Universidade de Aveiro
Ano 2023

MELANY MATEUS BERNAL

ANÁLISE DA LINHA COSTEIRA USANDO IMAGENS DE SATÉLITE NA ISLA FUERTE, COLÔMBIA

COASTLINE ANALYSIS USING SATELLITE IMAGES IN ISLA FUERTE, COLOMBIA

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Geológica, realizada sob a orientação científica do Doutor Jorge Medina, Professor Auxiliar do Departamento de Geociências da Universidade de Aveiro.

Dissertation presented to the Universidade de Aveiro to fulfill the requirements necessary to obtain the degree of Master in Geological Engineering, carried out under the scientific guidance of Doctor Jorge Medina, Assistant Professor of the Department of Geosciences of the Universidade de Aveiro.

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palavras-chave

Isla Fuerte, Sul do Caribe Colômbia, linha de costa, imagens de satélite, geologia marinha, erosão costeira.

resumo

Esta pesquisa centra-se na análise multi-temporal da linha costeira da Isla Fuerte, na Colômbia, usando imagens de satélite e técnicas de sensoriamento remoto, fornecendo um guia de referência prático. A análise envolveu a rasterização de imagens de satélite e a utilização de opções multibanda para permitir a identificação precisa da linha costeira.

Ao longo de 50 anos, a área total da ilha diminuiu consistentemente, totalizando 286,47 hectares. Essa diminuição coincidiu com a expansão de áreas urbanas e zonas agrícolas, acompanhadas por reduções substanciais em regiões florestais. Esses resultados destacam a perda contínua de terras da ilha e a necessidade urgente de proteger os manguezais, corais e áreas florestais em declínio. Essa conservação é vital para preservar a biodiversidade e reforçar a resiliência de Isla Fuerte às mudanças ambientais.

Além disso, este estudo enfatiza a importância da preservação de manguezais, corais e áreas de praia, que atuam como barreiras naturais de proteção para a ilha. As informações obtidas com esta pesquisa são inestimáveis para a tomada de decisões informadas e o planejamento sustentável em Isla Fuerte.

keywords

Isla Fuerte, Southern Caribbean Colombia, coastline, satellite images, marine geology, coastal erosion.

abstract

This research centers on a multi-temporal analysis of Isla Fuerte's coastline in Colombia using satellite imagery and remote sensing techniques, providing a practical reference guide. The analysis involved the rasterization of satellite images and the utilization of multi-band options to enable precise coastline identification.

Over 50 years, the island's total area has consistently decreased, ultimately amounting to 286.47 hectares. This decrease has coincided with the expansion of urban areas and agricultural zones, accompanied by substantial reductions in forested regions. These findings emphasize the island's enduring loss of landmass and the urgent need to protect diminishing mangroves, corals, and forested areas. Such conservation is vital for preserving biodiversity and bolstering Isla Fuerte's resilience to environmental changes.

Furthermore, this study underscores the importance of preserving mangroves, corals, and beach areas, which serve as natural protective barriers for the island. The insights derived from this research are invaluable for informed decision-making and sustainable planning in Isla Fuerte.

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1. INTRODUCTION

The advancement of technology, sciences, and communications has made life very different from just a couple of decades ago. However, not every part, not every community of the world has experienced the same level of progress (van Ham et al., 2021). Furthermore, technological advances have not always triggered positive effects on either societies nor their local environments, both at the local and global scales, as in fact, many of the interactions between Earth’s Spheres (geo-, atm-, hydro- and bio-sphere) are now out of balance due to anthropogenic activities with climate (Global Warming) and environmental change at the global scale being just two of the most prominent manifestations, i.e., a hallmark of the Anthropocene (National Geographic Society, 2019; Rodríguez et al., 2021).

Although global in nature, this crisis has local manifestations. One of the most common ones are the threats imposed on the very systems that support life at the local scale, many of which are associated with sea level rise, ocean acidification, and exacerbation of extreme meteorological events, among others (Oppenheimer et al., 2019). Several of these negative effects are particularly problematic for coastal communities, which is around 40% of the world's population who live less than 100 km from the coast (Oppenheimer et al., 2019; United Nations, 2023).

This is the case for a small island located in the Colombian Caribbean Sea called Isla Fuerte. The government's neglect has led the local inhabitants to make their own decisions and, though they may be acting in their best interest, the lack of formal and adequate education hinders the proper development of the community. On the contrary, sadly, may of the actions taken by local organizations or even individuals are conductive to various forms of environmental degradation in the form of fisheries over-exploitation, coral reef destruction, mangrove deforestation, improper interventions to “control” coastal erosion, over-extraction of groundwater (Barrios Díaz, 2020; Mateus Bernal, 2019).

For this reason, this thesis aims to provide a scientific approach to analyze spatiotemporal changes in some aspects of the natural environment of Isla Fuerte with emphasis on coastline advance-retreat. By documenting changes in vegetation patterns and the variations in the coastline over space and time, *i.e.*, understanding its changes over time using satellite images to provide information that would support not only a better understanding of the problems at hand but also come to grips to how these patterns of coastal advance-retreat take place and work towards identifying their causes and potential solutions.

The hypothesis is that Isla Fuerte has decreased its size primarily due to anthropogenic causes rather than normal natural causes of marine geology. The improper extraction of beach sands-gravel-rock for construction purposes, the deforestation of trees and mangroves, and the lack of care for the coral reefs during tourism activities are all anthropogenic factors that contribute to environmental degradation in Isla Fuerte, and that are particularly negative in terms of enhancing coastal erosion-retreat (Oppenheimer et al., 2019). However, due to limited knowledge of coastal geological dynamics by locals, the vulnerability of the population in terms of the interactions between the sea and the coastal zone could be increasing (Rangel-Buitrago et al., 2015).

This work seeks to be a methodological guide that serves as a reference for future works in the management of satellite images. The objective is to create a step-by-step guide that allows the handling of these images in a simple and didactic way accessible even to the education process at the island school students at Isla Fuerte's Institución Educativa (IFIE). For the development of this thesis, Isla Fuerte will be used as a case study, for the reasons previously described. Still, it is necessary to understand that this step-by-step guide is designed in a way that allow it to be applied at any desired location, adjusting the basic parameters for each case.

To carry out the analysis of coastal erosion on Isla Fuerte, a methodology that takes advantage of remote sensing technology will be used. In particular, satellite images provided by Landsat missions will be used. These data sources offer a valuable perspective in time and space, allowing the observation and monitoring of changes in the coastline over time. The combination of high spatial resolution images and multi-year monitoring capabilities facilitates the study of coastal erosion comprehensively and accurately.

In the methodology of this study, satellite images that meet a number of key criteria are used. These images must be easily accessible, offer the best available resolution, span several years to allow multi-temporal analysis, completely cover the study area, and be free of clouds. These parameters ensure that the images are suitable for the analysis of the coastline of Isla Fuerte.

The analysis is divided into two specific areas. The first covers a larger space and extends from the island to the mouth of the Sinú River, which is located on the continent at a distance of 25 Km and will serve as a reference for analysis regarding ocean dynamics. The second area is smaller and is concentrated exclusively on Isla Fuerte, this one is used as the main reference for the study of changes in the coastline, allowing a more detailed focus on the island itself. Once the appropriate satellite images have been selected, they are digitized and rasters are generated for each of the available years. This step is essential to prepare the data and facilitate its subsequent analysis.

Finally, the comparative analysis of data from different years is instrumental in identifying and understanding changes in land use and coastline over time. This stage is vital in comprehending Isla Fuerte's coastal dynamics and evaluating its evolution in response to diverse environmental and geographical factors. As the analysis revealed a noteworthy reduction in the total area of Isla Fuerte over the 50-year period. Consistently, urban expansion and agricultural land use are observed, indicating changes in economic activities and land management. Contrarily, there was a decline in forested areas, prompting concerns for the preservation of these vital ecosystems. Notably, the mangrove areas bordering the island displayed fluctuating patterns.

This work invites reflection on urban planning and land use in the context of urban growth. Managing urban development in a sustainable and balanced manner becomes essential to avoid negative impacts on natural ecosystems and promote harmonious coexistence between urban growth and island conservation.

The main objective of this study is to comprehensively evaluate the spatio-temporal changes on the coast of Isla Fuerte, using satellite images and remote sensing techniques. To achieve this, a defined series of specific goals is proposed. First of all, it seeks to rasterize and analyze the satellite images obtained from Isla Fuerte, which will allow obtaining a detailed understanding of the coastal transformation in the area. In addition, the relationship between changes in land use and modifications in the coastline will be delved into, with the purpose of identifying the underlying factors of these transformations. Finally, the aim is to create detailed maps that show the evolution of the Isla Fuerte coast over time, providing a valuable visual representation of this constantly changing coastal environment. Through these efforts, this study seeks to shed light on the complex interaction between human activities and natural processes that shape the island's coastal landscape.

2. STUDY AREA

In the middle of the American continent, within the paradisiacal Caribbean Sea, lies a small island known as “Isla Fuerte”. This island has become a popular tourist destination in recent years, thanks to its abundant biodiversity, rich flora and fauna, and numerous diving opportunities in its surroundings (Bernal Guevara, 2017; Casas Figueroa, 2011; Zanocchi, 2018).

The literal translation into English of "Isla Fuerte" would be "Fort Island", as it, perhaps, functioned as a small bastion or navigation guide for ships at sea during the times of conquest, colonization, and piracy around the region. Numerous recounts in both the oral vernacular and Spanish allude to the names of pirates that supposedly controlled the area. A small karstic cave is named after Morgan. The Island also has one of the formal navigation marks (Faro Isla Fuerte or Isla Fuerte Light House). Today, Isla Fuente still operates as a key littoral island in the trade of illegal drugs and arms smuggling as the country has not been successful in resolving these major sociopolitical and socioeconomic issues (Anderson, 1984; Bernal et al., 2021).

2.1 Location

Isla Fuerte is located in the Southern Sub Basin of the Caribbean Sea (Díaz et al., 1996) within Colombian territory, specifically near the Morrosquillo Gulf, as illustrated in Figure 1. It is part of a group of islands and shallows slightly aligned in a direction of N30E, that extends for almost 200 Km (Oppenheimer et al., 2019). Sits approximately at 11 Km from its closest point on the mainland, specifically the small town of "Paso Nuevo," which serves as a vital link between the island's inhabitants and the mainland. This rudimentary port is essential for the preparation and loading of boats with the necessary supplies to supply the island and also serves as the main embarking point for tourists and residents of the island.

In 1996, the island's area was recorded as 3,25 Km^2 (Díaz et al., 1996), whereas a recent study in 2022 reported a minor area of 2,896 Km^2 (Barreto Tejada, 2022; Restrepo Moreno, 2023). Although the reason for this difference is not specified, it could have several hypotheses: that there is indeed a reduction in the area of the island or that the measurements differ due to data quality in terms of the methodology and/or calibration of the used equipment.

Figure 1 - Location Isla Fuerte

Located in the southern part of the Caribbean Sea, to the southwest of the Gulf of Morrosquillo. The nearest population on the mainland is Paso Nuevo, but falls under the jurisdiction of Cartagena

The main port of the island, known as "Puerto Limón" (Lemmon Port), is located at coordinates 9°22'53"N and 76°10'46"W, see Figure 2. This port plays a central role in the life of Isla Fuerte, as it is the departure and arrival point for boats that transport both local residents and tourists visiting the island. In addition, Puerto Limón is the place where the island is supplied with products and merchandise that come from the mainland.

The only way to get to Isla Fuerte is by boat since there is no airport or roads that connect it to the mainland. Residents and tourists alike rely on these boat trips, which typically last around 45 minutes from Paso Nuevo, although the duration can vary depending on weather conditions and vessel´s moor power.

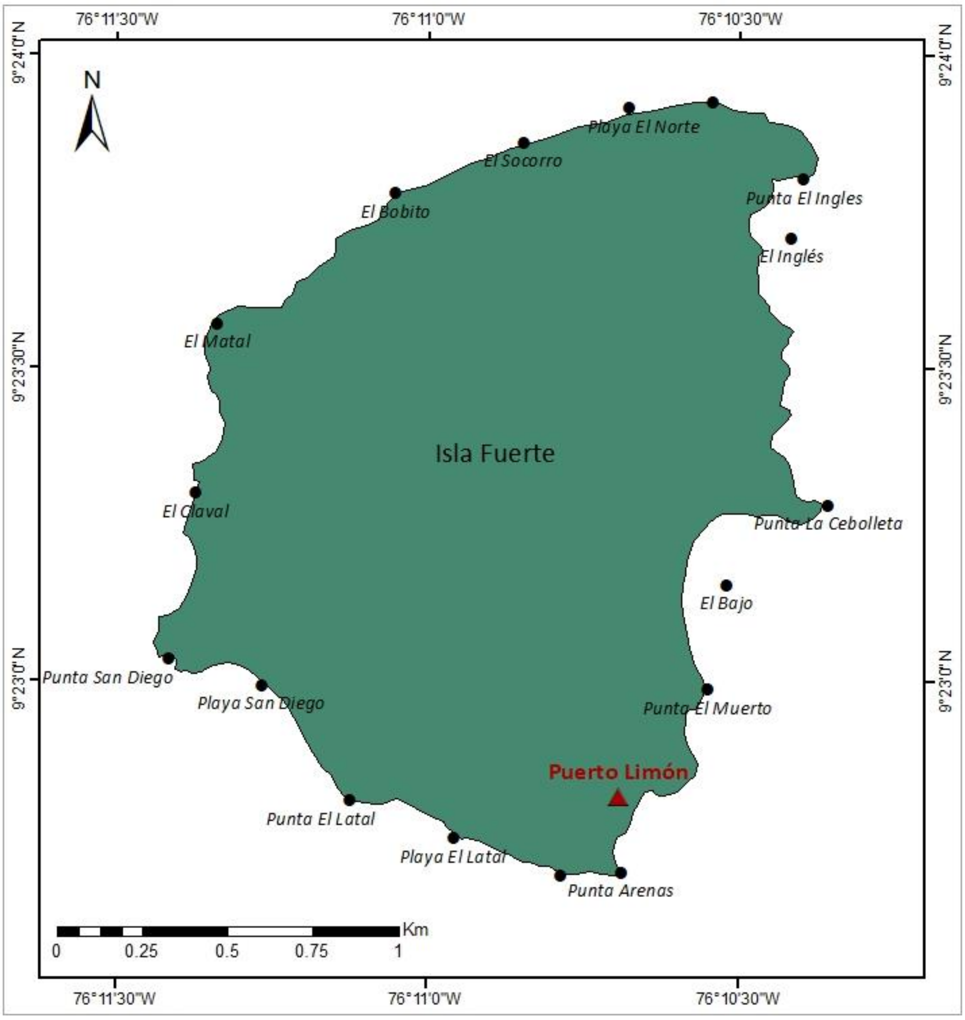

Figure 2 - Principal Beaches in Isla Fuerte

Prominent reference points bordering the island and its main beaches, which serve as popular tourist destinations

2.2 Administration

The political division of Colombia consists of 32 departments, each with its own capital responsible for administration. This island belongs to the department of Bolivar, with its capital being the city of Cartagena (Distrito Turístico de Cartagena), which further divides the territory into smaller municipalities for individual management (‘Constitución Política De Colombia’, 1991).

Isla Fuerte is so small that it doesn't even hold the status of a municipality within the department of Bolivar. Instead, it is classified as a "corregimiento" directly under the jurisdiction of the city of Cartagena, which is located more than 100 km away in a straight line, a situation that adds complexity to the administrative processes, making access to demonstrative processes more time-consuming and costly, consequently causing delays in the island's development This means that it represents a populated center within a relatively small rural region, relying on Cartagena for all political, administrative, and economic matters, as stipulated in the political constitution of Colombia (‘Constitución Política De Colombia’, 1991).

In October 2022, a meeting was held with the island community to understand the residents' perception of the Territorial Planning Plan (POT, for its acronym in Spanish), which serves as a knowledge base for municipal administration, since the community itself requires specific organization for the development of their lives in terms of education, mobility, sanitation, and more (*Isla Fuerte va Pa’ Lante Con El POT*, n.d.).

Colombia features a specialized administrative entity known as “Parques Nacionales Naturales de Colombia” (Natural National Parks of Colombia). Their primary mission is to safeguard the country's rich biological and cultural diversity while promoting sustainable development. Isla Fuerte is also part of one of these protected areas, known as the “Parque Nacional Natural Los Corales del Rosario y de San Bernardo” (*Parque Nacional Natural Corales Del Rosario y de San Bernardo*, n.d.).

This park has an area of almost 200 km^2 and includes several ecologically significant islands. It serves as a refuge and breeding ground for marine biodiversity, provides natural coastal erosion protection, supports commercially valuable fish and invertebrate species, boasts stunning landscapes that facilitate ecotourism, promotes the socio-cultural development of local communities, encourages environmental education and awareness, and offers opportunities for marine science research.

Additionally, within this protected area, there's a convergence of uses and expressions from Afro-descendant communities, who view the area as a platform for their socio-cultural development (*Parque Nacional Natural Corales Del Rosario y de San Bernardo*, n.d.).

2.3 Population

The population of the island can be classified into two groups: natives and tourists. Native residents of the island are primarily Afro-descendants belonging to black communities as well as individuals of indigenous descent (chilapos). As for tourists, they are occasional visitors who come from various regions of Colombia, with a smaller proportion coming from other countries (DANE, 2018), but there are also tourists from inland Colombia that own property (land, housing and hotel infrastructure, local commerce, etc.), although most of the properties (cabañas) are located towards the periphery of the Island as waterfront property (Luque Forero, 2011).

During the visit to Isla Fuerte, it was possible to evidence that many of those owners implement their own measures to prevent coastal erosion and potentl damage to their properties. In doing so, they chaotically intervene with the natural dynamics between sea and land, by establishing heavy infrastructure in the form of concrete and rock barriers (*espolones*, *enrocados*, etc) (Bernal R., 2012; Forero-Garzón & Gomez-Delgado, 2020).

The country's official censuses do not record the number of people residing on the island, as it is considered part of a group of islands that belong to the city of Cartagena. The information collected in Cartagena's records is not entirely clear because living conditions vary significantly between the mainland and the island, making it unadvisable to use them as a reference.

The only reliable censuses that specifically address the island itself date back to 1971 when the population was recorded at 700 residents. According to the official national census in 2005, the island's population had grown to 1018 inhabitants. Currently, the population is estimated to be around 2000, taking into consideration that more than 500 individuals are not residents but rather tourists, most of whom come from different regions of Colombia and some from abroad (Anderson, 1971; Barrios Díaz, 2020; Bernal et al., 2021; Luque Forero, 2011).

2.4 Weather

Unlike areas at higher latitudes, the location of the island near the equator does not provide for the occurrence of seasons like summer, fall, winter, and spring. The temperature remains nearly constant in its maximum and minimum values throughout the year with figures between about 24ºC and 30ºC (Díaz et al., 1996) . The hours of sunshine in the tropics vary very little, with 12 hours of sunshine and 12 hours of darkness being regular. Instead, the most significant variation in terms of climate-weather patterns is that of periods characterized by varying levels of rainfall, which can be categorized as follows (Beier et al., 2017; Bernal et al., 2010; Díaz et al., 1996):

- December-January-February (DJF): This period constitutes the main dry season, with low precipitation. The trade winds and the Caribbean Jet predominantly influence the local weather-climate system. Winds are prevalent throughout the season.
- March-April-May (MAM): During this season, lower levels of humidity are experienced.
- June-July-August (JJA): Known as the dry season with reduced intensity, it is sometimes called "San Juan Summer" in reference to a brief period of drier weather.
- September-October-November (SON): This is the main rainy season in the region.

These “seasons” simplify the understanding of the meteorological characteristics that influence the region. It is essential to clarify that while the months may align, these four seasons differ significantly from those commonly known in higher latitudes.

One of the factors that contributes to variations in the ocean-atmosphere relationship is the island's close proximity to the equator, which is known as the Intertropical Convergence Zone (ITCZ). In this region, the trade winds from both the Northern and Southern hemispheres converge. This zone is not stationary, just as the trade winds change in characteristics such as temperature and speed throughout the year, so does the position of the ITCZ relative to Colombia. During the DJF months, it is located between 5°S and 10°S. In MAM, its position moves northward between 5°S and 1°N. In JJA, it continues to advance northward between latitudes 8°N and 10°N. Finally, during SON, it retreats back to the equator (Guzmán et al., 2014).

The temperature on Isla Fuerte remains around 27°C throughout the year due to its equatorial location. Experiences minimal variations, which largely depend on the Intertropical Convergence Zone variations (Díaz et al., 1996).

Ocean Winds

Isla Fuerte experiences a variety of ocean winds that play a significant role in its climate and maritime conditions. These winds include the northeast trade winds, westerly winds during hurricane season, tropical breezes, and the winds associated with the ITCZ. Understanding these wind patterns is crucial for studying geological aspects and coastal erosion on the island (Guzmán et al., 2014; Ortega Arango, 2010).

Winds related to the ITCZ in the northern hemisphere, blow from the northeast to the southwest, generated by the flow of air around the North Atlantic Ocean anticyclone system. Simultaneously, winds from the southern hemisphere come from the southeast to the northwest, originating from the South Atlantic and Pacific Oceans. This convergence of winds with differing directions creates an area of strong winds, leading to tides, increased cloudiness, and higher rainfall in the region (Guzmán et al., 2014; Ortega Arango, 2010).

In the Colombian Caribbean basin, the prevailing winds are generally from the northeast and east. During the months of March, April, and May (MAM), the southern region experiences northeasterly winds. In the periods of June, July, and August (JJA), as well as September, October, and November (SON), the wind speed increases during El Niño events and decreases during La Niña, but the overall wind direction remains eastward across the basin. In SON, northeasterly and southeasterly winds are also observed, which are not typical during normal years or El Niño events (Mateus Bernal, 2019; Ortega Arango, 2010; Ruiz-Ochoa & Bernal Franco, 2009).

For the Colombian Caribbean Sea, two other predominant wind systems influence local climate-weather systems (Bernal et al., 2010; Ochoa et al., 2008; Ruiz-Ochoa & Bernal Franco, 2009):

- The Caribbean Tropical Surface Jet (ChTSC), also known as the Low-Level Jet of the Intra-American Seas, the San Andreas Tropical Surface Jet, or the Low-Level Jet in the Western Caribbean. It is a product of the trade winds from the northeast and prevails with speeds ranging from 5 to 7.7 m/s. Its peak activity occurs during the months of JJA and SON. In DJF and MAM, these trade wind speeds decrease. It is located at latitude 15°N 75°W, with an east-to-west direction.
- The Chorro Chocó or Chocó Low Level Jet, consists of a flow of humid winds that move from west to east over the Chocó region and into Colombia. Its impact is most pronounced during

the months when trade winds decrease in intensity, which typically happens during the JJA and SON seasons.

Ocean Currents

Ocean currents are the result of temperature and density differences within bodies of water, influenced by winds and the Coriolis force. Isla Fuerte is directly impacted by two main ocean currents, each with its own distinct characteristics (Ortega Arango, 2010):

- Colombian Caribbean Current (CCC): Flowing in a northeast-to-southwest direction, the CCC is strongly influenced by the trade winds.
- Panama Counter-Current (PCC): runs counter to the northward trade winds, flowing westward.

In the height of the dry season, during DJF when the trade winds gain strength, the CCC becomes the dominant ocean current. Consequently, it's when the CCC weakens that the primary wet season, SON, sets in. During this period, the Panama-Colombia cyclonic gyre takes control, reinforcing the PCC (Ortega Arango, 2010; Torres et al., 2022).

Rainfall

The region experiences an average annual precipitation of 1366 mm and according to data from a monitoring situated in San Bernardo del Viento, the nearest Municipality on the mainland to Isla Fuerte (Ortega Arango, 2010). Despite the potential for substantial rainfall in the region, it is essential to emphasize that evaporation rates in the Caribbean Sea typically surpass the volume of rainfall received (Beier et al., 2017). These climatic variations are closely linked to the months when the trade winds are at their strongest. During this period, drier conditions prevail. Conversely, when the intensity of the trade winds diminishes, aligning with the time when the climate regime is influenced by the Panama Jet, there is an observable increase in precipitation during those months (Beier et al., 2017).

One of the most notable aspects concerning rainfall on the island is its crucial role in sustaining the community's freshwater supply. The residents of Isla Fuerte heavily rely on rainwater collection or extraction from underground aquifers via pits, as they represent their two sole sources of freshwater. No creeks exist on the island. Historically, a small lake existed in the heart of the island, serving as an additional water source. However, due to a series of improper management practices of this resource, the lake has reduced its capacity (eutrophication and over-sedimentation) and the water is also polluted, thereby eliminating it as a viable option for the island's water supply.

The loss of this once-accessible water source has significantly impacted the island's inhabitants, compelling them to adopt rainwater harvesting as the primary means of meeting their freshwater needs. This dependence on rainwater underscores the importance of studying the island's precipitation patterns, as any variations or anomalies in rainfall can directly affect the community's access to clean, potable water. In essence, the island's resilience and sustainability are intrinsically tied to its ability to harness and manage this precious resource, making it a critical area of concern for the island's environmental and social well-being.

Tides

Tides are regular fluctuations in sea level that have a significant impact on the daily life of the local community. The magnitude of tides also controls land interactions and the types of ecosystems those littoral zones can support. These tides can be categorized into two main types: astronomical and meteorological (Lizano R., 2006; Ortega Arango, 2010).

- Astronomical Tides: are a consequence of the gravitational forces exerted by the Moon and the Sun on Earth. They follow a predictable pattern, featuring two high and two low tide cycles within a lunar day. The island's residents rely on these dependable tidal rhythms for essential activities like fishing and boating, ingraining them deeply into the island's way of life.
- Meteorological Tides: In contrast, meteorological tides arise from local climatic factors such as storms and winds. These tides can be less predictable and introduce variability in sea levels, impacting the island's coastal areas and activities. Understanding the intricate interplay between these two tide types is essential for Isla Fuerte's community as they navigate changing coastal conditions.

It is noteworthy that Isla Fuerte experiences a relatively high range of tidal variations. In the open sea, the levels can change from 30 cm to up to 1.5 m. This diversity of tides highlights the dynamic nature of sea level fluctuations in this part of the Colombian Caribbean. These tides are a natural phenomenon integral to many aspects of the island's daily life, influencing everything from livelihoods to safety (Ortega Arango, 2010).

Waves

Understanding the characteristics of waves is essential to make informed decisions in coastal management and Comprehensive Coastal Zone Management (ICZM) (Mesa García, 2009; Ortega et al., 2013; Quintero Medina, 2020; Thomas et al., 2011). In the Colombian Caribbean, the wave regime experiences variations influenced by various factors, such as the season of the year (wet vs. dry), wind patterns, and land and submarine topography (Ortega Arango, 2010). The wave pattern closely follows the seasons of the year and natural phenomena, such as hurricanes (Quintero Medina, 2020).

Direct monitoring of waves in Colombia faces challenges due to the small number of buoys available. The National Oceanic and Atmospheric Administration (NOAA), an entity of the government of the United States of America, has a buoy in Jamaica, while the Colombian Maritime Authority (DIMAR) has three buoys in Barranquilla, Puerto Bolívar, and Providencia, which are insufficient to obtain a complete view of the data in the region. As a result, mathematical simulations have been used to better understand wave behavior (*DIMAR*, n.d.; *NOAA*, n.d.; Ortega Arango, 2010).

To complement the lack of in situ data, global databases on visual waves are used. Colombia benefits from its proximity to the Panama Canal since this database is fed with information from merchant ships and is developed by the World Meteorological Organization (WMO) (Ortega et al., 2010).

In terms of seasonal variation, wave heights present a defined pattern. During the months of December, January, and February, significant heights are recorded due to strong winds, while they decrease in March, April, and May. Then, they intensify again in June, July, and August, with October being one of the months with the lowest waves (Lizano R., 2006). This bimodal behavior of the waves in the Colombian Caribbean is closely related to the northeast trade winds, which create two seasons of higher waves, coinciding with the seasons of less rain or low rainfall. Together, this information is vital to effectively understand and manage the coast and coastal ecosystems of this beautiful Colombian Caribbean region.

In the Colombian Caribbean Sea, specifically between 13° and 15° north latitude and the 75° and 80° west longitude meridians, the highest waves in the entire Colombian Caribbean region are found. Regarding the height of the waves in the region, it can reach up to 1.5 meters (Agudelo Restrepo et al., 2005; Quintero Medina, 2020)

The distribution of waves in Isla Fuerte exerts a major control on coastal erosion and marks the position of the coastline. The strongest waves are experienced in the north, the leeward side of the island facing towards the open sea, while the smallest and less powerful ones prevail in the south and SE portion of the island. In these locations, the coastal zone is primarily composed of sands (ranging from fine to coarse), so the size of the island strongly depends on wind and current patterns, as well as sediment availability (Bernal Franco et al., 2005; Torres-Bejarano et al., 2022)

2.5 Culture

Isla Fuerte is a true paradise, where human wealth creates unique spaces for exchange and coexistence with nature. The deep Afro-descendant roots are intertwined with the native heritage, forging a rich and unique tradition. In this remote corner, a culture full of vitality and hospitality comes to life. The highlight of Isla Fuerte is, without a doubt, the genuine warmth of its people, who make you feel at home.

The different traditions and customs that flourish in Isla Fuerte join the welcoming spirit of its community, creating a unique atmosphere. Together with the natural beauty of the island, these characteristics make this place a true paradise. The fusion of culture and nature on Isla Fuerte is as amazing as the diversity of its traditions, and together they weave a special charm that makes this island a truly exceptional destination.

Films

An event of great relevance in Isla Fuerte is the International Film Festival on the Island, known as "FECISLA", which serves as a space for meetings and cultural exchange. This festival not only celebrates the seventh art, but also promotes and highlights Afro-descendant culture, environmental awareness, and artistic expression in all its forms (*Cine En La Isla Film Festival*, 2023).

> *"…wonderful encounter full of unique moments fueled by the force of cinema, the word, sharing, traveling and recognizing, the drum, brotherhood, the sea and the heat of the collective experience…" (*Cine En La Isla Film Festival*, 2023)*

The most recent edition of this festival took place in January 2023, marking its ninth installment and calling on film lovers and those passionate about culture to participate in a unique experience. For six days, from January 17 to 22, Isla Fuerte becomes the epicenter of cinema, art, and culture, offering its visitors the opportunity to immerse themselves in an enriching and enriching celebration of life and cultural diversity (*Cine En La Isla Film Festival*, 2023).

The richness of the festival is reflected in its diversity of offerings. In addition to outdoor screenings that bring together the entire community, the festival includes guided tours of the island to promote sustainable tourism. There are also workshops on offer such as percussion for children and aerial acrobatics.

This wide range of activities enriches the festival experience and also underlines its commitment to culture, the environment, and community development. The festival is not limited to the big screen but becomes an opportunity for attendees to actively participate and connect with the beauty and diversity of Isla Fuerte.

Surf

One of the hidden attractions of Isla Fuerte lies in the surfing opportunities, although it is not widely recognized worldwide. This lack of renown brings a touch of exclusivity to the sport of surfing. With constant waves throughout the year, Isla Fuerte offers a unique experience that is appreciated by local residents and the fortunate visitors who discover it (Giraldo Cano et al., 2015; Zanocchi, 2018).

Thanks to its privileged location, Isla Fuerte has the potential to become a significant gathering point for surfers from around the world. Due to its geographical position in the Caribbean Sea, the island enjoys consistent wave conditions throughout the year. However, as we mentioned earlier, the most impressive waves can be experienced during the months of December to February and again mid-year (Ortega Arango, 2010).

The northern coast of the island is the one that offers the best waves for surfing, as it receives the full force of the waves originating from the center of the Caribbean Sea. The combination of favorable geography and seasonal variations in wave size creates a highly attractive landscape for residents and visitors interested in the sport of surfing (Zanocchi, 2018).

Diving

Isla Fuerte offers multiple diving spots that are attractive to both expert and beginner divers. The surroundings of the island are home to underwater riches that invite exploration in its crystal-clear waters. Various diving agencies and schools operate on the island that provide the opportunity to immerse in this exciting sport, either professionally or recreationally. Qualified instructors are available to guide divers and ensure safe and enriching experiences (Isla Fuerte Colombia Ecolodge & Diving Center, n.d.-a).

The beauty of the coral reefs, as well as the impressive diversity of marine flora and fauna, make Isla Fuerte one of the most outstanding diving destinations in the region. The vibrant colors of the corals and the opportunity to swim alongside a wide variety of aquatic species make this activity an unforgettable experience for those who visit the island (*Isla Fuerte Colombia Ecolodge & Diving Center*, n.d.-b; Zanocchi, 2018).

The island offers numerous locations suitable for diving up to 30 meters in depth, catering to both scuba diving and free diving enthusiasts. The island's unique coral platform grants access to relatively undiscovered underwater ecosystems, providing opportunities for exploration and research in less-explored marine environments (Isla Fuerte Colombia Ecolodge & Diving Center, n.d.-a).

2.6 Economy

The native population of the island has subsisted thanks to the relatively high offer of natural goods and services. The richness in fauna and flora has allowed the islanders to enjoy native cuisine, rich in fruits, vegetables, legumes, and, above all, seafood (Barreto G. et al., 1999). Natural wealth also supports other economic activities such as tourism. However, throughout the history of the island's development, significant changes have occurred that have also impacted the economic dynamics of the community and their very livelihoods, as the interactions with the natural surroundings have caused a sustained depletion of ecosystem services (Bernal Restrepo & Bernal Guevara, 2019; Luque Forero, 2011).

Fishing

Fishing has been the main source of livelihood for the island's inhabitants and the basis of the local economy. In times past, barter was the natural form of economy, where the exchange of goods between fishermen and farmers constituted everything necessary for the community (Bernal Restrepo & Bernal Guevara, 2019). This simple form of exchange ensured the sustenance of everyone that no one was in need and promoted collaboration and mutual help among the community (Bernal Guevara, 2017).

However, the current reality is very different. The arrival of foreign people, both from other parts of Colombia and from various parts of the world, has led the islanders to adapt to the use of money as a means of exchanging goods and services (Bernal Guevara, 2017; Castaño-Camacho & Moncaleano-Archila, 2007). With the growth of the total population on the island, which includes both inhabitants and visitors, the demand for local sources of food (seafood, fruits, and vegetables) has seen a notable increase.

In the case of sea food, a raise in demand has led local fishermen to move farther from the island and increasingly enter deeper waters that allow them to satisfy the dietary needs of the population but that make fishing arts more complex, risky, and costly (Bernal Guevara, 2017; Castaño-Camacho & Moncaleano-Archila, 2007; Ortega Arango, 2010).

This change in fishing dynamics has forced fishermen to modify their methods and equipment, as well as invest even more hours of work. The transition from the use of rowing boats to the use of motorized boats has meant a significant, although necessary, transformation in their work, resulting in even higher costs to obtain food since the use of engines and the acquisition of fuel have added new elements to their operating expenses(Bernal Guevara, 2017).

The fact that the fuel necessary to operate these motorized boats must be brought from the mainland has added another cost to the economy of local fishermen's families. This resource import logistics is essential to keep the vessels operating and ensure sustenance, a price that is reflected when the products are sold in the local markets, particularly at tourism peak season, making it in most cases virtually unaffordable for locals (Bernal Guevara, 2017).

Tourism

Tourism in Isla Fuerte has experienced a notable increase in recent years, reaching almost exponential levels (Luque Forero, 2011). During the holiday season, the number of visitors can double the native population in normal times. However, this growing influx of tourists has posed significant challenges that need adequate attention (Bernal Guevara, 2017).

One of the crucial aspects is to provide a pleasant environment for tourists, which not only ensures their satisfaction but can also attract more visitors in the future. The ideal image of a Caribbean island is often limited to the phrase "beach, breeze, sea," white sand beaches, and a warm gentle climate (Bernal Guevara, 2017; Luque Forero, 2011). Unfortunately, the search for this paradise has led to practices that are harmful to the island's natural environment, such as the felling of trees and mangroves, and the overexploitation of natural sources of drinking water.

In addition, the local economy has been notably affected by the growing dependence on tourism. Agriculture and food production, which were once fundamental to the community, have been displaced by tourist attractions. This has resulted in a significant decrease in local production and the need to import most food products. As a consequence, many residents have been left economically excluded, unable to compete with the income of foreign tourists (Barreto G. et al., 1999; Bernal Guevara, 2017; Luque Forero, 2011). Although tourism can be a lucrative business in the short term, its long-term impact on the island has not been adequately sized.

The land use that was previously dedicated to agriculture has now become mainly a tourist attraction. This dependence on imports and declining agricultural production poses significant economic challenges and highlights the importance of balancing tourism growth with long-term economic sustainability on the island.

Even though the Island poses great potential for the establishment of forms of tourism based on nature (e.g., eco-tourism, geo-tourism, etc.) around small patches of dry forest, mangrove stands, beaches of diverse kinds, proximal coral reefs in a stage of recovering, etc,, the predominant form of tourism is one related to beach partying, which negatively impacts the Island in many ways realms including the disruption of normal life activities due to excessive sound amplification, alcohol and drug abuse, prostitution, trash production, high demands on the consumption of fresh water, electricity, and other resources, among others (Luque Forero, 2011).

2.7 Geology

The current morphology and composition of the island is the result of a complex interaction between factors of purely geological origin and biological elements, which have given Isla Fuerte its distinctive features of a coral island (Díaz et al., 1996).

Origin

The continental shelf on which Isla Fuerte is located presents notable geological characteristics that combine the folding of Oligocene to Miocene sedimentary sequences of the Sinú San Jacinto Fold Belt -SSJFB and mud diapirism within the same sequence. Both have given rise to positive relief in this region of otherwise subdued topography, i.e., the Caribbean Plains of Colombia. These diapiric features comprise a variety of features, including bulges, elongated hills, domes, folds, and diapiric plumes, as well as the presence of mud volcanoes and gas outpourings in the area(Aristizábal et al., 2009; Briceno & Vernette, 1992).

The diapirs are bodies of previously stratified mud layers that are characterized by having a lower density than the overlying and surrounding medium, which allows them to rise through the overlying rock layers (Trejos-Tamayo et al., 2020). Observations and analysis of these structures have revealed that they are mainly composed of clays and mud. The composition of these materials and their grain size properties are key factors that contribute to their ability to ascend through the surrounding rock layers of sandstone and conglomerate (Anderson, 1971; Aristizábal et al., 2009; Briceno & Vernette, 1992; Díaz et al., 1996).

These diapirs are formed not only thanks to the presence of materials that allow their rise, but also due to active tectonics deforms the rock layers and promotes pressure increases that can trigger these movements. In particular, this region has a conjugate system of strike-slip and thrust faults that plays a crucial role in the formation (Aristizábal et al., 2009).

The phenomenon of the rise of these diapir masses is observed significantly along the northern coast of Colombia, particularly south of latitude 10°30'N, where Isla Fuerte is located. The strike-slip faults in this area of the Caribbean show a preferential northeast-to-southwest direction and are characterized by a sequence of successive sinistral and dextral movements. These fault movements delimit blocks with lateral displacements in apparent NW and SE directions. As a result of this complex tectonic interaction, diapirs emerge from the underlying layers and manifest as elevations on the continental shelf, with significant impacts on the geology and topography of the region both on land and on the sea floor (Aristizábal et al., 2009).

More recently, in the Quaternary period, the region underwent substantial sea-level fluctuations driven by cycles of glaciation and deglaciation (Bernal et al., 2010). During phases when the area was entirely submerged marine life colonized this environment, capitalizing on the favorable water conditions, including temperature and chemical composition. These conditions allowed various coral species to thrive and accumulate in the region, contributing to the formation of a diverse coral reef ecosystem (Anderson, 1971; Díaz et al., 1996).

The age of Isla Fuerte has been dated to the Holocene, with analyzed limestones estimated to be between 5000 and 10000 years old. These estimates agree with the ages of other neighboring islands(Anderson, 1971; Díaz et al., 1996).

These corals played a pivotal role in shaping the current reef complexes in the portion of the Caribbean. When sea levels declined, whether due to tectonic shifts or shifts in climate, or a combination of both, corals lost their optimal conditions for reproduction and eventually perished. However, their enduring limestone or calcium carbonate structures remain, creating a thick calcareous layer at least 25 meters thick (Bernal R., 2012; Casas Figueroa, 2011; Díaz et al., 1996).

Reef complex

Isla Fuerte is a reef complex that, perhaps due to tectonic tilt, slopes slightly in a north-south direction. It is mainly composed of a calcareous platform covering a total area of 13 km^2, although only a small part, approximately 3.5 km^2, emerges from the water. The greatest depth of the complex is 30 m, and its maximum elevation above sea level is 12 m (Anderson, 1971; Díaz et al., 1996).

Various coral complexes are found on the island, comprising a total of 29 species of coral. It should be noted that Porites porites, Siderastrea siderea, Agaricia tenuifolia, Montastraea faveolata and Colpophyllia natans stand out as the dominant species within these complexes. Despite their environmental importance as a tourist attraction, the coral reefs near the island face a problem of degradation due to inadequate snorkeling practices and the effects of nearby navigation. Surprisingly, its deterioration has reached a worrying 51.1%, highlighting the urgent need for conservation efforts (Casas Figueroa, 2011).

Sediments

The sediments on Isla Fuerte, which include both terrigenous and calcareous, play a key role in its geology. The terrigenous sediments come mainly from the Sinú River sediment plume; whose mouth is located 25 Km east of the island. These sediments and the dynamics of the river have a significant impact on the formation and geological characteristics of the island.

The Sinú River rises in the "Nudo del Paramillo" at an altitude of 3400 m.a.s.l. and extends for 350 Km in total, see Figure 3 - Sinú River. As it flows into the Caribbean Sea, it is divided into three slopes known as Mireya, Medio, and Corea, this region is called “Boca de Tinajones” (Acosta, 2013; Ochoa et al., 2008).

The seasonal variation of the river flow is very marked. The months of January to March record the lowest flow rates at the Sinú River mouth, with values fluctuating between 100 and 200 m^3/s which corresponds to the driest season inlands that extends through the months of December, January, and February.

As the months pass by the flow rate increases considerably, corresponding to the humid season of the year, so that for the months from May to November the Sinú discharge reaches the highest flow rates, which vary between 300 and 600 m^3/s, or even up to maximums of 800 m^3/s. In the summer of the San Juan (JJA), there is no variation in the flow as marked at the end of the year (Ochoa et al., 2008; Torres-Bejarano et al., 2022).

The total average annual flow of the rivers that flow into this basin is estimated at 15397 m^3/s. These seasonal variations in river flows play a fundamental role in the dynamics of the region and its impact on the surrounding ecosystems (Acosta, 2013). The amount of sediment contributed to the marine environment varies throughout the year. In particular, a significant increase is observed during the rainy season, resulting in higher rates of sediment transported by rivers. The concentration of Total Suspended Solids (TSS) in water is closely related to river flows.

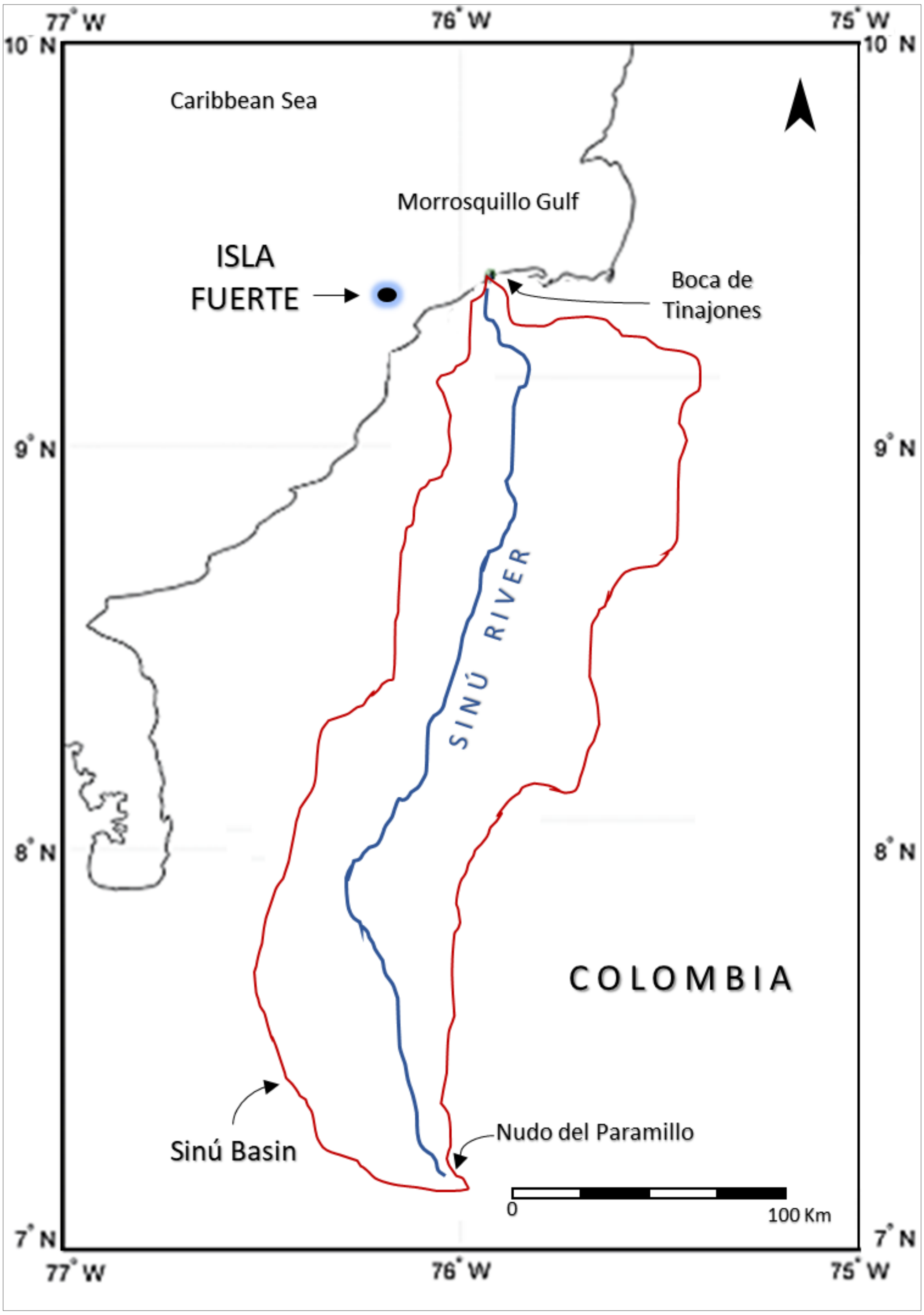

Figure 3 - Sinú River

Modified from (Ochoa et al., 2008). The hydrographic basin of the Sinú River, tracing its course from its source at the Nudo del Paramillo to its outlet at the Caribbean Sea in Boca de Tinajones

Mathematical modeling has been carried out to estimate the concentration of TSS in water at different times of the year. During periods when rivers have flows of around 600 m^3/s, *i.e.,* humid months, these rates can reach up to 250 mg/L of TSS. On the other hand, in dry months, such as January and February, an average of 80 mg/L of TSS has been calculated (Ochoa et al., 2008; Torres-Bejarano et al., 2022).

Due to the lack of direct data taken *in situ*, these models help understand and predict fluctuations in sediment concentration in water and their impact on the marine ecosystem. The variability of environmental conditions and river dynamics throughout the year makes it difficult to obtain accurate data consistently. These models are essential to understand and managing changes in TSS concentration, especially during the rainy season. Additionally, season variations in sea currents and wind velocity and direction affect the input of sediments from the Sinú River into Isla Fuerte. Fishermen refer to the moths of most sentient input of the Sinú Plum as “El Bombaz”, a condition that reduces the depth of the photic zone and makes it difficult for fisherman to efficiently complete their tasks either by net, line, or snorkeling, and harpoon (Castaño-Camacho & Moncaleano-Archila, 2007).

Underwater Topography:

The emerged area represents around 20% of the total reef and consists of a terrace with uniform planar to slightly undulating topography (Anderson, 1971; Díaz et al., 1996). These terraces extend towards the southwest and deepen. Towards the west side, the topography of the terrace extends for almost 2 km before plunging to depths of between 7 m and 8 m, known as the "Bajo El Bobito". On the north and northeast side of the terrace, the reef descends into a slope up to 28 m deep (Díaz et al., 1996).

The underwater topography of the island is shown in Figure 4. A plan view map with contour lines highlighting the complex topographic structure of the reef, which extends largely below sea level. This cartographic representation allows to appreciate the significant depth of the surrounding waters.

The Figure 5 provides a profile view corresponding to line AB, further highlighting the notable altimetric variation of the island. This graphic representation visually demonstrates the abrupt transition from deep waters to the Earth's surface. The maximum depth reaches almost 40 m in this section, while the maximum height above sea level is just 12 m. These data reveal the island's unique topography and the importance of its underwater environment in terms of altimetric-bathymetric variability.

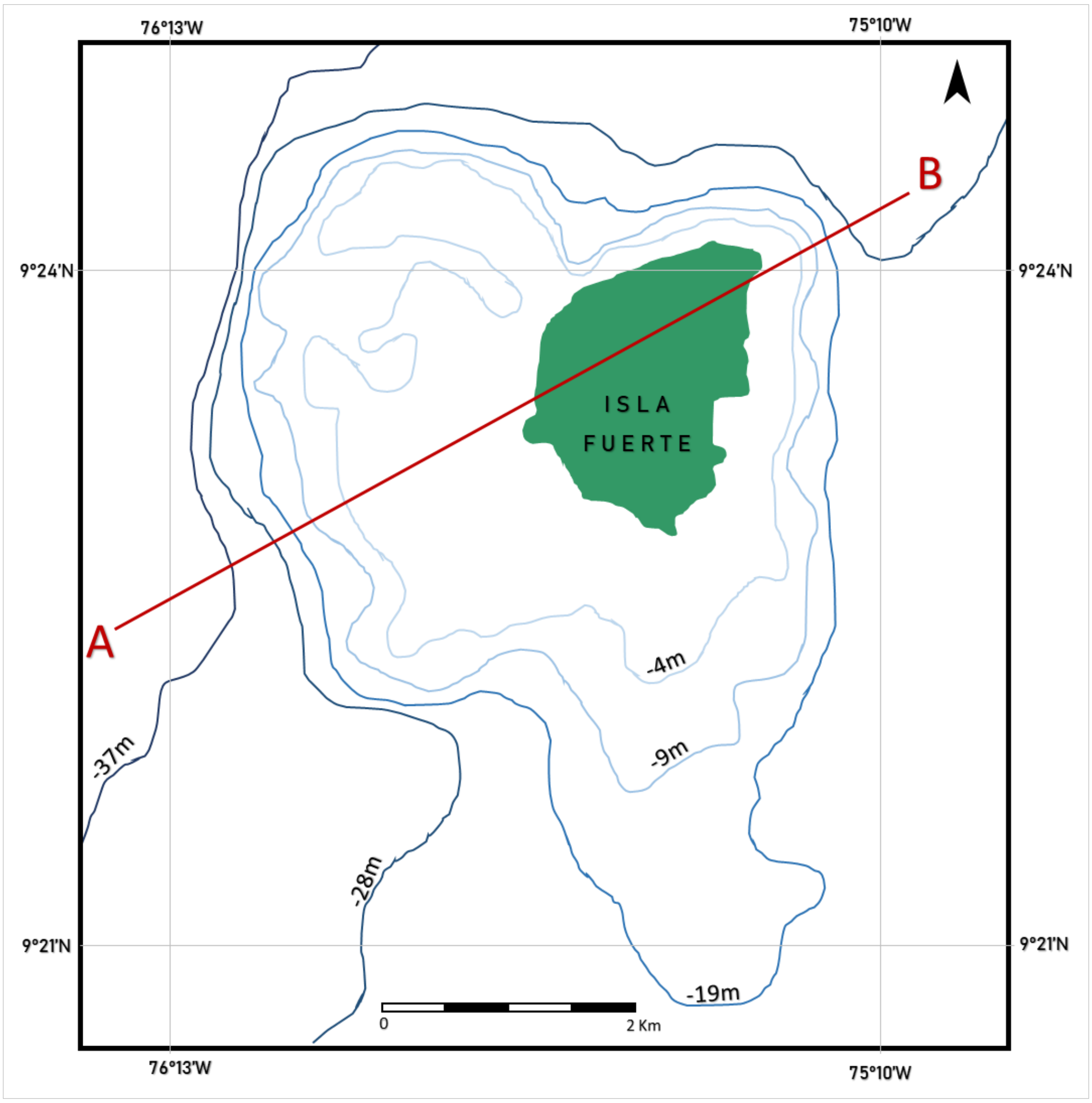

Figure 4 - Plan view of the Reef Complex

Modified from (Díaz et al., 1996). Plan view of the reef complex, featuring contour lines indicating depth relative to mean sea level

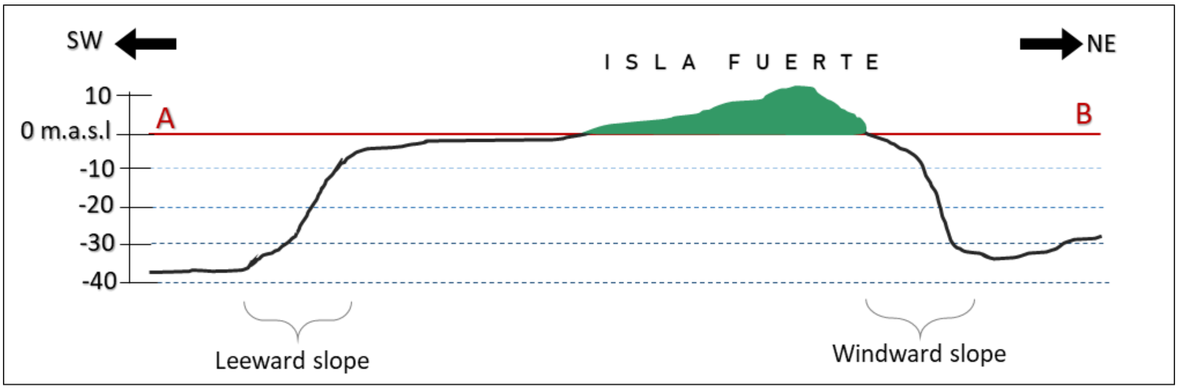

Figure 5 - Profile view of the Reef Complex

Modified from (Díaz et al., 1996). detailed cross-sectional view of the reef complex, extending from the southwest to the northeast. It emphasizes the varying depths of the terraces along the western side

3. STATE OF THE ART

The analysis of the change in the coastline plays a fundamental role in the precise understanding of the current state of Isla Fuerte. This assessment not only provides us with a realistic view of the resources available on the island but also allows to identify the land interactions leading to notable transformations over time. The application of a multi-temporal analysis is essential to evaluate the changes experienced. This comparison will give us a deeper understanding of the conditions on the island and, even more importantly, establish a solid basis for the decision-making necessary for the development of the island. The knowledge obtained from this study becomes an essential resource in various fields of research and development. Additionally, the importance of community participation and knowledge-based is emphasized.

As mentioned in the Objectives Section, the purpose of this project is to establish a scientific basis that can be considered in decision-making on the island, supporting future planning and protection with the collaboration of all entities involved. The island community will play a central role in this effort, as much of its development depends on them. Likewise, it is intended that all of us who love the island and feel part of it can contribute with our knowledge to an in-depth study of a key aspect of the Island's sustainability such as the stability of the coastline. The relevance of this study lies in its potential to fill this knowledge gap and provide the community, local authorities and stakeholders with a detailed and specific understanding of coastline change in the region. Additionally, this analysis will contribute to global knowledge on coastal variability and the application of satellite imagery in unique contexts.

3.1 Effects of Climate Change

Climate change, and its consequences such as sea level rise, trigger coastal erosion, a critical challenge affecting coastal areas around the world. To address this problem, various management strategies have been developed including defense, adaptation, retreat, and non-intervention. These strategies seek to mitigate the adverse effects of erosion and protect coastal areas of high ecological and economic value (Zhang et al., 2004).

3.2 Potential Solutions

In addressing coastal erosion challenges, several potential solutions emerge as viable options. These include considering strategies like constructing coastal defenses, adapting to shifts in the coastline, implementing coastal management plans, and establishing managed setback areas. However, the selection of appropriate management strategies necessitates a comprehensive assessment, taking into account economic, legal, and aesthetic considerations (Williams et al., 2018).

These strategies offer a range of possibilities for managing coastal erosion, each with its unique set of advantages and challenges. Coastal defenses, for instance, can provide immediate protection but often require ongoing maintenance. Adapting to changes in the coastline requires a flexible approach that considers long-term sustainability. Implementing comprehensive coastal management plans and creating managed setback areas are also crucial steps toward ensuring the resilience of coastal regions (Prasad & Kumar, 2014; Williams et al., 2018).

Furthermore, the importance of understanding the current state of coastal erosion cannot be overstated. It is essential for evaluating associated risks and informing decision-making processes. Additionally, ongoing monitoring and research into coastal erosion provide invaluable insights for sustainable coastal development planning and effective adaptation to the ever-changing dynamics of our coastlines, particularly in the face of climate change.

3.3 Mathematical Analysis

Recent technological advancements have significantly expanded our ability to conduct mathematical analyses, providing profound insights into coastal erosion and the effectiveness of various mitigation strategies. These advanced modeling techniques empower us to anticipate the potential consequences of environmental changes, such as rising sea levels and intensified storm events, on coastal regions (van Rijn, 2011).

One illustrative example of such mathematical analysis is the application of empirical formulas, like the Bruun Rule, which plays a pivotal role in assessing changes in the coastline. The Bruun Rule, for instance, is employed to estimate shoreline retreat resulting from sea-level rise. According to this rule, the shoreline is expected to recede by an amount equal to the sea-level rise multiplied by a beach retreat factor. This retreat factor reflects the beach's slope and its capacity to accommodate the rising sea levels. While widely utilized in coastal erosion studies and coastal management planning, it's important to note that the applicability of such rules under natural, open-coast conditions is an ongoing topic of debate within the scientific community. In reality, numerous factors can influence shoreline retreat beyond sea-level rise, raising questions about the rule's accuracy in complex coastal settings (van Rijn, 2011).

Nonetheless, these mathematical analyses, not only enhance our understanding of coastal dynamics but also inform decision-making processes concerning mitigation strategies and coastal management. They serve as essential tools for developing sustainable approaches to address the multifaceted challenges posed by coastal erosion (van Rijn, 2011; Williams et al., 2018).

3.4 Importance of Understanding Coastal Erosion

Understanding and assessing coastal erosion is paramount in effectively managing and safeguarding coastal zones. It provides the essential foundation for making well-informed decisions regarding the preservation and protection of these vulnerable areas, allowing for the implementation of suitable strategies aimed at minimizing adverse impacts on both the environment and the communities residing along the coastlines. Moreover, the study of coastal erosion yields valuable insights crucial for the planning of sustainable coastal development and preparing for the challenges posed by climate change (Zhang et al., 2004).

Recognizing the critical need to comprehensively evaluate the condition of our shorelines and trace their historical changes is integral to achieving a deeper understanding of coastal dynamics. This endeavor presents a substantial challenge, as it requires the collaboration of experts from various disciplines to ensure a comprehensive and accurate analysis. Coastal analysis demands the collective efforts of professionals with diverse expertise who can contribute to a holistic assessment.

The significance of gaining insight into the current state of coastal erosion stems from the imperative to comprehend and assess the associated risks linked to this phenomenon. Such an understanding is pivotal for devising effective strategies and action plans aimed at mitigating these risks.

Additionally, it is essential to enhance our preparedness and response measures to safeguard both coastal environments and the well-being of coastal communities.

The coastal analysis cannot be overstated. It serves as the foundation for informed decision-making, fosters a more profound appreciation of coastal processes, and mobilizes multidisciplinary efforts to address the complexities of coastal erosion, ultimately contributing to the sustainable management and resilience of our coastal regions.

3.5 GIS and Remote Sensing

Geographic information technologies, particularly GIS (Geographic Information System), and remote sensing techniques are indispensable tools in the study of coastal erosion. They serve as powerful means for gathering, analyzing, and visualizing spatial data, greatly facilitating the monitoring of shoreline transformations over time. Moreover, GIS and remote sensing allow for the integration of data from diverse sources, providing a comprehensive grasp of the underlying processes influencing the coastline (Prasad & Kumar, 2014).

Furthermore, GIS and remote sensing technologies can be harnessed to model and predict future coastal erosion, enabling the assessment of the vulnerability of various coastal areas and informed decision-making in coastal management and planning. In essence, GIS and remote sensing furnish potent instruments for researching coastal erosion by simplifying the collection, analysis, and visualization of spatial data. They aid in comprehending the mechanisms driving erosion, monitoring temporal changes, and making well-informed choices for coastal management and planning (Prasad & Kumar, 2014).

Among GIS software options, ArcGIS stands out due to its extensive functionality and its ability to seamlessly integrate and analyze spatial data from diverse sources. Esri, the company behind ArcGIS, has maintained a leading position in the geospatial industry for decades, setting industry standards. Additionally, it boasts a large user community and a wealth of support resources, including documentation, tutorials, and discussion forums, facilitating user learning and problem-solving (Environmental Systems Research Institute, 1969; Prasad & Kumar, 2014).

Several modeling software tools play a pivotal role in coastal management, including SWAN for wave modeling, SBEACH for sediment transport modeling, and LITPACK for coastline evolution modeling. These models utilize field data and measurements to simulate coastal behavior and forecast the impact of sea-level rise on the coastline (Zhang et al., 2004).

As for remote sensing, it's worth noting that satellite imagery offers a cost-effective and efficient means to monitor coastal changes over vast areas and extended periods. Satellite imagery excels in identifying erosion and accretion zones, tracking shoreline shifts, and assessing the repercussions of natural events such as storms on coastal regions. Additionally, when combined with other data sources like field measurements and aerial photography, satellite imagery provides a more comprehensive comprehension of coastal processes. The increasing importance of remote sensing techniques, such as satellite imagery, in coastal management and planning cannot be understated.

3.6 Decision Making

Managing coastal erosion involves considering multiple disciplines and priorities, often leading to complexity and lack of coordination among stakeholders. Lack of government wisdom and institutional mistrust can make it difficult to effectively implement management measures. Active community participation is essential, as it is residents who directly experience the impacts of coastal erosion on their lives and property. Its inclusion in decision-making guarantees adequate and sustainable solutions (Prasad & Kumar, 2014; van Rijn, 2011; Williams et al., 2018).

Limitations

While this thesis aims to provide valuable insights into the analysis of coastal erosion using satellite imagery and GIS, it's important to acknowledge certain limitations that may affect the scope and depth of the research.

- Data Accessibility: One notable limitation is the availability of data. Not all relevant data, especially recent or high-resolution imagery, may be openly accessible to researchers. Limited access to certain datasets or proprietary information can restrict the comprehensiveness of the analysis.

- Resolution: The use of satellite imagery with a 30-meter resolution, while widely available and cost-effective, may present limitations in capturing fine-scale coastal changes. Higher-resolution imagery could offer more detailed insights into erosion processes but might come with increased costs and data processing challenges. Thus, the choice of resolution represents a trade-off between data quality and feasibility.

- Temporal Limitations: The temporal scope of the analysis may be constrained by the availability of historical satellite imagery. Some regions or periods may have limited data coverage, potentially affecting the ability to track long-term coastal changes comprehensively.

- External Factors: Coastal erosion is influenced by a multitude of factors, including climate patterns, human activities, and geological conditions. While this thesis aims to focus on satellite imagery and GIS analysis, it's important to recognize that external factors may introduce complexities that extend beyond the scope of the research.

- Uncertainties: Like any scientific study, there may be uncertainties associated with the analysis. Factors such as image quality, data processing techniques, and the interpretation of results can introduce uncertainties that should be considered when concluding.

Despite these limitations, this thesis seeks to provide a valuable contribution to the understanding and management of coastal erosion. By acknowledging these constraints, researchers can make informed decisions and work towards overcoming some of these limitations in future studies

4. THEORETICAL FRAMEWORK

4.1 Coastal Line

The coastline is the natural boundary that exists between land and sea. It is not a static boundary but rather a dynamic edge that responds to surrounding conditions both inland and in the sea. These dynamics can be influenced by a variety of factors, and the position of the coastline can change over time as the boundary can advance or retreat (Tarbuck & Lutgens, 2004). The coastline experiences constant changes due to a complex interaction of natural factors and human activities. These changes can manifest themselves both in short periods, such as seasonal variation, as well as in longer periods, such as the effects of ice ages (Boggs, 2006).

Wave Breakers

Waves can be described as an oscillatory movement on the sea surface, the result of the superposition of waves propagating in the same direction. They are generated due to temperature gradients in the atmosphere, caused mainly by the sun, which acts as the main warming agent. This geographic space is known as FETCH, and it is where these waves form in open water (Boggs, 2006; Ortega Arango, 2010).

As open water waves approach the shore, they experience a breakdown of their energetic motion as they collide with the beach berm, see Figure 6. Propagation speed decreases, the wavelength shortens, and the energy disperses toward the wave crest, resulting in an increase in wave height. In the "swash zone" water moves toward land, transporting sediment as it moves on a positive slope, which contributes to beach formation. It is also the place where the water recedes in the process known as "backwash", which also causes the transport and deposition of sediments (Boggs, 2006).

Sediments and erosion

Coastal processes, including erosion, transportation, and deposition, have been extensively studied from both qualitative and quantitative perspectives. In the geological context, beaches and their morphology are understood as the outcomes of dominant wave actions (Boggs, 2006).

Beaches are primarily shaped by the interplay of various wave characteristics, including wave swash, storm waves, and nearshore currents. Additionally, wind serves as the primary means of transporting finer sands, which accumulate on the dry portion of the beach, forming dunes. These dunes mark the beginning of the area commonly referred to as the 'beach'. The different areas that make up a typical beach profile are represented in Figure 6. Each of these areas plays a crucial role in the coastal ecosystem and the overall beach experience (Boggs, 2006).

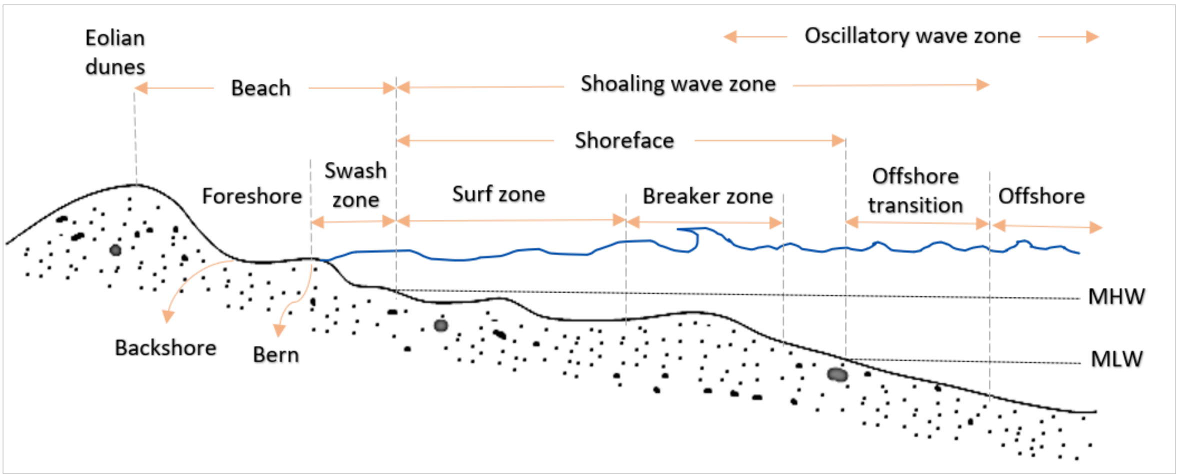

Figure 6 - Seashore morphology

Modified from (Boggs, 2006). Wave influence zones along the coastline, featuring a typical cross-sectional profile of a sandy beach, the interaction between wave dynamics and coastal morphology.

4.2 Coastline Changes

The coastline faces significant challenges, including flooding, erosion, pollution, and fluctuations in sea level (Boggs, 2006). For example, coastal erosion can be caused by natural processes, such as wave action, storm events, and long-term coastal processes, such as sea level rise. Additionally, human activities such as coastal development, sand mining, and modification of sediment transport pathways can also contribute (Bruun, 1962; Davidson et al., 2017; Gutierrez Elorza, 2008).

In general, there is a tendency to experience higher erosion rates during the winter months, especially at higher latitudes. In the case of the tropics, this trend is observed in the months of June to November, when several factors, including temperature changes, contribute to the increase in hurricanes and cyclones. The peak of these weather events usually occurs between August and November (Gutierrez Elorza, 2008; National Geographic, 2003; Ramesh et al., 2015).

Identifying these changes facilitates a more precise understanding of coastal dynamics, possible variations, emerging challenges and, most importantly, how to address them. Therefore, it is essential to consider spatial and temporal variability when identifying this area (Garcia Barrera, 2016; Navarrete-Ramirez, 2014).

Those changes can manifest themselves at various time and area scales, and their relevance varies depending on the time scale considered. The same event can acquire greater importance when analyzed on the appropriate time scale; while on the wrong scale, it could go unnoticed. Below, we summarize these changes ranging from macro to micro scale (Garcia Barrera, 2016; Navarrete-Ramirez, 2014; Sánchez-Arcilla Conejo & Jiménez, 1994).

- Over time scales of 100 000 to 10 000 years, coastal changes are related to eustatic variations in sea level, resulting from cyclical glaciation times. These changes have a global reach.
- In the interval of 10 000 to 1 000 years, coastal changes can be attributed to recent eras of deglaciation and their influence is observed regionally.
- Time scales of 1 000 to 10 years are marked by beach changes influenced by geomorphological factors, human action, and temporal variations in storms. These changes also affect the coastal shear zone.
- On an even finer time scale, ranging from 1 year to 1 hour, coastal changes are due to factors such as wave action and storm energy, both high and low.

It is important to highlight that changes and modifications in coastal zones are not attributable to a single agent, but are the result of the interaction and joint action of multiple dynamic factors, both in terms of time scales and spatial scales. This highlights the complexity and multifaceted nature of coastal processes, which can be influenced by a variety of environmental and human variables (Garcia Barrera, 2016; Navarrete-Ramirez, 2014; Sánchez-Arcilla Conejo & Jiménez, 1994).

Erosion

Beach monitoring plays a fundamental role in obtaining information on patterns and cycles of erosion and accretion along coasts. This process allows the establishment of a solid database that facilitates informed analysis for the implementation of preventive measures and planning in coastal areas (Hernandez Castañeda, 2009; Navarrete-Ramirez, 2014).

In the context of the Caribbean Sea, one of the most significant challenges on the coasts is related to variations in sedimentation and erosion. This phenomenon has been attributed to so-called "hard engineering", which involves solid, rigid structures such as dikes, retaining walls and breakwaters built with materials such as concrete or stone (Sánchez-Arcilla Conejo & Jiménez, 1994). However, "soft engineering" is more environmentally friendly and represents a perhaps more valuable and viable alternative, as it includes the replanting of mangroves and shrubs, the protection of reefs, and the artificial replenishment of beaches (Rangel-Buitrago et al., 2015; Restrepo & López, 2008).

On the northern coast of Colombia, it has been recorded that approximately 48% of its extension, equivalent to about 1182 km, is under a significant threat of coastal erosion. On the other hand, around 18.5% of this region shows sediment accumulation, which corresponds to about 450 km. The remaining 33.2%, approximately 812 km of this area, has stability in its coastal configuration. Erosion rates in the coastal area closest to the island are estimated to range from 1.7 to 2 m per year (Rangel-Buitrago et al., 2015). This not only has implications for land loss but also affects the integrity of coastal ecosystems, infrastructure and local communities. Therefore, monitoring and understanding these erosion rates are essential for the development of adaptation and mitigation strategies that contribute to protection and preservation.

Since the first recorded map of Isla Fuerte in 1500, a reduction in the size of the beach has been observed in the southern part of the island, known as "Punta Arena". This change in the coastline highlights the importance of continuous monitoring and analysis of historical data to understand coastal dynamics and its implications for coastal planning and management (Anderson, 1984).

4.3 Sources of Information for this Study

Satellite images play a fundamental role in the analysis of the coastline of Isla Fuerte. These images cover a wide range of periods, allowing changes and evolutions in the coastal configuration to be observed and quantified over different moments. Landsat imagery, in particular, has been used as a primary source, providing valuable historical perspective and a solid foundation for the study of coastal dynamics. The choice of images with this broad temporality is revealed as an essential resource to understand the processes of coastal erosion and accretion in the context of the island, thus contributing to a more complete and precise vision of the evolution of the coastline.

Landsat

The Landsat program is an initiative of the Government of the United States of America and is managed by the National Aeronautics and Space Administration (NASA) and the United States Geological Survey (USGS) (U.S. Geological Survey, n.d.). Each of the satellites in their missions has specific characteristics that allow them to capture diverse information by recording data in different bands of the electromagnetic spectrum (spectral resolution) and through the years (temporal resolution) (N.A.S.A., n.d.). Improvements have been made and more satellites have been launched into orbit within the Landsat series (Alonso, 2019; N.A.S.A., n.d.; U.S. Geological Survey, n.d.).

> *"Landsat is the only U.S. satellite system designed and operated to repeatedly observe the global land surface at a moderate scale that shows both natural and human-induced change"* (N.A.S.A., n.d.)

- Landsat 1:

  Originally known as the Earth Resources Technology Satellite (ERTS), it was launched on July 23, 1972, and operated until January 1978. It featured two key instruments: The Return Beam Vidicon (**RBV**), developed by the Radio Corporation of America (RCA), and the Multispectral Scanner (**MSS**). The MSS recorded data in four spectral bands, including green, red, and two infrared bands, with a spatial resolution of 60 m per pixel.

- Landsat 2:

  Launched on January 22, 1975, Landsat 2 operated until February 5, 1982, and featured sensors RBV and MSS. It had a spatial resolution of 60 m per pixel.

- Landsat 3:

  Launched on March 5, 1978, and operated until March 1983. It also had sensors RBV and MSS and used four spectral bands, with an additional fifth thermal band that initially experienced some issues shortly after launch. Landsat 3 had a spatial resolution of 30 m.

- Landsat 4:

  Launched on July 16, 1982, and operational until June 15, 2001, Landsat 4 did not feature the RBV sensor. Instead, it continued to use the MSS with a Thematic Mapper (**TM**), which improved spectral and spatial resolution to 30 m. Landsat 4 had seven spectral bands covering various portions of the electromagnetic spectrum.

Table 1 - Landsat 1, 2, 3, and 4

<table>
<tr><td rowspan="5">LANDSAT
1, 2, 3 and 4</td><td>BAND</td><td>NAME</td><td>SPECTRUM
(microns)</td></tr>
<tr><td>4</td><td>Blue</td><td>0.50 - 0.60</td></tr>
<tr><td>5</td><td>Green</td><td>0.60 - 0.70</td></tr>
<tr><td>6</td><td>Red</td><td>0.70 - 0.80</td></tr>
<tr><td>7</td><td>Near InfraRed</td><td>0.80 - 1.1</td></tr>
</table>

- Landsat 5:

  Launched on March 1, 1984, and remained operational until June 2013. It featured the same RBV and TM bands as Landsat 4. Landsat 5 earned a Guinness World Record for being the

"Longest-operating Earth observation satellite" completing 28 years and 10 months of service.

Table 2 - Landsat 5

	BAND	NAME	WAVELENGTH (µm)	RESOLUTION (m)
LANDSAT 5	1	Blue	0.45 - 0.52	30
	2	Green	0.52 - 0.60	30
	3	Red	0.63 - 0.69	30
	4	Near InfraRed 1	0.76 - 0.90	30
	5	Near InfraRed 2	1.55 - 1.75	30
	6	Thermal InfraRed	10.4 - 12.5	120
	7	InfraRed	2.08 - 2.35	30

- Landsat 6:

  Launched on October 5, 1993, Landsat 6 was lost due to a failure to reach the required orbital speed.

- Landsat 7:

  Launched on April 15, 1999, Landsat 7 featured the Enhanced Thematic Mapper Plus (**ETM+**) sensor along with a panchromatic band with a spatial resolution of 15 meters, 5% absolute radiometric calibration, and a thermal IR channel with a 60-meter spatial resolution. It is still operational, although its Scan Line Corrector (**SLC**) failed on May 31, 2003, resulting in zigzag patterns in its images along its path.

Table 3 - Landsat 7

	BAND	NAME	WAVELENGTH (µm)	RESOLUTION (m)
LANDSAT 7	1	Blue	0.45 - 0.52	30
	2	Green	0.52 - 0.60	30
	3	Red	0.63 - 0.69	30
	4	Near InfraRed 1	0.76 - 0.90	30
	5	Near InfraRed 2	1.55 - 1.75	30
	6	Middle Infrared	2.09 - 2.35	30
	8	Panchromatic	0.52 - 0.90	15

- Landsat 8:

  Launched on February 11, 2013, Landsat 8 is equipped with the Operational Land Imager (**OLI**) and the Thermal Infrared Sensor (**TIRS**). It has 11 bands providing seasonal coverage of the global landmass at various spatial resolutions: 30 meters (visible, NIR, SWIR), 100 meters (thermal), and 15 meters (panchromatic).

- Landsat 9:

  Launched on September 27, 2021, Landsat 9 has a design very similar to Landsat 8. When combined, they offer an improved revisit time for data collection every 8 days.

Table 4 - Landsat 8 and 9

	BAND	NAME	WAVELENGTH (µm)	RESOLUTION (m)
LANDSAT 8 and 9	1	Coastal	0.43 – 0.45	30
	2	Blue	0.45 – 0.51	30
	3	Green	0.53 – 0.59	30
	4	Red	0.63 – 0.67	30
	5	NIR	0.85 – 0.88	30
	6	Short-Wave Infrared 1	1.57 – 1.65	30
	7	Short-Wave Infrared 2	2.11 – 2.29	30
	8	Panchromatic	0.50 – 0.68	15
	9	Cirrus	1.36 – 1.38	30
	10	Thermal Infrared 1	10.60 – 11.19	100
	11	Thermal Infrared 2	11.50 – 12.51	100

Nomenclature

These satellites follow an orbit pattern that allows them to cover the entire Earth's globe. The time it takes for a Landsat satellite to complete one orbit around the Earth is approximately 16 days. This orbit is divided into "paths" and "rows" to facilitate the location of specific images. The Figure 7 shows the grid over Colombia, including the Isla Fuerte study area (N.A.S.A., n.d.).

The reading is done by first considering the path number and then the row number. In our study area, two zones overlap represented as 010_053 and 010_054.

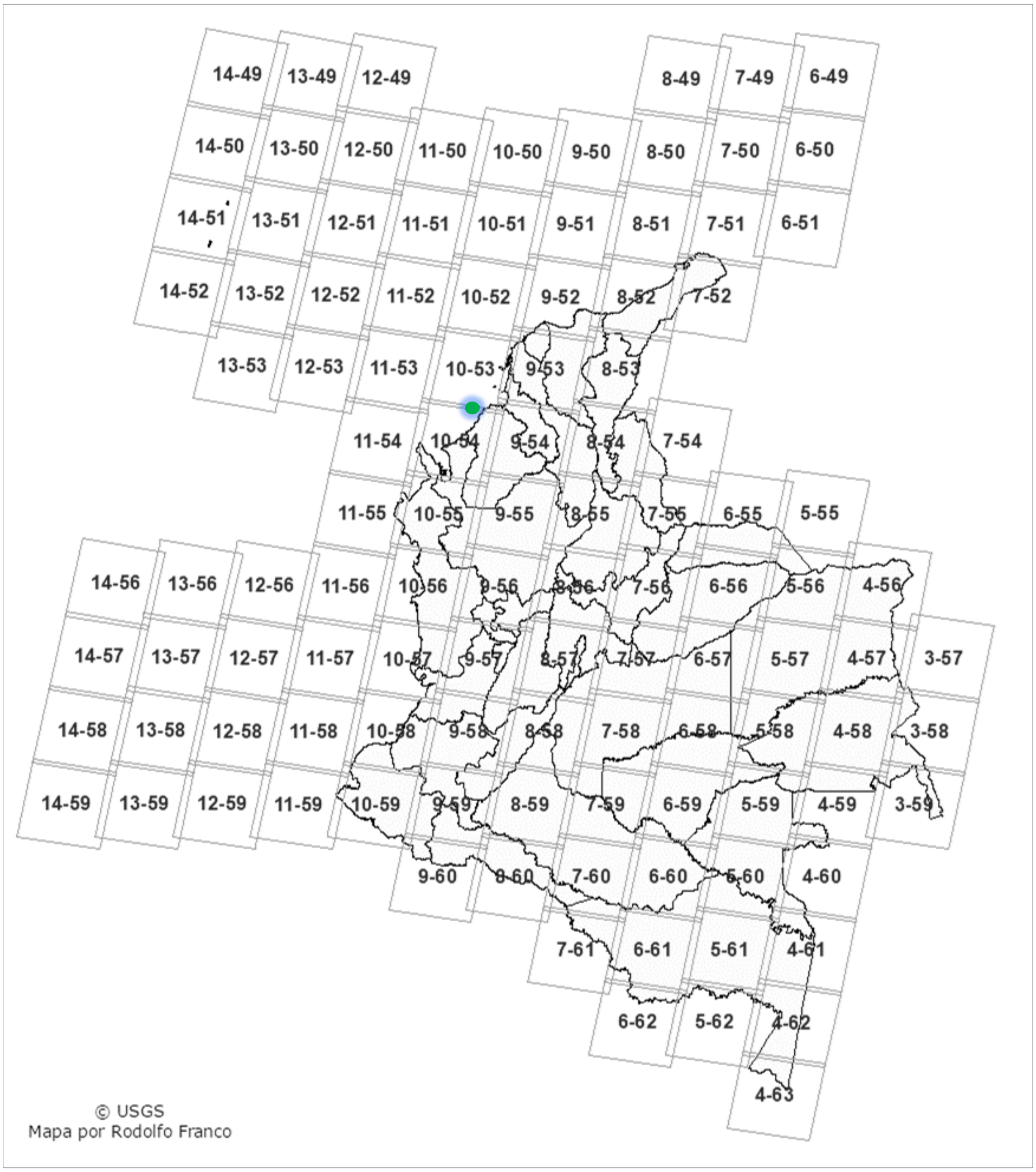

Figure 7 - Colombia Paths and Rows

Modified from (N.A.S.A., n.d.).Complete coverage of Colombia's territory using the row and column nomenclature of Landsat satellite imagery, a comprehensive overview of the systematic organization of satellite data for the entire country

Each Landsat image is composed of several files that contain all the information from the sensors used, acquisition date, path, and row as follows. This is how the image filename is read:

LXSS_LLLL_PPPRRR_YYYYMMDD_yyyymmdd_CC_TX

Where each letter represents:

- L: Landsat
- X: Image capture sensor.
  - C = OLI/TIRS
  - O = OLI
  - T = TIRS, TM
  - E = ETM+
  - M = MSS
- SS: Satellite generation, from 1 to 9
- LLLL: Image processing level, geometric and geometric correction (L1TP, L1GT or L1GS)
- PPP: Path
- RRR: Row
- YYYYMMDD: Image acquisition date in year/month/day format
- yyyymmdd: Image processing date in year/month/day format
- CC: Collection number
- TX: Category of the collection
  - RT = Real Time
  - T1 = Tier 1 → present correction in precision and radiometry
  - T2 = Tier 2 → do not present geometry corrections due to orbit inaccuracy.

The use of the Landsat sensor has been fundamental in this study due to its ability to offer wide temporal coverage, providing open and free information that is easily accessible. These characteristics make it a versatile tool that can be applied in various analysis contexts. Furthermore, its availability has allowed research challenges to be addressed more effectively, supporting informed decision making and understanding of the coastal dynamics of Isla Fuerte. This versatility and accessibility have been essential for the development of this research and offer opportunities for future analyzes and applications.

4.4 Software

For the analysis of satellite images and geospatial data management, the use of ArcGIS was chosen due to its versatility and wide range of geospatial analysis tools. ESRI, the company behind ArcGIS, has made significant improvements to its products, including the transition to ArcGIS Pro, which has enabled greater efficiency in manipulating geospatial data (Black, n.d.). It is important to note that, although ArcGIS is used in this study, the tools developed and the methods used can be adapted to other satellite image processing programs, each with their own advantages and disadvantages, thus providing flexibility in the choice of software according to the specific needs of future researchers

In recent years, ESRI has been on a remarkable innovation journey, particularly in the realm of image analysis, as evidenced by the evolution from ArcMap to ArcGIS Pro. These innovations have not only strengthened its usability but have also ushered in a new era of efficiency. In particular, the optimization of pixel image classification algorithms has led to a substantial acceleration in processing speed, simultaneously raising the accuracy of the results (Black, n.d.; Environmental Systems Research Institute, 1969). The adoption of these refined and improved features has played a crucial role in the present study, mainly due to their exceptional efficiency and user-friendly nature.

Notably, the seamless integration of a wide variety of GIS capabilities into ArcGIS Pro has been critical to understanding and interpreting the results of this research. It is worth mentioning that this software is widely recognized worldwide, extending its usefulness not only in the research community but also in various industrial sectors, highlighting its ubiquitous presence and its recognition as a leading solution for geospatial analysis and management (Black, n.d.).

Specifically, in this study, we took advantage of the following tools and functionality provided by ArcMap and ArcGIS Pro:

- ✓ Training Samples Manager

  This tool is crucial for organizing and managing a classification scheme, which categorizes features in images into different classes. Additionally, it allows the creation of training samples, which define areas belonging to specific classes according to the established classification scheme.

- ✓ Classify

  ArcGIS offers the ability to classify data using both supervised and unsupervised classification techniques. The software processes the images based on the specified classification algorithm and parameters. In supervised classification, users determine the class categories to which pixels or segments are assigned, following the established classification scheme. After classification, it may be necessary to review and reassign misclassified areas to the correct class according to the scheme.

- ✓ Intersect

  The Intersect tool calculates the geometric intersection of input features, identifying features or segments that overlap multiple layers or feature classes. This tool is valuable for comparing land cover changes.

These tools, in conjunction with the extensive capabilities of ArcGIS Pro, have significantly contributed to the success of our research in geospatial analysis and interpretation (Black, n.d.; Environmental Systems Research Institute, 1969). Its efficiency and versatility have proven invaluable in our approach to understanding and addressing complex geospatial issues, cementing ArcGIS Pro's critical role in geospatial research and management (Black, n.d.).

5. METHODOLOGY

This thesis focuses on the study and analysis of the coastal line in Isla Fuerte, and it seeks to be a practical reference for future works that involve the manipulation of satellite images focused on coastal areas. The steps followed in the work for data collection and processing of satellite images are described below.

5.1 Image Acquisition

For the acquisition of satellite images, there are several easily accessible portals that offer a large amount of data. In this work, we chose to use the United States Geological Survey (USGS) website, which is a valuable resource that offers open-access data without download limits. The main data source used in this study is satellite images captured by the Landsat program. The Landsat program has been operational since the 1970s and has been a reliable source of Earth imagery, providing long-term data continuity.

The selection of images considers the temporal spacing between them, which allows us to make a comparison between the images and evaluate any changes that may have occurred. This is essential to identify possible causes of these changes.

5.2 Processing

In terms of image processing, our choice fell on ArcGIS software for its user-friendly accessibility, intuitive interface, and widespread recognition within academic and professional circles. This decision presents a distinct advantage over other software options that may carry usage restrictions. While we acknowledge the existence of alternative programs capable of conducting similar or even more advanced satellite image analyses, our selection of ArcGIS is primarily motivated by its ubiquity and acceptance within the scientific and professional communities.
Satellite image processing constitutes a critical stage in the analysis of spatial data and the evaluation of changes in the Earth's surface over time.

Create a New Project

Open ArcGIS

→ Add Data: Import all spectral bands of the image

Each one of the bands will be loaded as an independent file. The next step is to combine these bands into a single composite image, allowing us to visualize and analyze their characteristics in an integrated manner

Composite Bands

To facilitate analysis, it's necessary to create a composite image that combines all the bands into one instead of analyzing each band separately.

→ Go to the "Windows" menu.
  → Select "Image Analysis."
    → In the new window, choose the bands from B1 to B7.
      → Click on "Composite Bands."

In the next stage of the process, we will generate an image by combining three of the seven available spectral bands in different sequences, depending on the specific requirements of our analysis. This flexibility allows us to explore diverse perspectives of the Earth's surface and adapt our approach to the particular needs of our research.

The satellite image encompasses a significantly larger geographical area than our specific regions of interest. To delineate our study areas, we have established two distinct rectangles:

- The biggest rectangular area is designated for analyzing oceanic dynamics that exert influence on the island.
- The minor rectangular area, focusing only on Isla Fuerte, serves the purpose of characterizing satellite images and conducting a comprehensive analysis of multi-temporal changes.

These predefined rectangles serve as the boundaries within which we will conduct our detailed analysis and observations. The boundaries of each rectangle are:

Table 5 - Boundaries study area

°	'	"	
9	30	00	N
9	18	00	N
76	17	60	W
75	54	00	W

°	'	"	
9	24	10	N
9	22	30	N
76	10	00	W
76	12	00	W

To crop the image, we will use the following steps

In the ArcToolbox

- Data Management Tools
  - Raster
    - Raster processing
      - Clip

We crop the raster created using "composite," which includes all the bands of the satellite image regarding the bounding box of our study area, see Figure 8. The name of this new raster will correspond to the year of the image, making it easier for future comparisons.

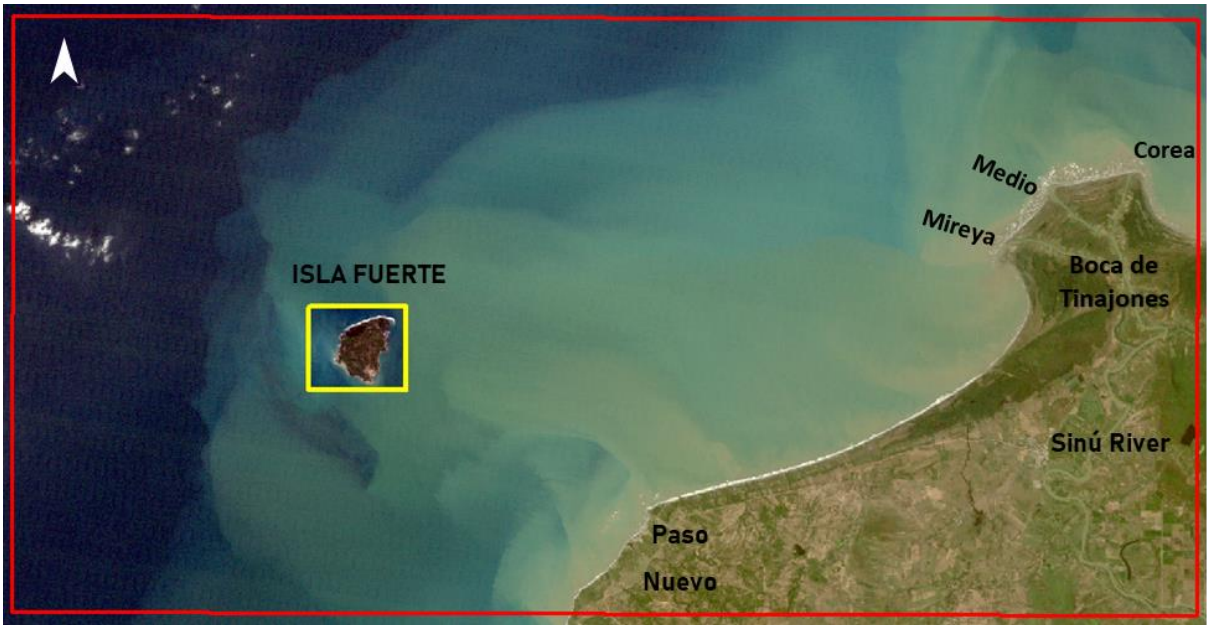

Figure 8 - Boundaries study area

Taken by Landsat 1 in 1973, vividly illustrates the impact of sediment from the Sinú River as it converges at Boca de Tinajones, in its three distinct branches: Corea, Medio, and Mireya. Oceanic dynamics drive the transport of terrestrial sediments onto the island's beaches, showcasing the interplay of riverine and marine influences

5.3 Supervised Classification

The next step is to characterize the image we have through supervised classification. In this process, we program the software to recognize the different areas or elements needed for our study.

- Catalog
  - In the project folder
    - Create a new folder
      - Point shapefile.

For the characterization of land use, the study relies on the Corine Land Cover regulations, originally developed in Europe and adapted for Colombia in its 2018 version, see Figure 9. The land use classification is organized into six main categories, adapted from the Corine Land Cover guidelines, to accurately represent the diversity of landscapes and terrain features in the region.

Select points or polygons on the image, categorizing them into the following classes:

I. Urban
II. Agriculture with native vegetation
III. Dense vegetation
IV. Mangroves, bodies of water, flood areas
V. Beach or wave-breaking zone
VI. Sea

As control points are created, also manipulate the combination of different bands, as each one reveals specific features of the image that assist in identifying various areas more easily. Each point must be assigned a number that identifies its zone type among the 6 categories chosen for the study of the island.

These band combinations are crucial for the identification of diverse features and characteristics in Landsat imagery. To facilitate the adaptation of these combinations to the specific Landsat image being used, this guide includes a comprehensive comparison table (Table 6). Whether working with Landsat 5, 7, 8, or 9, this table serves as a valuable reference for modifying band combinations, allowing for consistency and accuracy in the analysis of land use and cover across different Landsat missions

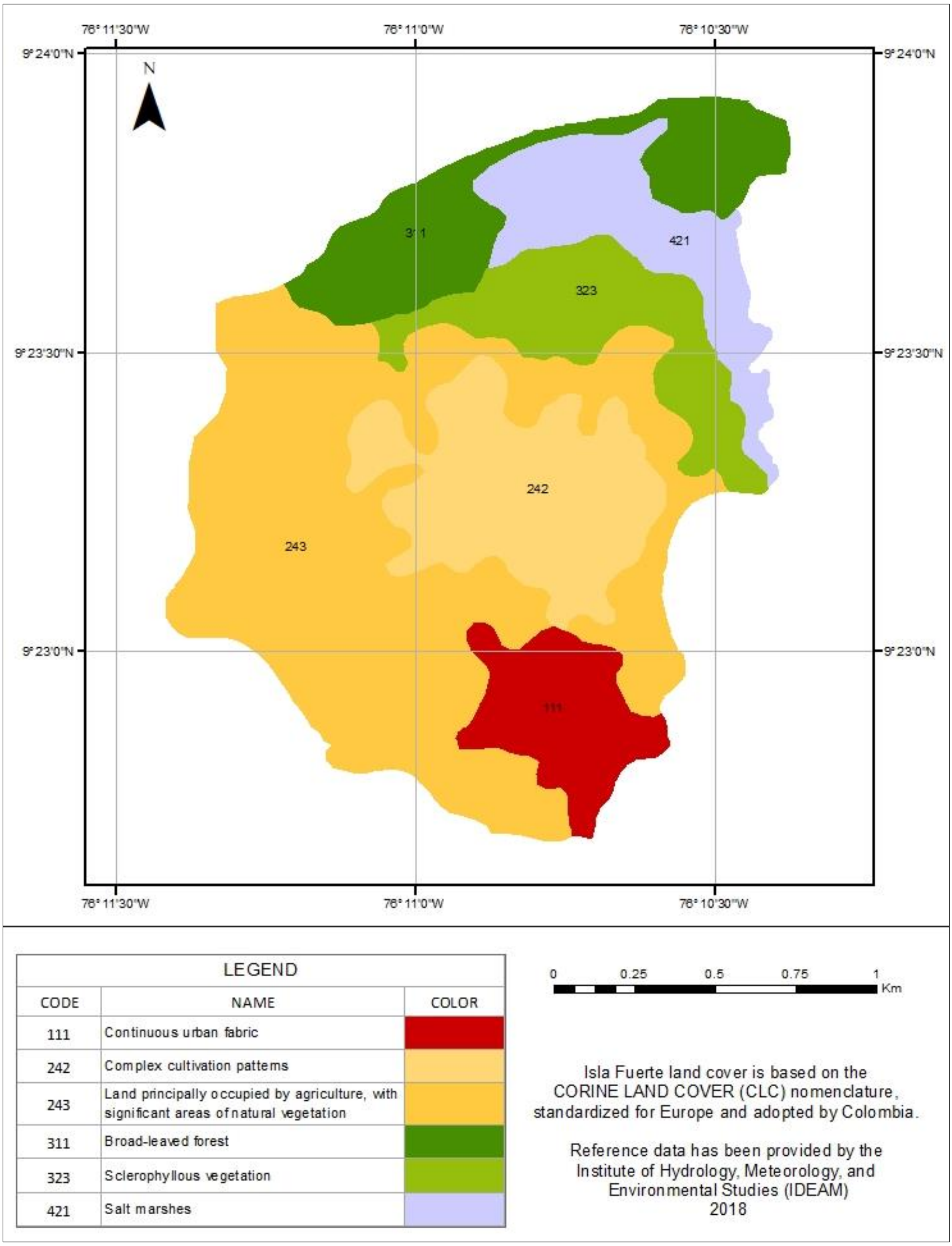

Figure 9 - Corine Land Cover for Isla Fuerte

The official land cover classifications of Colombia, as of the most recent data available in 2008, harmonized with the European Corine Land Cover nomenclature. It offers a comprehensive overview of the country's land use and cover patterns in alignment with international standards

Table 6 - Band Combinations

BAND COMBINATIONS			L5, L7	L8, L9
R	G	B	321	432
NIR	R	G	432	543
SWIR 1	NIR	R	543	654
NIR	SWIR 1	R	453	564
SWIR 2	NIR	G	742	753
SWIR 2	SWIR 1	R	753	764
SWIR 2	SWIR 1	NIR	754	765
SWIR 1	NIR	B	541	652
NIR	SWIR 1	B	451	562
SWIR 1	R	B	531	642
SWIR 2	R	B	731	742

This procedure was applied to a Landsat image from 1999, captured during the Landsat 5 mission. Therefore, the specific combinations of colors described here are tailored to this example. Each Landsat mission may have variations in its spectral bands and characteristics, so the chosen combinations are designed to suit the spectral properties of the missions with 7 bands. The approach and principles outlined in this methodology can be adapted to images from other satellites and missions, but adjustments may be needed to accommodate differences in spectral bands and sensor characteristics.

The combination 321 will display the actual colors in the visible spectrum, which will allow to check some general characteristics, plus, the following combinations will allow to check even more specific:

I. Urban

For the first zone, which represents the urban area, we will use the following band combinations to compare and select pixels that meet these characteristics:

- Combination 543 will display the urban area in pink.
- Combination 451 will display the urban area in white or cyan colors.
- And bands 742 will present it in magenta.
- Bands 432 will display it in cyan

II. Agriculture with native vegetation

- Bands 541 will highlight vibrant green vegetation.
- Bands 451 will display healthy vegetation in colors such as red, brown, orange, and yellow. Non-vegetated areas will appear green or brown, while grasslands will be gray.
- Bands 742 will show green areas as grasslands and darker tones as forested areas.
- Bands 453 will represent vegetation in shades of green, brown, and yellow.

III. Dense vegetation

- Bands 541 will display very bright green.
- Bands 742 will produce olive green tones for forests.
- Bands 451 will show healthy vegetation in colors like red, brown, orange, and yellow, but match the combinations mentioned earlier, indicating forested areas.

IV. Mangroves, flood zones, or bodies of water

- We can complement the real colors with combination 321 with:
- Bands 543 will render water in black.
- Bands 453 will display soil moisture in dark blue.

V. Beach or wave-breaking zone

- We will observe white or very light brown shades using the real color combination 321.

VI. Sea

To distinguish coastal lines from water, in addition to the real color combination 321, we can use:

- Bands 754 to outline water in black and vegetation in blue.
- Bands 451 to indicate deep water in black or light blue for shallow waters and dark blue for deep waters.
- Combination 753 will show water in black or blue.
- Similarly, combination 543 will reveal water in black.
- Bands 453 will render water in black or dark blue, highlighting areas with high moisture.

Once all control points have been created and categorized from 1 to 6 according to their respective land cover or land use classes, we save the changes. This labeled dataset serves as the key reference that allows us to characterize the entire image using the predefined standards and criteria we've established in our example.

Signature

The control points serve as the basis for creating a signature that enables the software to classify each pixel within the entire image. This classification process assigns one of the six predefined values to each pixel, characterizing it based on the established criteria. These values correspond to the different land cover or land use categories that we have defined for our study areas, facilitating the subsequent analysis and interpretation of the image.

ArcToolbox
- Spatial Analyst Tools
  - Multivariate
    - Create Signatures

Select the composite raster of the designated small area along with the corresponding control point shapefile containing the appropriate numbering
Save the signature as a text file, which contains all the statistical information about the number of points and their corresponding values in the raster image.

ArcToolbox
- Spatial Analyst Tools
  - Multivariate
    - Maximum Likelihood Classification

Once again, select the composite bands raster and load the newly created signature.

This method yields a raster image in which each pixel is associated with a numerical value, allowing for precise data characterization, as seen in
Figure 10 - Supervised Classification. Consequently, these numerical values enable rigorous comparisons between images from various years, facilitating the analysis of temporal changes and patterns.

To improve the accuracy of the classification process, it is necessary to perform manual adjustments to the information. As shown in

Figure 10, beach and wave-breaking areas were initially classified as yellow zones. However, in the context of our work with Landsat images where the pixel resolution is 30 m and the beach around the island is relatively small, a single pixel can span from the dune to the beach, the wave break and the sea.

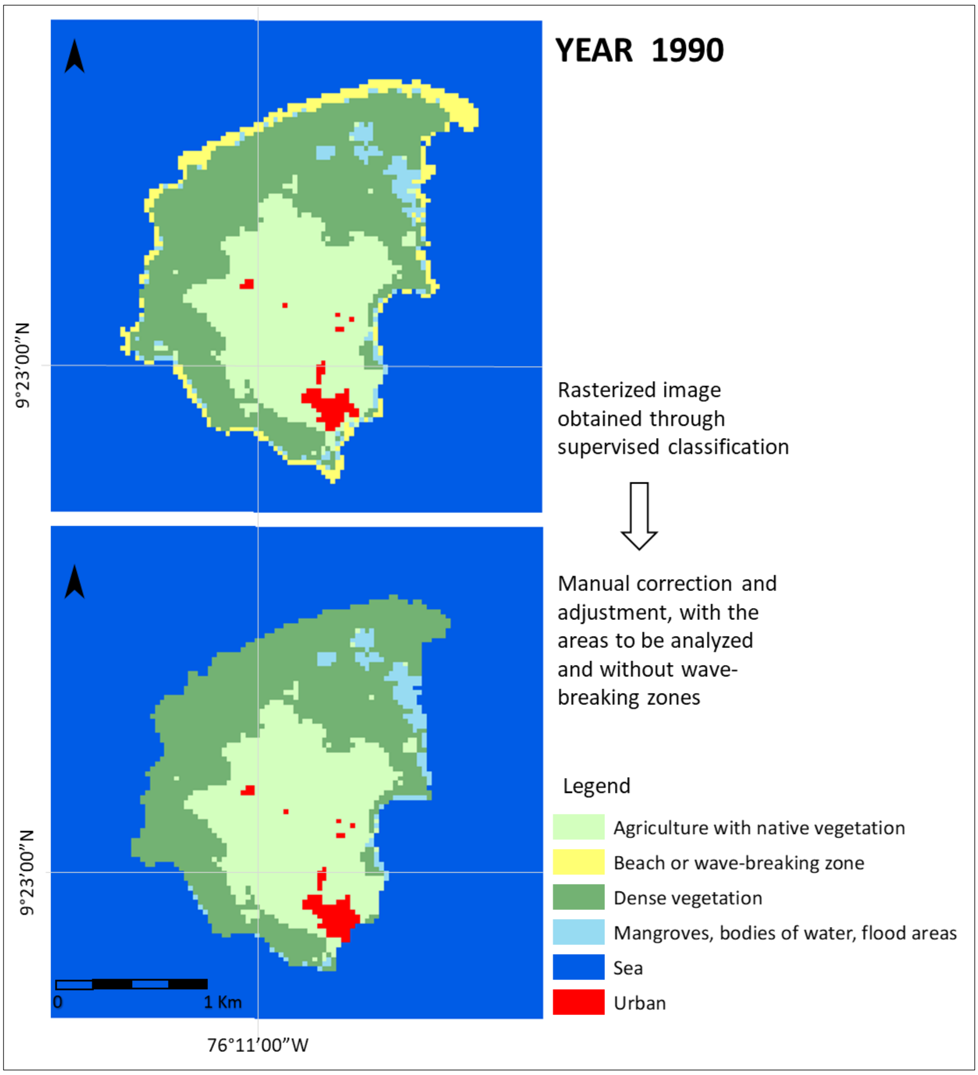

Figure 10 - Supervised Classification and Adjustment

A side-by-side comparison of the initial rasterized images before and after applying supervised classification and subsequent manual adjustments. The result illustrates the final image for each of the analyzed years, highlighting the refinement process in land cover classification

To overcome this challenge, the alternative is to exclude beach areas from the analysis in all years, as shown in Figure 10. This decision ensures the accuracy of our results. The exclusion is necessary because Landsat images lack the required resolution to distinguish these shallow areas effectively. Furthermore, we've implemented standardized criteria for year-to-year comparisons. This approach simplifies the analysis of multi-temporal changes and guarantees consistency in our evaluations

5.4 Comparison

With the raster satellite images fully developed, the next step involves comparing these images with one other to identify changes in land use and in the position of the coastline. An effective strategy to achieve this is to convert image classifications into polygons. This approach has the advantage of streamlining the process of obtaining the areas corresponding to each land use category, which facilitates the analysis of changes.

To Polygon

Using the ArcGIS tool, we follow the steps outlined below to achieve the desired land use change analysis

ArcToolbox
- Conversion Tools
  - From Raster
    - Raster to Polygon

In the popup window, select the manually adjusted raster that is created. Here, there is an option to create simplified polygons that smooth the continuous lines connecting each pixel. However, for this specific case, it is not advisable to use this option because the study area is relatively small compared to the pixel size of 30 m. Enabling the "Simplify" option results in an averaging of the raster, which significantly deviates from the original data.

Given that this process is mechanized and serves as a guide, it is recommended to use pixelated polygons to ensure the final analysis remains as faithful as possible to the initial input, which is the satellite imagery.

Intersect

The next stage of the analysis of satellite images leads to the identification of the coastline on Isla Fuerte. So, proceed to the intersection of the polygons that represent the different land use categories previously defined. This process is carried out using the ArcGIS "Intersection" tool, which compares the spatial content of each shape, which represents the land cover defined at the beginning of our study.

ArcToolbox
- Analysis Tools
  - Overlay
    - Intersect

In the pop-up window, shapes for polygon comparison will be attached. For a better understanding, it is recommended to carry out this process for each change of year, which will provide a step-by-step follow-up of the evolution and facilitate a more precise understanding of the variations that have occurred on the coastline over the years.

The advantage of working with polygons is that, after this intersection, the resulting shape already incorporates the calculation of the area of each of the zones, both those that present similarities in land use and those that have experienced changes in their use. This data is essential for subsequent analysis, since it provides us with detailed information about the areas that retain their original use and the areas that have undergone modifications.

The combination of the intersection of polygons and the calculation of areas provides a solid basis for monitoring the evolution of the coastline and identifying areas that require special attention in terms of management and conservation. As shown in Figure 11, it is accurate to obtain the change in land use between the years 1990 and 2023. This approach is fundamental for this study, as it focuses on the evaluation of changes in the coastline throughout this period

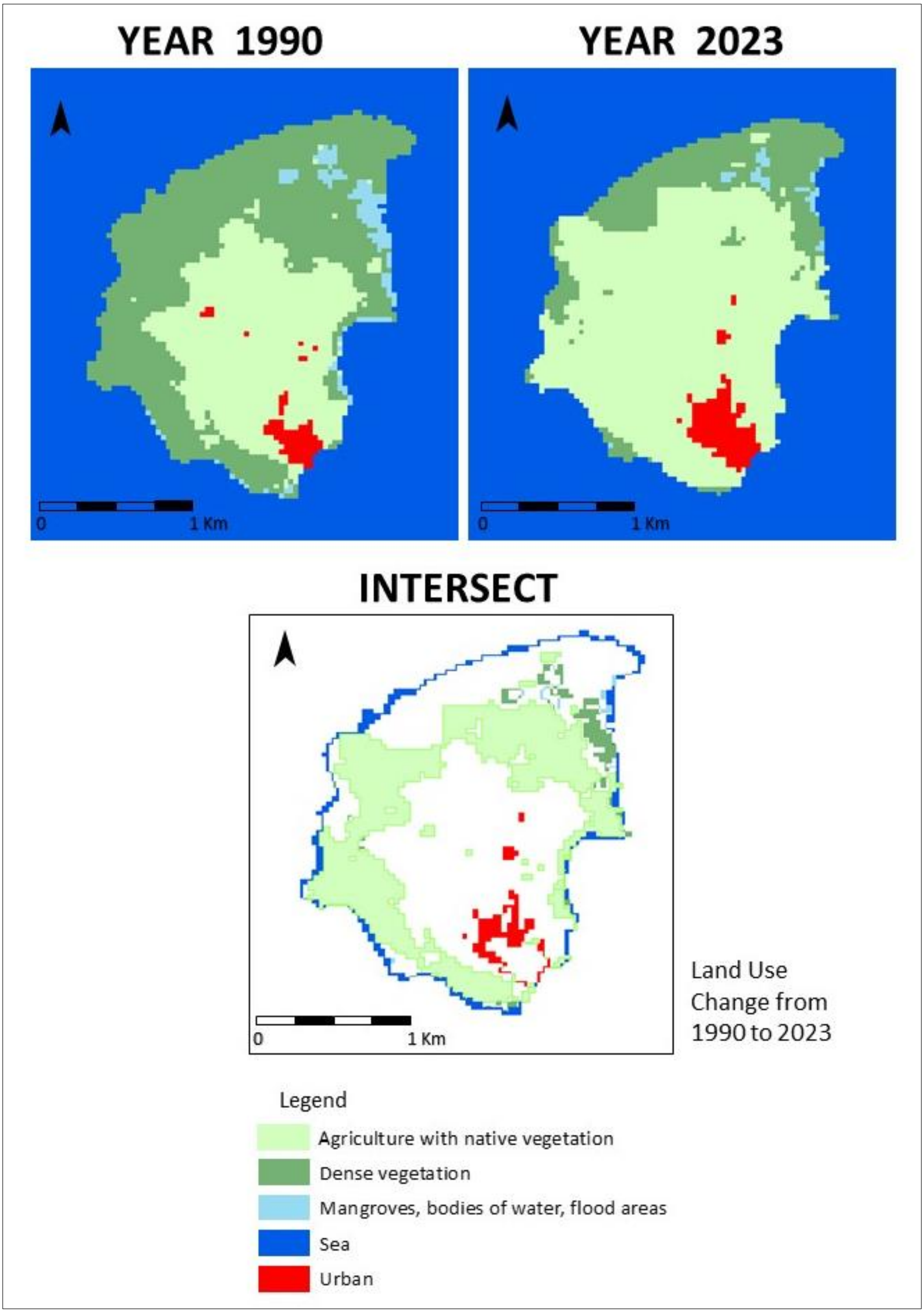

Figure 11 - Land Use Change

Comparison of land cover changes over time, emphasizing areas of intersection that reveal alterations and their resulting new land cover. It provides a visual depiction of evolving landscape dynamics

5.5 Validation

To verify the accuracy of the processing of satellite images, a map generated from photographs captured by drones that flew over the island was used. This map is the result of a research project called "La Isla Laboratorio” (The Laboratory Island), carried out in collaboration between the Universidad Nacional de Colombia and National Geographic (2019-2023). The incorporation of this resource provided a valuable reference source to ensure the reliability of the data obtained through the analysis of satellite images.

Orthophoto

To guarantee precision and detail in our validation, we have chosen to use an orthophoto produced in 2022 (Restrepo Moreno, 2023). The choice of this image is based on its notable resolution per pixel, which reaches 20 centimeters. This provides us with an updated and highly detailed view of our study territory, allowing us to carry out a thorough and precise comparison with the results of the supervised classification of Landsat images.

Visual Comparison

Visual comparison represents a crucial tool to contrast the results derived from supervised classification and the reference orthophoto. In this comparison, we choose to use the satellite image of the year 2023, due to its temporal proximity to the 2022 reference. This choice is justified by its ability to provide an updated representation of the state of the island, including the conditions of land use and, particularly, the main focus: the coastline.

- Comparison with Polygons:

  The polygons representing the five designated categories (Urban, Agriculture with native vegetation, Dense vegetation, Mangroves, Bodies of water, flood areas, and Sea) undergo a thorough analysis to determine their alignment with the orthophoto.

  This assessment seeks to identify areas that coincide with and correspond to the orthophoto, as well as those that do not exhibit equivalence. Furthermore, the examination involves the identification of patterns or changes within these areas, offering insights into the factors contributing to the alignment or lack of coherence between the classification results and the orthophoto.

This process aids in understanding the characteristics and conditions associated with the matched and unmatched areas, facilitating a more comprehensive evaluation of the classification accuracy.

- Comparison with the Original Satellite Image:

By checking with the original satellite image, the one that served as the primary source of information, allows for a direct comparison regarding the equivalence of the information. This direct comparison serves to identify possible patterns that elucidate the congruence or divergence in the classification of areas.

Moreover, various combinations of spectral bands from the original satellite image can be strategically adjusted to enhance the identification of each element under scrutiny. This adaptable approach ensures a comprehensive examination of the classification results in relation to the original satellite imagery. It aids in gaining a deeper understanding of the factors influencing the accuracy of the land use classification and shoreline changes assessment, particularly in areas where uncertainties may arise, where classifications are accurate, and where potential errors may be present.

These processes allow to identify areas of consistency and discrepancy in land use classification and shoreline changes, offering a deeper understanding of such phenomena in the research. However, it is essential to acknowledge that field validation would represent an invaluable additional step, providing certainty about land cover and its actual boundaries. This approach could be a subject of future work in the next phase of this project, where on-site validation would further enhance the reliability of the findings.

6. RESULTS

The study undertook an examination of the Isla Fuerte coastline's transformation and alterations in land use across 50 years. The research hinged upon the utilization of satellite imagery obtained from the Landsat program, which offered the most extensive temporal coverage commencing from their inaugural mission in 1970 up to the present day. Despite the initial images featuring a resolution of 60 m, subsequently enhanced to 30 m, this approach has afforded an invaluable perspective in comprehending the dynamic analysis of Isla Fuertes's geographical transformation.

6.1 Satellite Images

The primary foundation of this project resides in the careful selection of satellite imagery. With the aim of covering a comprehensive 50 year time span, a deliberate approach was taken to space these image acquisitions by approximately 10 years. This strategy was implemented to strike a balance between achieving substantial temporal coverage and allowing for the emergence of noticeable land use changes.

Furthermore, during the image selection process, a cautious preference was given to images captured during the month of January. As revealed through the course of this thesis, the period encompassing December to February corresponds to the dry season when trade winds are at their peak. Consequently, this dry season exhibits significantly reduced cloud cover, resulting in cleaner, less cloud-obstructed images that are pivotal for the accuracy of our analysis

LM01_L1TP_010053_19730103_20200909_02_T2

LT05_L2SP_010053_19900302_20200916_02_T1

LE07_L2SP_010053_20000101_20200918_02_T1

LC08_L2SP_010053_20150102_20200910_02_T1

LC09_L2SP_010053_20230201_20230311_02_T1.

These images have been thoughtfully selected to perfectly meet our analysis requirements. They provide extensive coverage of our study area, guaranteeing a comprehensive representation. Importantly, their temporal range effectively covers the entire period of interest, and, notably, they are free from cloud cover and distracting zigzag patterns. Furthermore, our methodology involves the incorporation of one image from each available Landsat mission, spanning from Landsat 1 to Landsat 9. This inclusive approach enhances our ability to gain a comprehensive understanding of long-term changes and offers a holistic perspective on the evolving landscape of our study area.

6.2 Land cover

Based on the supervised classification carried out for each of the selected images, the identification of areas that correspond to each of the six categories of interest was carried out. The raster image resulting from this classification process is shown below, along with the image derived from manual adjustment. These results provide a detailed view of the distribution of the categories in the study area and serve as a starting point for our further evaluation and analysis.

After completing the supervised classification, manual adjustment of the pixels is made in the areas that generate uncertainties and doubts. In this process, a fundamental decision was made: to redefine the "beach or wave-breaking zone" as part of the marine area.

This decision was essential for the analysis, especially taking into account the particularities of Isla Fuerte as a coral complex. This island exhibits notable features on what we consider its coastline. In this context, the accumulation of sand to form extensive beaches is limited, and these areas are exposed to currents and marine dynamics. As a result, the distance from the sea to the vegetation, passing through the surf zone, the beach, and the dunes, is relatively short.

This unique geographical setting means that a single pixel, representing a distance of 60 meters or 30 m in a straight line, covers this entire area, from the sea to the vegetation. This particularity makes it difficult to accurately identify the coastline. To minimize this error, it is decided not to consider this area in the identification of the coastline. Instead, the coastline is defined as the transition point between land and sea, marking the beginning of the vegetation as the beginning of the island.

This choice is justified based on the working scale allowed by the images and contributes to reducing the error in the analysis. Furthermore, from a statistical perspective, since the vegetation covers a greater area, the pixel will reflect a value (color) more representative of the vegetation, which increases the accuracy of coastline identification.

To facilitate the reading of the results, Table 7 shows the legend that classifies land use is presented. Furthermore, it is important to clarify that in this analysis the measurement system in hectares (Ha) will be used, where 1 hectare is equivalent to 0.01 square kilometers (km^2) or 10000 square meters (m^2)

	Agriculture with native vegetation
	Beach or wave-breaking zone
	Dense vegetation
	Mangroves, bodies of water, flood areas
	Sea
	Urban

Table 7 - Legend

- ✓ 1973 → LM01_L1TP_010053_19730103_20200909_02_T2

For the first image there is a resolution per pixel of 60 m. A large part of the island is seen covered by dense vegetation and a reduced area for the urban area, see Figure 12. Despite having the lowest resolution, this image is of great importance for multi-temporal study since it provides us, to the extent possible, with an approximation of the state of the island 50 years ago.

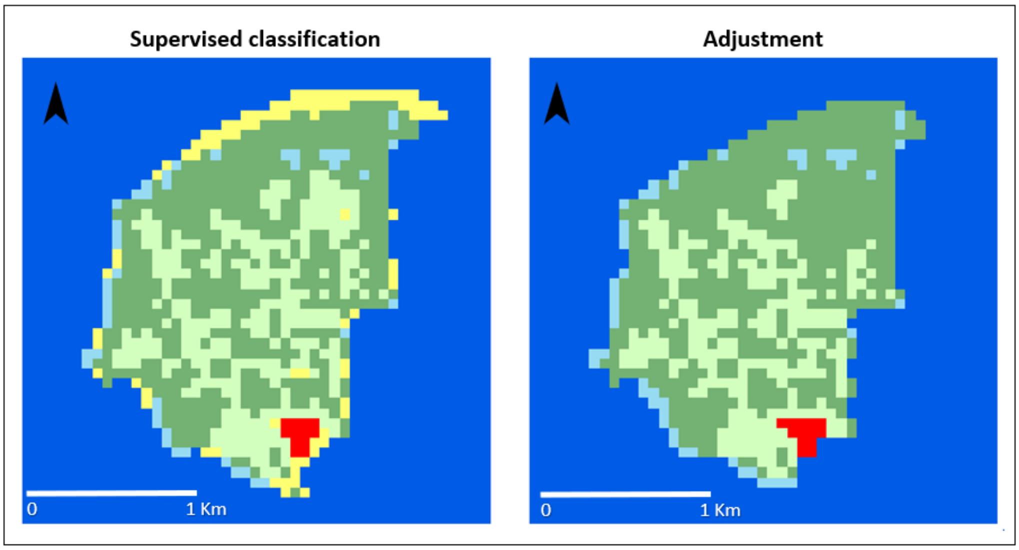

Figure 12 - Raster 1973

✓ 1990 → LT05_L2SP_010053_19900302_20200916_02_T1

This image belonging to the Landsat 5 mission already has a resolution of 30 m per pixel. As shown in Figure 13, supervised classification allows better clustering in terms of crops and dense vegetation. Urban and cultivated areas are notable in this image.

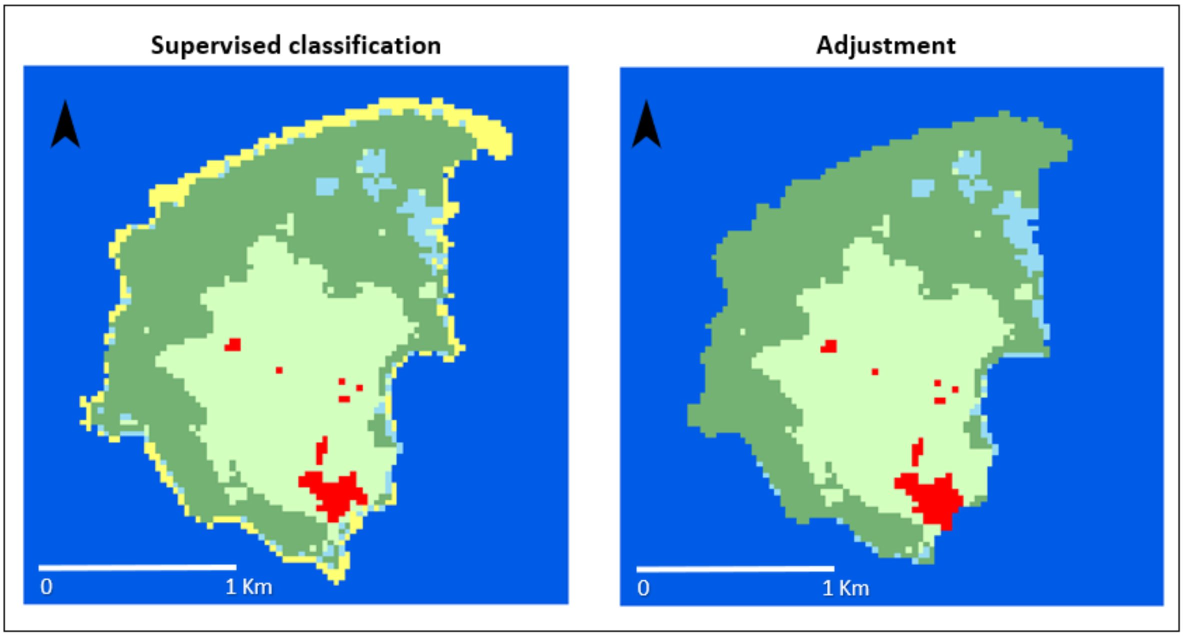

Figure 13 - Raster 1990

- ✓ 2000 → LE07_L2SP_010053_20000101_20200918_02_T1

It belongs to the Landsat 7 mission. Both the urban and cultivated areas have increased, see Figure 14. A minor beach line is also identified, which indicates that the satellite is more precise when identifying the shallowly submerged areas, differentiating them from the wave-topping area.

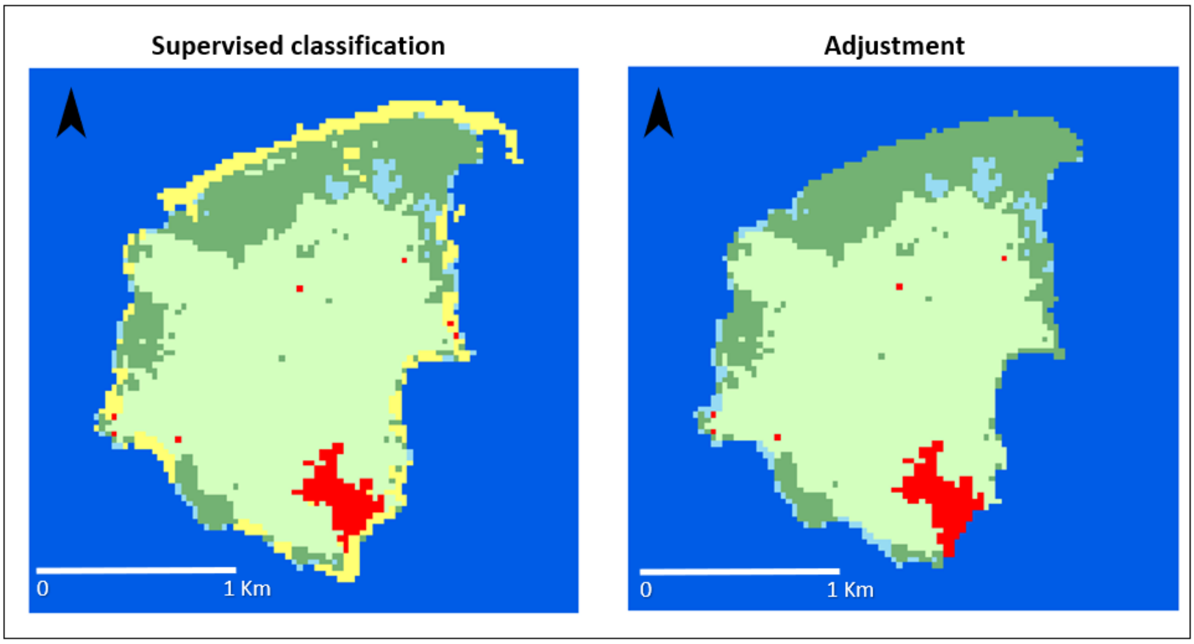

Figure 14 - Raster 2000

- ✓ 2015 → LC08_L2SP_010053_20150102_20200910_02_T1

Belonging to the Landsat 8 mission, the trend to increase the urban area and the cultivated area continues, see Figure 15 - Raster 2015. A smaller area is also identified to the north of the island, where in the supervised classification the wave-breaking area is better than the previous ones.

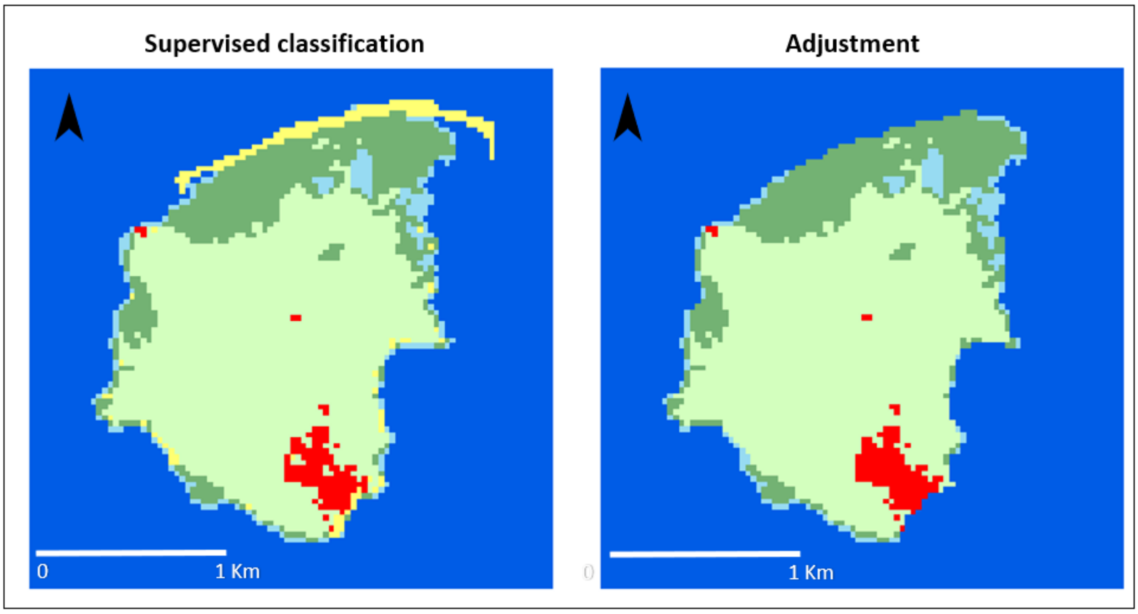

Figure 15 - Raster 2015

- ✓ 2023 → LC09_L2SP_010053_20230201_20230311_02_T1.

It belongs to the latest mission, Landsat 9. In this image, a rectangular area stands out in the northern part, on the border between the cultivated area and the forest, see Figure 16. Despite this peculiarity, the trend of increase in urban and cultivated areas continues. Furthermore, an improvement is noted in the identification of the area to the north of the island, where the supervised classification presents fewer errors in the delimitation of the wave-breaking area.

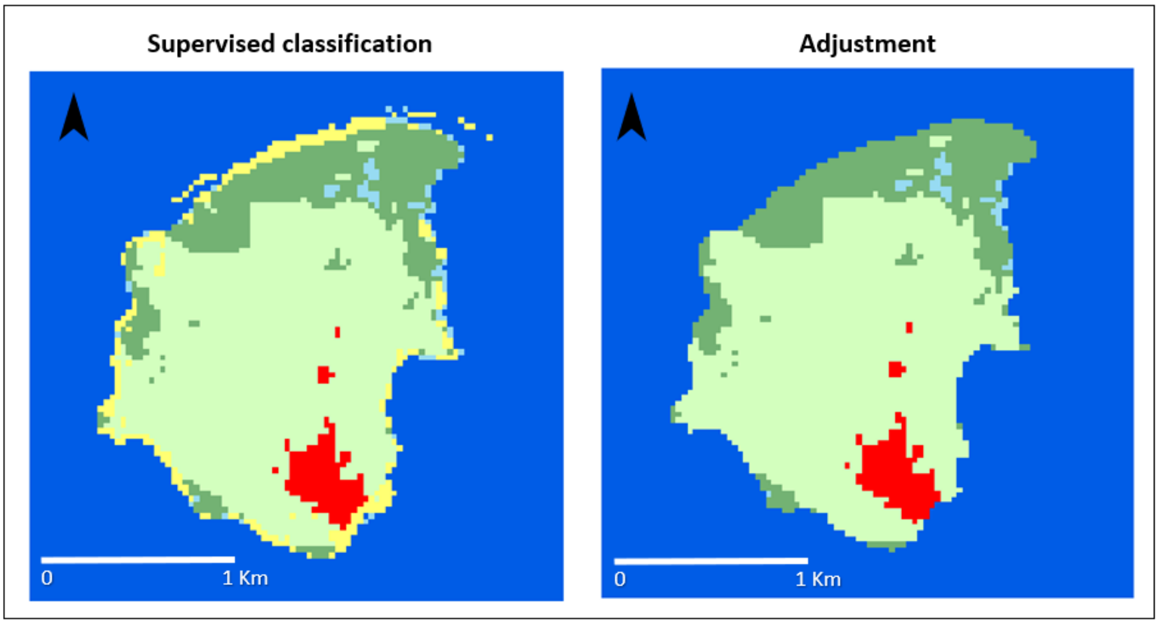

Figure 16 - Raster 2023

6.3 Changes in Time

Analyzing Isla Fuerte's land use changes over the last 50 years helps us comprehend the coastline, both its identification and the factors behind its alterations. The 5 categories considered include Urban, Agriculture with native vegetation, Dense vegetation, Mangroves or bodies of water with flood zones, and Sea. These categories enable us to assess how the coast has evolved and its correlation with changing land use dynamics over time.

For a better understanding, the results are presented step by step, showcasing changes at approximately 10-year intervals in alignment with the satellite image dates.
The changes between 1973 and 1990 are presented in Figure 17, but due to the differing resolutions in each of the images, they may not be entirely reliable for comparing changes across the two years. Nevertheless, they serve as a starting point.

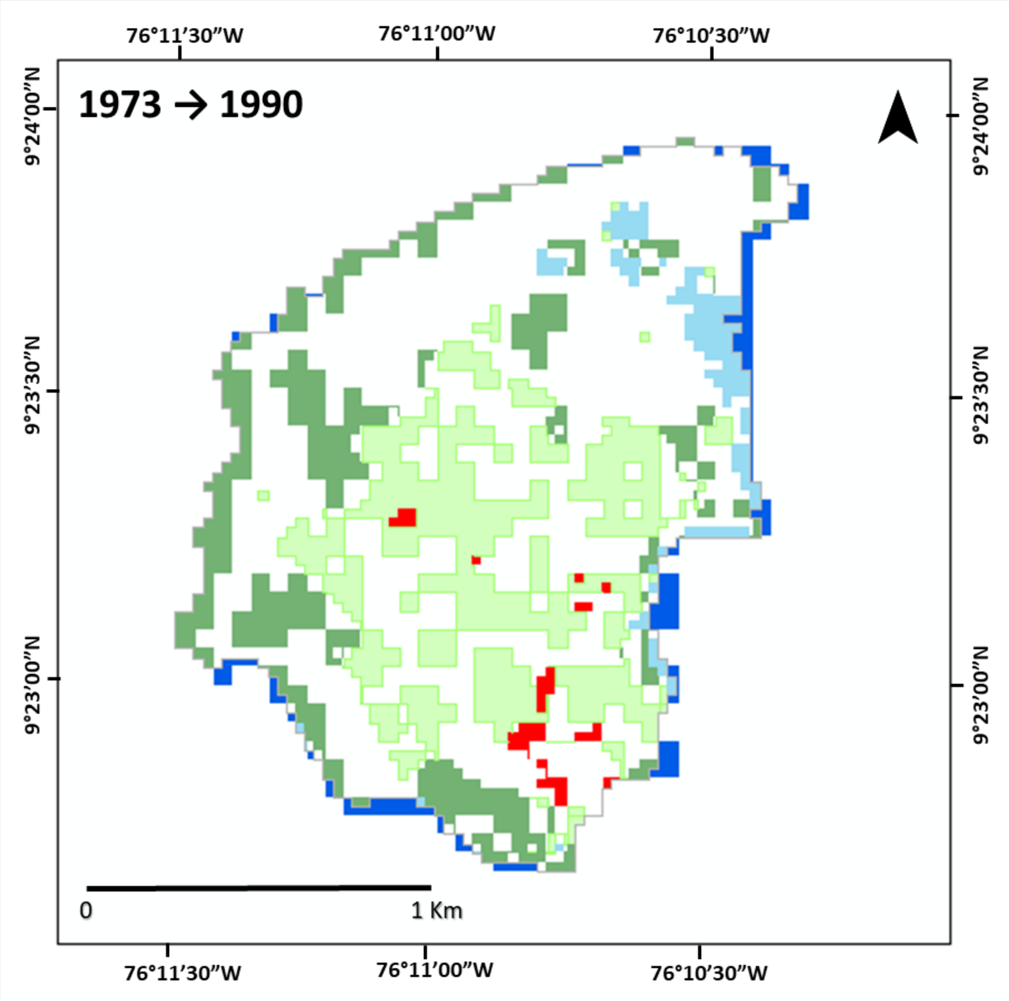

Figure 17 - Land Use Change 1973 → 1990

Significant changes in land use are evident from 1973 to 1990. There is an expansion of cultivated areas, along with growth in the urban area. Additionally, several areas transitioned to the sea category. The total areas with new land uses are as follows:

- Urban = 3.49 Ha
- Agriculture with native vegetation = 61.73 Ha
- Dense vegetation = 48.52 Ha
- Mangroves, bodies of water, flood areas =11.26 Ha
- Sea = 11.48 Ha

In the following time interval, from 1990 to 2000, as shown in Figure 18, there is an even greater increase in cultivated areas. It expands from the southeast in all directions, nearly covering the entire southern part of the island. The urban area also expanded into its surroundings, with some additional constructions on the western side. Notably, there is a variation in the coastline, with an increase in mangroves on the southern and western sides, while the eastern side is now covered by the sea.

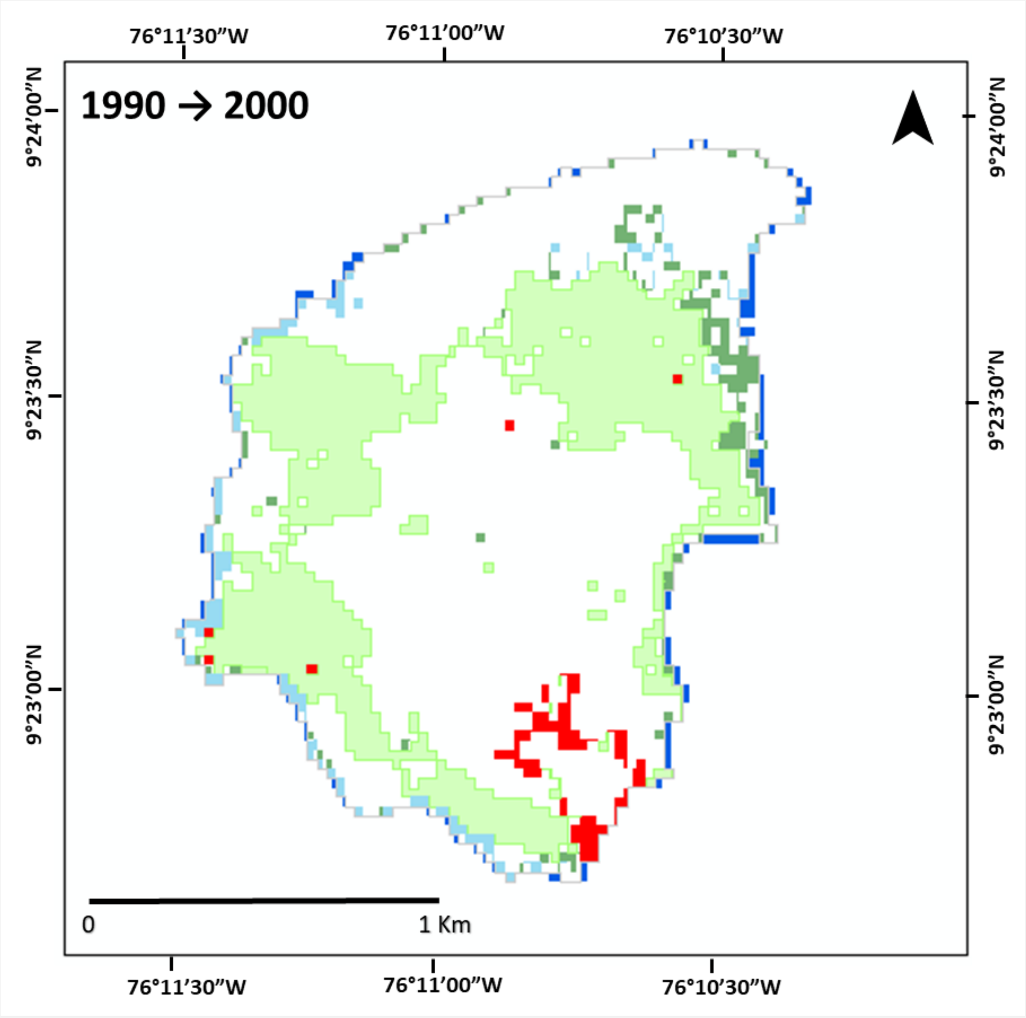

Figure 18 - Land Use Change 1999 → 2000

The total areas with new land use from 1990 to 2000 are:

- Urban = 5.30 Ha
- Agriculture with native vegetation = 86.29 Ha
- Dense vegetation = 8.5 Ha
- Mangroves, bodies of water, flood areas = 7.59 Ha
- Sea = 5.94 Ha

During the time period from 2000 to 2015, Figure 19, the changes are not as drastic, except for the urban area, which continues its expansion towards the northeastern part of the island. Other than a few alterations in terms of cultivation and dense vegetation within the island, the most notable changes are observed along the edges. In the northeast there is an increase in mangrove areas, while in the south and southwest, several zones are now submerged

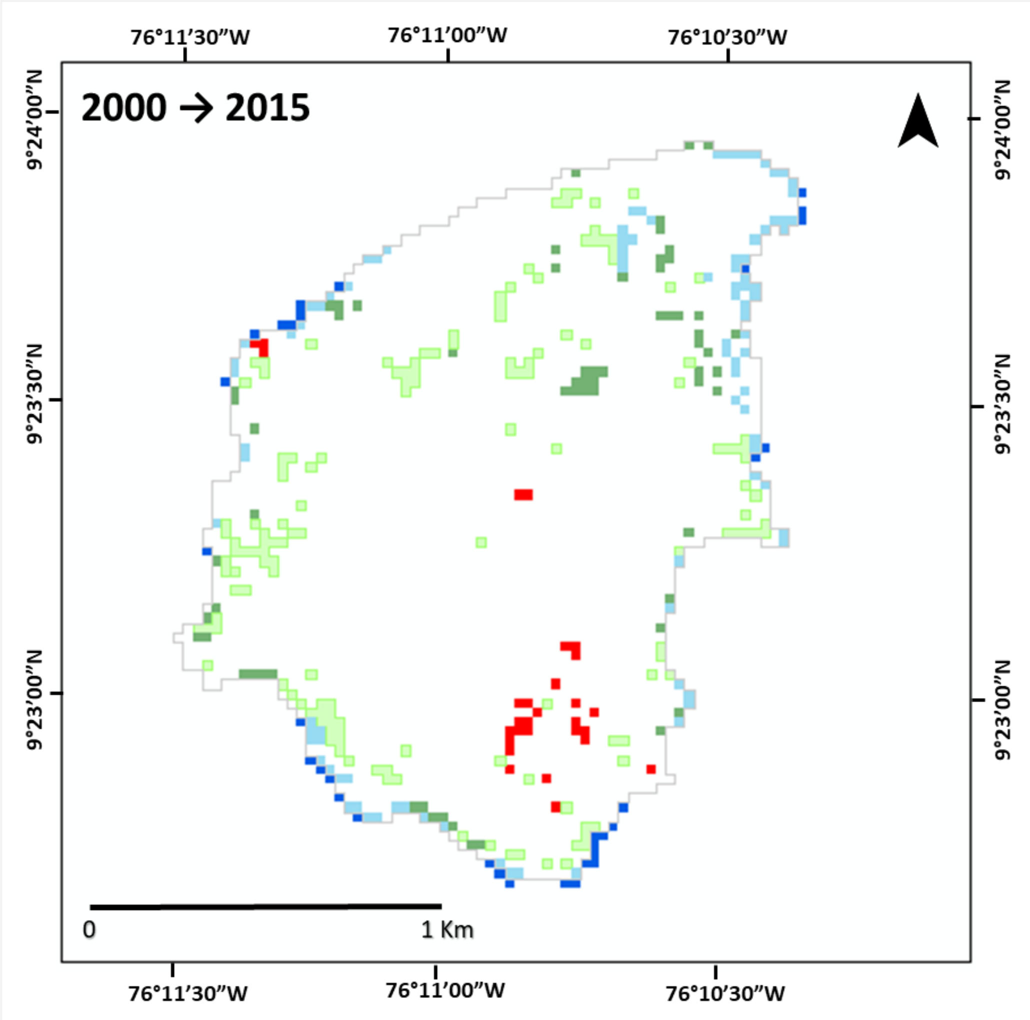

Figure 19 - Land Use Change 2000 → 2015

The total areas with new land use from 2000 to 2015 are:

- Urban = 2.61 Ha
- Agriculture with native vegetation = 13.23 Ha
- Dense vegetation = 5.76 Ha
- Mangroves, bodies of water, flood areas = 8.47 Ha
- Sea = 2.98 Ha

In the last decade from 2015 to 2023, see Figure 20, there is a drastic increase in areas that are now classified as sea. This difference is consistent along the entire perimeter of the island, except for the eastern side. The urban area continues its expansion and concentration in the southeast. Additionally, some other areas with minor impact have transitioned to cultivation.

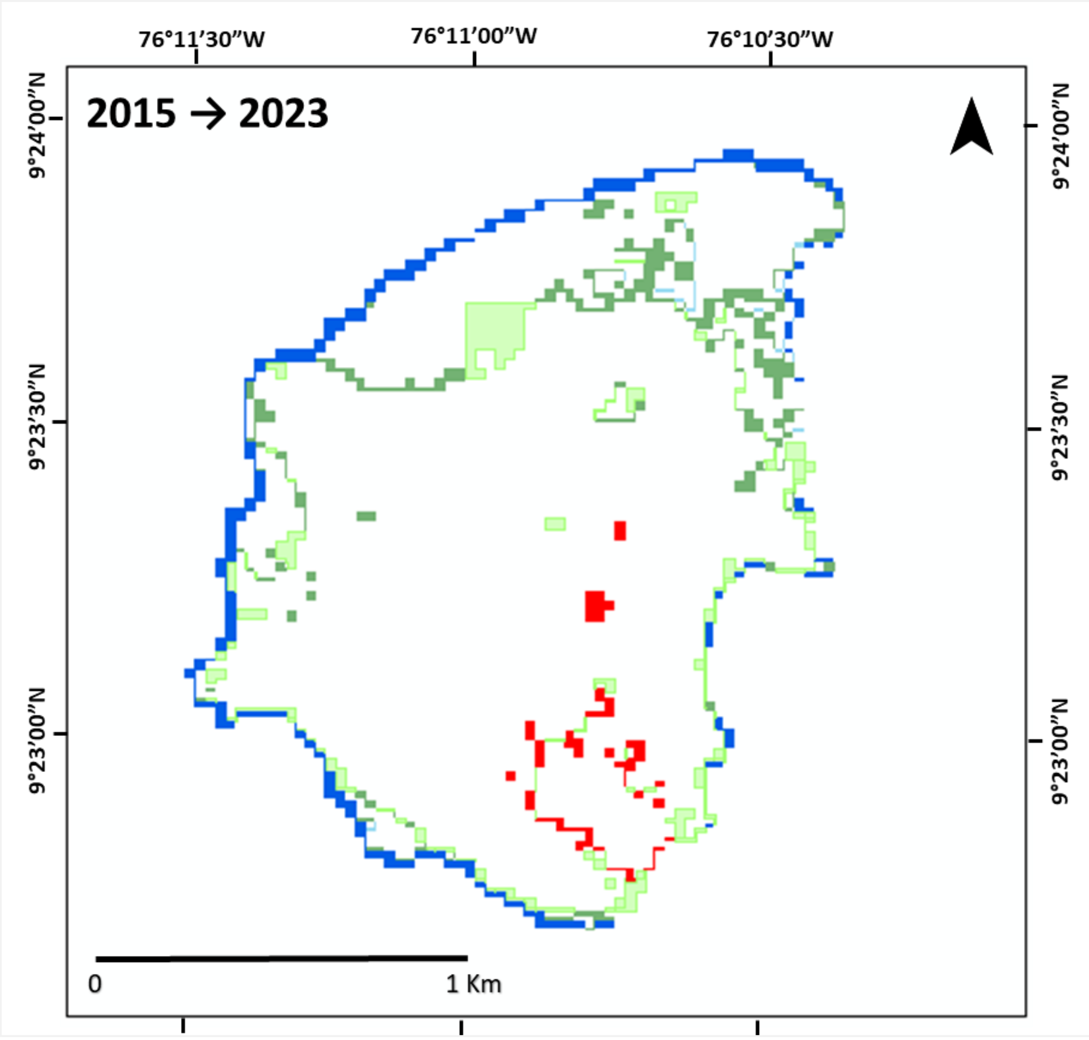

Figure 20 - Land Use Change 2015 → 2023

The total areas with new land use from 2000 to 2015 are:

- Urban = 3.82 Ha
- Agriculture with native vegetation = 11.87 Ha
- Dense vegetation = 12.53 Ha
- Mangroves, bodies of water, flood areas = 0.47 Ha
- Sea = 13.71 Ha

The evolution of Isla Fuerte's coastline, as defined by the transition from vegetation to the sea, was closely examined throughout the analysis. Coastal dynamics were influenced by the growth of urban areas and shifts in land use. The 50 year analysis period revealed changes that were initially driven by cultivation expansion and later characterized by more stable periods with marginal alterations. The coastline saw substantial variations, particularly with the increase in mangroves and areas below sea level along the island's southern and western edges. The most pronounced change occurred in the 2015-2023 interval, with a significant increase in sea areas around most of the island's perimeter. These results enhance our understanding of land use and shoreline dynamics on Isla Fuerte, providing valuable insights for future coastal management and environmental preservation efforts.

6.4 Coastal Line Changes

The evolution of the coastline over several decades in Isla Fuerte is analyze. It is important to note that for this analysis, the transition point between the vegetation and the sea has been taken as a reference as the definition of the coastline. This choice is based on the difficulty of clearly delimiting the beach area due to the scale of work with which it is operating. Since our data sources are satellite images with a resolution of 30 meters per pixel, a single pixel covers a wide area that may in some cases include the sea, the wave break, the beach, the dunes, and the coastal vegetation.

it's worth mentioning that although the use of the panchromatic band could have increased the resolution from 30 to 15 meters in the Landsat images, this option was ruled out due to the lack of availability of this band in all images and the need to maintain homogeneity in the analysis.

The comparison of areas over the years highlights a consistent trend of decreasing land area on Isla Fuerte. The measurement system used is hectares, and the results reveal the following:

- In 1973, the land area was 303.48 Ha.
- In 1990, the land area was calculated at 300.78 Ha.
- By the year 2000, the area had reduced to 299.25 Ha.
- In 2015, the land area further decreased to 298.44 Ha.
- Finally, in 2023, the area was measured at 286.47 Ha.

These findings underscore a gradual reduction in land area on the island, which may have significant implications for its ecological and environmental dynamics.

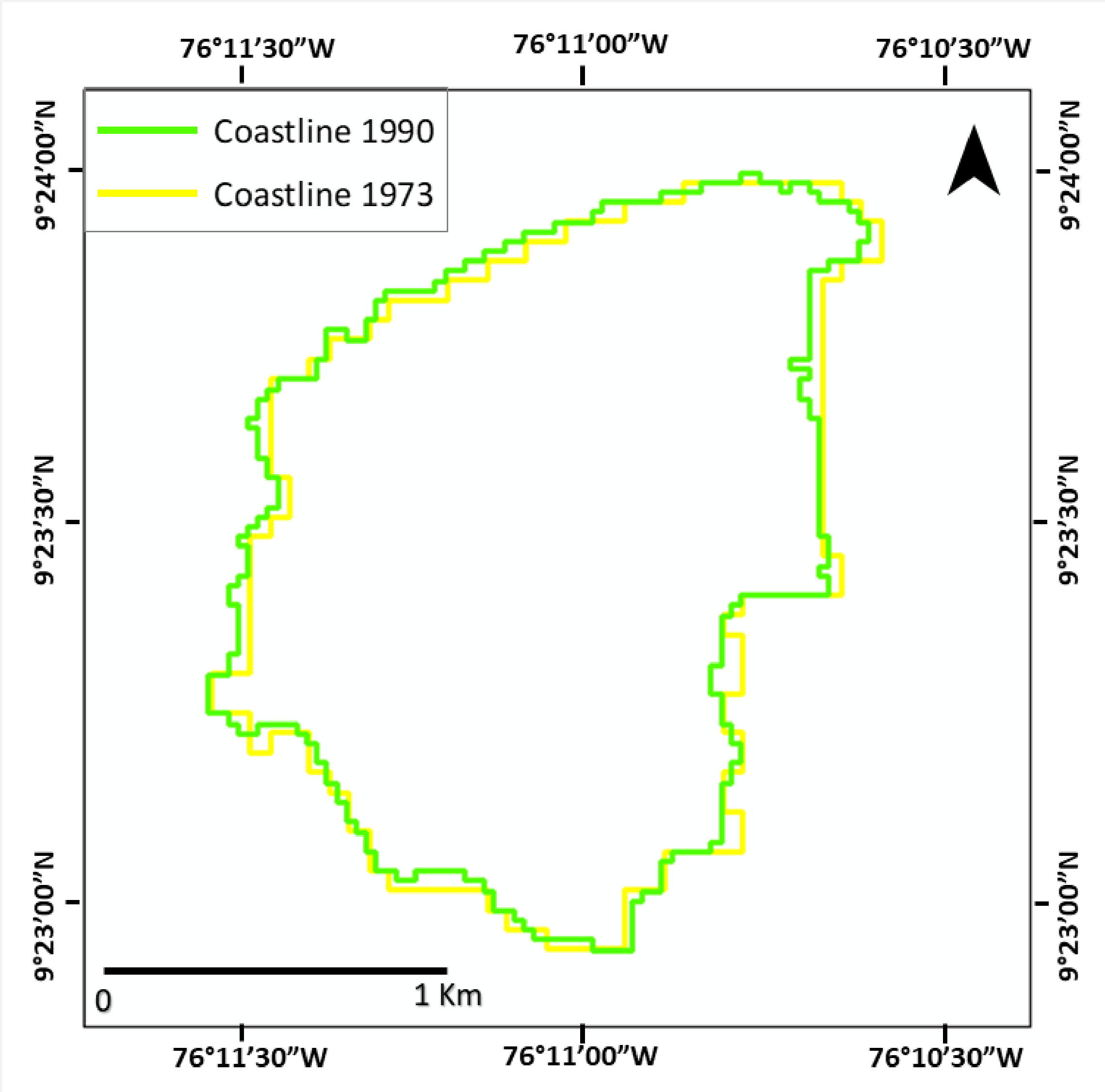

Figure 21 - Coastline Comparison 1973 → 1990

The first change in the coastline is observed when comparing the results of 1973, with an area of 303.48 Ha, and 1990 with 300.78 Ha, see Figure 21. This change can be attributed, in part, to differences in satellite images used. In 1973, a Landsat 1 image has a resolution of 60 m, while in 1990 the Landsat 5 image has a resolution of 30 m. This disparity is particularly evident in the marked perimeter, some differences are noted, such as the straight line on the east side of the island. This variation could be explained by the limitation of resolution, since a single pixel covers a considerable area, making it difficult to precisely specify the transition between land and sea.

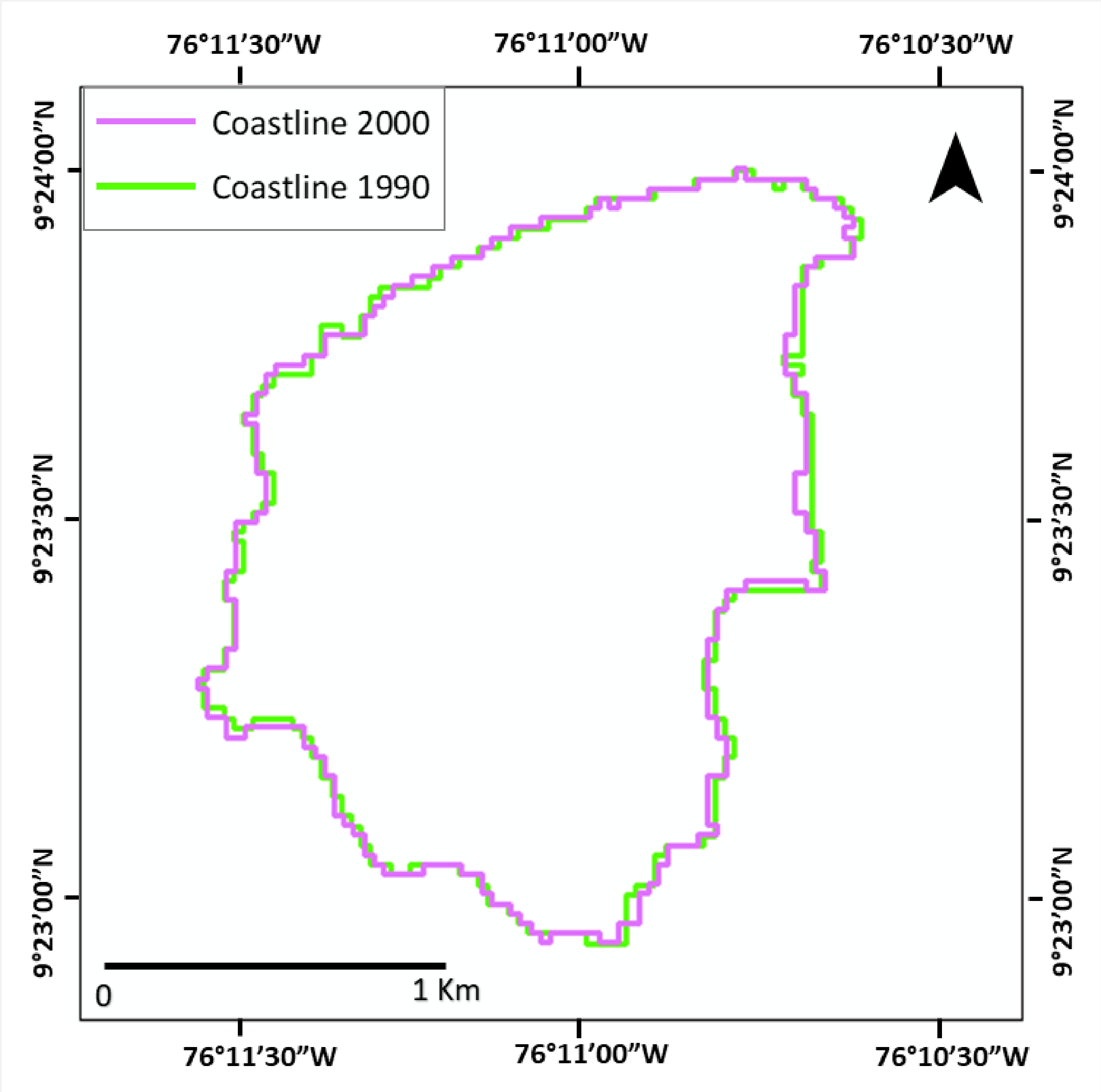

Figure 22 - Coastline Comparison 1990 → 2000

From this point onwards, all the images have the same resolution of 30 meters. Therefore, the year 1990 with an area of 300.78 Ha is considered the starting point for the coastline analysis. The transition from 1990 to 2000 with an area of 299.25 Ha, shows a closer relation with minimal changes, which may be the result from variations in certain pixels, see Figure 22. The most significant difference is still noticeable on the eastern side of the island, as previously mentioned. This region is classified as mangrove or flood zone, suggesting that the changes in these areas are possibly a response to both land use transformations and meteorological conditions during that period.

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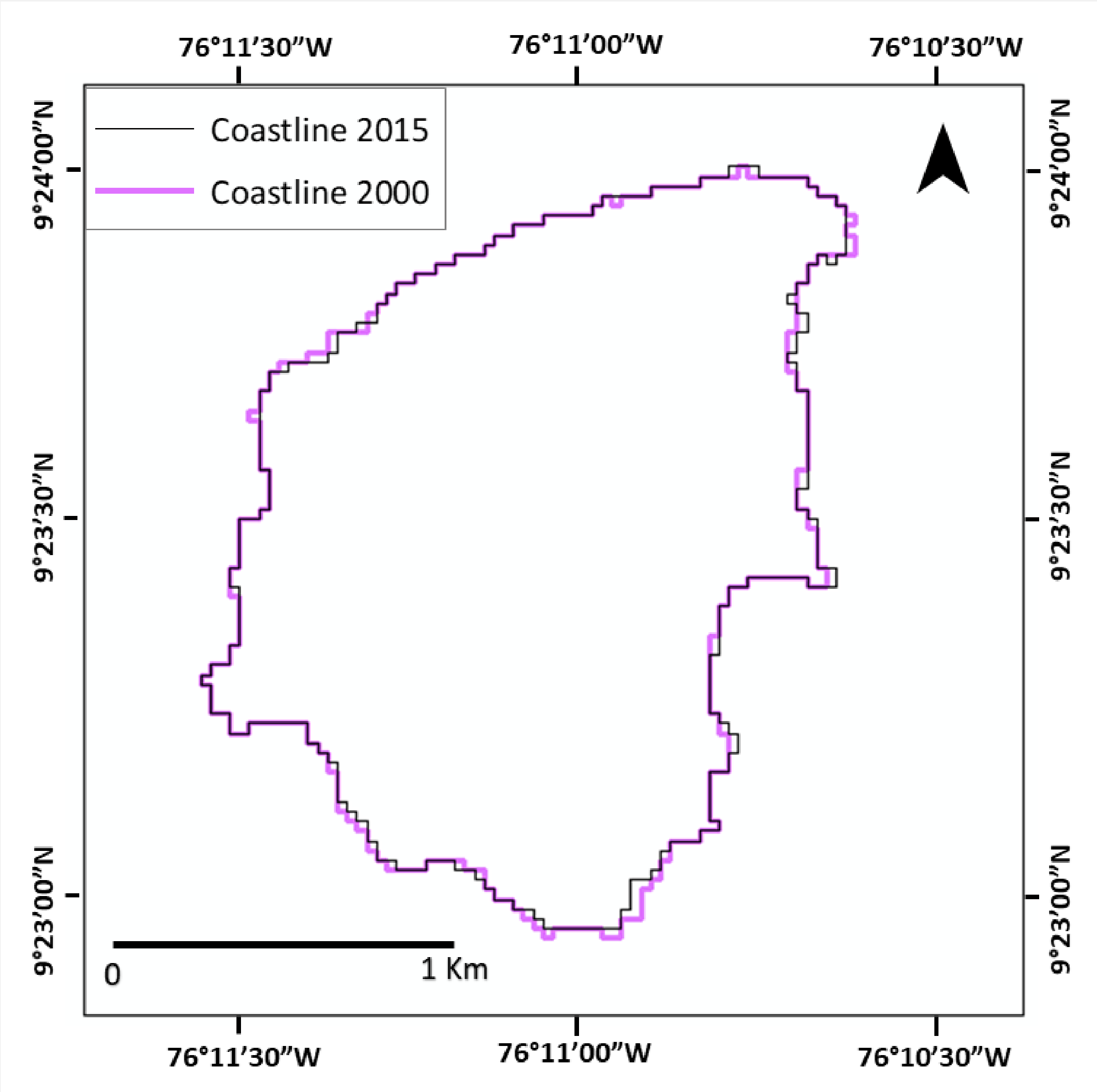

Figure 23 - Coastline Comparison 2000 → 2015

The period from 2000 with 299.25 Ha to 2015 with 298.44 Ha exhibits the least variation in area, see Figure 23. However, there are a few notable alterations in areas classified as mangroves. These changes in the coastline can be attributed to the transformation of these mangrove zones, which directly influences the configuration of the coastline.

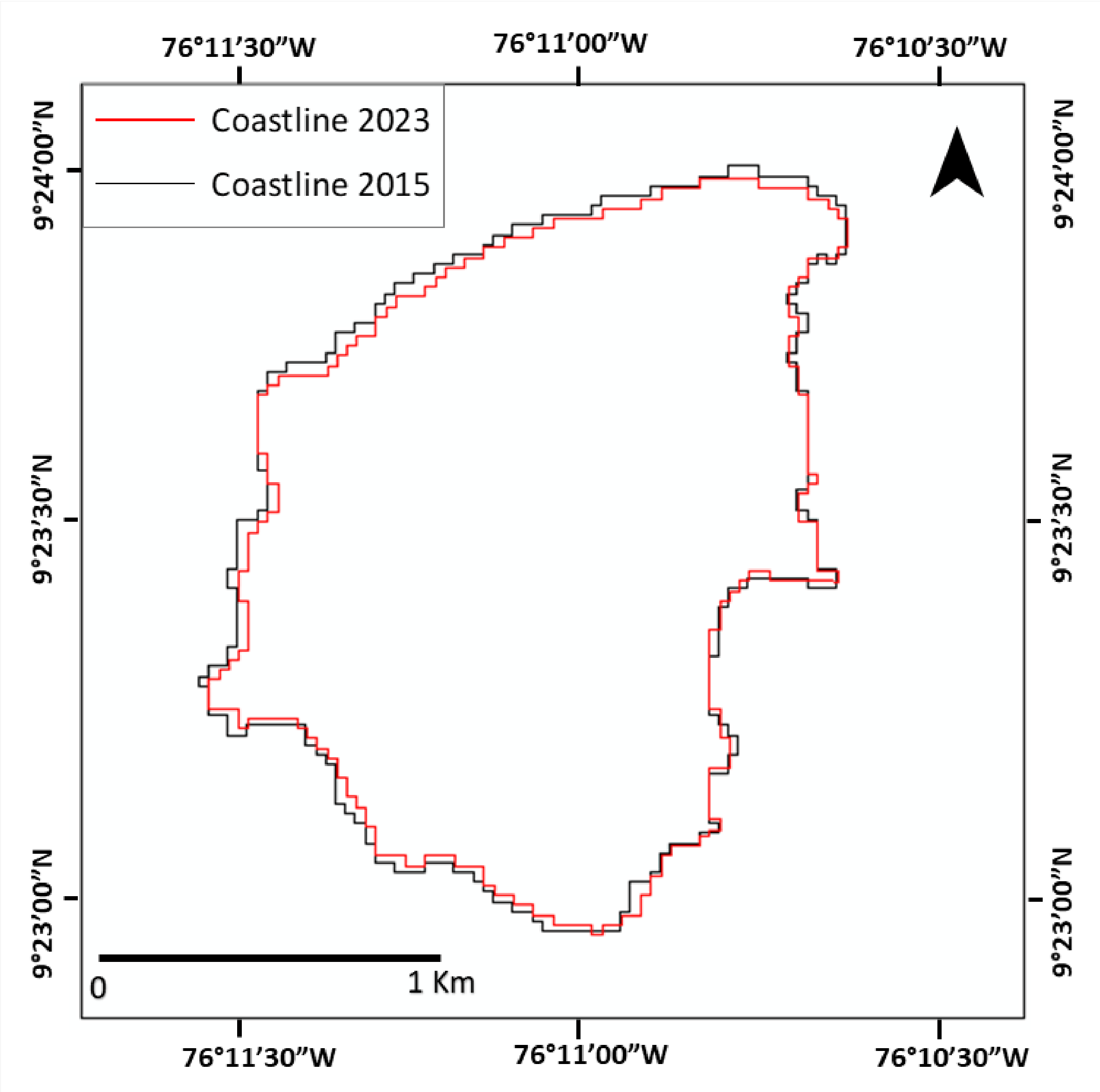

Figure 24 - Coastline Comparison 2015 → 2023

The most noticeable change occurs in the transition from 2015 with an area of 298.44 Ha, to 2023 with 286.47 Ha, see Figure 24. This period witnesses a substantial reduction in area, primarily attributed to the mangrove zones. However, the most significant change is observed on the north side of the island, where the greatest area loss corresponds to the forest category.

7. CONCLUSIONS

Area

- ✓ Over the 50 years analysis, an evident reduction has been observed in the total area of Isla Fuerte. The changes in the perimeter of the island have become an undeniable reality as we move forward in time.

- ✓ A highlight aspect is the consistency in area decline over the years. The results of this study showed an area of 2,864 km^2 in 2023, which is comparable to the research carried out by Diaz in 1996 (Díaz et al., 1996), who reported an area of 3.25 km^2 and later the work of Barreto-Tejada in 2022 (Barreto Tejada, 2022; Restrepo Moreno, 2023), who reported 2,969 km^2. Although a decrease in the area is reported in a single year (2022 and 2023), it is important to mention that the discrepancy can be justified due to differences in the work methodology of each project. However, regardless of this variation, this study supports the reduction trend over the course of 50 years, evidencing an undeniable decrease in the island's area.

Erosion

- ✓ An important discovery of this study is the significant erosion in both mangrove areas and forests or areas of dense vegetation. These valuable and diverse ecosystems have declined over the decades, raising significant concerns about the conservation of these natural environments.

- ✓ Another notable aspect is the constant variation in the extent of the mangroves that border the island. These ecosystems have experienced fluctuations over time, with the northeastern area of the island being the only one that has maintained relative constancy

- ✓ A clear retreat of the coastline and the loss of beach areas is observed, mainly on the east side of the island, especially in the period from 1970 to 1990. This phenomenon could be attributed to the initial resolution of the image used (60 meters in 1970). For the period of years 2015-

2023, the retreat of the coast affects the island as a whole, although its magnitude is more pronounced from the north to the west of Isla Fuerte

Land use

- ✓ The analysis of the change in land use in Isla Fuerte has revealed significant transformations over the 50 years studied. These changes include a noticeable increase in the urban area, especially in the "Puerto Limón" area, along with the appearance of some other constructions away from the urban core.
- ✓ A marked increase is observed in areas destined for agriculture, with increases of up to 80 hectares in each interval studied. This expansion began in the vicinity of the urban area in the southeast of the island and subsequently spread to the extreme west and north, gradually reaching the northern coast, could indicate changes in economic activities and land use on the island.
- ✓ The substantial decrease in the area of dense vegetation throughout the decades, a significant change was observed between 1970 and 1990, with a reduction of 48.52 Ha, followed by additional decreases of 8.5 Ha between 1990 and 2000 and 5.75 Ha between 2000 and 2015. However, in the last study period, between 2015 and 2023, an increase in the reduction rate was recorded, with a decrease of 15.53 Ha. These findings highlight the urgent need for conservation and environmental management measures to address the loss of dense vegetation in the region and underline the importance of a sustainable approach in future planning.

Information sources:

- ✓ It is essential to highlight that this type of analysis has been carried out thanks to the availability of information and access to these sources. Landsat images have played an essential role in this study by providing free and instant access.

Limitations

- ✓ The decision NOT to include the area classified as beach or wave-break zone in the year-over-year comparisons was necessary due to visual and resolution limitations of the images. The extension of the beach covers an area much larger than the geographical delimitation of the island itself. Working with the same parameters in all images ensures greater consistency in the results obtained.

Recommendations

- ✓ To enhance the identification of areas of interest and reduce uncertainties, it is suggested that image resolution be improved. This enhancement could lead to greater precision in the analysis, yielding more robust and detailed results.
- ✓ Field validation of the areas identified in the images is recommended. This on-site confirmation would enable the verification of the accuracy of the results derived from remote analysis, thus bolstering the reliability of the conclusions.

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