as resilient as its community' (Urban Land Institute, 2022). Therefore, improving the resilience of the community of Sisal could prove to be useful to prepare its local population for potential natural hazards in the future. Community resilience is essential for strengthening the area's environmental, social, and economic capacity to manage shocks and stresses (Al-Manji et al., 2021). The following section delves into recommendations regarding social resilience.

8.2.1. Advocacy for policy changes

Transforming the government's current top-down policies to coastal management and tourism developments in Sisal to an inclusive decision-making process will lead to positive effects on the community's resilience. As collaboration among multiple levels of stakeholders will increase awareness and can contribute to the encouragement of initiatives (Velayo et al., 2024). Participatory stakeholder engagement approaches will for example lead to the development of better integrated flood risk management strategies (Awah et al., 2024). Furthermore, it results in improved benefit-sharing in the tourism sector (Heslinga et al., 2019)

The success of these approaches largely depends on transparency by policymakers and successful local participation from the design phase onwards (Mendoza-González et al., 2021), however, this is currently not the case. To achieve this result, improved collaboration and a solid relationship between local public, private actors, and state institutions is needed (Mendoza-González et al., 2021), which should be instigated by authoritative organizations. Yet, the passive attitude of the government is currently preventing this shift, which seemingly will not change in the near future.

A way to achieve these policy changes is to promote community-based and community-involved nature-based tourism, that fosters the natural areas of Sisal, without further ecosystem degradation. As tourism also provides opportunities for nature protection, since it plays a role in creating awareness, public support and generates funding for nature protection (Heslinga et al., 2019).

Even though it is not the responsibility of UNAM to propel these changes, advocating a policy shift in ways that are fitting to the values and role of the organization could result in nudges in the 'right' direction. A means to achieve this is through white papers, as these guide policymakers with opinions, recommendations, and research by experts (Hermanm, 2012). Decision-makers can subsequently use these white papers to learn about a policy problem and its possible solutions (George Mason University, n.d.). Determining internally if UNAM's organization is willing to use time and resources to stimulate this shift can therefore be valuable.

8.2.2. Building awareness and communicative relationships

Secondly, it remains essential to keep the local population informed on the coastal developments of Sisal, including associated risks and mitigation actions (Al-Manji et al., 2021). As a key element to foster transformation is the community's degree of awareness on both the current and future working of the system (Lyon et al., 2020). Furthermore, keeping the community updated will likely result in improved communicative relationships and knowledge networks (Rölfer et al., 2024), as it creates mutual understanding (Heslinga et al., 2019).

Therefore, developing an active program of public education on coastal developments could be useful (Al-Manji et al., 2021). This can be achieved through organizing workshops and citizen science initiatives, like various researchers of UNAM have already done in previous studies. Through participation in citizen science, communities can directly contribute to the local evidence base to inform management strategies and solutions for balancing social, environmental, cultural and economic values in dynamic coastal settings and their associated risks (Harley & Kinsela, 2022).

A citizen science approach that could be directly integrated into the web tool is the data provided by the CoastSnap set-up at the pier of Sisal, as it will provide significant benefits for the community in improving their understanding of the changing coastline (Harley & Kinsela, 2022). Workshops with the community to identify and explore relevant coastal information can result in similar effects (Sweetman et al., 2024). Other participatory approaches can be combined with these initiatives, like the method of mental mapping, as it could be used direct Sisal's developments (Frantál et al., 2017).

Therefore, exploring the potential for establishing an education program to regularly inform the local population on coastal developments could be crucial for informing the community and sophisticating the results of UNAM's studies.

8.3. Further research

The following section delves into potential future research initiatives that build on the findings of this study to sophisticate results. Moreover, proposals are given for additional research topics that broaden the scope.

8.3.1. Technical research

In conducting this coastal analysis, a range of factors influencing coastal resilience were examined. Besides the presented results and discussion, this also led to a list of recommendations for future research to improve the robustness and adaptability of the the used methods. These recommendations arose from both the choices made during the analysis process and from the insights gained from the results. The most critical recommendations for future research include expanding of the resilience indices and the data sources. Below, the most important recommendations for further research are briefly addressed:

- Construct a resilience index for the west domain or develop a comprehensive indicator to allow compensations between the two sides.
- Include the effect of vegetation into the resilience indices, as it is considered an important parameter in previous research.

- Extend the domain of which shoreline advance/retreat rates are computed using satellite data.
- Investigate the performance of the SRI on other domains of Yucatan's coastline.
- Investigate the possibilities to use the future predictions obtained by the model to implement in a resilience index for a more robust future prediction.
- Investigate the possibility to use the data obtained from drone flights to fill the gap in the data on the west domain.
- Make the computation of the shadow zone dynamic. Meaning that it will get updated with the advance of erosion.
- Find a way of quantifying the bypassing and then calibrate the factor with this. Also take into account the velocity of the rate of the bypassing.
- Calibrate the S-phi curve with some measurement of sediment transport and not with results directly from the model.
- Incorporate meteorological and hydrological factors such as wind speed, wave direction, and storm surge height to better understand their effects on coastal change after storm events.
- Employ drone imagery to enhance shoreline monitoring and fill existing data gaps for more accurate storm impact assessments.

8.3.2. Social research

Future research on the social dynamics of Sisal should aim to acquire data from a larger number of stakeholders, as it will improve the credibility of the result. Studies should aim to not only increase the amount of participants, but should also intent to broaden the selection of their backgrounds, as it will likely lead to new insights that can subsequently be checked against other findings. In particular, additional representatives of various relevant governmental institutions should be approached, such as representatives from real-estate developers, the ministry of tourism (SECTUR) and the ministry for coastal management of Mexico (SEMARNAT), as they are currently under-represented in this study.

Additionally, follow-up research should aim to get a more thorough understanding on the reasoning behind previously made decisions by policymakers, as this might result in the needed clarity on current coastal management and economic development strategies. For instance, regarding the rationale behind the magic town denomination of Sisal. This information is expected to contribute to a better understanding on decision-making processes and more effective development strategies.

9

Conclusion

The Sisal Resilience Index (SRI), constructed to assess the coastal performance of transects eastwards of Sisal's port, provides valuable insights into the resilience quality of the coastline. The eastern domain of the coast generally performs resilient due to its positive growth in key indicators. However, findings suggest that human interventions are significantly impacting local profiles on their coastal resilience, as transect with large anthropogenic perturbations perform inadequately. In contrast, the coastline westwards of the port is characterized by lee side erosion and a retreating scarp. A trend that conflicts with the region's current real-estate development plans. Additionally, the results gathered by a 1D-model indicate that erosion and accretion magnitudes are likely to continue with the same trend over the next 25 years, following a primarily linear behaviour. This trend also suggests that sediment transport effects will continue extending both westward and eastward from the breakwater, gradually influencing a wider area along the shoreline.

Surprisingly, storm events have had little to no negative impact on the coastal resilience. However, the community itself appears vulnerable to such natural disturbances. This underscores the observations from social analyses, as environmental hazards and increased tourism activities are amplifying infrastructural pressures on the local population, resulting in a low community resilience. This is, among others, caused by ineffective coastal management strategies and a lack of participatory decision-making processes, limiting the local community in their ability to cope with significant socio-economic transformations.

To conclude, the resilience of Sisal - across both the socio-economic and natural system - is threatened by ineffective decision-making processes, inadequate coastal planning and increasing infrastructural pressure. This emphasizes the need for a shift towards adaptive and more sustainable management strategies that support ecological stability and community resilience. Transitioning towards building with nature strategies, as well as forms of coastal protection and nature preservation, will be critical to reposition the developmental pathway of Sisal's coastal system.

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A

Appendix A - CoastSat Process

A.1. Generated Transects

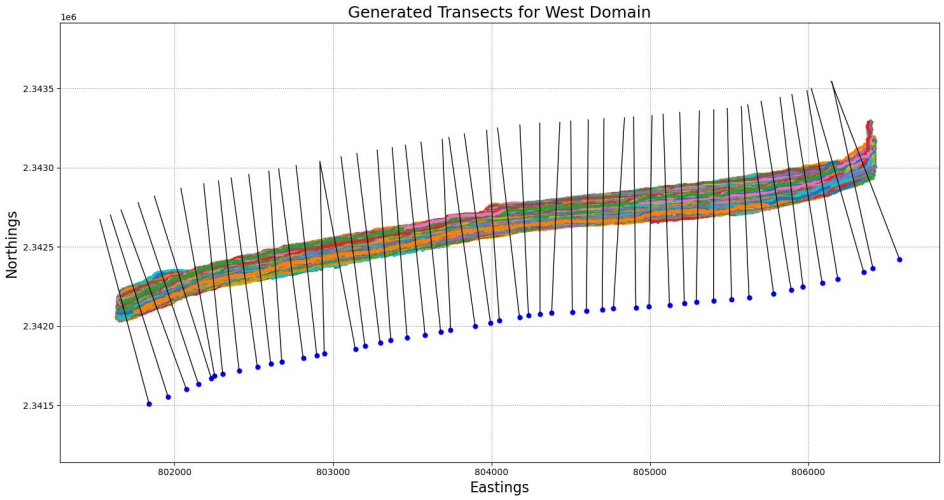

Figure A.1: West CoastSat Coastlines with generated transects every 100m

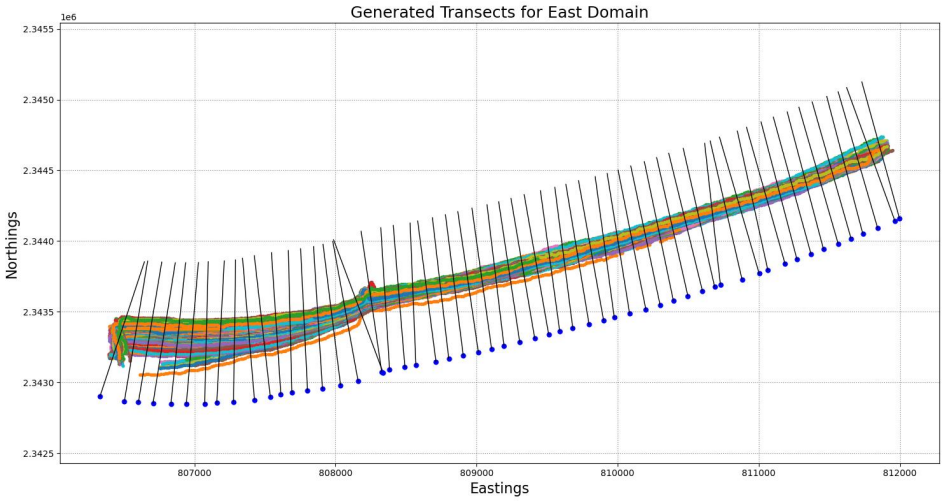

Figure A.2: East CoastSat Coastlines with generated transects every 100m

A.2. Tidal Correction

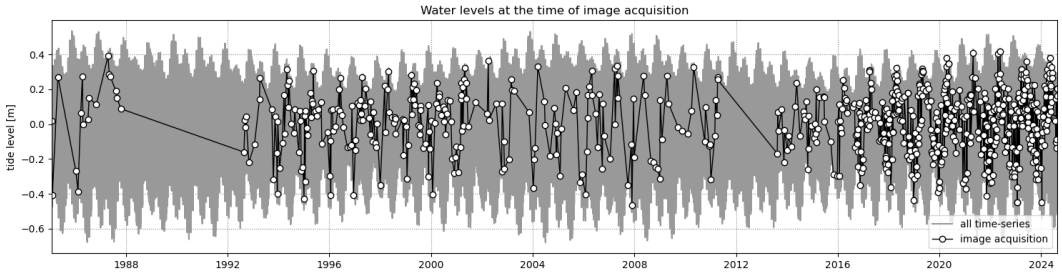

Figure A.3: West domain satellite image acquisition times, plotted relative to the ERA tidal signal near Sisal from 1985 till 2024.

B

Appendix B - Interview templates

B.1. Semi-structured interview template (English)

Interviewer(s):	Date:
Interviewee(s):	Location:
Relation to project:	Interview number:

General

1. Can you tell us a bit about yourself and your connection to Sisal?

Development of Sisal

2. In your opinion, how has Sisal changed in terms of its economic or touristic development over the past few years or decades? For example, the difference before and after 2020?

3. What do you know about the coastal development in Sisal over the previous years or decades? Have there been any significant changes or challenges that you have noticed?

   - If any difference is noted: Has this change caused you to feel less safe or more vulnerable to climate change and associated flood risk?

Communication

4. Have you had any communication or collaboration with other stakeholders regarding Sisal's coastal development or its economic/touristic growth? Think of policymakers (government), inhabitants, researchers, entrepreneurs, tourism representatives, nature preservationists and/or the press?

5. (If answer to the previous was affirmative) With whom have you been in contact?

   - How frequent has this contact been?
   - What type of communication was this mainly? Receiving, sending or both?
   - And would you deem this communication to have been pleasant and effective?

The present and future of Sisal

6. Which of the following areas do you consider most important for Sisal? Rank the following six subjects from 'most' to 'least' important.

   - Liveability and development (Housing, amenities, improved quality of life, …)
   - Fishing industry (The port, jobs created by fishery, …)
   - Coastal health (The degradation of the beach, waste, water quality, …)
   - Nature (The natural reserve of El Palmar, mangroves, …)
   - Tourism (Amounts of tourists, tourism agencies, jobs created by tourism, …)

- Expanding Sisal (More housing and infrastructure, more inhabitants, …)

7. What is your opinion on the future development of Sisal, particularly in terms of the coastal environment and the local economy?

- Do you think climate change and development of Sisal will have a negative impact on the area? If so, how?

8. Could you draw a mental map of what Sisal should look like in 2070 according to you?

- Draw a future Sisal according to your own memory. It does not need to be complete. Draw what first comes to your mind and your own experiences.
- What opportunities do you see in the future, draw these.
- What threats and risks exist for the future of Sisal, draw these.

B.2. Semi-structured interview template (Spanish)

Entrevistador(s):	Fecha:
Entrevistado(s):	Ubicación:
Relación con el proyecto:	Número de entrevista:

General

1. ¿Nos puede comentar un poco acerca de usted y acerca de cómo y cual es su conexión con Sisal?

Desarrollo de Sisal

2. En su opinión, ¿como es que Sisal ha cambiado respecto a su desarrollo económico y/o turístico en los últimos años o décadas? Por ejemplo, ¿la diferencia antes y después de 2020?

3. ¿Que es lo que sabe del desarrollo costero en Sisal en los últimos años o décadas? ¿Ha notado cambios o retos significativos?

- Si se observa alguna diferencia ¿Este cambio le ha hecho sentirse menos seguro o más vulnerable al cambio climático y al riesgo de inundación asociado?

Comunicación

4. ¿Como es que la comunidad de Sisal ha cambiado en los últimos años? ¿Hacia donde cree que se orienta el futuro de la comunidad o cuales serían los aspectos más importantes en el futuro?

5. Si responde positivamente la anterior. ¿Con quién ha sido esta comunicación? ¿La interacción fue positiva, efectiva? ¿O como fue el desarrollo de la comunicación?

- ¿Con qué frecuencia se ha producido este contacto?
- ¿Qué tipo de comunicación ha sido principalmente? ¿Recibir, enviar o ambas?
- ¿Y consideraría que esta comunicación ha sido agradable y eficaz?

Presente y futuro del Sisal

6. ¿Cuál de las siguientes áreas considera usted más importante para Sisal? Divida por favor los siguientes tópicos en ‘Muy importante’, ‘Relativamente importante’ y ‘Menos importante’

- Habitabilidad y desarrollo (vivienda, servicios, mejora de la calidad de vida, ...)
- Industria Pesquera (El puerto, puestos de trabajo creados por la pesca, ...)
- Salud costera (La degradación de la playa, los residuos, la calidad del agua, ...)
- Naturaleza (La reserva de El Palmar, manglares, ...)
- Turismo (Cantidad de turistas, agencias de turismo, empleos creados por el turismo, ...)

- Crecimiento de Sisal (Más viviendas e infraestructuras, más habitantes, ...)

7. ¿Cuál es su opinión acerca de los planes para el futuro desarrollo de Sisal, particularmente en términos del medio costero y la economía local?

- ¿Cree que el cambio climático y el desarrollo de Sisal tendrán un impacto negativo en la zona? En caso afirmativo, ¿cómo?

8. Respecto a su propia opinión, ¿podría dibujar un mapa mental o un esquema de cómo es que Sisal debería de verse en 2070?

- Dibuje un Sisal en el futur basándose en su propia memoria. No se preocupe por ser preciso, dibuje lo primero que se le viene a la mente y cosas de acuerdo a su propia experiencia y su propia subjetividad.
- ¿Que oportunidades ve en el futuro? Dibújelas
- ¿Que amenazas y riesgos cree que existo en el futuro de Sisal? Dibújelas

B.3. Short interview template (English)

Interviewer(s):	Date:
Interviewee(s):	Location:
Relation to project:	Interview number:

General

1. Can you tell us a bit about yourself and your connection to Sisal?

Development of Sisal

2. In your opinion, how has Sisal changed in terms of its economic or touristic development over the past few years or decades? For example, the difference before and after 2020?

Communication

3. Have you ever been in contact with the government, UNAM, fishing/tourism industry and/or inhabitants about Sisal's development? If so, how often?

The present and future of Sisal

4. Which of the following areas do you consider most important for Sisal? Rank the following six subjects from 'most' to 'least' important.

- Liveability and development (Housing, amenities, improved quality of life, …)
- Fishing industry (The port, jobs created by fishery, …)
- Coastal health (The degradation of the beach, waste, water quality, …)
- Nature (The natural reserve of El Palmar, mangroves, …)
- Tourism (Amounts of tourists, tourism agencies, jobs created by tourism, …)
- Expanding Sisal (More housing and infrastructure, more inhabitants, …)

5. What is your opinion on the future of Sisal?

B.4. Short interview template (Spanish)

Entrevistador(s):	Fecha:
Entrevistado(s):	Ubicación:
Relación con el proyecto:	Número de entrevista:

General

1. ¿Puede hablarnos un poco de usted y de su relación con Sisal?

Desarrollo de Sisal

2. En su opinión, ¿cómo ha cambiado Sisal en cuanto a su desarrollo económico, turístico y costero en las últimas décadas? O específicamente, ¿antes y después del estatus de pueblo mágico en 2020?

Comunicación

3. ¿Ha estado alguna vez en contacto con el gobierno, la UNAM, la industria pesquera/turística y/o los habitantes sobre el desarrollo de Sisal? En caso afirmativo, ¿con qué frecuencia?El presente y el future de Sisal

Presente y futuro del Sisal

4. ¿Cuál de las siguientes áreas considera usted más importante para Sisal? Divida por favor los siguientes tópicos en 'Muy importante', 'Relativamente importante' y 'Menos importante'

- Habitabilidad y desarrollo (vivienda, servicios, mejora de la calidad de vida, ...)
- Industria Pesquera (El puerto, puestos de trabajo creados por la pesca, ...)
- Salud costera (La degradación de la playa, los residuos, la calidad del agua, ...)
- Naturaleza (La reserva de El Palmar, manglares, ...)
- Turismo (Cantidad de turistas, agencias de turismo, empleos creados por el turismo, ...)
- Crecimiento de Sisal (Más viviendas e infraestructuras, más habitantes, ...)

5. ¿Cuál es su opinión sobre el futuro de Sisal?

C

Appendix C - Interview summaries

This appendix presents a summary of each individual interview, following the interview template described in appendix B.

C.1. Interview with Carlos Rosas

Interviewer(s): Carlos Rosas	Date: 23/09/2024
Interviewee(s): Jip Kuiper & Jim van Ruth	Location: UNAM, Sisal
Relation to project: Researcher at UNAM	Interview number: 1

General

1. Can you tell us a bit about yourself and your connection to Sisal?

He began his career at UNAM 30 years ago, starting in Campeche, where he worked for about seven years. After a hurricane destroyed the facilities, the laboratory was relocated to Ciudad del Carmen, where he also spent around seven years. However, the working conditions in Ciudad del Carmen were not ideal. Eventually, an agreement was reached between UNAM and the State to establish a new campus in Sisal. At the time, the coastal area around Sisal was largely unexplored, and there was ample space for the new campus. The pristine coastline and high-quality sea water were particularly attractive for the research projects planned for the area.

In the early days, the relationship between the researchers and the local community was strained. Many locals mistakenly believed that UNAM was connected to the United Nations, which complicated the relationship. There was also a widespread expectation that the arrival of UNAM would lead to increased employment opportunities, which did not materialize as much as the community had hoped.

He has now been with UNAM for 43 years, with 23 of those years spent in Sisal. Although he has worked in Sisal for many years, he has never lived there, residing instead in Mérida and currently in Hunucmá.

Development of Sisal

2. In your opinion, how has Sisal changed in terms of its economic or touristic development over the past few years or decades? For example, the difference before and after 2020?

He noted that the involvement of Sisal's inhabitants in scientific research or experiments has been minimal, and there has been significant criticism of the work conducted by UNAM in Sisal. Currently, they are working on a project with local Sisal women that focuses on octopus farming. However, overall, UNAM remains somewhat isolated in terms of community involvement.

In the early years of UNAM in Sisal, many students were involved, including some from Sisal itself. However, he mentioned that the educational level of local students often did not meet the standards required for scientific studies.

While employees and students from UNAM do make use of local services, such as restaurants and boats, he stated that their presence has not had a significant impact on Sisal's local economy. He also recalled that in the early days of UNAM in Sisal, there was no internet connection, but UNAM's pressure on the state led to the construction of a telephone tower, which also benefited the local community.

3. What do you know about the coastal development in Sisal over the previous years or decades? Have there been any significant changes or challenges that you have noticed?

- If any difference is noted: Has this change caused you to feel less safe or more vulnerable to climate change and associated flood risk?

He stated that before the pandamic, the Sisal community was a lot closer. But that is changed now: young people migrate to find work or study and the fathers and grandfathers are staying in Sisal. UNAM in sisal is still trying to improve community involvement, he refers to Paulo's project. But more project are coming lately to increase involvement of the community.

He emphasized that UNAM is not seen as a major factor in the community and that interactions with the local population remain difficult, with many social problems tied to politics. He highlighted that UNAM often refrains from taking sides in conflicts, such as those related to illegal constructions or developments in ecological areas. He mentioned that when Bernardo and Patricia made statements to a reporter regarding coastal erosion and environmental changes, their words were misinterpreted. Despite giving recommendations to beach house owners and clarifying that their aim was conservation, not conflict, Bernardo eventually faced legal issues as a result of his comments.

Currently, palapas are being constructed on the dunes, further exacerbating coastal erosion. Patricia has ongoing projects to restore the dunes, but dialogue with the palapa owners is challenging due to their need for income and their belief that they are entitled to the land because of Sisal's status as a "magical town." This status, granted by the state, is meant to bring investment for local improvements, such as infrastructure and electricity. However, the cost of living in Sisal has increased, partly due to platforms like Airbnb, and restaurants have become more expensive compared to Mérida. While tourism is benefiting local business owners, particularly in the hospitality sector, only a portion of the population is reaping the rewards.

He also addressed concerns about overfishing, stating that while some claim fisheries are overexploited, the real issue is the warming sea. Over the past 20 years, the water temperature has risen significantly (now around 29°C at 10 meters depth), causing marine species to move into deeper waters. Fishermen report smaller catches and octopuses, which marks a major change in the ecosystem. Meanwhile, tourism continues to grow, increasing demand for marine animals, further stressing the environment.

He noted that the construction of palapas has damaged the dunes, and the development of the east coast has led to the disappearance of roads, replaced by expensive housing. Despite the dynamic and complex nature of the coastline, he described the coast as relatively safe due to its flatness, with waves not reaching great heights, even during storms. The Progreso harbor, however, has had a significant impact, contributing to the accumulation of sand in the Sisal area.

Communication

4. Have you had any communication or collaboration with other stakeholders regarding Sisal's coastal development or its economic/touristic growth? Think of policymakers (government), inhabitants, researchers, entrepreneurs, tourism representatives, nature preservationists and/or the press?

5. (If answer to the previous was affirmative) With whom have you been in contact?

- How frequent has this contact been?
- What type of communication was this mainly? Receiving, sending or both?
- And would you deem this communication to have been pleasant and effective?

He mentioned that UNAM has been in contact with the local political organization, specifically the municipality and its mayor, to offer their facilities and expertise. This collaboration aimed to conduct an environmental impact assessment for the construction of houses in the reserve. Although they had positive and ongoing communication with the mayor and also reached out to the state government,

their efforts were largely rejected. UNAM had formed a group to assist in providing information, but their initiative was turned down.

Despite this, the contact with officials remained cordial. UNAM also engaged with people from Mexico City's economic sector and established another group in collaboration with the municipality of Hunucmá to offer various activities, such as artisanal crafts and shoes, and to organize expositions.

He noted that municipalities have only a three-year term to address basic problems like education, which often takes priority over other concerns, such as environmental issues. Communication with the local community has been difficult, and their new project, aimed at educating fishermen about the marine refuge, faced challenges. The first meeting only attracted five participants, and the second was cancelled due to a lack of interest. Another meeting is scheduled for October 4th 2024.

The present and future of Sisal

6. Which of the following areas do you consider most important for Sisal? Rank the following six subjects from 'most' to 'least' important.

- Liveability and development (Housing, amenities, improved quality of life, …)
- Fishing industry (The port, jobs created by fishery, …)
- Coastal health (The degradation of the beach, waste, water quality, …)
- Nature (The natural reserve of El Palmar, mangroves, …)
- Tourism (Amounts of tourists, tourism agencies, jobs created by tourism, …)
- Expanding Sisal (More housing and infrastructure, more inhabitants, …)

He explained that UNAM has been trying to build trust with fishermen, but confidence in UNAM is low, as previous efforts have not led to tangible solutions. A further issue is that many of the academic papers produced by UNAM are in English, which is not accessible to the local community. Efforts are being made to make these materials more understandable and relevant to the local population.

He stated that housing, liveability and amenities should be one category. Same for the nature and coastal health. With that in mind this were his order:

Very important: Community development, Fishing industry, The nature, Coastal health.

Relatively important: Amenities, Housing and Liveability, Infrastructure, Tourism.

Least important: Expanding Sisal.

Fishing is not an industry, its artisanal craft. Important for community. Palmar reserve is not complete, it should be nature. Hospitals are very important since there are a lot of old people in Sisal. Since the fishing activities will decrease in the future, many fishermen will become tourism guides on sea due to their knowledge of the sea. That's is why tourism is very important.

7. What is your opinion on the future development of Sisal, particularly in terms of the coastal environment and the local economy?

- Do you think climate change and development of Sisal will have a negative impact on the area? If so, how?

If the people move to the city, they loose their roots. The community will be an artificial community, like Cancun. In the coast, we can design a refuge of a certain area on sea. To improve quality of the ecosystem. Promoting restabilising of ecosystem health. If you reduce stress of the community the ecosystem the tolerance of the animals with related to warmth are better contained. Such that fishes will be more abundance then in open zones. But at the same time the refuge reduces the fishing zones. Currently working on offshore fish farming which will positively impact the fishermen, who can keep living in sisal. Currently in the process with Chinese people to improve housing with solar panels.

8. Could you draw a mental map of what Sisal should look like in 2070 according to you?

- Draw a future Sisal according to your own memory. It does not need to be complete. Draw what first comes to your mind and your own experiences.

- What opportunities do you see in the future, draw these.
- What threats and risks exist for the future of Sisal, draw these.

C.2. Interview with Gabriella Medellín Mayoral

Interviewer(s): Jip Kuiper & Auke Dijkstra	Date: 26/09/2024
Interviewee(s): Gabriella Medellín Mayoral	Location: UNAM, Sisal
Relation to project: Researcher at UNAM	Interview number: 2

General

1. Can you tell us a bit about yourself and your connection to Sisal?

She did a postdoc project in 2013. In 2014/15 there was program that opened new positions for the university in a research project about observing the coastal resilience and cc in sisal. In 2015 started with measuring the beach profiles. In 2019 hired by university UNAM. And continiud observing the beach.

Development of Sisal

2. In your opinion, how has Sisal changed in terms of its economic or touristic development over the past few years or decades? For example, the difference before and after 2020?

She investigates beach profile dynamics. In the first 6 years it was explainable. After that, infrastructure around the beach was created, this influenced the beach profile different than just the morphology and hydraulic forces. The main concern is not tourism itself, but the way it is organized. Around covid Sisal was named to 'magic town' and this increased the exposure of Sisal by a lot.

3. What do you know about the coastal development in Sisal over the previous years or decades? Have there been any significant changes or challenges that you have noticed?

- If any difference is noted: Has this change caused you to feel less safe or more vulnerable to climate change and associated flood risk?

She notices much more dogs on the beach. If she has seen changes in the beach dynamics itself is hard to say. Of course the accretion and erosion rates are very noticeable. It has not stopped but grown continuously. Before this land use was not used at all, now there is has more economic interest. Sisal lives from basic services that can manage the local community but is a big concern for if more people stay here (even for temporary stay). She has not felt unsafe but realities the effect of Climate change. UNAM is built on a vulnerable location. But does not feel unsafe. Also, cold fronts will decrease in frequency and magnitude. SLR is larger threat regarding SLR. Biggest threat is coastal management.

Communication

4. Have you had any communication or collaboration with other stakeholders regarding Sisal's coastal development or its economic/touristic growth? Think of policymakers (government), inhabitants, researchers, entrepreneurs, tourism representatives, nature preservationists and/or the press?

5. (If answer to the previous was affirmative) With whom have you been in contact?

- How frequent has this contact been?
- What type of communication was this mainly? Receiving, sending or both?
- And would you deem this communication to have been pleasant and effective?

Policy makers; Federal or municipal: No direct contact, but indirect worked for projects. Usually, one researcher has contact with the policy makers. One year long project with field campaign other part of Yucatan. Policy makers want a fast response, but often it takes researchers longer to reply.

Often negative advice from researchers. Example: Exchange of information between researchers UNAM and policy makers. UNAM made slides and presentation and gave negative advise for placing structures. Other party had a very small presentation and for Gabi it felt more like they had to just check the box, rather than listening carefully

Local businesses: They have had workshops with UNAM. She speaks with palapas owners regularly. Some feel responsible, others don't. Workshops are only organized twice a year, but you get a grasp of what other people think. Workshops are really diverse.

Fishing industry: Giving them a lift from Hunucmá to Sisal. Then she hears stories. They do not earn a lot of money with fishing. Other fisherman get money from government for not fishing. The fishermen believe the erosion is happening because of the port of Progreso. They are very stubborn. They are not interested in the erosion. But some care more than others

The present and future of Sisal

6. Which of the following areas do you consider most important for Sisal? Rank the following six subjects from 'most' to 'least' important.

- Liveability and development (Housing, amenities, improved quality of life, …)
- Fishing industry (The port, jobs created by fishery, …)
- Coastal health (The degradation of the beach, waste, water quality, …)
- Nature (The natural reserve of El Palmar, mangroves, …)
- Tourism (Amounts of tourists, tourism agencies, jobs created by tourism, …)
- Expanding Sisal (More housing and infrastructure, more inhabitants, …)

a) Most important. Lack of basic services, if that is fixed a lot of other problems will get fixed as well. Usually in 'magic towns' the town received a budget to improve it. Improve the roads, paint the houses etc. Now it is just the name. Also, all the budget for Sisal goes to Honucma and they also have a lot of needs.

b) Fishing industry, but especially the port

c) Coastal health. Of course she cares a lot about the beach, but she thinks people must have good quality of life.

d) Nature

e) Tourism

f) Expanding Sisal

7. What is your opinion on the future development of Sisal, particularly in terms of the coastal environment and the local economy?

- Do you think climate change and development of Sisal will have a negative impact on the area? If so, how?

She is scared that there will be huge investment that will cause a lot of damage, for the people and the environment.

She would like a plan and an observation about the current situation to estimate what is needed. The highway was an improvement.

So, first she wants a diagnosis, then solve the outcoming problem, and then potential development and expanding. Improving the town will also improve the tourism.

Then some regulation, for example on the palapas, but the communication has to be good. Regulations that are not expensive, would be a good improvement before going to the next step in development. Yucatan coastline is public, that is good.

Climate change not a significant threat, because cold fronts are predicted to have less energy. If they manage to maintain a healthy coastal system, she does not see a horror climate change scenario that causes a lot of flooding or damage.

The people are more a danger than climate change for now. There is a lack of good management.

8. Could you draw a mental map of what Sisal should look like in 2070 according to you?

- Draw a future Sisal according to your own memory. It does not need to be complete. Draw what first comes to your mind and your own experiences.
- What opportunities do you see in the future, draw these.
- What threats and risks exist for the future of Sisal, draw these.

C.3. Interview with Gemma Franklin

Interviewer(s): Jip Kuiper & Jim van Ruth	Date: 26/09/2024
Interviewee(s): Gemma Franklin	Location: UNAM, Sisal
Relation to project: Researcher at UNAM	Interview number: 3

General

1. Can you tell us a bit about yourself and your connection to Sisal?

Gemma has been in Sisal for 10 years, initially arriving for her PhD. She started with a postdoc at Lanresc and then continued her research at UNAM. Her focus has been on beach protection and how reef structures influence coastal dynamics and flooding. She started working on coastal protection and hydrodynamics. Gemma has not lived in Sisal, but in Merida.

Development of Sisal

2. In your opinion, how has Sisal changed in terms of its economic or touristic development over the past few years or decades? For example, the difference before and after 2020?

Since Sisal received its “Magical Town” designation, the local infrastructure has struggled to keep up with the increased tourism. There has been significant development, with large buildings altering the landscape. Many people, even in nearby Merida, are unaware of the university’s presence in Sisal.

There has been a noticeable rise in development along the coast, but the waste management systems are not equipped for the growing population. Previously a nature reserve, El Palmar is no longer protected, and there are issues with water infrastructure. For example, during emergencies, such as fires, the community struggles due to inadequate water supply.

3. What do you know about the coastal development in Sisal over the previous years or decades? Have there been any significant changes or challenges that you have noticed?

Although the increase in population hasn’t made her feel less safe, she is concerned about the impacts of climate change, particularly erosion. She noted that if there weren’t buildings along the coast, the situation wouldn’t be as critical, but rising sea levels pose a significant risk.

- If any difference is noted: Has this change caused you to feel less safe or more vulnerable to climate change and associated flood risk?

Communication

4. Have you had any communication or collaboration with other stakeholders regarding Sisal’s coastal development or its economic/touristic growth? Think of policymakers (government), inhabitants, researchers, entrepreneurs, tourism representatives, nature preservationists and/or the press?

5. (If answer to the previous was affirmative) With whom have you been in contact?

- How frequent has this contact been?
- What type of communication was this mainly? Receiving, sending or both?
- And would you deem this communication to have been pleasant and effective?

Most of her interactions occur through projects like GII and Lanresc. While she participates in larger meetings with policymakers, these are infrequent (1/Y) . She enjoys these communications and appreciates hearing from local fishermen, who often share valuable insights based on their long-term experiences in the area. For example, the fishermen are seeing an accelerated reduction in beach width in places where vegetation is removed.

The present and future of Sisal

6. Which of the following areas do you consider most important for Sisal? Rank the following six subjects from 'most' to 'least' important.

- Liveability and development (Housing, amenities, improved quality of life, …)
- Fishing industry (The port, jobs created by fishery, …)
- Coastal health (The degradation of the beach, waste, water quality, …)
- Nature (The natural reserve of El Palmar, mangroves, …)
- Tourism (Amounts of tourists, tourism agencies, jobs created by tourism, …)
- Expanding Sisal (More housing and infrastructure, more inhabitants, …)

Gemma highlighted several key areas of concern for Sisal. She believes that the most important issue is the liveability of the inhabitants, as this impacts their quality of life. She stressed that improving housing, amenities, and overall living conditions should take priority. For the local community, especially those in vulnerable situations, having a safe and comfortable living environment is essential.

The fishing industry is the second most important area in her view. It serves as the backbone of Sisal's economy, providing jobs and sustenance for many residents. Gemma emphasized that without the fishing industry, Sisal would not have its current identity or economic foundation.

Coastal health is also a significant concern. Gemma pointed out that issues like beach erosion and water quality are critical threats that need attention. She mentioned that pollution is an ongoing problem, affecting the natural environment and the livelihoods of those who depend on the sea.

Gemma discussed the importance of preserving nature and the natural reserves, such as El Palmar and the mangroves, which play essential roles in protecting the coast from erosion and providing habitat for local wildlife. She expressed that these natural areas are not only valuable for biodiversity but also contribute to the overall resilience of the coastal environment.

While tourism is vital for economic growth, she emphasized that it needs to be balanced with the preservation of Sisal's natural beauty and resources. Gemma expressed that the community should focus on sustainable tourism practices that do not compromise the coastal environment.

Lastly, she mentioned the expansion of Sisal in terms of housing and infrastructure. While growth is unstoppable, she cautioned against uncontrolled development, which could lead to the loss of natural areas and negatively impact liveability.

7. What is your opinion on the future development of Sisal, particularly in terms of the coastal environment and the local economy?

- Do you think climate change and development of Sisal will have a negative impact on the area? If so, how?

All inclusive hotels, mass tourism. More income, more hotels. Some of the plots are build in half a dozen plots. Shopping centre in the marina. Turns into Cozumel. They risk losing their natural beauty by developing it too much. Or a Playa del Carmen, which she has seen for herself 25 years ago. Destroyed by development. She thinks its impossible to stop the development.

8. Could you draw a mental map of what Sisal should look like in 2070 according to you?

- Draw a future Sisal according to your own memory. It does not need to be complete. Draw what first comes to your mind and your own experiences.
- What opportunities do you see in the future, draw these.
- What threats and risks exist for the future of Sisal, draw these.

Looking ahead, Gemma expressed concerns about Sisal's trajectory. She acknowledged that development is likely to continue, particularly with the rise of all-inclusive hotels and mass tourism, which could generate significant income for the area. However, she warned that this could be at the expense of the local environment, risking the loss of Sisal's natural beauty.

She described the potential transformation of Sisal into a highly commercialized tourist destination similar to other overdeveloped areas. She recalled places she had seen that were once beautiful but are now heavily altered by extensive development. Gemma is particularly worried about how this shift could diminish the unique character of Sisal and negatively affect both the local community and the ecosystem.

Moreover, Gemma raised concerns about the implications of unchecked growth on community dynamics. As new hotels and businesses spring up, she fears that local traditions and the close-knit community might be compromised.

C.4. Interview with Roger Pacheco

Interviewer(s): Jip Kuiper & Jim van Ruth	Date: 26/09/2024
Interviewee(s): Roger Pacheco	Location: UNAM, Sisal
Relation to project: Researcher at UNAM	Interview number: 4

General

1. Can you tell us a bit about yourself and your connection to Sisal?

Roger came to UNAM in Sisal for his PhD in 2017. He didn't know Sisal beforehand and has never lived there. He is officially employed by the government and not UNAM, though he collaborates with the university as part of a federal government program.

Development of Sisal

2. In your opinion, how has Sisal changed in terms of its economic or touristic development over the past few years or decades? For example, the difference before and after 2020?

Roger noticed an increase in people visiting Sisal, particularly for vacations or leisure. He has seen more traffic and fuller parking spots but hasn't observed major changes in other aspects, as his experience of Sisal is limited to commuting. However, he mentioned that after Sisal received its "Magical Town" status, there was more tourism promotion, especially on social media.

3. What do you know about the coastal development in Sisal over the previous years or decades? Have there been any significant changes or challenges that you have noticed?

- If any difference is noted: Has this change caused you to feel less safe or more vulnerable to climate change and associated flood risk?

He stated that, there seems to be an increase in variations of in the groundwater closer to the coast.

Communication

4. Have you had any communication or collaboration with other stakeholders regarding Sisal's coastal development or its economic/touristic growth? Think of policymakers (government), inhabitants, researchers, entrepreneurs, tourism representatives, nature preservationists and/or the press?

Roger's simulations suggest that sea-level rise could push saltwater further inland, leading to groundwater salinization. The most important well for Sisal, 5 km upstream, could be affected, leading to freshwater loss.

5. (If answer to the previous was affirmative) With whom have you been in contact?

- How frequent has this contact been?
- What type of communication was this mainly? Receiving, sending or both?
- And would you deem this communication to have been pleasant and effective?

The present and future of Sisal

6. Which of the following areas do you consider most important for Sisal? Rank the following six subjects from 'most' to 'least' important.

- Liveability and development (Housing, amenities, improved quality of life, …)
- Fishing industry (The port, jobs created by fishery, …)
- Coastal health (The degradation of the beach, waste, water quality, …)
- Nature (The natural reserve of El Palmar, mangroves, …)
- Tourism (Amounts of tourists, tourism agencies, jobs created by tourism, …)
- Expanding Sisal (More housing and infrastructure, more inhabitants, …)

Roger has worked with CONAGUA, the national water authority, for permits and infrastructure, and they've established a good relationship, lending each other equipment. However, his interactions with local authorities, such as Hunucmá municipality and Sisal's local government, have been less effective. Locals are suspicious of outsiders, leading to a strained relationship. There was even a protest where locals blocked the road to UNAM, blaming the university for taking up land that belonged to the community.

His contact with policymakers has been mostly for permits, and they don't typically ask for research results despite Roger making them available. He interacts with the government once a year. His relationship with fishermen is particularly difficult. Since Fishermen believe UNAM took wrongfully valuable land, and communication is mainly through one local family.

7. What is your opinion on the future development of Sisal, particularly in terms of the coastal environment and the local economy?

- Do you think climate change and development of Sisal will have a negative impact on the area? If so, how?

a. Livability and development

b. Nature

c. Coastal health

d. Fishing industry

e. Tourism

f. Expanding Sisal

8. Could you draw a mental map of what Sisal should look like in 2070 according to you?

- Draw a future Sisal according to your own memory. It does not need to be complete. Draw what first comes to your mind and your own experiences.
- What opportunities do you see in the future, draw these.
- What threats and risks exist for the future of Sisal, draw these.

C.5. Interview with Fatima Puc

Interviewer(s): Jip Kuiper & Leonardo Alonso	Date: 27/09/2024
Interviewee(s): Fatima Puc	Location: Palapa Santa Cruz, Sisal
Relation to project: Palapa owner and nature preservationist	Interview number: 5

General

1. Can you tell us a bit about yourself and your connection to Sisal?

She works at a Palapa in Sisal and has a different tourism agency job as well. Her connection in Sisal is that she has lived here her entire life. She thinks she will die in Sisal as well. She works as a 'Todologa': she provides education for the children, works in waste collection for the beach and the nature, and has a palapa with a group. She is in a groupschat with several people that work in the palapas, they have meetings and they discuss problems. In the palapas people can rent tables, chairs and food. They cook the food themselves. She is also a tour guide and is in a group for that. She works with the fishermen as well, but right now there's a lot of tourism so it is not needed as much.

Development of Sisal

2. In your opinion, how has Sisal changed in terms of its economic or touristic development over the past few years or decades? For example, the difference before and after 2020?

The tourism has always existed, but after 2020 the tourism increased a lot, after the magic town status. The palapa was built in 2020, after the covid pandemic, because of the tourism increase. Before 2020 the tourism was mainly from the state (Yucatan), after that more people came from other states in the country. First, she did not want Sisal to have the magic town status, but then she learned what it means. Right now, she wants Sisal to have the magic town status, because it increases the economy and development of the area. However, the development was mainly private. In 2020 the people did not have the information on what the magic town status was and what it would mean for them, so that is why they did not want it. Also because people from outside the community would build things, which the people from Sisal did not like.

3. What do you know about the coastal development in Sisal over the previous years or decades? Have there been any significant changes or challenges that you have noticed?

- If any difference is noted: Has this change caused you to feel less safe or more vulnerable to climate change and associated flood risk?

There are more (private) buildings and structures, like palapas. There is more waste too, due to increase in tourism. Fatima has made signs to clean up the waste. Most workers of the palapas do it right, but a lot of tourists don't.

20 years ago the sea has had a lot of accretion, but there is a lot of erosion one kilometre further to the East and around the reserve of El Palmar. Fatima thinks the erosion and accretion happens because of the climate change. Old people that are know dead have more information on the history of the coastal development. The reason that the erosion and accretion happens is because they think it is caused by the port in Progreso. She has a photo of before and after the construction of the port in Sisal around 20 years ago, but the construction was longer then. She says this place is more vulnerable for climate change in the future. 30 years ago when the port did not exist, the boats arrived at the beach and they were a lot more vulnerable to storms.

Communication

4. Have you had any communication or collaboration with other stakeholders regarding Sisal's coastal development or its economic/touristic growth? Think of policymakers (government), inhabitants, researchers, entrepreneurs, tourism representatives, nature preservationists and/or the press?

5. (If answer to the previous was affirmative) With whom have you been in contact?

- How frequent has this contact been?
- What type of communication was this mainly? Receiving, sending or both?
- And would you deem this communication to have been pleasant and effective?

Not a lot of contact with UNAM, about ones a year. She had contact with Paulo during a workshop in Sisal.

She was at a seminar a few years back that was organised by the state, there were also people from UNAM. The seminar was about Sisal and its residents.

10 years ago she works with a project for the reproduction of fish. Before 2020 she worked at UNAM for import. When UNAM arrived in Sisal, the local community did not appreciate their establishment, as UNAM took a big surface area of Sisal to construct their facilities. This one of the reasons that the local community still do not like UNAM. However, for her, it is important to remain in contact to receive important information.

The present and future of Sisal

6. Which of the following areas do you consider most important for Sisal? Rank the following six subjects from 'most' to 'least' important.

- Liveability and development (Housing, amenities, improved quality of life, …)
- Fishing industry (The port, jobs created by fishery, …)
- Coastal health (The degradation of the beach, waste, water quality, …)
- Nature (The natural reserve of El Palmar, mangroves, …)
- Tourism (Amounts of tourists, tourism agencies, jobs created by tourism, …)
- Expanding Sisal (More housing and infrastructure, more inhabitants, …)

1. D 2. A 3. E 4. F 5. C 6. B

The fishing was very important 10 years ago, but it gets less and less important now, so it is not as important as it used to be.

7. What is your opinion on the future development of Sisal, particularly in terms of the coastal environment and the local economy?

- Do you think climate change and development of Sisal will have a negative impact on the area? If so, how?

She was in Veracruz first. There was a problem with the amount of water there. The town is small due to the barrier island effect. In 10 years more there will be problems, because the big hotels will create a lot of waste. The hotel will be done in one year. We need an equilibrium, as the development is good, but it should not be too much. The development should be slow not very fast.

She thinks they need better coastal management, especially because the storms will be worse and worse. She does not know what will happen with Sisal in the coming ten years. She thinks the future of Sisal is good, if they can stop building the private-owned buildings by people that are outside the community. She thinks a big wave could come that could destroy a lot of the infrastructure in other towns like Sisal. However, Sisal is different because it has vegetation on the dunes that can protect from cold fronts and storms, in comparison to Cancún for example.

The problem with the infrastructure with the fire is a bit fishy. The police doesn't do anything about it.

She thinks a lot more hotels will be build around the village and a lot of private houses in the reserve, she is not a fan of this. This infrastructure will cause a lot of problems in the water availability and the water quality, because of waste. Furthermore, the beach will become full.

8. Could you draw a mental map of what Sisal should look like in 2070 according to you?

- Draw a future Sisal according to your own memory. It does not need to be complete. Draw what first comes to your mind and your own experiences.

- What opportunities do you see in the future, draw these.
- What threats and risks exist for the future of Sisal, draw these.

C.6. Interview with Gabriela Mendoza González

Interviewer(s): Jip Kuiper & David Garagorri Linares	Date: 30/09/2024
Interviewee(s): Gabriela Mendoza González	Location: Online (Zoom)
Relation to project: Researcher at UNAM	Interview number: 6

General

1. Can you tell us a bit about yourself and your connection to Sisal?

She lives in Sisal. She has monitored the beaches for 16 years. Furthermore, she does transdisciplinary analyses of stakeholders on the coast environment. From socio-economical sciences to geophysical monitoring of dunes and flower records of the coastal environment.

Development of Sisal

2. In your opinion, how has Sisal changed in terms of its economic or touristic development over the past few years or decades? For example, the difference before and after 2020?

Sisal at the beginning was mainly commerce (1900s) even more important than Progreso. After that it was a port mainly dedicated to the fishing industry and now there is a shift to tourism industry. This last one mainly because in 2019 the denomination of magic town was given to Sisal.

This created big changes for the city, both with good and bad impacts. This created an increase in tourism activity, but this created also a lot of challenges for a small town like Sisal. Increase of number in palapas, increase in prices for everything, like 4 times as it used to be causing gentrification on the city. Also, the town felt that this decision was not consulted to them, the denomination was made by people from outside the town but the impacts were suffered by the people living on the town. They were afraid of losing their autonomy on their own territory.

3. What do you know about the coastal development in Sisal over the previous years or decades? Have there been any significant changes or challenges that you have noticed?

In the last 3 years there has been severe deforestation of the dunes. Clear accretion on the east side of the port and erosion on the west side of the port.

- If any difference is noted: Has this change caused you to feel less safe or more vulnerable to climate change and associated flood risk?

Communication

4. Have you had any communication or collaboration with other stakeholders regarding Sisal's coastal development or its economic/touristic growth? Think of policymakers (government), inhabitants, researchers, entrepreneurs, tourism representatives, nature preservationists and/or the press?

5. (If answer to the previous was affirmative) With whom have you been in contact?

Yes, for example political representatives. There have been workshops with different parts of the community of Sisal, but product of our research, where they defined the most important concerns for the community and gave a hierarchy. Drainage to the beach, vehicles entering the community, garbage and erosion where the most important concerns. The people assisting to these workshops where the government representatives like comisarios, SOFEMA, CEMARNA, municipality authorities, but also touristic guides, environmental groups, people in charge of commerce, etc.

- How frequent has this contact been?

- What type of communication was this mainly? Receiving, sending or both?
- And would you deem this communication to have been pleasant and effective?

The present and future of Sisal

6. Which of the following areas do you consider most important for Sisal? Rank the following six subjects from 'most' to 'least' important.

- Liveability and development (Housing, amenities, improved quality of life, …)
- Fishing industry (The port, jobs created by fishery, …)
- Coastal health (The degradation of the beach, waste, water quality, …)
- Nature (The natural reserve of El Palmar, mangroves, …)
- Tourism (Amounts of tourists, tourism agencies, jobs created by tourism, …)
- Expanding Sisal (More housing and infrastructure, more inhabitants, …)

Results of the workshops

1. C 2. F 3. A 4. E 5. B 6. D

Her opinion

1. F 2. D 3. C 4. A 5. E 6.B

7. What is your opinion on the future development of Sisal, particularly in terms of the coastal environment and the local economy?

- Do you think climate change and development of Sisal will have a negative impact on the area? If so, how?

The dunes system on the coast will disappear. More Hotels, more restaurants, more urban development. All of this comes with bad or no planning at all, so it is not organized and not well done. This will become a version of Progreso. Also, natural area will be lost, filling of mangroves its a problem that already exists and will become worst.

Challenges of the future of sisal:

Water access, the water gets shut down if any natural disaster happens (fires). All the water is from underground and the growth of the city can create problems like depression of phreatic level as well as contamination of soil, leading to contamination of the aquifer. This mainly because of the non-existence of drainage system or bad maintenance of septic ponds.

The same happens with communication services, signal also gets shut down when disaster happens.

8. Could you draw a mental map of what Sisal should look like in 2070 according to you?

- Draw a future Sisal according to your own memory. It does not need to be complete. Draw what first comes to your mind and your own experiences.
- What opportunities do you see in the future, draw these.
- What threats and risks exist for the future of Sisal, draw these.

C.7. Interview with Elsa Noreña Barosso

Interviewer(s): Jip Kuiper & Jim van Ruth	Date: 30/09/2024
Interviewee(s): Elsa Noreña Barroso	Location: Online (Zoom)
Relation to project: Researcher at UNAM	Interview number: 7

General

1. Can you tell us a bit about yourself and your connection to Sisal?

Elsa obtained a bachelor's degree in biology in her master's in marine biology followed by a PhD in marine sciences. She has been working with pollutants (pesticides, organic pollutants, hydrocarbons, sewage contamination, etc.) since her undergraduate. Analysing the pollutants present in different water sources (e.g. drinking water) is part of her job.

She has been working with Lanresc from 2016 onwards. She is currently the coordinator of a coastal observatory. She stated that this function is multi-faceted, complex and over spans a large observatory and therefore thinks she is not very good at it (jokingly) and spend most of her time in the laboratory (instead of on fieldwork in Sisal). Elsa has never lived in Sisal, and is currently a resident of Merida.

Development of Sisal

2. In your opinion, how has Sisal changed in terms of its economic or touristic development over the past few years or decades? For example, the difference before and after 2020?

She stated that, there is currently an investigation going on to analyse the levels of pesticides in the ground and mangrove water, but too early to make conclusions. Also, they are currently investigating the levels of caffeine in the mangroves, sea, springs and groundwater. Caffeine is a tracer for pollutants which originate from houses (sewage). Since Sisal does not have a sewage system, many people use septic tanks of which many are faulty and leaking waste water into the environment. The data currently suggests that, higher levels of caffeine is found at the entrance for the town in the wetlands, at this point the population density is relatively high. In addition, seasonal effects seem to present and high amounts of precipitation lead to high amounts of tracer in water bodies. Another investigation examines the effects of tourism on water quality, where the measurements are taken bi-monthly. However, this is still a work in progress and conclusions cannot yet be drawn.

3. What do you know about the coastal development in Sisal over the previous years or decades? Have there been any significant changes or challenges that you have noticed?

- If any difference is noted: Has this change caused you to feel less safe or more vulnerable to climate change and associated flood risk?

She stated that she has been working in Merida for UADY since 2017. She noted that Sisal has changed a lot since then. In the beginning Sisal was a coastal town like any other in Yucatan, with lots of tourists during summer holiday periods and eastern. Outside of those periods, Sisal was very quiet with almost no tourism, apart from some large beach houses with foreign owners. Present day, much more tourists are going to sisal at periods like eastern, last year she even experienced the first traffic jam when coming to Sisal. In contrast to the 2007 period, buses with tourists now visit sisal in off season, such as months like December. She stated that she has no numbers on tourism to substantiate the claims made earlier, but from a personal perspective, the difference is (visually) very noticeable.

In addition, students from UADY are experiencing more difficulty in finding accommodation and prices of restaurants seem to have relatively increased much in Sisal. She is unsure if all effects mentioned earlier are due to the magical town status, since all of the coast of Yucatan seems to be developed in an accelerating way.

Communication

4. Have you had any communication or collaboration with other stakeholders regarding Sisal's coastal development or its economic/touristic growth? Think of policymakers (government), inhabitants, researchers, entrepreneurs, tourism representatives, nature preservationists and/or the press?

5. (If answer to the previous was affirmative) With whom have you been in contact?

- How frequent has this contact been?
- What type of communication was this mainly? Receiving, sending or both?
- And would you deem this communication to have been pleasant and effective?

She stated that contact with the local government has happened once or twice during her appointment as coastal observatory coordinator(?). She has had brief contact with an ecologist in service of the municipality of Hanucma, who was busy with regulations of beach houses and palapas in the reserve area.

She has had a multiple meetings with researcher from UNAM. She has had indirect contact with the Coordinator of Sisal.

The social network of Lanresc has helped laying contact with shareholders. Discussion panels are helpful, for getting in contact with shareholders like: the secretary of ecology of Yucatan, researchers from UNAM, teachers, entrepreneurs, professors, state representatives.

She has no direct contact with fishermen, or fishermen representatives. However, often fishermen's partners are present during workshops.

No contact with 'new' beach house owners.

No contact with entrepreneurs or beach owners. Only to hire boats or kayaks to perform measurements on sea or in the mangroves.

Has had contact with people from the school in Sisal on waste handling and garbage recycling. However, this has stopped after some time. Not involved in the local community.

The present and future of Sisal

6. Which of the following areas do you consider most important for Sisal? Rank the following six subjects from 'most' to 'least' important.

- Liveability and development (Housing, amenities, improved quality of life, …)
- Fishing industry (The port, jobs created by fishery, …)
- Coastal health (The degradation of the beach, waste, water quality, …)
- Nature (The natural reserve of El Palmar, mangroves, …)
- Tourism (Amounts of tourists, tourism agencies, jobs created by tourism, …)
- Expanding Sisal (More housing and infrastructure, more inhabitants, …)

1. C 2. B 3. A 4. D 5. E 6. F

7. What is your opinion on the future development of Sisal, particularly in terms of the coastal environment and the local economy?

- Do you think climate change and development of Sisal will have a negative impact on the area? If so, how?

Future of sisal, sisal is going to expand and unfortunately, no expectations of good planning. Developers only thinking about income, many houses and real estates will be added. Many people from Hunucmá to sisal. Problems with birds, fish, water quality due to expansion (more buildings). More and more tourism. if the beach is nice they'll have tourism. more amenities. Gentrification: more people are selling there houses to people that live in Merida, going to be a problem. Many people here have two houses, sell one and live here (in sisal) not sure if that is for everyone. No information on people selling their houses.

climate change, bc more extreme events. Dryer – higher temp. – more heavy rains. Houses destroys coastal dune, but maybe people in sisal know better? Sisal are doing a better job in hurricane resilience (not sure) Sisal is in a good place for hurricanes. No much worries about that.

8. Could you draw a mental map of what Sisal should look like in 2070 according to you?

- Draw a future Sisal according to your own memory. It does not need to be complete. Draw what first comes to your mind and your own experiences.
- What opportunities do you see in the future, draw these.
- What threats and risks exist for the future of Sisal, draw these.

C.8. Interview with Daniel Vargas Mendes

Interviewer(s): Jip Kuiper & Leonardo Alonso	Date: 03/10/2024
Interviewee(s): Daniel Vergas Mendes	Location: Home of Daniel Vargas Mendes, Sisal
Relation to project: (Beach) home owner in Sisal	Interview number: 8

General

1. Can you tell us a bit about yourself and your connection to Sisal?

Daniel Vargas Mendes. He was born in Merida. He lived in the house of his grandparents. He went to a place with another port at a different location for holidays. His father decided to come to Sisal for sport fishing. His father bought a house here initially and bought and built more houses later. Daniel was eight years old when he came here, he is now 73. When Daniel retired, he started to live here more often. He uses the house in Sisal as a summer house. He has another house in Merida.

Development of Sisal

2. In your opinion, how has Sisal changed in terms of its economic or touristic development over the past few years or decades? For example, the difference before and after 2020?

Daniel has been coming here for more than 50 years. In 50 years he did not see a change in Sisal's community, it was like an equilibrium. After 2020, with the magic town status, there was a big change. He and other people from Sisal did not like this magic town status, as the change has caused for rising prices. A lot of people from outside Sisal started to come here, buying and developing infrastructure. Prices started to rise because the demand was a lot higher. Magic towns often received money from the state to improve the infrastructure within the town, but Sisal did not receive that. People that were born in Sisal do not like the magic town status, because it changes the community. There's a lot more waste on the beaches. Other beach areas in the east of Mexico are a lot more developed. The state did not prepare Sisal for the magic town status, which has a very bad impact on the local community, with only a relatively small amount of people benefitting from the change.

3. What do you know about the coastal development in Sisal over the previous years or decades? Have there been any significant changes or challenges that you have noticed?

- If any difference is noted: Has this change caused you to feel less safe or more vulnerable to climate change and associated flood risk?

The palapas and the new hotels are not good for the beach and for Sisal. For many years there have been no plants in front of the house. The owners have tried to plant more vegetation in front of the house in a regulated manner, so it looks better. The palapa owners do not like the vegetation, because it removes access to the palapas. Palapa owners have apparently removed vegetation. Daniel thinks the vegetation is important to manage flood risk.

He sees that erosion is happening, just like in Chelem. He sees that people are building structures to prevent erosion, but that did not help. The state then decided to remove the structures, which helped the coastal system to recover. Then the port was build and the shore started to accrete a lot. This is good for here, but he thinks it is bad for the reserve of El Palmar. However, he knows it is bad, but it is good for the fishing industry.

Communication

4. Have you had any communication or collaboration with other stakeholders regarding Sisal's coastal development or its economic/touristic growth? Think of policymakers (government), inhabitants, researchers, entrepreneurs, tourism representatives, nature preservationists and/or the press?

5. (If answer to the previous was affirmative) With whom have you been in contact?

- How frequent has this contact been?
- What type of communication was this mainly? Receiving, sending or both?
- And would you deem this communication to have been pleasant and effective?

He does have a lot of contact with policymakers, both in Sisal and Hunucma, about the concession for their part of the coast. He pays taxes in Hunucma. Their concession is that he has to keep the beach the way it is. Hunucma has to give their permission for the concession. He goes to the Comisario in Sisal first, then to Hunucma for the papers, and then to the federal government. They have a chat on the internet.

He does not have contact with UNAM. He does know that UNAM is been taking care of the shore. Daniel and his family are trying to make the beach more natural, but the palapa owners are not doing their part. He has made a complaint about that, but nothing is happening. If the magic town status is given, people should be prepared to do the work for it as well.

He has been in contact with palapa owners and restaurants, which are often the same owners. The palapa owners often make a mess of the palapa and the state does nothing about it.

He sometimes has contact with the fishing industry to go fishing himself. The fishermen do not talk about the beach degradation a lot, but they too do not like the magic town status.

He receives some things from the state with the chats of the state. There are various (WhatsApp?) groups from the people within Sisal. Daniel has been in multiple of these groups. For example, one for beach home owners. Daniel has received information, but he would like to receive different information. For example, on the developments. He thinks some corruption is going on with the permissions for regulations.

Finally, sometimes in the summer they even close off Sisal, as it is too busy. This is a bad thing.

Even though, the state says that fishing is not allowed around a certain time, fishermen remain fishing.

The present and future of Sisal

6. Which of the following areas do you consider most important for Sisal? Rank the following six subjects from ‘most’ to ‘least’ important.

- Liveability and development (Housing, amenities, improved quality of life, …)
- Fishing industry (The port, jobs created by fishery, …)
- Coastal health (The degradation of the beach, waste, water quality, …)
- Nature (The natural reserve of El Palmar, mangroves, …)
- Tourism (Amounts of tourists, tourism agencies, jobs created by tourism, …)
- Expanding Sisal (More housing and infrastructure, more inhabitants, …)

1. A 2. F 3. C 4. D 5. E 6. B

7. What is your opinion on the future development of Sisal, particularly in terms of the coastal environment and the local economy?

- Do you think climate change and development of Sisal will have a negative impact on the area? If so, how?

He thinks that it could become something very good, if they do it correctly. Right now, that is not happening, because there is no control by the state whatsoever. If they do it correctly, the new developments that are planned could be a positive outcome. Every time someone does something irregular, like building houses that are too high (hotel next to the house), no one does anything. He thinks it goes wrong with the people giving the permission.

About the coast, in all the years he is coming here, the coast has always adapted. Every couple of years it grows and it decreases, it has a natural coast line. It is changing all the time. It does not happen here because of the port.

8. Could you draw a mental map of what Sisal should look like in 2070 according to you?

- Draw a future Sisal according to your own memory. It does not need to be complete. Draw what first comes to your mind and your own experiences.
- What opportunities do you see in the future, draw these.
- What threats and risks exist for the future of Sisal, draw these.

C.9. Interview with Carlos Renan Herdia Kuing

Interviewer(s): Jip Kuiper & Leonardo Alonso	Date: 03/10/2024
Interviewee(s): Carlos Renan Herdia Kuing	Location: Palapa of Carlos Kuing, Sisal
Relation to project: Palapa owner and ex-fishermen	Interview number: 9

General

1. Can you tell us a bit about yourself and your connection to Sisal?

Carlos Renan Heredia Kuing. He is from Progreso, Yucatan. He was born in 1950. He came to Sisal in 1962, 62 years ago. He was an 'alfarero' for 10 years, that means he was protecting the varo. In Sisal he was only a fishermen. He was a fishermen for 60 years total.

Development of Sisal

2. In your opinion, how has Sisal changed in terms of its economic or touristic development over the past few years or decades? For example, the difference before and after 2020?

After the magic town status, a lot more tourism came to Sisal. Before, the economy was only related to the fishing industry, but after the magic town status a lot more opportunities came to make money in the tourism industry. For example, the palapa and restaurant owners that have a lot more opportunities to make money. He likes the magic town status for that reason. Before 2020, he was only a fishermen, but works in the palapas know. The fishermen like the magic town as well, because the fishermen can change their job to work in the tourism industry, because it is a lot easier than the fishing industry. This is a good change for them.

3. What do you know about the coastal development in Sisal over the previous years or decades? Have there been any significant changes or challenges that you have noticed?

- If any difference is noted: Has this change caused you to feel less safe or more vulnerable to climate change and associated flood risk?

He thinks the entire coast of Yucatan is eroding, not only in Sisal. So Progreso, Chelem, Celestun, etc. as well. He thinks the erosion is happening in the beach in front of the palapas as well, not only in the reserve of El Palmar. He thinks the port is not necessarily bad, not good either. He thinks the vegetation for the dunes is important for the water, strong winds and storms. The vegetation has not changed around the palapa. Furthermore, the cold front protection is not necessarily changed, but the vegetation is very important for the hurricanes, as it protects the village.

Right now, there is a lot of new houses around Sisal in comparison to 50 years ago. He thinks it is too much.

Communication

4. Have you had any communication or collaboration with other stakeholders regarding Sisal's coastal development or its economic/touristic growth? Think of policymakers (government), inhabitants, researchers, entrepreneurs, tourism representatives, nature preservationists and/or the press?

5. (If answer to the previous was affirmative) With whom have you been in contact?

- How frequent has this contact been?
- What type of communication was this mainly? Receiving, sending or both?
- And would you deem this communication to have been pleasant and effective?

He does not have any contact with policymakers. He is in contact with the Comisario sometimes. Sisal is part of Hunucma. The Comisario is most important in Sisal, he then talks to the president of Hunucma. Carlos talks about work with Comisario, for example if there is a problem with the palapa or if there is a problem with the police.

No contact with UNAM or other universities.

He talks with other tourism industry people, because they work together. People go to do a tour and eat a palapa for example.

He talks a lot with the fishing industry. The fishermen use a little ship for a tour, they then talk to Carlos and other palapa owners to take people on the tour. So, if people are at Carlos' palapa, he asks them if they want to do a tour and he calls the fishermen so they can pick them up. A lot of fishermen work in the fishing industry, as well as the tourism industry. They use their boats for tours for example.

The present and future of Sisal

6. Which of the following areas do you consider most important for Sisal? Rank the following six subjects from 'most' to 'least' important.

- Liveability and development (Housing, amenities, improved quality of life, …)
- Fishing industry (The port, jobs created by fishery, …)
- Coastal health (The degradation of the beach, waste, water quality, …)
- Nature (The natural reserve of El Palmar, mangroves, …)
- Tourism (Amounts of tourists, tourism agencies, jobs created by tourism, …)
- Expanding Sisal (More housing and infrastructure, more inhabitants, …)

1. B 2. E 3. F 4. A 5. C 6. D

7. What is your opinion on the future development of Sisal, particularly in terms of the coastal environment and the local economy?

- Do you think climate change and development of Sisal will have a negative impact on the area? If so, how?

He thinks the future development of Sisal is good. If they're building more infrastructure, more work will come for the people of the community. He thinks it is important to protect and respect the vegetation of the dune. So, the development is good, but the vegetation and other parts of the nature have to be respected. The impact of the storms in Sisal will be very small in the future, because the protection of the dune is present.

8. Could you draw a mental map of what Sisal should look like in 2070 according to you?

- Draw a future Sisal according to your own memory. It does not need to be complete. Draw what first comes to your mind and your own experiences.
- What opportunities do you see in the future, draw these.
- What threats and risks exist for the future of Sisal, draw these.

C.10. Interview with Rodrigo Peña

Interviewer(s): Jip Kuiper & Leonardo Alonso	Date: 03/10/2024
Interviewee(s): Rodrigo Peña	Location: Restaurant La Brisa del Mar, Sisal
Relation to project: Manager of a restaurant in Sisal	Interview number: 10

General

1. Can you tell us a bit about yourself and your connection to Sisal?

Rodrigo Peña. He was born in Merida, and moved to Sisal when he was young. He has lived here since. He studied as a physiotherapist in Merida. Right now, he is the manager of the restaurant 'La Brisa del Mar' in Sisal. He has connection with the tourism industry. He has palapas, the restaurant and other tourism agencies work/connections.

Development of Sisal

2. In your opinion, how has Sisal changed in terms of its economic or touristic development over the past few years or decades? For example, the difference before and after 2020?

There are a lot more people here after the magic town status. It was a lot better for the restaurant, because a lot of people went to the restaurant in comparison to before. Right now, there are more people and the economy is better. Before 2020, there are no palapas on the beach. After 2020, they were built and were selling food from the palapas. This was not good, as the restaurant had a lot more competition. He thinks for people outside of the tourism industry, the magic town status is bad.

3. What do you know about the coastal development in Sisal over the previous years or decades? Have there been any significant changes or challenges that you have noticed?

The dunes were a lot different before the palapas were built. After the palapas were built a lot of dunes were removed, to make room for the palapas. Because of the difference in tourism, a lot of dunes were altered, because people were walking on the beach etc. In the reserve of El Palmar, there is a lot of erosion and in Sisal there is erosion as well, but not as much. In the other side, like calbonera, there is erosion too. He thinks the vegetation on the dune is very important to protect the area against cold fronts, storms, hurricanes, etc.

- If any difference is noted: Has this change caused you to feel less safe or more vulnerable to climate change and associated flood risk?

Communication

4. Have you had any communication or collaboration with other stakeholders regarding Sisal's coastal development or its economic/touristic growth? Think of policymakers (government), inhabitants, researchers, entrepreneurs, tourism representatives, nature preservationists and/or the press?

5. (If answer to the previous was affirmative) With whom have you been in contact?

- How frequent has this contact been?
- What type of communication was this mainly? Receiving, sending or both?
- And would you deem this communication to have been pleasant and effective?

They have a group of people that work in the restaurant, they help each other with problems, paying taxes, etc. For the people that work in the palapas, the Comisario helps them with the documentation.

He does not have a lot of contact with the state and the Comisario from the restaurant, as they usually figure it out themselves within the restaurant. Sometimes there is contact with the Comisario, it is not necessarily good or bad. The Comisario then talks to people from Hunucma.

There is no contact with UNAM or other universities.

He has contact with fishermen to buy their products.

They have contact with palapa owners.

The present and future of Sisal

6. Which of the following areas do you consider most important for Sisal? Rank the following six subjects from 'most' to 'least' important.

- Liveability and development (Housing, amenities, improved quality of life, …)
- Fishing industry (The port, jobs created by fishery, …)
- Coastal health (The degradation of the beach, waste, water quality, …)
- Nature (The natural reserve of El Palmar, mangroves, …)
- Tourism (Amounts of tourists, tourism agencies, jobs created by tourism, …)
- Expanding Sisal (More housing and infrastructure, more inhabitants, …)

1. A 2. C. 3. D 4. B. 5. E 6. F

7. What is your opinion on the future development of Sisal, particularly in terms of the coastal environment and the local economy?

- Do you think climate change and development of Sisal will have a negative impact on the area? If so, how?

He thinks in ten or twenty years a lot more people will arrive in Sisal. It is very good for people in the tourism industry, but it is not good for the other local community members, as they are more reserved and don't appreciate a busy area. The services in Sisal is not good at the moment, for example the electricity and the water, which has to be fixed first. If more people will come this will become a major problem. In that way, Sisal will likely become another town like Tulum, Playa del Carmen and Cancun.

8. Could you draw a mental map of what Sisal should look like in 2070 according to you?

- Draw a future Sisal according to your own memory. It does not need to be complete. Draw what first comes to your mind and your own experiences.
- What opportunities do you see in the future, draw these.
- What threats and risks exist for the future of Sisal, draw these.

C.11. Interview with Elmer Arturo Bojorquez Novello

Interviewer(s): Jip Kuiper & Leonardo Alonso	Date: 03/10/2024
Interviewee(s): Elmer Arturo Bojorquez Novello	Location: Restaurant El Amigo Chivero, Sisal
Relation to project: Owner of a restaurant in Sisal	Interview number: 11

General

1. Can you tell us a bit about yourself and your connection to Sisal?

His name is Elmer Arturo Bojorquez Novello. He was born in Hunucma. He moved to Sisal when he was 8 years old. He has lived in Sisal since then. The restaurant is 35 years old at the moment, before that he was a fisherman in Sisal. He was a fisherman for 20 years before that. He built the restaurant 35 years ago and is still the owner.

Development of Sisal

2. In your opinion, how has Sisal changed in terms of its economic or touristic development over the past few years or decades? For example, the difference before and after 2020?

After 2020 a lot more people arrived because of the magic town status, this was not the case before 2020. People still came before 2020, but definitely not us much as now. The magic town status was good for the palapas, but not necessarily for the restaurant, because people eat there. A reason why the restaurant was not as visited as others, is because of its location. It is not in the centre, therefore only people that know the restaurant beforehand come there. People come back because the food is good. In that sense, the difference before and after 2020 is not very noticeable.

Three years ago the government repaired the street. A lot of people have arrived to develop new infrastructure, like hotels and other developments. However, the electricity system was not built for that, as it is not very reliable. This is similar with the internet, which can be worse when the weather is bad.

3. What do you know about the coastal development in Sisal over the previous years or decades? Have there been any significant changes or challenges that you have noticed?

A big difference is the amount of new palapas. A lot of palapas were built after the magic town status, before the magic town status only around 10 palapas existed.

The characteristics of the beach change with the season. Some seasons the beach is bigger and other seasons it is smaller. In general the beach is bigger around the pier and the changes in equilibrium that was there before is less noticeable. 40 or 50 years ago, the beach was way smaller. The water could sometimes be all the way at the houses that were there. In El Palmar this is the opposite, there is a lot more erosion there. The beach gets smaller.

He thinks the dune is good, but only the dunes, not the vegetation. The vegetation can hurt your feet and they can become places were people leave their trash.

- If any difference is noted: Has this change caused you to feel less safe or more vulnerable to climate change and associated flood risk?

Communication

4. Have you had any communication or collaboration with other stakeholders regarding Sisal's coastal development or its economic/touristic growth? Think of policymakers (government), inhabitants, researchers, entrepreneurs, tourism representatives, nature preservationists and/or the press?

5. (If answer to the previous was affirmative) With whom have you been in contact?

- How frequent has this contact been?
- What type of communication was this mainly? Receiving, sending or both?
- And would you deem this communication to have been pleasant and effective?

He has contact with the Comisario, depending on the problem. Sometimes the communication is with the Comisario, but if the problem is bigger it would be with the municipality of Hunucma. For example, whenever there is a fight in the restaurant or something similar. It is important to call with the people that are responsible for the law around those times.

There is sometimes contact with other universities from Merida to do an interview about the tourism in Sisal and the food in the restaurant. This is usually for publicity and tourism research. People sometimes come to ask him about joining TV shows and other publicity. This happens at his restaurant and at restaurant 'Palapa de Soco'. He has had contact with UNAM before, but not frequently. Two or three people from UNAM have come at his restaurant to ask questions about the tourism.

He has a lot of contact with the fishermen. For example, he goes to the port to pay fishermen for their products. He also talks to people from the tourism industry, but mainly about their clients coming to his restaurants to eat. The people that have a palapa and are involved in tourism have it better however, as they own the 'complete package' to offer to tourists.

The present and future of Sisal

6. Which of the following areas do you consider most important for Sisal? Rank the following six subjects from 'most' to 'least' important.

- Liveability and development (Housing, amenities, improved quality of life, …)
- Fishing industry (The port, jobs created by fishery, …)
- Coastal health (The degradation of the beach, waste, water quality, …)
- Nature (The natural reserve of El Palmar, mangroves, …)
- Tourism (Amounts of tourists, tourism agencies, jobs created by tourism, …)
- Expanding Sisal (More housing and infrastructure, more inhabitants, …)

1. C 2. A 3. B 4. E 5. F 6. D

7. What is your opinion on the future development of Sisal, particularly in terms of the coastal environment and the local economy?

- Do you think climate change and development of Sisal will have a negative impact on the area? If so, how?

He thinks in 20 years he (or Sisal) might not even be here any more. He thinks that Sisal is very safe and quiet right now, but if more people arrive more criminality could also happen. This could mean that the safety of Sisal will become worse. In 20 years, a lot more houses and hotels will be built. The services that are in Sisal right now are not prepared for that, this is a problem.

Since the beach is bigger and the vegetation is there, that is good for the storms, as they provide protection. He does not know what will happen in 20 years, as climate change has already caused a lot of differences to the beach of Sisal during the last decades.

There is a place further to El Palmar. There used to be a rock there that was easily visible, but right now this rock is not visible any more. This is a sign for him that the beach is changing. He is not even sure if the port will exist in the future, just like in Calbonera. This is similar to the main road, which used to connect Celestun to Sisal and another village to the East, but hurricanes and other effects have made it impossible to connect the areas now.

8. Could you draw a mental map of what Sisal should look like in 2070 according to you?

- Draw a future Sisal according to your own memory. It does not need to be complete. Draw what first comes to your mind and your own experiences.
- What opportunities do you see in the future, draw these.
- What threats and risks exist for the future of Sisal, draw these.

C.12. Interview with Laura Vidal

Interviewer(s): David Garagorri Linares	Date: 08/10/2024
Interviewee(s): Laura Vidal	Location: Online (Zoom)
Relation to project: Researcher at UNAM	Interview number: 12

General

1. Can you tell us a bit about yourself and your connection to Sisal?

She studies coastal management and policies over coastal areas from a complex systems approach. This means considering different variables and entities that affect the area of study.

Development of Sisal

2. In your opinion, how has Sisal changed in terms of its economic or touristic development over the past few years or decades? For example, the difference before and after 2020?

Sisal has undergone significant changes due to shifts in its main economic activities. Historically a fishing community, the area suffered from overexploitation of marine resources, making it increasingly difficult to sustain fishing as a livelihood. As fish populations declined, greater effort was required to catch fewer fish, placing further strain on the industry.

At the same time, tourism has seen a sharp rise, not only along the beaches but also in the surrounding natural areas, which are now protected. The presence of UNAM (National Autonomous University of Mexico) has also contributed to changes within the town.

Sisal's designation as a "Magic Town" further boosted tourism, but this recognition came without the necessary infrastructure, planning, or a holistic approach. As a result, the local community has faced negative impacts.

The city's expansion has also encroached on nearby natural areas. The growth of urban areas near the reserve has affected local wildlife, with issues like pollution, new access paths, and the introduction of non-native animals such as dogs disrupting the ecosystem. Also the filling of mangroves is a big issue here.

3. What do you know about the coastal development in Sisal over the previous years or decades? Have there been any significant changes or challenges that you have noticed?

- If any difference is noted: Has this change caused you to feel less safe or more vulnerable to climate change and associated flood risk?

Communication

4. Have you had any communication or collaboration with other stakeholders regarding Sisal's coastal development or its economic/touristic growth? Think of policymakers (government), inhabitants, researchers, entrepreneurs, tourism representatives, nature preservationists and/or the press?

5. (If answer to the previous was affirmative) With whom have you been in contact?

- How frequent has this contact been?
- What type of communication was this mainly? Receiving, sending or both?
- And would you deem this communication to have been pleasant and effective?

Yes, she has provided consulting services to INFONAVIT, focusing on urban planning. However, their interest was solely on the urban areas, while a comprehensive assessment must also include the natural areas. It doesn't make sense to analyze the urban environment in isolation. Furthermore, their approach was predominantly economic, which overlooks the importance of integrating a vulnerability perspective. This can only be achieved by incorporating natural areas into urban planning.

There has also been collaboration with tourism groups.

Regarding communication on the construction of new infrastructure, there is a notable lack of transparency. Environmental impact reports are almost never published, and when they are, it's often during times like summer or Christmas, when public access is limited. In some cases, these reports are not published at all, and requests for them go unanswered.

There has also been communication with engineers working at the state level, but they often fail to recognize the challenges and issues specific to the area.

The present and future of Sisal

6. Which of the following areas do you consider most important for Sisal? Rank the following six subjects from 'most' to 'least' important.

- Liveability and development (Housing, amenities, improved quality of life, …)
- Fishing industry (The port, jobs created by fishery, …)

- Coastal health (The degradation of the beach, waste, water quality, …)
- Nature (The natural reserve of El Palmar, mangroves, …)
- Tourism (Amounts of tourists, tourism agencies, jobs created by tourism, …)
- Expanding Sisal (More housing and infrastructure, more inhabitants, …)

1.C 2. D 3. B 4. A 5. E 6. F

7. What is your opinion on the future development of Sisal, particularly in terms of the coastal environment and the local economy?

- Do you think climate change and development of Sisal will have a negative impact on the area? If so, how?

The government tends to undervalue natural areas, and the local population is often passive in response to changes. While some may disagree with decisions, they rarely take action to express this dissent. This passivity stems from a lack of effective communication tools and a limited understanding of the consequences of these measures. However, this isn't always the case. Some ejidos (community land trusts, a concept worth exploring) do collaborate with the government to protect the environment, as seen in Ejido San Crisanto. Unfortunately, such cases are rare.

Looking to the future, Sisal is likely to see a decline in its native population due to rising living costs, driven by increased tourism, urbanization, and entertainment options. This will also likely lead to a reduction in protected areas. It will be interesting to see whether this urban growth happens vertically or horizontally. Horizontal expansion is limited because Sisal is surrounded by preserved natural areas.

From a water access perspective, two main challenges will emerge. First, the depletion of the phreatic levels (groundwater) due to the proliferation of wells, which will increase with new infrastructure. Second, water quality will deteriorate. The lack of a proper sewage system has led to informal waste disposal sites and poorly maintained septic systems, further compromising water safety.

8. Could you draw a mental map of what Sisal should look like in 2070 according to you?

- Draw a future Sisal according to your own memory. It does not need to be complete. Draw what first comes to your mind and your own experiences.
- What opportunities do you see in the future, draw these.
- What threats and risks exist for the future of Sisal, draw these.

C.13. Interview with Gemma Franklin

Interviewer(s): David Garagorri Linares	Date: 09/10/2024
Interviewee(s): Addy Cruz & Raul Palomo	Location: Online (Zoom)
Relation to project: Engineers at governmental institute CONAGUA	Interview number: 13

General

1. Can you tell us a bit about yourself and your connection to Sisal?

Networks. They measure around Sisal. Water quality, water level on the wells and hydraulic conductivity of the wells (related to discharge capacity for water access). There is a well close to Sisal (5-10km) that he has monitored over the last years.

Development of Sisal

2. In your opinion, how has Sisal changed in terms of its economic or touristic development over the past few years or decades? For example, the difference before and after 2020?

The response was more focused on the wells state around the Yucatan area. He recognised there was salt intrusion, but that the capacity of the aquifer was big compared to the discharge needed for the population on the area. There is no contamination on the aquifer and the phreatic level is cyclical but there are no anomalies on the water levels.

He has observed though a change on the town after the denomination of magic town. As a kid he used to go saying that it remained the same until the denomination happened. Now there are much more people and an increase on urbanization as well.

3. What do you know about the coastal development in Sisal over the previous years or decades? Have there been any significant changes or challenges that you have noticed?

- If any difference is noted: Has this change caused you to feel less safe or more vulnerable to climate change and associated flood risk?

Communication

4. Have you had any communication or collaboration with other stakeholders regarding Sisal's coastal development or its economic/touristic growth? Think of policymakers (government), inhabitants, researchers, entrepreneurs, tourism representatives, nature preservationists and/or the press?

5. (If answer to the previous was affirmative) With whom have you been in contact?

Mainly no. He knows that the population knows about the erosion problem. He also knows that the gentrification exists, that development is not always positive. This can create big challenges for the local people that lives there. The classical phrase of 'the local people is always forgotten' (by the politicians) is mentioned.

- How frequent has this contact been?
- What type of communication was this mainly? Receiving, sending or both?
- And would you deem this communication to have been pleasant and effective?

The present and future of Sisal

6. Which of the following areas do you consider most important for Sisal? Rank the following six subjects from 'most' to 'least' important.

- Liveability and development (Housing, amenities, improved quality of life, …)
- Fishing industry (The port, jobs created by fishery, …)
- Coastal health (The degradation of the beach, waste, water quality, …)
- Nature (The natural reserve of El Palmar, mangroves, …)
- Tourism (Amounts of tourists, tourism agencies, jobs created by tourism, …)
- Expanding Sisal (More housing and infrastructure, more inhabitants, …)

1. D 2.C 3. B 4.A 5. E 6. F

7. What is your opinion on the future development of Sisal, particularly in terms of the coastal environment and the local economy?

- Do you think climate change and development of Sisal will have a negative impact on the area? If so, how?

He says that the population and the urbanization will be at least double. This will lead to insecurity for sure, because of new people arriving. Garbage on the beach for sure. This is all caused by tourism but tourism itself is not bad, it is the bad implementation of this economic activity, as well as the culture of the people working on it that makes this activity have bad consequences.

He says again that there will not be water problems, there is enough discharge for the population as well as the quality.

Problems in the drainage system is something that exists, but building it is complex due to soil type. It requires a long project, but the political conditions are not suitable for this type of projects. The politicians offer fast solutions, long term projects are not attractive for them because they only care on the projects that take 2-3 years (the time they are on the power position). Therefore he thinks this problem will remain and only got worse with time.

8. Could you draw a mental map of what Sisal should look like in 2070 according to you?

- Draw a future Sisal according to your own memory. It does not need to be complete. Draw what first comes to your mind and your own experiences.
- What opportunities do you see in the future, draw these.
- What threats and risks exist for the future of Sisal, draw these.

C.14. Interview with Karol Granada

Interviewer(s): David Garagorri Linares	Date: 14/10/2024
Interviewee(s): Karol Granada	Location: Online (Zoom)
Relation to project: Researcher at LANRESC	Interview number: 14

General

1. Can you tell us a bit about yourself and your connection to Sisal?

Her name is Karol Granada, and she is the project coordinator at the National Coastal Resilience Laboratory, where Sisal is the main headquarters.

Development of Sisal

2. In your opinion, how has Sisal changed in terms of its economic or touristic development over the past few years or decades? For example, the difference before and after 2020?

3. What do you know about the coastal development in Sisal over the previous years or decades? Have there been any significant changes or challenges that you have noticed?

- If any difference is noted: Has this change caused you to feel less safe or more vulnerable to climate change and associated flood risk?

The National Autonomous University of Mexico (UNAM) has had a significant cultural impact, from the influx of new people to the area they occupy. The designation of ”Pueblo Mágico” has also transformed the town’s economic activities. Regarding erosion, it is indeed important, but it is not labeled as critical, especially when compared to other beaches like Progreso. It is classified as moderate. In Progreso, the annual erosion rate is roughly double or triple that of Sisal.

Communication

4. Have you had any communication or collaboration with other stakeholders regarding Sisal’s coastal development or its economic/touristic growth? Think of policymakers (government), inhabitants, researchers, entrepreneurs, tourism representatives, nature preservationists and/or the press?

5. (If answer to the previous was affirmative) With whom have you been in contact?

- How frequent has this contact been?
- What type of communication was this mainly? Receiving, sending or both?
- And would you deem this communication to have been pleasant and effective?

Yes, primarily through the production of report cards for each of the resilience labs. These report cards are shared with the government, environmental entities, and the general community. However, the primary purpose of these report cards is to inform policymakers about the state of the beach. They are typically produced every five years.

She also mentioned that the people of Sisal sometimes feel overwhelmed by the numerous interviews conducted with the population. There is a lot of research, but they do not see tangible changes, leading them to believe that any effort is futile. They ask, ”What do I gain by participating in initiatives if, in the end, the community does not benefit?”

The present and future of Sisal

6. Which of the following areas do you consider most important for Sisal? Rank the following six subjects from ‘most’ to ‘least’ important.

- Liveability and development (Housing, amenities, improved quality of life, …)
- Fishing industry (The port, jobs created by fishery, …)
- Coastal health (The degradation of the beach, waste, water quality, …)
- Nature (The natural reserve of El Palmar, mangroves, …)
- Tourism (Amounts of tourists, tourism agencies, jobs created by tourism, …)
- Expanding Sisal (More housing and infrastructure, more inhabitants, …)

1. C 2. A 3. B 4. D 5. E 6. F

7. What is your opinion on the future development of Sisal, particularly in terms of the coastal environment and the local economy?

- Do you think climate change and development of Sisal will have a negative impact on the area? If so, how?

8. Could you draw a mental map of what Sisal should look like in 2070 according to you?

- Draw a future Sisal according to your own memory. It does not need to be complete. Draw what first comes to your mind and your own experiences.
- What opportunities do you see in the future, draw these.
- What threats and risks exist for the future of Sisal, draw these.

C.15. Interview with Fernando Mex

Interviewer(s): Jip Kuiper & David Garagorri Linares	Date: 15/10/2024
Interviewee(s): Fernando Mex	Location: House of Fernando Mex, Sisal
Relation to project: Fishermen in Sisal	Interview number: 15

General

1. Can you tell us a bit about yourself and your connection to Sisal?

He is a fishermen, but that is not his only job any more. He works together with UNAM a lot, as he organizes field trips for various parts of the university.

Development of Sisal

2. In your opinion, how has Sisal changed in terms of its economic or touristic development over the past few years or decades? For example, the difference before and after 2020?

He knows about the magic town status. This statement made the city more known and people wanted to visit more, and developing the tourism industry.

UNAM impacted directly giving some job opportunities but also the perspective is negative because they took a big piece of terrain from the town. Also, they have negative experiences with UNAM students partying.

Fishing has got way more expensive and also complex. Increase on fishermen because of local migration in the 80s and 90s and better technology made fishing more effective, depleting the resources.

There were shrimp farms in the 80s, an opportunity for development but that then it became private property from foreign owners.

People are not happy with the magic status denomination and also with the way that tourism has been handled in the last years.

3. What do you know about the coastal development in Sisal over the previous years or decades? Have there been any significant changes or challenges that you have noticed?

- If any difference is noted: Has this change caused you to feel less safe or more vulnerable to climate change and associated flood risk?

Communication

4. Have you had any communication or collaboration with other stakeholders regarding Sisal's coastal development or its economic/touristic growth? Think of policymakers (government), inhabitants, researchers, entrepreneurs, tourism representatives, nature preservationists and/or the press?

5. (If answer to the previous was affirmative) With whom have you been in contact?

- How frequent has this contact been?
- What type of communication was this mainly? Receiving, sending or both?
- And would you deem this communication to have been pleasant and effective?

No communication between UNAM and the people or not so much. Government as well no communication at all. Even the magic town status was sketchy.

The present and future of Sisal

6. Which of the following areas do you consider most important for Sisal? Rank the following six subjects from 'most' to 'least' important.

- Liveability and development (Housing, amenities, improved quality of life, …)
- Fishing industry (The port, jobs created by fishery, …)
- Coastal health (The degradation of the beach, waste, water quality, …)
- Nature (The natural reserve of El Palmar, mangroves, …)
- Tourism (Amounts of tourists, tourism agencies, jobs created by tourism, …)
- Expanding Sisal (More housing and infrastructure, more inhabitants, …)

1. A 2. C 3. B 4. E 5. D 6. F

7. What is your opinion on the future development of Sisal, particularly in terms of the coastal environment and the local economy?

- Do you think climate change and development of Sisal will have a negative impact on the area? If so, how?

A lot of tourism and hotels. He thinks the fishing industry will not exist anymore in the future, as it is not going to survive the increase in tourism and the changing climate.

More tourism, growth of housing industry and gentrification.

Fernando has a theory that something unethical has happened regarding the denomination of the magic town status. Land to the East and West of Sisal in both natural reserves has apparently been bought by entrepreneurs in previous years, seeing opportunities to build revenue by selling the land for profit. Unfortunately for these entrepreneurs, the land in the close vicinity of Sisal did not seem to be increasing in value over the years, as Sisal was not as popular yet. Fernando believes that the owners of the land wanted to increase the profit that they could receive for the land, and therefore had something to do with the magic town denomination.

According to Fernando, the magic town status is not given by the government to locations that they see fit, but is the status actually applied for by the location itself. If this is the case, it could also explain why none of the community members of Sisal knew of the magic town denomination decision when it happens. The question who did decide to apply for the status remains however. Fernando believes that this could have been a group of both governmental representatives and owners of the land, with the goal to increase the value of the land by making Sisal a more popular location. The governmental representatives could have possibly shared some of the revenue that this could have created.

8. Could you draw a mental map of what Sisal should look like in 2070 according to you?

    - Draw a future Sisal according to your own memory. It does not need to be complete. Draw what first comes to your mind and your own experiences.
    - What opportunities do you see in the future, draw these.
    - What threats and risks exist for the future of Sisal, draw these.

D

Appendix D - Background analysis of interviewed individuals

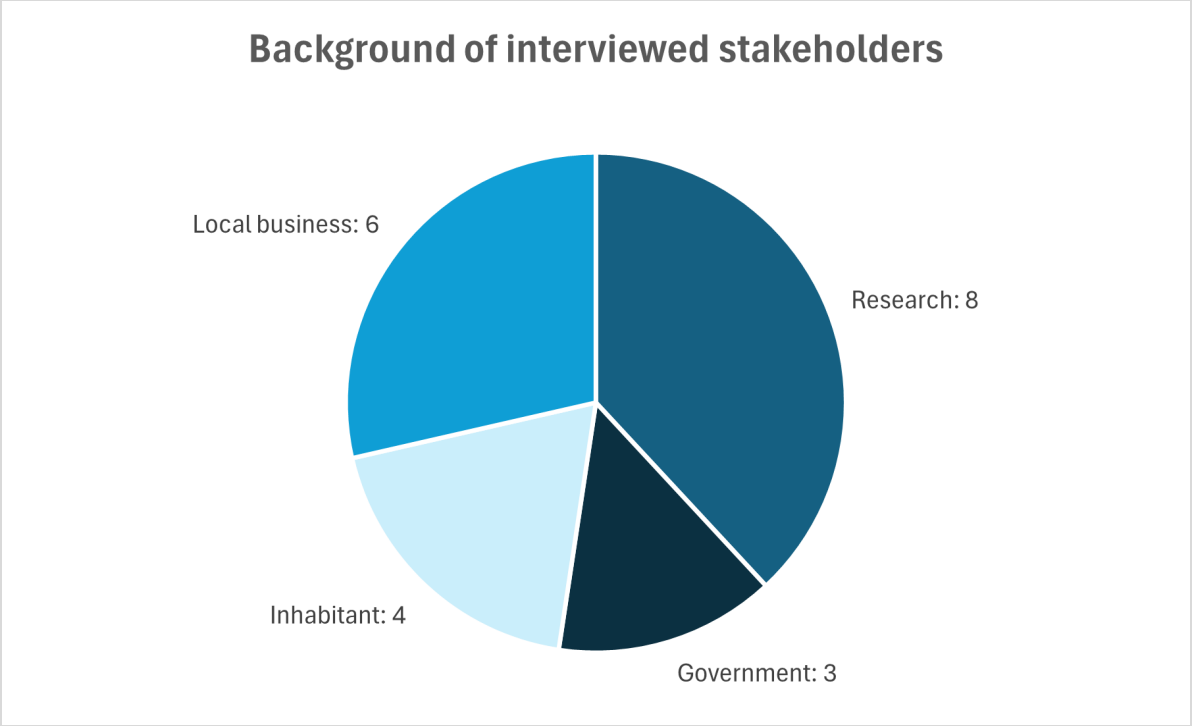

Figure D.1: Occupational/social background of interviewed stakeholders

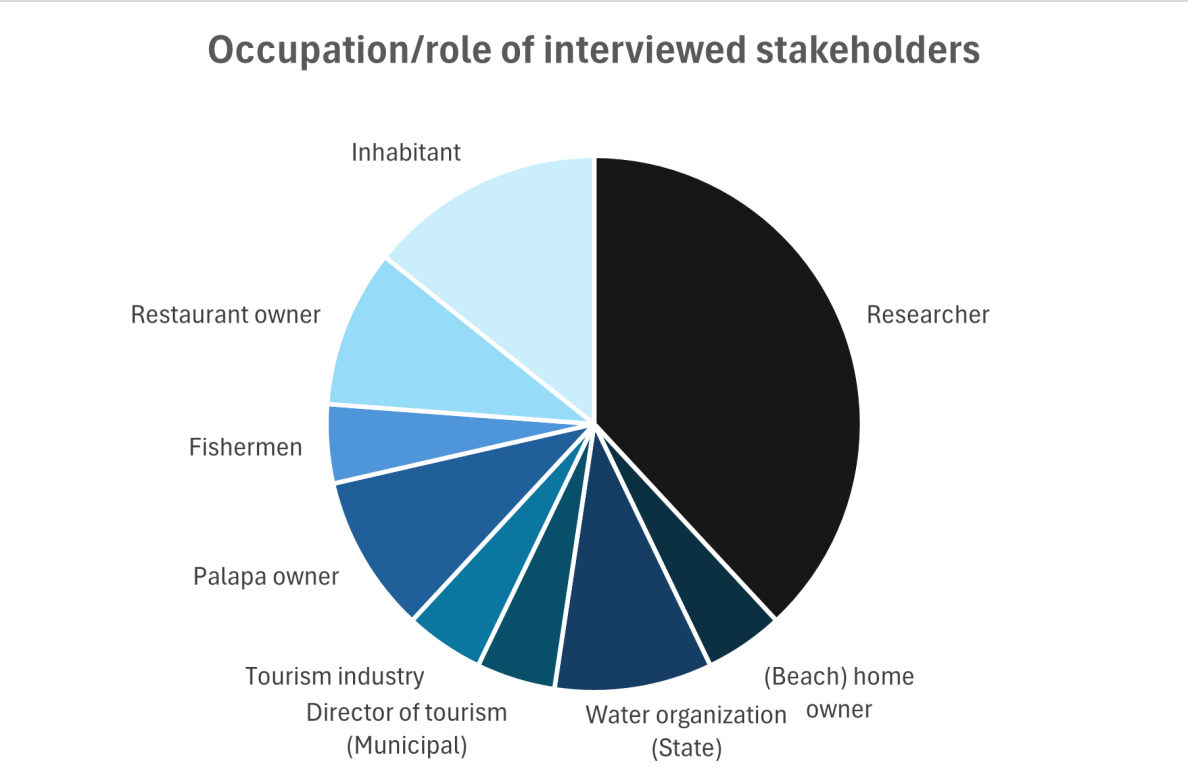

Figure D.2: Occupation/role of interviewed stakeholders

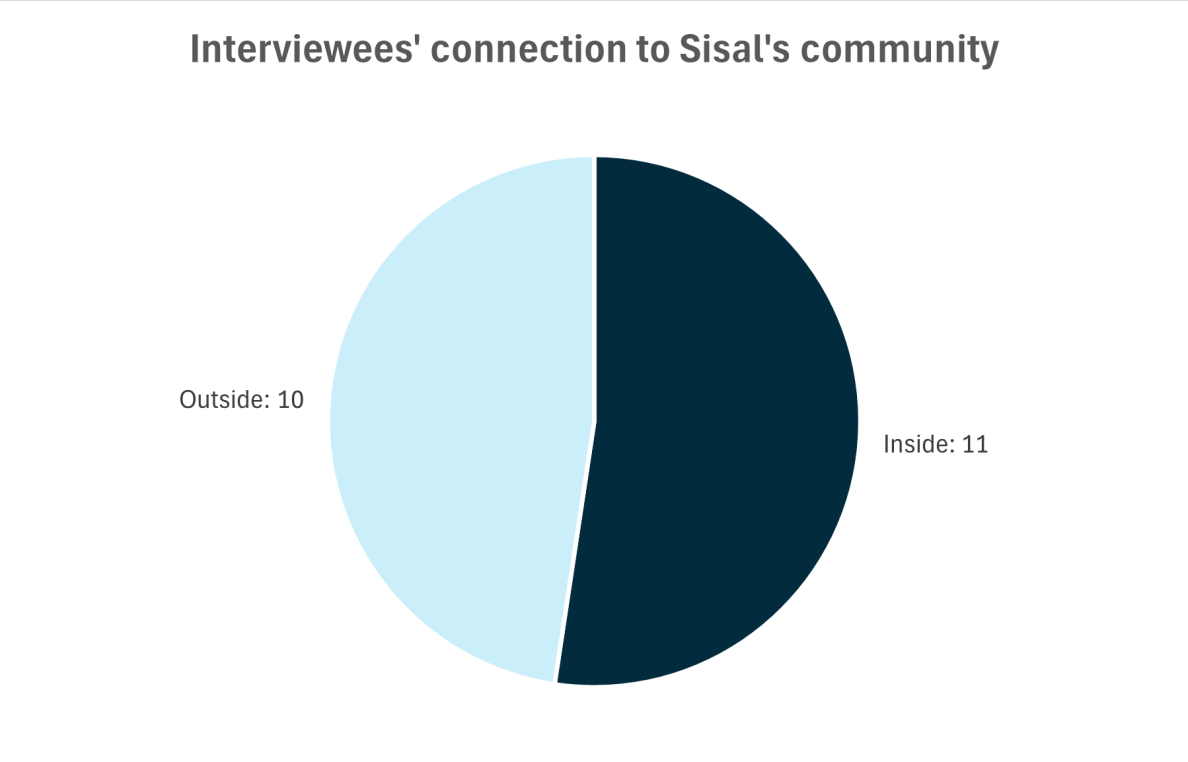

Figure D.3: Ratio of interviewed stakeholder's being in- or outside Sisal's community

E

Appendix E - Mental Maps

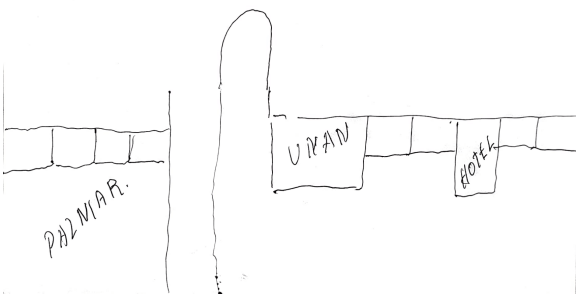

Figure E.1: Mental map of Carlos Kuing

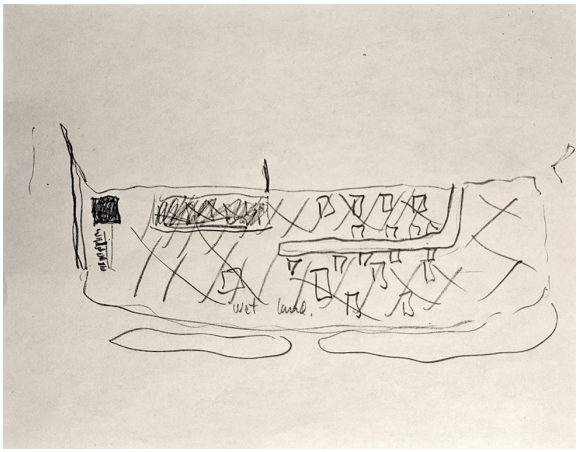

Figure E.2: Mental map of Carlos Rosas

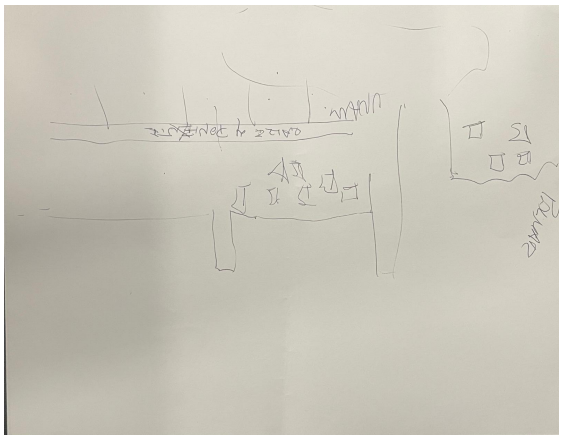

Figure E.3: Mental map of Daniel Vargas

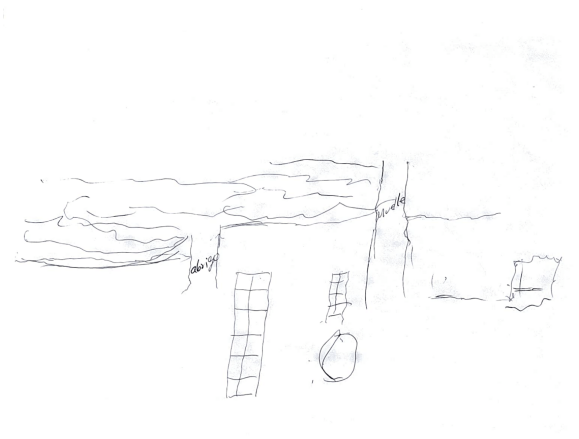

Figure E.4: Mental map of Elmer Novello

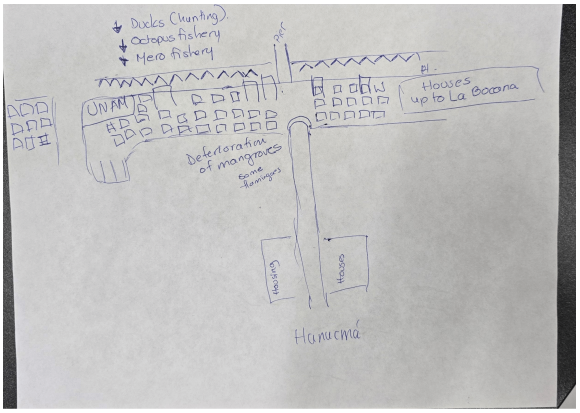

Figure E.5: Mental map of Elsa Noreña

Figure E.6: Mental map of Fatima Puc

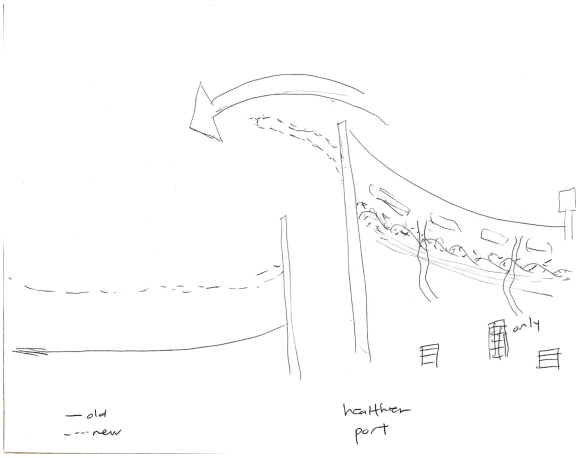

Figure E.7: Mental map of Gabriela Medellín Mayoral

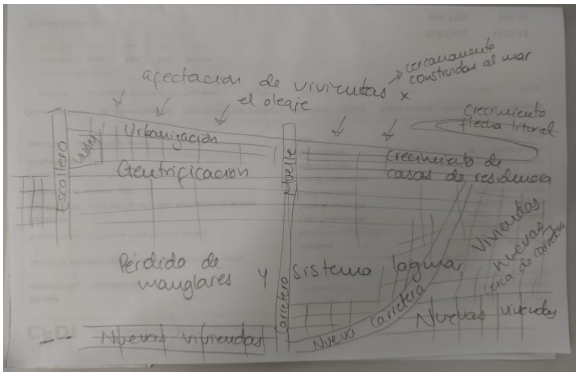

Figure E.8: Mental map of Gabriela Mendoza González

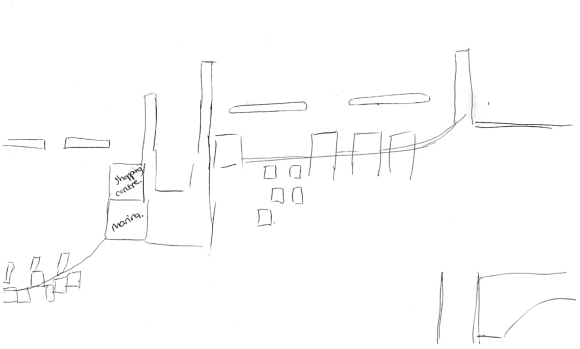

Figure E.9: Mental map of Gemma Franklin

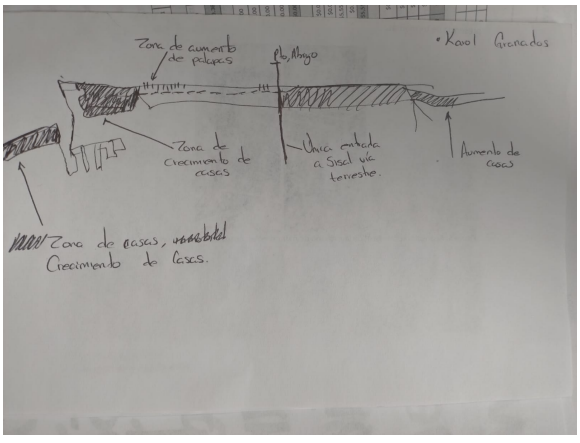

Figure E.10: Mental map of Karol Granada

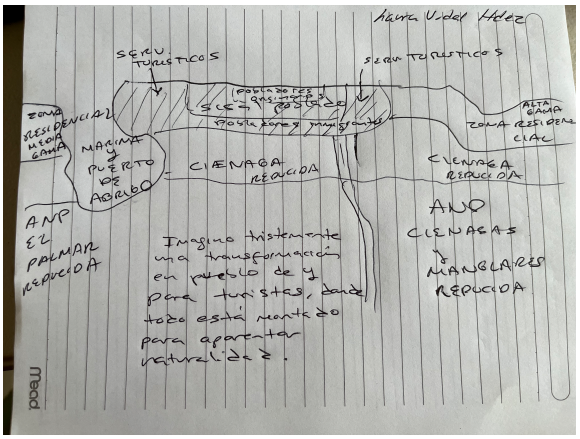

Figure E.11: Mental map of Laura Vidal

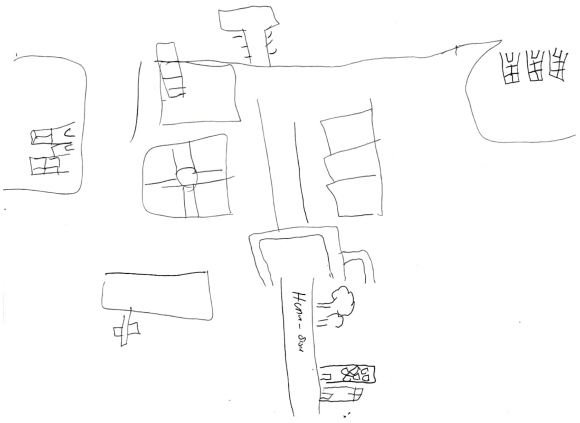

Figure E.12: Mental map of Rodrigo Peña

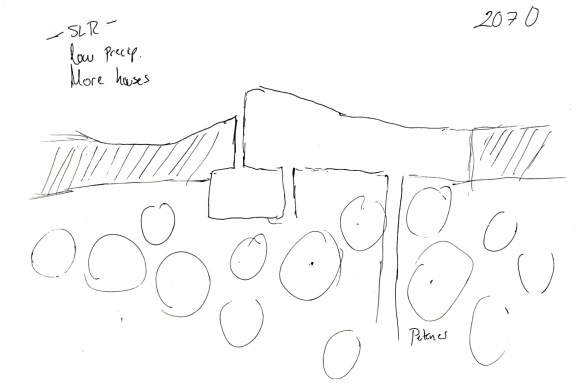

Figure E.13: Mental map of Roger Pacheco

F

Appendix F - Storm analysis

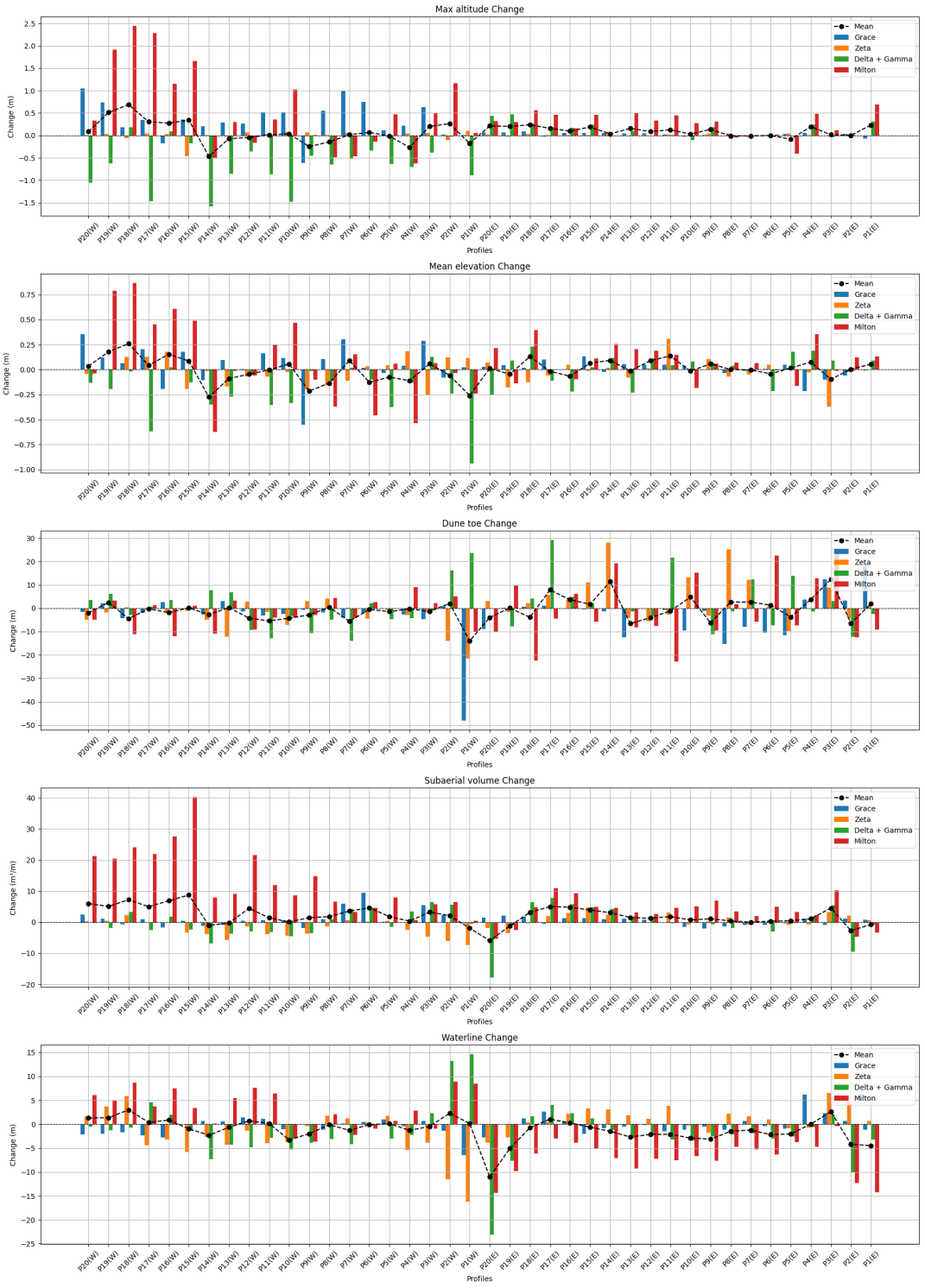

Figure F.1: Indicator response per transect per storm

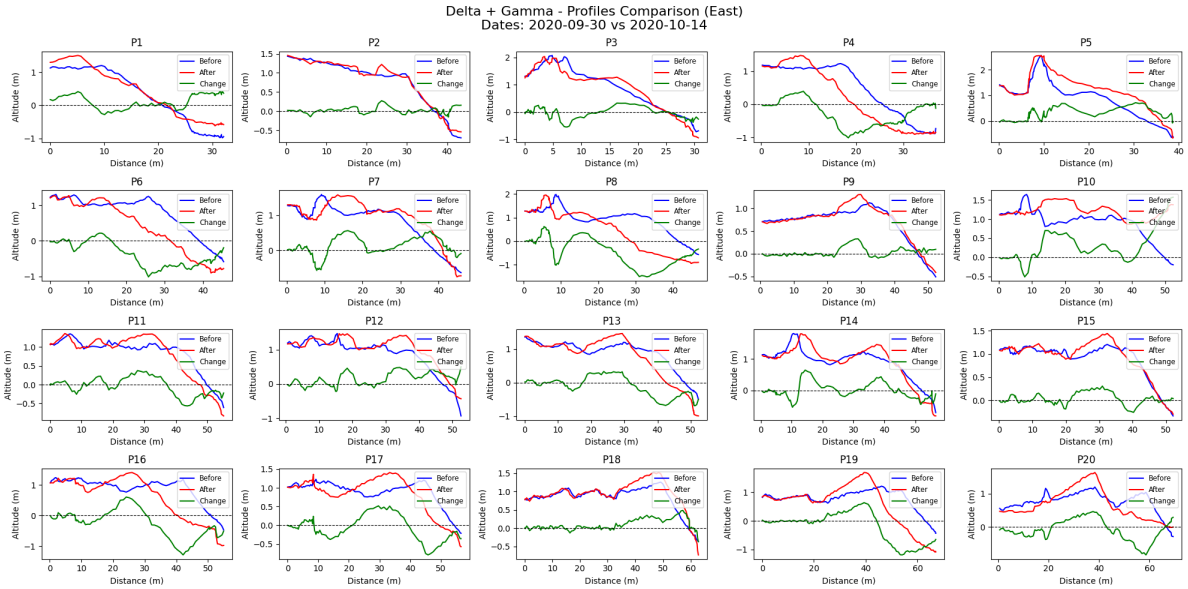

Figure F.2: Profiles Comparison for Delta + Gamma - East Side

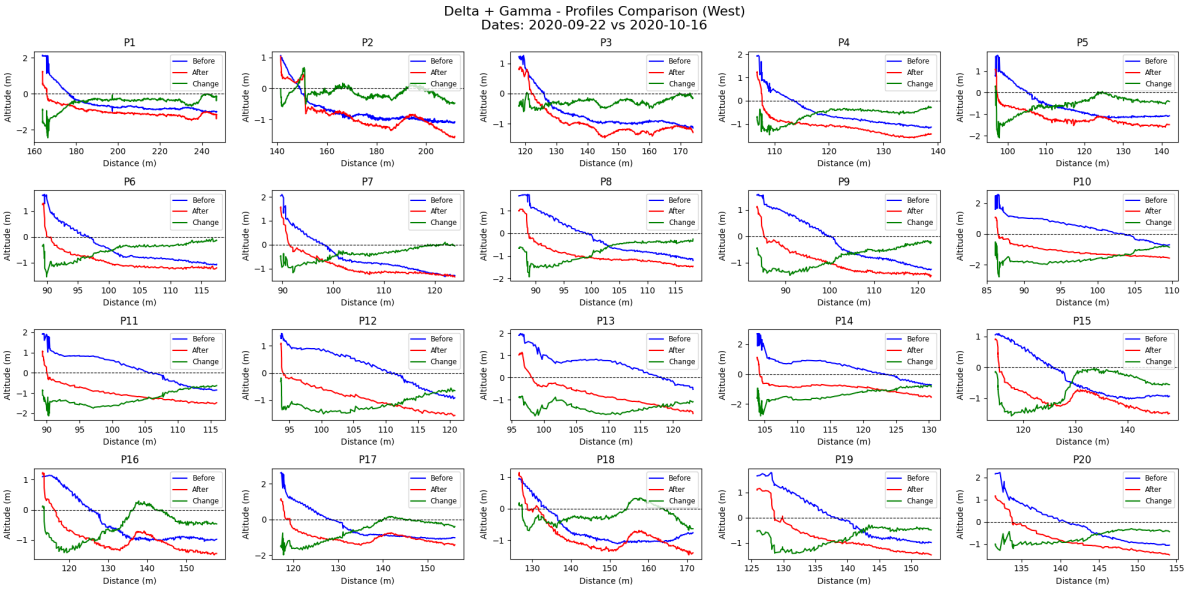

Figure F.3: Profiles Comparison for Delta + Gamma - West Side

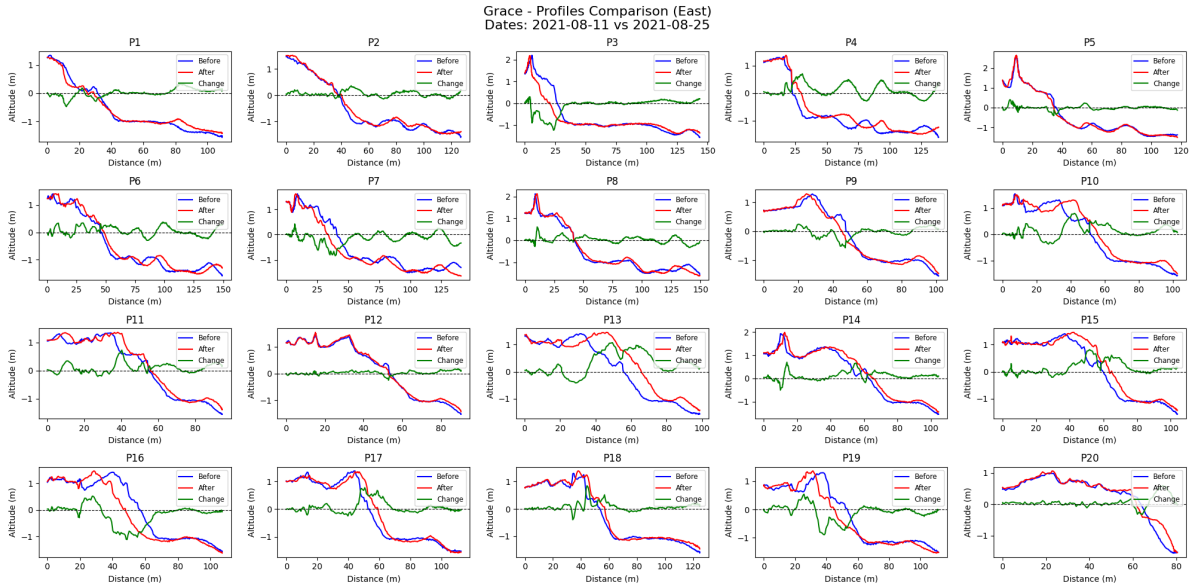

Figure F.4: Profiles Comparison for Grace - East Side

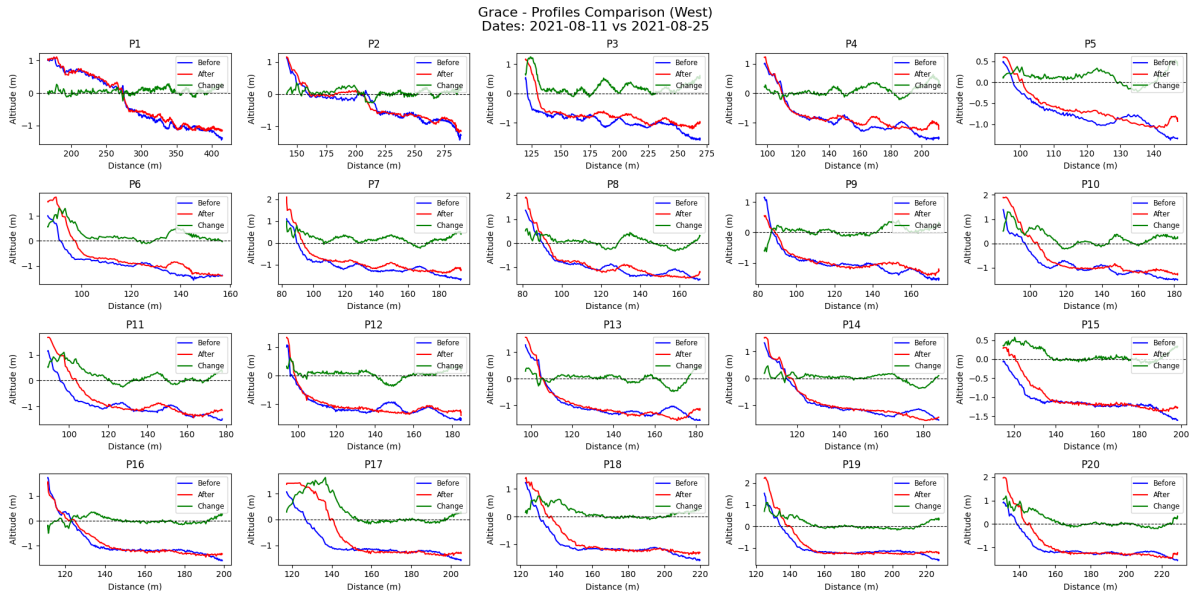

Figure F.5: Profiles Comparison for Grace - West Side

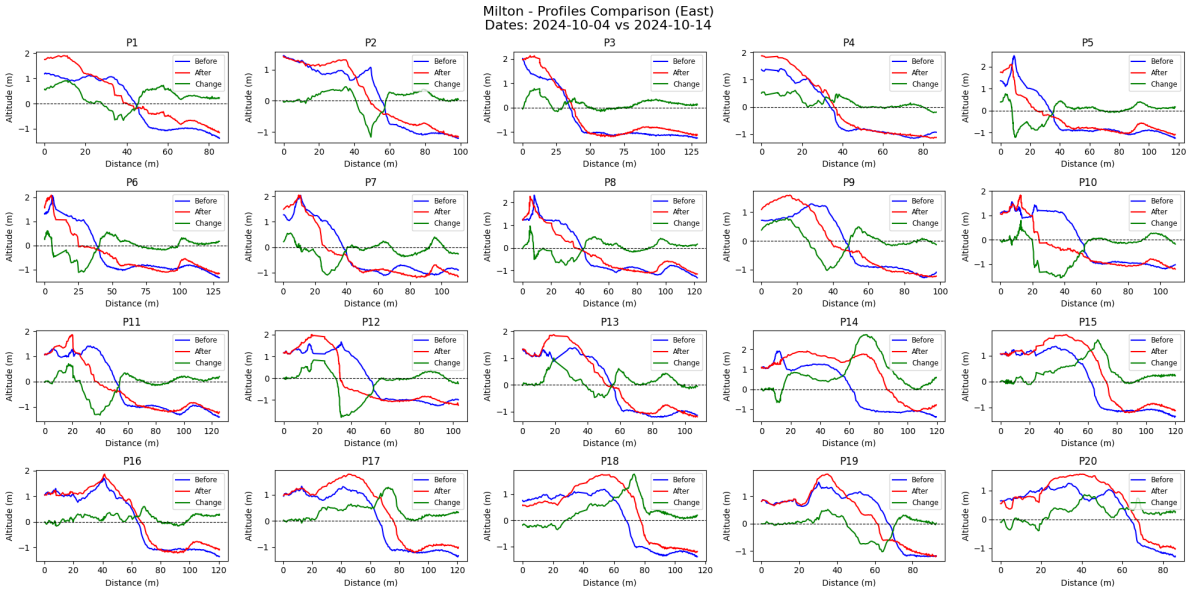

Figure F.6: Profiles Comparison for Milton - East Side

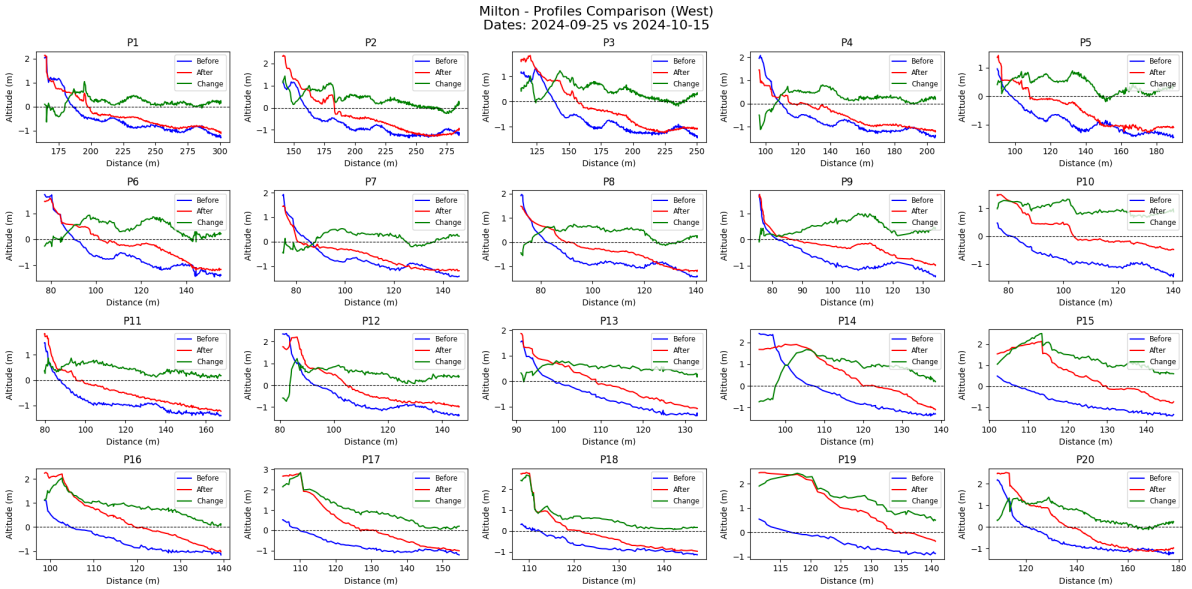

Figure F.7: Profiles Comparison for Milton - West Side

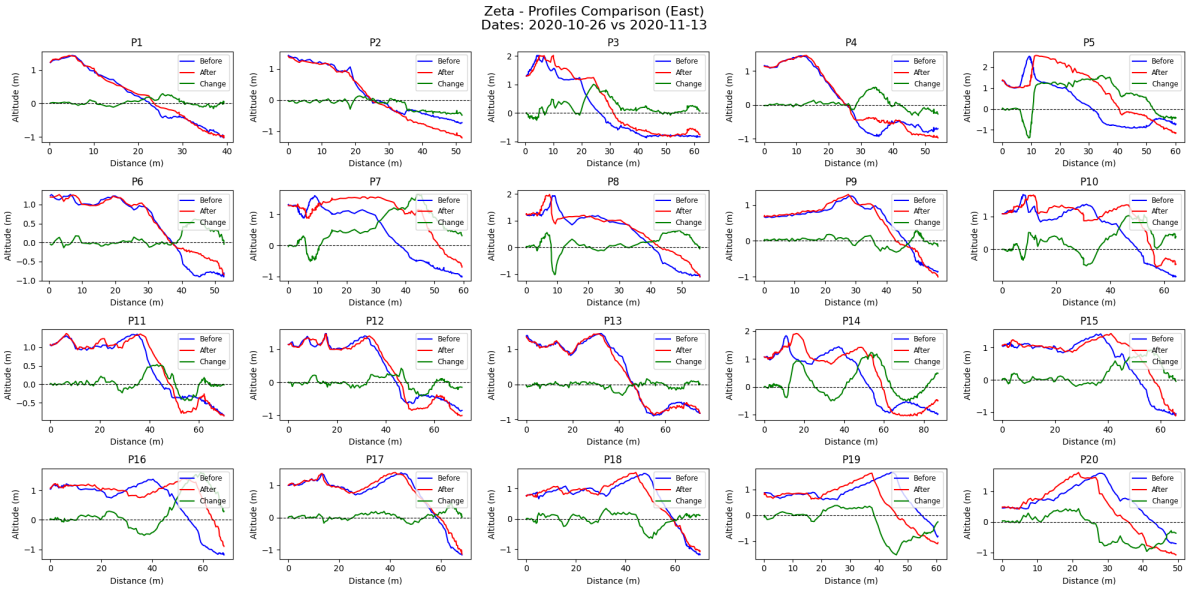

Figure F.8: Profiles Comparison for Zeta - East Side

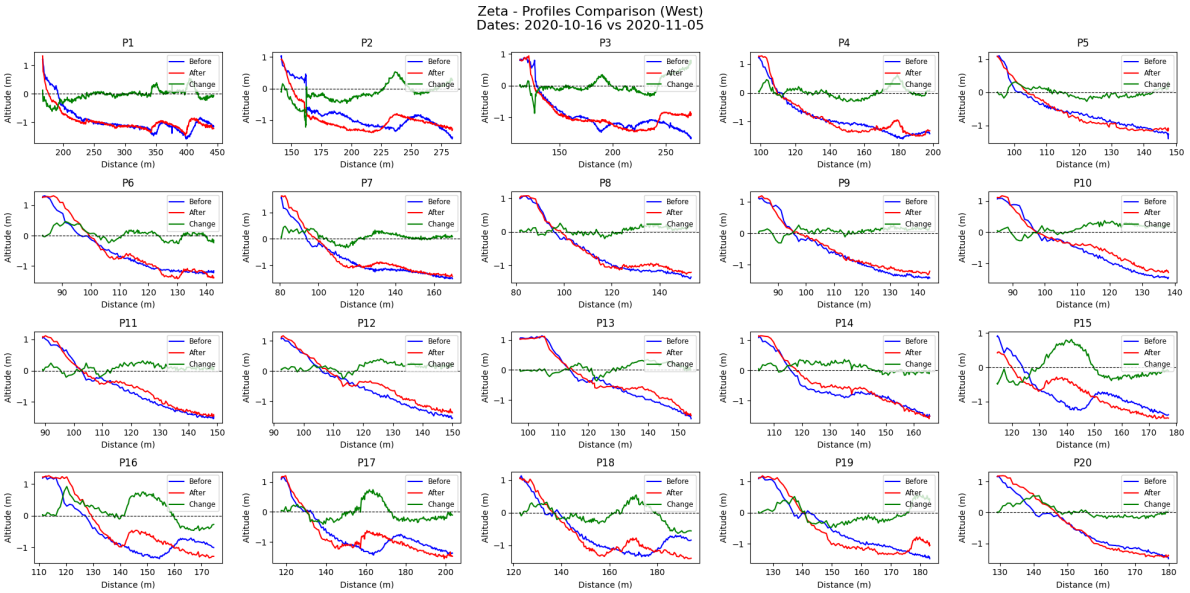

Figure F.9: Profiles Comparison for Zeta - West Side

G

Appendix G - Sea level rise

In this analysis, we utilized multiple datasets to determine a the sea level rise trend from historical sea levels and give insights in future scenarios under varying climate conditions. Table G.1 summarizes the datasets used.

Dataset	Source	Measurement Technique	Location / Details	Temporal and Spatial Resolution	Time Span
ECCO v4r4	NASA Sea Level Analysis Tool (ECCO Consortium)	Satellite altimetry (TOPEX/Poseidon, Jason-1, Jason-2, Jason-3)	Gulf of Mexico (21.00°N – 22.00°N, 91.00°W – 90.00°W)	Monthly 1° × 1°	Jan 1992 – Dec 2017
LANRESC	Copernicus Marine Service (CMEMS) via AVISO+	Satellite altimetry (Sentinel-3, TOPEX/Poseidon, Jason missions)	Sisal, Yucatán (21.1660°N, 90.0497°W)	Daily (resampled to monthly) 0.25° × 0.25°	Jan 1993 – Jun 2023
Global Mean Sea Level	Copernicus Marine Service	Satellite altimetry (Sentinel-3, Jason-1, Jason-2, Jason-3)	Global Coverage	Monthly N/A	1993 – ongoing
Local Tidal Port Sensor	Tidal gauge station at the Port of Sisal	In-situ sensor (tide gauge)	In-situ measurements at Port of Sisal (21.161°N, 90.048°W)	1-minute intervals (resampled to monthly) N/A	2011 – 2024

Table G.1: Summary of Sea Level Rise Datasets Used in the Study

The analysis reveals that Sisal has experienced, as expected, significant sea level rise over the past three decades. Using ECCO v4r4 data, we identified a mean sea level rise trend of 4.58 mm/year from 1992 to 2017 (see Figure G.1). This rate aligns with regional trends in the Gulf of Mexico, which has been identified as an area experiencing higher-than-average sea level rise compared to other regions globally. The LANRESC dataset, which reflects localized fluctuations, recorded a slightly higher trend of 4.99 mm/year. In comparison, global mean sea level trends over the same period show a more conservative increase of approximately 3.35 mm/year. The slower global trend reflects the averaging of sea level dynamics across the world, where some regions experience slower rises.

Data from the local tidal sensor at the Port of Sisal presents the steepest increase, with a trend of 9.58 mm/year between 2011 and 2024. This rapid rise suggests the influence of additional local factors or measurement uncertainties. The accuracy of the tidal sensor data may require further validation.

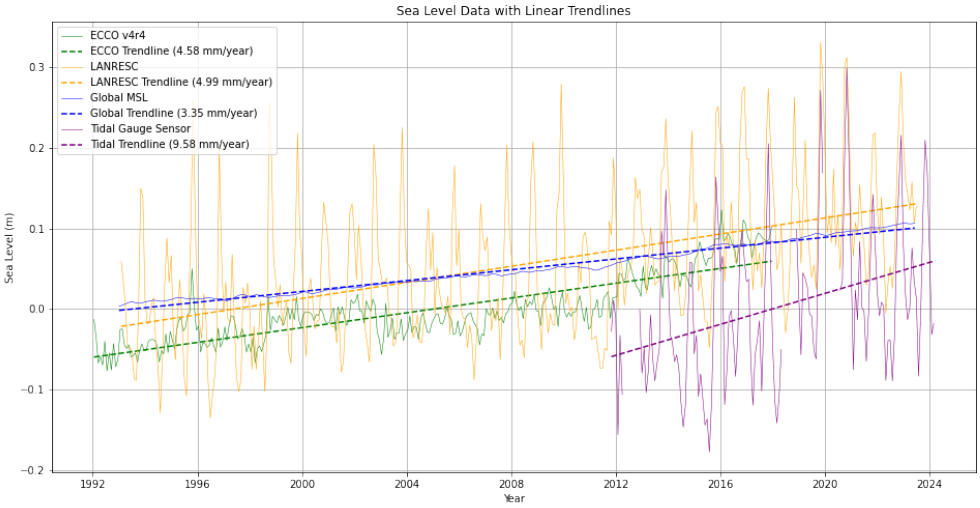

Figure G.1: Sea Level height data series with linear trend lines

H

Appendix G - Palapa analysis

Introduction

The palapa structures along the beaches of Sisal serve as sun shelters and recreational spaces mainly for tourists. However, their presence impacts the natural dune system, often leading to the removal of vegetation and flattening of the dune, which affects coastal vulnerability. To monitor the spatial development of these palapas and analyse trends over time, drone images (Table 3.1 were used in combination with QGIS to identify and measure their surface area.

Methodology

Drone images were used annually in the month of August for the years 2021, 2022, 2021 and 2024. The use of drone imagery allowed for high-resolution coverage of the coastline, ensuring that even small palapas could be identified and included. The images were processed in QGIS by manually drawing the outlines of the palapas visible on each image. These polygons were then used to calculate the total surface area of palapas for each year.

The following steps summarize the workflow:

1. **Image Acquisition:** High-resolution drone images were collected for the same month (August) across four years.
2. **Polygon Mapping:** Each visible palapa was outlined manually using the QGIS.
3. **Surface Area Calculation:** QGIS's attribute table function was used to calculate the total surface area for all polygons.
4. **Trend Analysis:** The calculated areas were compared across years to identify trends.

Results

The analysis revealed the following trends in palapa surface area from 2021 to 2024:

- **2021:** Minimal surface area, likely due to reduced tourism and COVID-19 restrictions.
- **2022-2024:** A steady increase in palapa coverage, reflecting a recovery in tourism activities.

The following table summarizes the results:

Table H.1: Total Palapa Surface Area (m^2) from 2021 to 2024

Year	Total Palapa Surface Area (m^2)	Observations
2021	1979	Minimal coverage likely due to COVID-19 restrictions.
2022	3684	Recovery begins with tourism activities increasing.
2023	4894	Continued rapid growth
2024	5280	Continued reduced growth

Discussion

The analysis suggests that tourism activity and palapa construction are closely linked, with *COVID-19* acting as a significant disruption in 2021, resulting in a low palapa coverage. While the change in surface area from 2022 onward indicates a steady increase, the lack of *pre-2021* data limits our ability to assess whether the current coverage exceeds or is equal to *pre-COVID-19* coverage.

Appendix I - Python Profile Class Code

Listing I.1: Python Script for Profile Analysis

```python
import numpy as np
import pandas as pd
import geopandas
from matplotlib import pyplot as plt
from shapely.geometry import LineString
import os
import glob
import streamlit as st
from scipy.interpolate import CubicSpline
from scipy.signal import find_peaks
from matplotlib import pyplot as plt

# Smoothing using a moving average
def moving_average(arr, window_size):
    return np.convolve(arr, np.ones(window_size)/window_size, mode='same')

# Smoothing using a moving average with padding
def moving_average(arr, window_size):
    pad_size = window_size // 2
    arr_padded = np.pad(arr, pad_size, mode='edge')
    smoothed = np.convolve(arr_padded, np.ones(window_size)/window_size, mode='same')
    smoothed = smoothed[pad_size:-pad_size]
    return smoothed[:len(arr)]

# Define profile class
class Profile:
    def __init__(self, location: str = None, name: str = None, x_loc: list = None,
                 y_loc: list = None, altitude: list = None, distances: list = None,
                 date: str = None):
        self.location = location
        self.name = name
        self.x_loc = x_loc
        self.y_loc = y_loc
        self.altitude = altitude
        self.distances = distances
        self.date = date

    def max_altitude(self):
        if self.altitude == []:
            return None
        return max(self.altitude)

    def water_line_point(self):
        """
        Interpolates to find the waterline point where altitude is 0.
        Returns the interpolated x, y coordinates of the waterline point.
        """
        if not self.altitude or len(self.altitude) != len(self.x_loc) or len(self.altitude)
            != len(self.y_loc):
            return None

        if 0 in self.altitude:
```

```
            return self.x_loc[self.altitude.index(0)], self.y_loc[self.altitude.index(0)],
                self.distances[self.altitude.index(0)]

        for i in range(1, len(self.altitude)):
            alt1, alt2 = self.altitude[i-1], self.altitude[i]

            if not isinstance(alt1, (int, float)) or not isinstance(alt2, (int, float)):
                continue

            if alt1 * alt2 < 0:
                t = -alt1 / (alt2 - alt1)
                x_interp = self.x_loc[i-1] + t * (self.x_loc[i] - self.x_loc[i-1])
                y_interp = self.y_loc[i-1] + t * (self.y_loc[i] - self.y_loc[i-1])
                distance_interp = self.distances[i-1] + t * (self.distances[i] - self.
                    distances[i-1])
                self.x_loc.insert(i, x_interp)
                self.y_loc.insert(i, y_interp)
                self.altitude.insert(i, 0)
                self.distances.insert(i, distance_interp)

                return x_interp, y_interp, distance_interp

        return None

    def beach_width(self):
        max_alt = self.max_altitude()
        max_alt_index = self.altitude.index(max_alt)

        wl_point = self.water_line_point()
        if wl_point is None:
            return None

        if self.location == 'east':
            bw = wl_point[2] - self.distances[0]

        if self.location == 'west':
            scarp_toe = self.get_scarp_toe()

            if scarp_toe is None:
                return None

            bw =  wl_point[2] - scarp_toe[2]

        return bw

    def mean_elevation(self):
        if self.altitude == []:
            return None
        altitude = [x for x in self.altitude if isinstance(x, (int, float))]
        altitude = [x for x in altitude if (x > 0)]

        if altitude == []:
            return None

        if self.location == 'east':
            distance = [x for x in self.distances if isinstance(x, (int, float))]
            distance = distance[:len(altitude)]
        elif self.location == 'west':
            scarp_toe = self.get_scarp_toe()
            if scarp_toe:
                altitude = altitude[altitude.index(scarp_toe[3]):]
                distance = [x for x in self.distances if isinstance(x, (int, float))]
                distance = distance[distance.index(scarp_toe[2]): distance.index(scarp_toe
                    [2]) + len(altitude)]
            else:
                return None

        beach_volume = np.trapz(altitude, distance)
        mean_elevation = beach_volume / (max(distance) - min(distance))

        return mean_elevation
```

```
120
121     def get_scarp_toe(self, window=150):
122         if self.altitude == [] or self.x_loc == [] or self.distances == []:
123             return None
124
125         altitude = [x for x in self.altitude if isinstance(x, (int, float))]
126         if altitude == []:
127             return None
128
129         altitude = np.array(self.altitude)
130         distances = np.array(self.distances)
131
132         if not np.all(np.diff(distances) > 0):
133             dis, unique_indices = np.unique(distances, return_index=True)
134             alt = altitude[unique_indices]
135             print("Warning: 'dis' is not strictly increasing")
136         else:
137             alt = altitude
138             dis = distances
139
140         if not np.all(np.diff(dis) > 0):
141             print("Warning: 'dis' is not strictly increasing")
142
143         spline = CubicSpline(dis, alt)
144         x = np.linspace(min(dis), max(dis), len(dis) * 10)
145         y = spline(x)
146         y_smooth = moving_average(y, window)
147
148         index_y_max = np.argmax(y_smooth)
149         index_wl_y = None
150         for i in range(1, len(y_smooth)):
151                 y1, y2 = y_smooth[i-1], y_smooth[i]
152                 if y1 * y2 < 0 or y1 == 0 or y2 == 0:
153                     index_wl_y = i
154                     break
155
156         if index_wl_y is None:
157             return None
158
159         if index_y_max > index_wl_y:
160             return None
161
162         dy_dx = np.gradient(y_smooth, x, edge_order=2)
163         dy2_dx2 = np.gradient(dy_dx, x, edge_order=2)
164         curvature = dy2_dx2 / (1 + dy_dx**2)**1.5
165         curvature = curvature[index_y_max:index_wl_y]
166
167         if len(curvature) == 0:
168             raise ValueError("Curvature array is empty, cannot compute scarp toe.")
169
170         max_curvature_index = np.argmax(curvature)
171         quarter_length = len(curvature) // 4
172         if max_curvature_index < quarter_length:
173             remaining_curvature = curvature[quarter_length:]
174             second_max_curvature_index = np.argmax(remaining_curvature) + quarter_length
175             max_curvature_index = second_max_curvature_index
176
177         corresponding_distance = x[index_y_max + max_curvature_index]
178         original_index = np.argmin(np.abs(np.array(distances) - corresponding_distance))
179         return self.x_loc[original_index], self.y_loc[original_index], self.distances[
                original_index], self.altitude[original_index]
180
181 class Profiles:
182     def __init__(self, profile_list: list = []):
183         self.profile_list = profile_list
184
185     def add_profile(self, profile):
186         self.profile_list.append(profile)
```

J

Appendix: Climate Profile and Climate Change Impacts

J.1. Climate profile

Sisal's climate is shaped by its location along the Gulf of Mexico (INEGI, n.d.-b). The region's weather patterns are influenced by a combination of tropical systems, atmospheric phenomena, and seasonal variability. Meteorological data from the UNAM weather station in Sisal, shown in Figure Figure J.1, highlights these trends over a five-year average.

Sisal experiences a tropical savanna climate (Aw) according to the Köppen classification system (Peel et al., 2007). This classification aligns with observed temperature patterns, where daily averages hover around 26°C, with peak temperatures reaching 35°C during the wet season. The warmer months, from May to September, coincide with increased precipitation and humidity. In contrast, the dry season, from November to May, is characterized by lower humidity and minimal rainfall, providing more favourable conditions for tourism (SMN, n.d.).

During winter months, Sisal is affected by cold fronts known as "El Norte," which bring cooler air masses from North America, resulting in a drop in temperatures and stronger winds. The elevated wind speeds displayed in the averaged data, particularly from November to March, reflect the impact of these events (see Figure).

Sisal is also vulnerable to tropical storms and hurricanes during the Atlantic hurricane season, spanning from June to November (NOAA, n.d.). As illustrated in Figure Figure J.2, numerous storms have passed within a 50-mile radius of Sisal, some reaching high intensity levels. The low-pressure systems visible in atmospheric data during these months further highlight the impact of these tropical systems on the region's weather patterns (CONAGUA, n.d.).

The El Niño-Southern Oscillation (ENSO) also affects Sisal's climate but follows an irregular cycle every 2 to 7 years. El Niño events typically bring drier conditions, causing water shortages and stress on local ecosystems (NOAA, n.d.). In contrast, La Niña events bring increased rainfall, which can lead to flooding and exacerbate the impact of tropical storms (SMN, n.d.).

Sisal's two primary seasons influence local biodiversity and human activities. During the wet season, from June to October, frequent thunderstorms and heavy rainfall replenish groundwater supplies and support the region's ecosystems (CONAGUA, n.d.). However, the wet season also increases the risk of mosquito-borne diseases such as dengue fever (SSA, n.d.). The dry season, from November to May, offers favourable weather for tourism but presents challenges like wildfire risks in surrounding areas (CONAFOR, n.d.).

J.2. Climate change impacts

Sisal, as a low-lying sandy barrier island along the Gulf of Mexico, is increasingly vulnerable to climate change impacts. The region faces significant threats from sea level rise, increased storm intensity and frequency, extreme weather events, salinization, habitat loss, increased erosion, coastal flooding, and saltwater intrusion (Weissenberger & Chouinard, 2015). These changes pose risks to both the

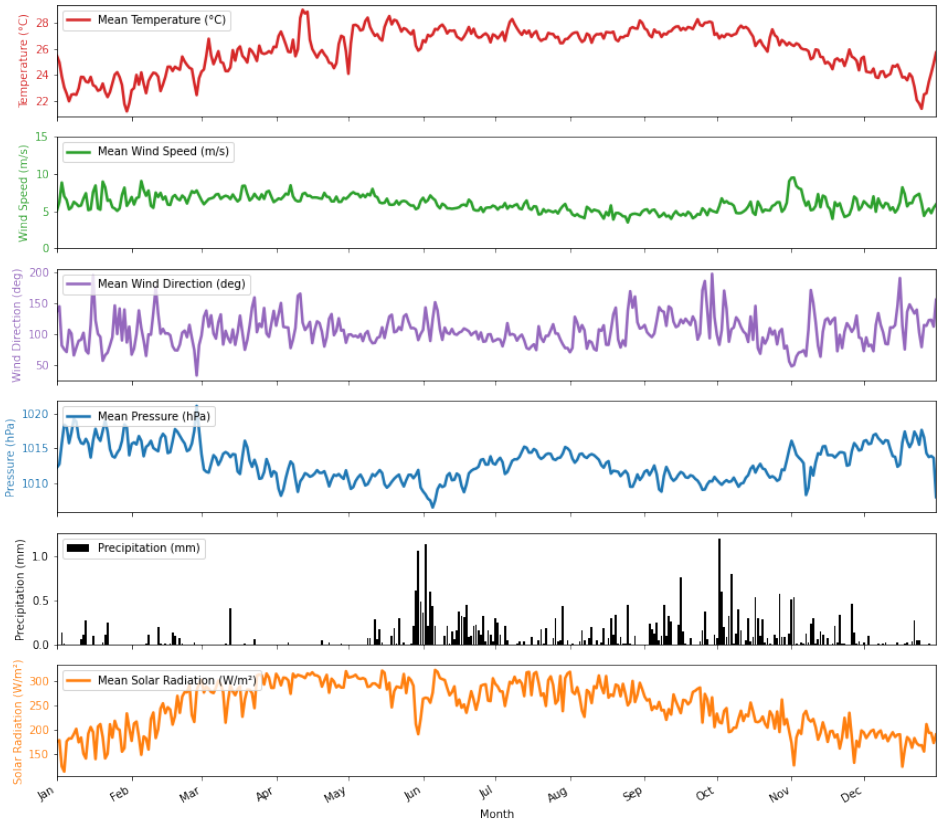

Figure J.1: Five-year average meteorological data for Sisal, showing seasonal trends.

ecological integrity of coastal ecosystems and the socio-economic stability of local communities. Below, we examine these impacts in detail.

J.2.1. Ecological impacts

Habitat alteration and loss

Rising sea levels lead to the inundation of coastal habitats, altering landscapes and causing loss of ecosystems such as wetlands, mangroves, and beaches. These changes disrupt habitats and reduce biodiversity. In Sisal, the loss of wetlands diminishes ecosystem services like carbon storage, water filtration, and habitat provision for numerous species (Fernández-Díaz et al., 2022; Kidwell et al., 2017).

Increased salinity and water stress

Frequent tidal flooding and storm surges increase salinity in coastal ecosystems, stressing plant and animal species not adapted to these conditions. Increased salinity disrupts mangrove and coastal habitats, impacting local flora and fauna (Desantis et al., 2007).

Loss of dune vegetation

Sea level rise also threatens Sisal's dune vegetation. Increased inundation and erosion lead to habitat loss, compromising the resilience of coastal ecosystems and increasing vulnerability to storm impacts (Martínez et al., 2008; Zhang et al., 2004).

Increased storm intensity and frequency

Climate change has increased the intensity and frequency of tropical cyclones and hurricanes. The Yucatán Peninsula faces heightened risk from these extreme weather events, which accelerate erosion and damage ecosystems (C. Appendini et al., 2019).

J.2.2. Socio-economic impacts

Impact on fisheries and tourism

Degraded coastal ecosystems reduce fish habitats, affecting livelihoods reliant on fishing (Fernández-Díaz et al., 2022). Loss of beaches and natural attractions due to erosion also impacts tourism (Weissenberger & Chouinard, 2015).

Community displacement

Rising sea levels and frequent storms heighten flood risk, potentially displacing communities. Loss of land and infrastructure has profound social impacts, including threats to homes, livelihoods, and cultural heritage (Hauer et al., 2020).

Health risks

Salinization of water resources due to SLR can contaminate drinking water, posing health risks. Flooding and habitat changes may also spread vector-borne diseases, while increased temperatures contribute to heat stress, especially among vulnerable populations (Weissenberger & Chouinard, 2015).

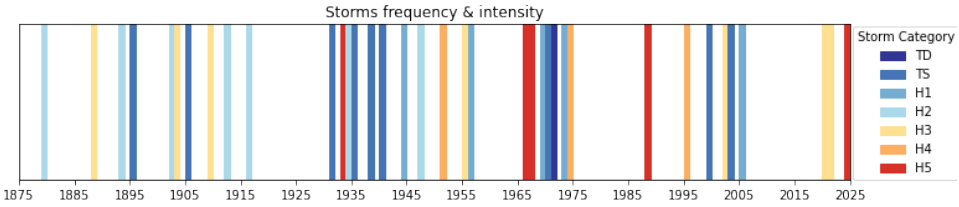

Figure J.2: Storm frequency and intensity in Sisal region.