University of Puerto Rico Mayagüez Campus

College of Arts and Sciences

Department of Geology

Shoreline Analysis of southern Playa Salinas, Cabo Rojo during the last 94 years

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Abstract

Numerous studies have examined shoreline changes along the coast of Puerto Rico, but Playa Salinas, part of the *Salinas National Wildlife Refuge* in Cabo Rojo, remains unstudied. This research aims to investigate the causes of severe erosion affecting this area by analyzing spatial and temporal shoreline changes along a 0.83 km stretch using the *Digital Shoreline Analysis System (DSAS)*. The analysis incorporates aerial imagery from 1930, 1950, 1983, 2009, and 2017, along with a 2024 GPS survey, providing a comprehensive 94-year assessment of coastal erosion trends. The results indicate a long-term shoreline erosion rate of -0.68 m/yr from 1930 to 2024, with an average accretion rate of +0.10 m/yr. However, the long-term trend is less precise because shoreline changes typically occur on shorter timescales. That is why to understand recent changes, short-term trends between 2017 and 2024 reveal maximum erosion and accretion rates of -16.01 m/yr and +0.23 m/yr. These findings confirm the hypothesis that extreme erosion in the study area is driven by mangrove loss. The use of the *Normalized Difference Vegetation Index (NDVI)* highlights the critical role of natural barriers, such as vegetation, in protecting beaches from erosion.

Keywords: Playa Salinas, mangroves, shoreline, erosion, tombolo

Introduction:

Shorelines across the globe are retreating inland due to coastal erosion (Pilkey et al., 2009). This phenomenon is particularly widespread in Puerto Rico, where sandy shorelines are in a constant state of change, with erosion playing a significant role (Bush et al., 1995). Puerto Rico includes 44 coastal municipalities and boasts a coastline of approximately 799 miles (Barreto et al., 2019). This diverse shoreline includes 1,225 beaches, with 30% consisting of sandy shores, 28% vegetated areas, 15% rocky shorelines, and 18% developed structures (Barreto, 2017); where all types of shorelines represent some of the most dynamic environments on Earth, due to its constant change (Bush and Young, 2009).

Approximately 80% to 85% of the Earth's shorelines are retreating due to factors, such as, sea level rise, reduced sand supply, and increased storm activity (Pilkey et al., 2009). Puerto Rico is particularly vulnerable to these hazards, including coastal erosion, storm-surge flooding, and wave attack from hurricanes like Maria and Fiona. Additionally, less frequent events such as earthquakes can cause co-seismic land level changes, leading to shoreline migration (Jackson et al., 2012). Tombolos, which form in areas with abundant sediment, are especially influenced by waves, wind, and currents, resulting in significant shape changes although they may gradually recover sand over time (Earle, 2015).

In Puerto Rico, various shoreline change projects have been carried out, but none have specifically focused on Playa Salinas, Cabo Rojo (**Figure 1**). This national reserve showcases a variety of shoreline formations, including two distinct limestone knobs connected to mainland by a tombolo, which is bordered by a narrow beach (Kaye, 1959). The Salinas of Cabo Rojo comprises several ecosystems, particularly mangrove forests, which act as a natural barrier for the narrow beaches (Griswold et al., 2024). In 2019, 48% of the mangroves in the Salinas of Cabo Rojo Natural Reserve, covering approximately 61,990 m^2 of the total 130,336 m^2, were dead, marking a significant increase in mangrove loss since 2004, whereas in 1998, there had been no mangrove deaths in the reserve (Escalera et al., 2020). In addition to mangroves, this reserve also includes subtropical dry forests, natural salt flats, and hypersaline lagoons.

Tropical islands, like Puerto Rico, are highly vulnerable to atmospheric events such as tropical storms and hurricanes. Mangroves, which are tidal forests found in subtropical and tropical regions, play a crucial role in protecting shorelines from significant erosion during

Figure 1: The study area of Playa Salinas, Cabo Rojo, Puerto Rico (Esri, 2024).

extreme weather events (Baldwin et al., 2001) often severely impact mangrove forests due to powerful winds, storm surges, and waves.

Among mangrove species, red mangroves are typically located closest to ocean waters, making them particularly exposed to wind and wave energy (Lugo and Snedaker, 1974). Despite their vulnerability, red mangroves demonstrate remarkable resilience by stabilizing sediments and providing critical coastal protection. The study area has experienced frequent atmospheric events, including storms and hurricanes. Recent major events, such as Hurricane Maria and Hurricane Fiona, have caused significant damage to the region (**Figure 2**), underscoring its vulnerability and the pressing need for effective coastal resilience measures.

The study of shoreline changes in Puerto Rico has been conducted multiple times since 1994 by Dr. Robert Thieler, a geologist from the USGS in Woods Hole, Massachusetts. In 2007, Thieler et al. analyzed shoreline changes over 70 years (1936-2006) along 8 km of the coast of Rincón, Puerto Rico. Using the *Digital Shoreline Analysis System (DSAS)* for temporal shoreline analysis, they determined that the area's erosion was primarily due to human-induced factors (Thieler et al., 2007). The study also highlighted other factors impacting shorelines, such as waves, currents, long-term sea-level rise, and structures built to mitigate wave impact (Thieler et al., 2007).

Several UPRM geology undergraduate research projects, including those by Manuel Ramos Rodríguez (2017, 2018), Yanira Santiago Pérez (2015), and Héctor Crespo Jones (2013), have utilized DSAS for shoreline analysis. Building on their work, this study will not only apply DSAS for temporal shoreline analysis but also investigate the causes of extreme erosion, with a focus on mangrove loss as a primary factor. Vegetation changes will be analyzed using the Normalized Difference Vegetation Index (*NDVI*) from the 1980s to the

Figure 2: Mangrove wetland degradation in the southern region of Playa Salinas, Cabo Rojo, Puerto Rico, specifically in coordinates 17°56’57” N, 67°11’29.67” W. The photograph was taken on May 21, 2024 by Valeria A. Pérez Rivera.

present through satellite images (**Figure 3**). The study site covers 0.84 km (**Figure 4**), an area from 17° 56' 57" N, 67° 11' 29.67" W to 17° 56' 55" N, 67° 11' 33" W, aiming for a comprehensive understanding of coastal changes.

The primary objective of this research was to statistically quantify the extreme erosion occurring in Playa Salinas, Cabo Rojo, Puerto Rico. Given the dynamic nature of this area; influenced by currents, tides, waves, and wind, understanding the underlying processes driving these changes became a key focus. This study hypothesized that the severe erosion rates will coincide with the lowest NDVI values.

Methodology

Aerial Photographs

This research analyzed a series of five aerial photographs from the years 1930, 1950, 1983, 2009, and 2017 to study the coastal changes in the selected area. The 1930 and 1950 photographs were sourced from the *"Porto Rico 1930 Georeferenced: A Coastal Mosaic"* website. These images are black-and-white mosaics of georeferenced aerial photographs with a spatial resolution of one meter. The 2009 photograph was acquired from *NOAA-Digital Coast's Data Access Viewer*. This georeferenced true-color photograph has three bands and offers a spatial resolution of 0.30 meters. The 1983 photograph, acquired from the *USGS Earth Explorer* website, required georeferencing using *ESRI ArcGIS 10* software. This process involved aligning it with the 2009 photograph using key landmarks as ground control points to ensure accurate spatial representation.

The 2017 image was downloaded from the National Geodetic Survey conducted by NOAA, taken two to six days after Hurricane Maria. The data were downloaded in *ArcGIS*

Figure 3: Examples of both dead and living mangroves were identified in a 2023 image of the study area (ESRI, 2024).

Figure 4: Study area in the southern part of Playa Salinas, Cabo Rojo, adjacent to the sea salt ponds (Esri, 2024).

Pro 10 in WMTS format, allowing access to all data collected across the island during that time frame. These data encompass the period from September 22 to 26 of the previously mentioned year. The WMTS format allows efficient access to large spatial datasets by dividing the map into smaller tiles that load quickly across different zoom levels. This setup

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Shoreline Analysis

The shoreline changes over the past 94 years was analyzed with the *Digital Shoreline Analysis System (DSAS)* software, version 6.0, which was originally developed as an ArcGIS tool but became a standalone application in April 2024, while still being integrable with GIS for comprehensive analysis (Thieler et al., 2024). Developed by the U.S. Geological Survey, DSAS calculates rate-of-change statistics by analyzing multiple shoreline positions, allowing researchers to quantify erosion and accretion trends over time (Thieler and Danforth, 1994). While the 94-year analysis provides valuable long-term trends, its accuracy may be limited, prompting the decision to conduct two short-term analyses. These short-term analyses, focusing on data from 1930–1950 and 2017–2024, were crucial in verifying the study's hypothesis.

Shorelines were mapped using *ArcGIS Pro* software, and an onshore baseline was created to serve as a reference for the study. After tracing all shorelines, they were merged into a single file for efficient processing and converted into *.geojson* format to ensure compatibility with DSAS (Himmelstoss et al., 2021). Once the data was converted, it was uploaded into DSAS. After uploading the baseline and shoreline data, transects were generated at regular intervals along the shoreline (**Figure 5**). These transects were spaced 10 meters apart and extended 2,500 meters in length (**Figure 6**), allowing for the measurement

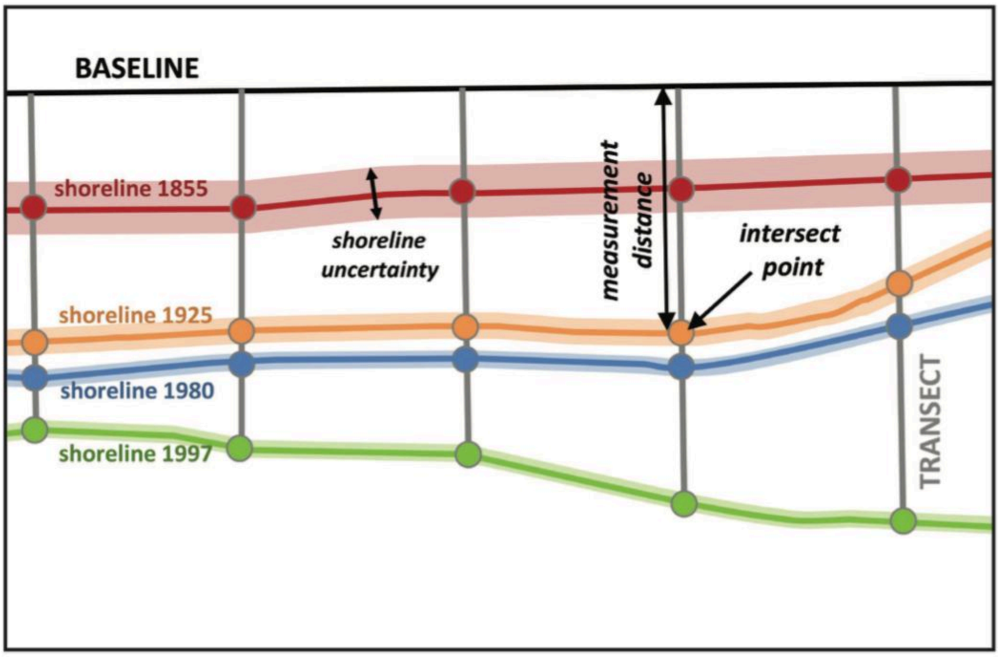

Figure 5: The software creates the transect from the baseline and different years of shoreline digitalization added by the user (Himmelstoss et al., 2021).

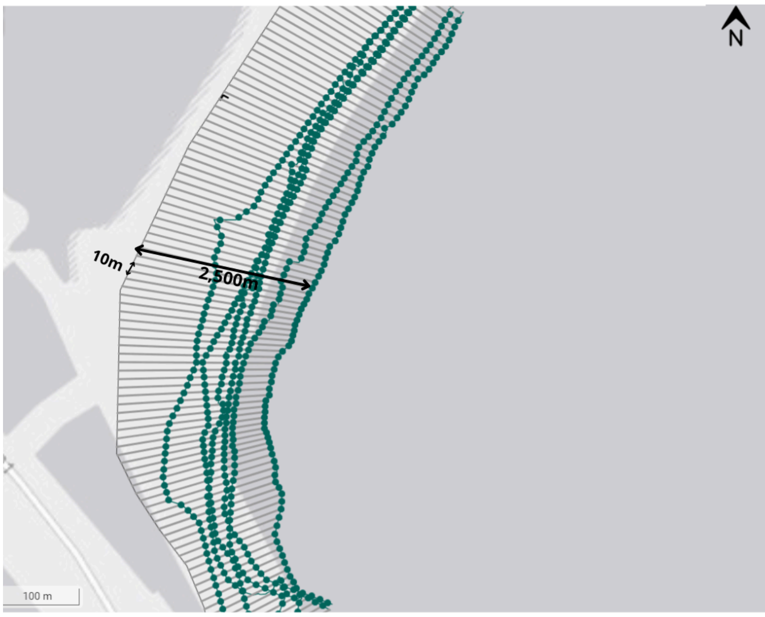

Figure 6: The transects generated by the DSAS standalone software were spaced 10 meters apart and extended to a length of 2,500 meters.

of changes by comparing historical shoreline positions. After DSAS generated the transects, multiple shoreline analyses were conducted using various methods. These included the Net Shoreline Movement (NSM), which measures the distance between the oldest and most recent shoreline positions, and the End Point Rate (EPR), which calculates the annual rate of shoreline movement (**Figure 7**; Thieler et al., 2009). Additionally, the Shoreline Change Envelope (SCE) that is the calculation of the farthest shoreline from the closet to baseline transect (Thieler et al., 2009) DSAS also provides a summary report with all the data calculated.

GPS Survey

A field survey was conducted on October 13, 2024 targeting specific locations between the mentioned coordinates of the study site to accurately capture the current shoreline position of southern Playa Salinas. A GPSMap 76CS device (**Figure 8**) from the UPRM GERS Lab recorded geospatial data by walking along the shoreline and logging coordinates at regular intervals, providing a precise record of the present coastline. The shoreline was established by walking along the edge of the sargassum (**Figure 9**), and sometimes at the top of the sargassum (**Figure 10**). It’s important to note that shoreline measurements can vary depending on the time of day the GPS survey is conducted. This survey was conducted between 12:00 PM and 3:00 PM during a tide change (**Figure 11**), which influenced the results. To account for variability, the survey was repeated three times, enabling the calculation of an average from the two most accurate data sets. The processed GPS data were integrated with historical shoreline data from aerial photographs. The 2024 shoreline was compared with a Sentinel-2 aerial image from November 2, 2024, which has a spatial resolution of 10 meters. The Sentinel-2 image, captured by the Multispectral Imager (MSI), provides data across multiple wavelengths of light, including visible and near-infrared

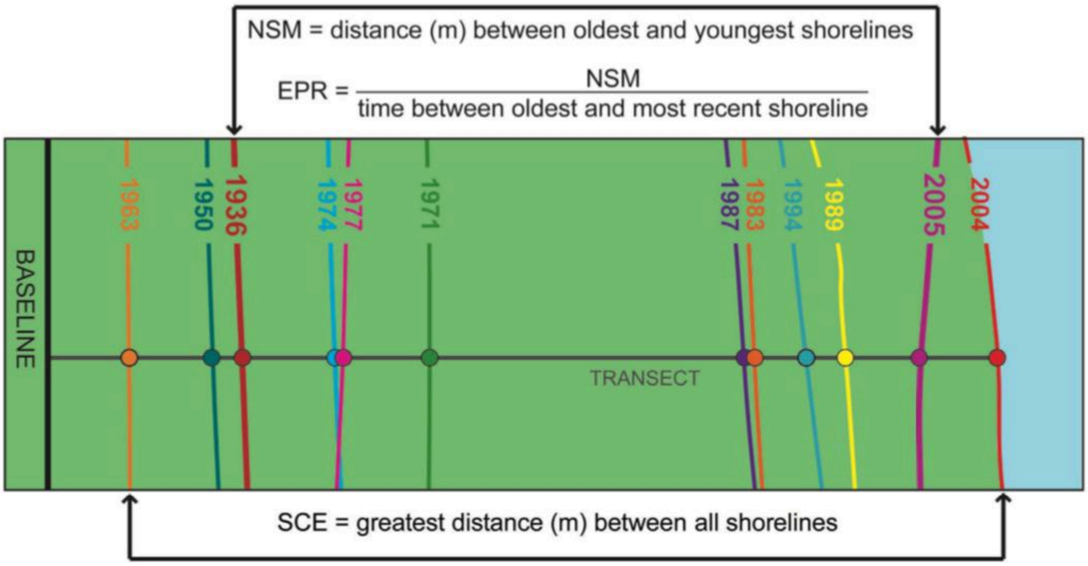

Figure 7: Net Shoreline Movement (NSM) calculates the distance between the oldest and youngest digitized shorelines. The End Point Rate (EPR) divides this distance NSM by the 94-year period between these shorelines. The Shoreline Change Envelope (SGE) represents the greatest distance between all digitized shorelines (Himmelstoss et al., 2021).

Figure 8: Garmin HandHeld GPS instrument that was utilized for the field survey of the current shoreline.

Figure 9: The GPS survey involved walking the 0.83 km on Playa Salinas three times to ensure more accurate sampling data.

Figure 10: The GPS survey involved walking through 0.83 km on Playa Salinas three times to ensure more accurate sampling data. At times, walking on top of the sargassum was required, which was interpreted as the boundary between the dry and wet portions of the shoreline.

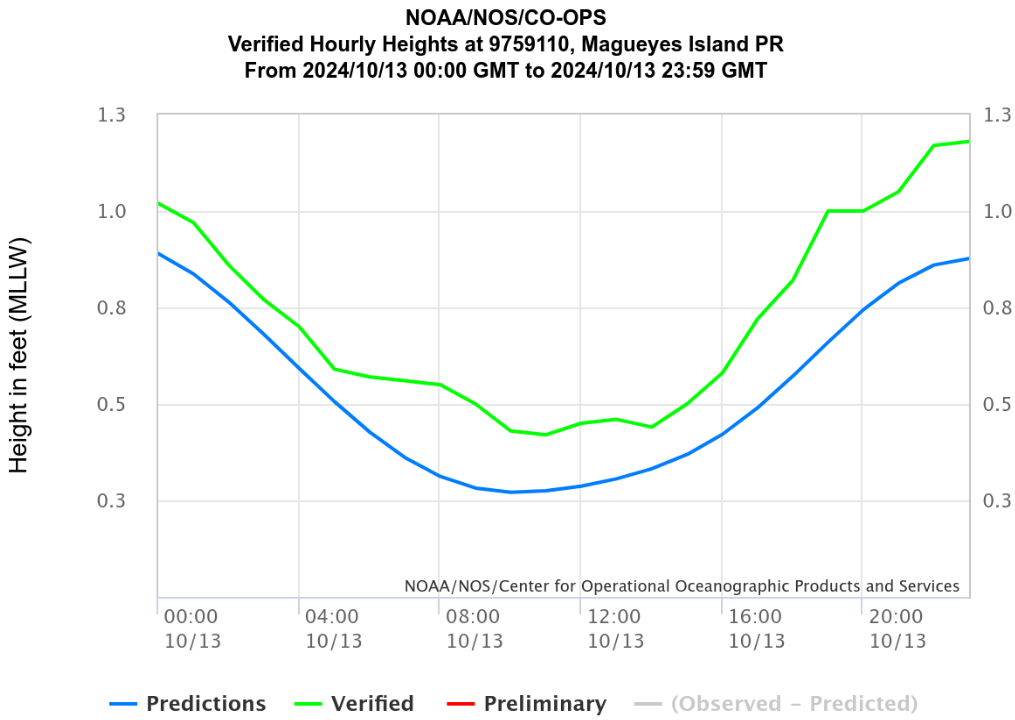

Figure 11: The tidal data for the GPS survey corresponds to the same date and was obtained from the nearest buoy in *La Parguera* (CARICOOS, 2024).

and shortwave infrared. It helps monitor Earth's land and coastal areas by providing detailed data on vegetation, water quality, soil, and land changes.

NDVI Calculation

This study evaluated the changes in mangrove coverage as related with the shoreline changes. This aspect was investigated, with four images from 2017, 2020, 2022, and 2024, taken by the *Landsat-9 OLI-2* sensor that were downloaded from the USGS-Earth Explorer website to calculate the Normalized Difference Vegetation Index (NDVI). Also, an aerial image from 2009 was utilized for NDVI analysis, to know what was the change in the four dates selected before. This estimation was made using the NDVI tool within ENVI Software for the four *Landsat-9 Oli-2* images, but ArcGIS Pro was utilized for NDVI analysis of the 2009 image. The tools, both in ENVI and ArcGIS Pro, use the same following equation:

$$\mathrm{NDVI}=\frac{NIR-R}{NIR+R}$$

NIR: reflectance value in the near-infrared band of the electromagnetic spectrum.

R: reflectance value in the red band of the electromagnetic spectrum.

The NDVI values (using a green palette) range from **-1 to +1**, with each range indicating different surface characteristics. Negative values (e.g., -1 to 0) correspond to non-vegetative surfaces such as water, snow, or barren land (white values). Values close to 0 represent areas with sparse or no vegetation, like rocks or soil (pale color). Positive values (e.g., 0.2 to 1) indicate vegetated areas, with higher numbers signifying denser and healthier vegetation (more intense color). For instance, NDVI values between 0.2 and 0.5 suggest sparse vegetation, while values between 0.5 and 0.7 indicate moderate to dense vegetation. Very dense and healthy vegetation typically falls within the range of 0.7 to 1. This scale allows researchers to effectively monitor vegetation changes over time.

Results and Discussion

The shoreline dynamics of Playa Salinas, Cabo Rojo, exhibit significant and ongoing changes closely tied to its geomorphological features, a tombolo. This unique landform, formed by sediment deposition that connects an island to the mainland, is continuously changing due to interplay of ocean currents, wave action, and wind-driven processes (Earle, 2015). These forces contribute to the tombolo's inherent instability, leading to fluctuations in sediment deposition and erosion over time (Earle, 2015). Consequently, the structure and position of the tombolo experience persistent changes, which influence the surrounding coastal environment.

Historical shoreline observations reveal a complex pattern of change over time. Between 1930 and 1950 (**Figure 12**), the shoreline experienced sediment accretion, gaining material over 20 years. However, in the subsequent 33 years, significant erosion occurred, resulting in a notable reduction of the shoreline (**Figure 13**). From that point onward, the shoreline has continued to decline, culminating in its current state (**Figure 14**). Although some periods of sediment accretion were observed, the overall trend shows a predominant net loss of sediment. According to the NSM analysis, 95 transects exhibited negative distances, indicating that 97% of the shoreline experienced erosion. NSM calculates the net change in shoreline position by measuring the distance between the oldest (1930) and most recent (2024) shorelines over 94 years. The NSM analysis revealed an average shoreline retreat of -63.89 meters, with the greatest reduction occurring at transect ID 85, where the shoreline receded by -107.17 meters (**Figure 15**). The EPR, which divides this change by the elapsed time, revealed a consistent shoreline retreat rate of -0.68 m/yr, underscoring the severity of erosion in the area. While erosion was the dominant process, brief accretion occurred in just

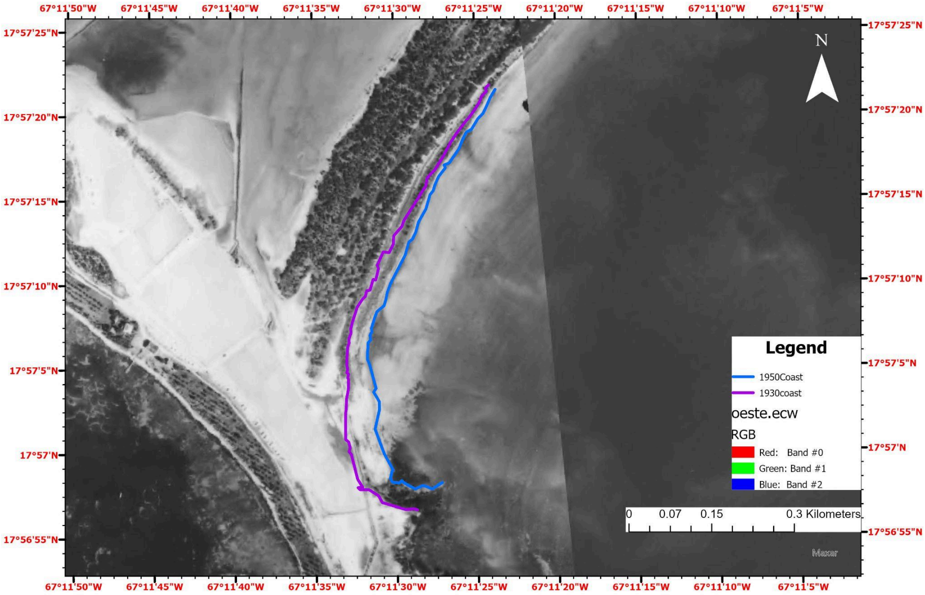

Figure 12: Black and white aerial photograph of Playa Salinas from 1950, illustrating shoreline changes between 1930 (purple line) and 1950 (blue line).

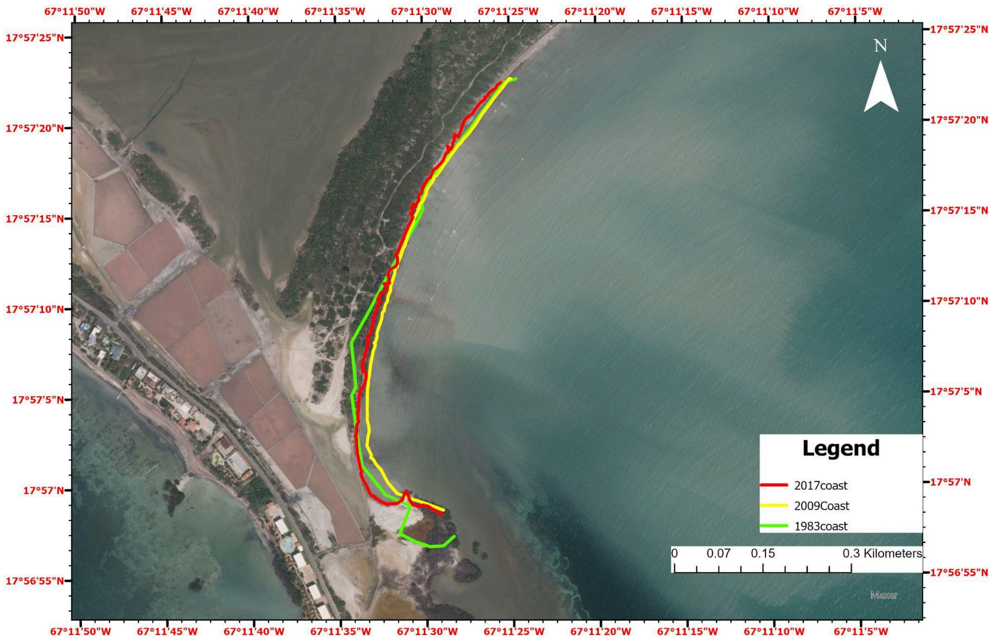

Figure 13: True color aerial imagery of 2017 displaying 1983 (green line), 2009 (yellow line), and 2017 (red line) shorelines.

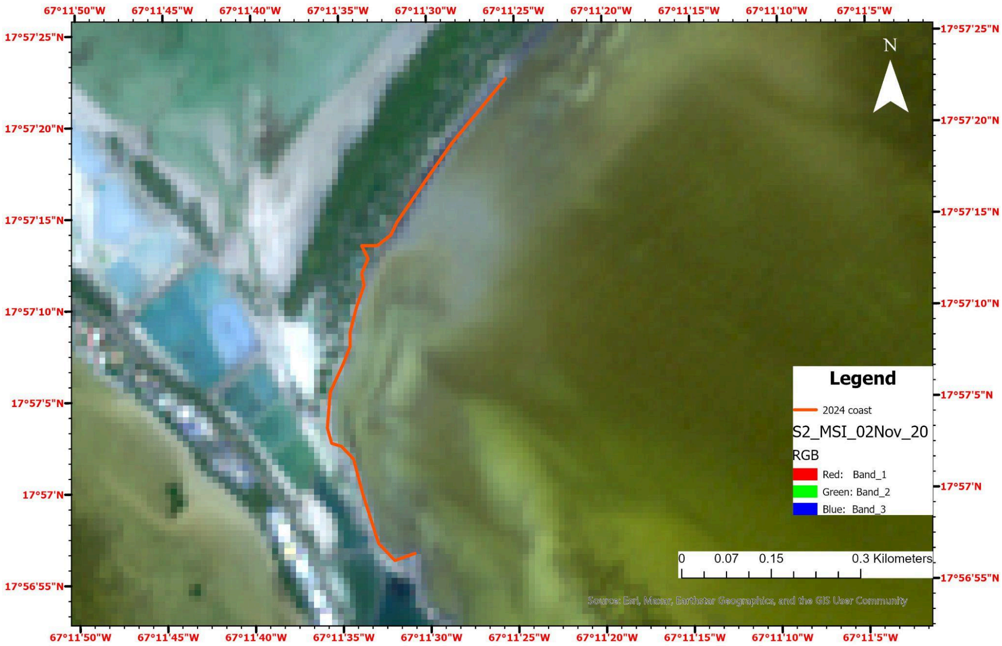

Figure 14: True color Sentinel-2 image with a spatial resolution of 10 m from November 2, 2024 displaying 2024 (orange line) shoreline made during a GPS survey.

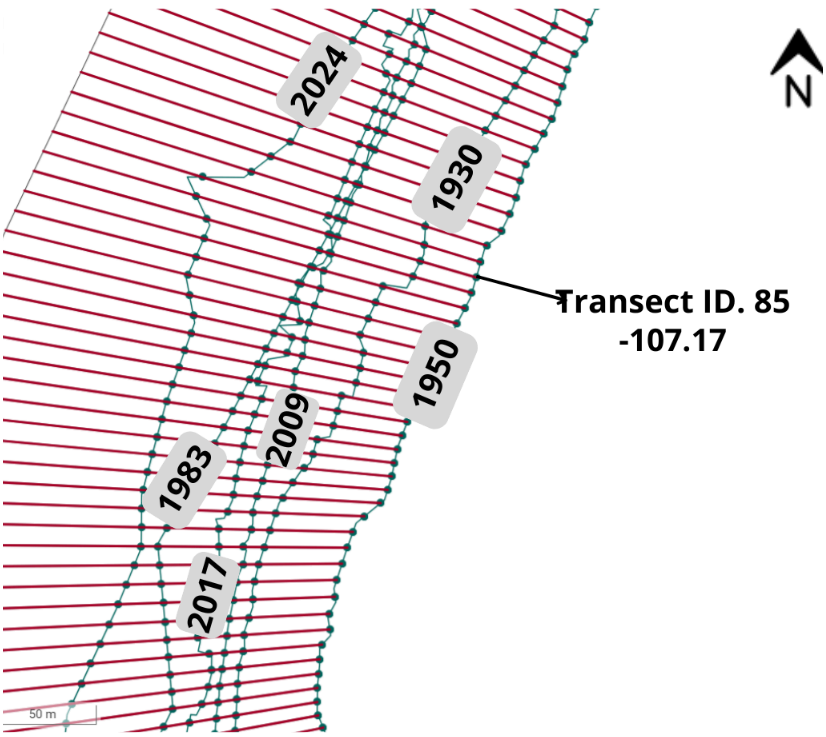

Figure 15: Transect ID 85 exhibited the maximum shoreline retreat in Playa Salinas with -107.17 meters.

three of the 98 transects, with a maximum rate of 0.10 m/yr, highlighting its minimal and isolated nature. Spanning nearly a century, this long-term analysis captures persistent trends but may mask short-term variations, which supplemental observations and shorter-term studies confirm and contextualize.

A short-term variation analysis was conducted to better understand and quantify regression and deposition events along the shoreline. The analysis of shorelines from 1930 and 1950 revealed an average accretion of 35.92 meters over the 20-year period, with a rate of 1.80 m/yr. This accretion may have been influenced by the impact of an unnamed Category 2 hurricane that struck the study area in 1926 (**Figure 16**), causing significant erosion along the 1930 shoreline and potentially setting the stage for subsequent recovery and sediment accumulation. The recovery could have happened by increased sediment supply that had come from near rivers or creeks along the southwest coast. The longshore current likely transported sediment from the mouths of rivers and creeks or from areas southwest of Puerto Rico. Upon reaching the study area, the sediment became trapped among the extensive mangrove roots and over time, it was subsequently deposited in Playa Salinas. This process was further influenced by localized reductions in wave energy and natural recovery mechanisms following storm events.

Another short-term shoreline analysis was conducted by comparing the 2017 and 2024 shorelines. In 2017, Hurricane Maria struck Puerto Rico, making landfall in Yabucoa and moving northwest across the island before exiting between Quebradillas and Isabela in the island's northwest region. The records indicate that the weakest areas impacted by Hurricane María were located in the southwest region of the island, including Playa Salinas. The effects of wind, currents, and waves were less severe in that region (**Figure 17)**. Five years later, Hurricane Fiona impacted the area as a Category 1 hurricane (**Figure 18**).

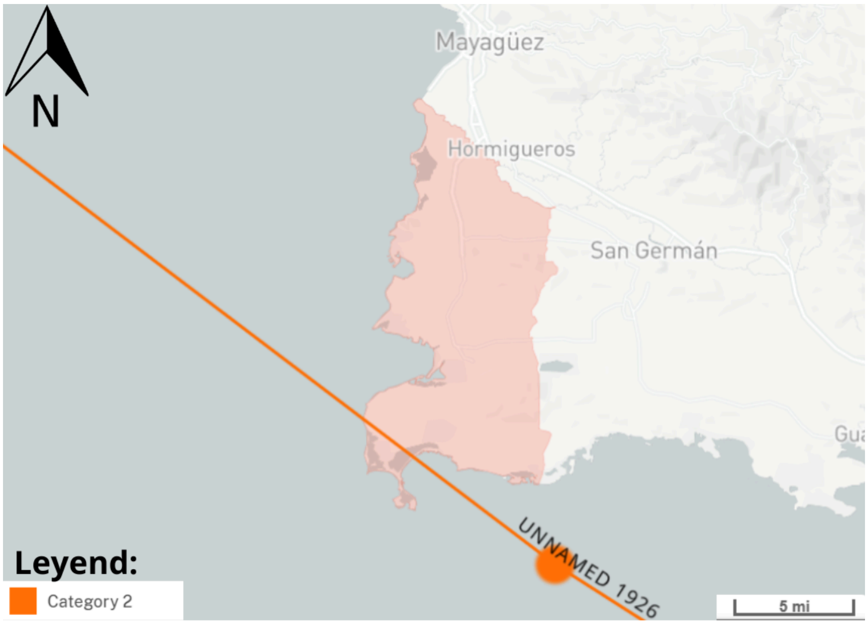

Figure 16: The unnamed Category 2 hurricane that impacted or passed near the study area in 1926.

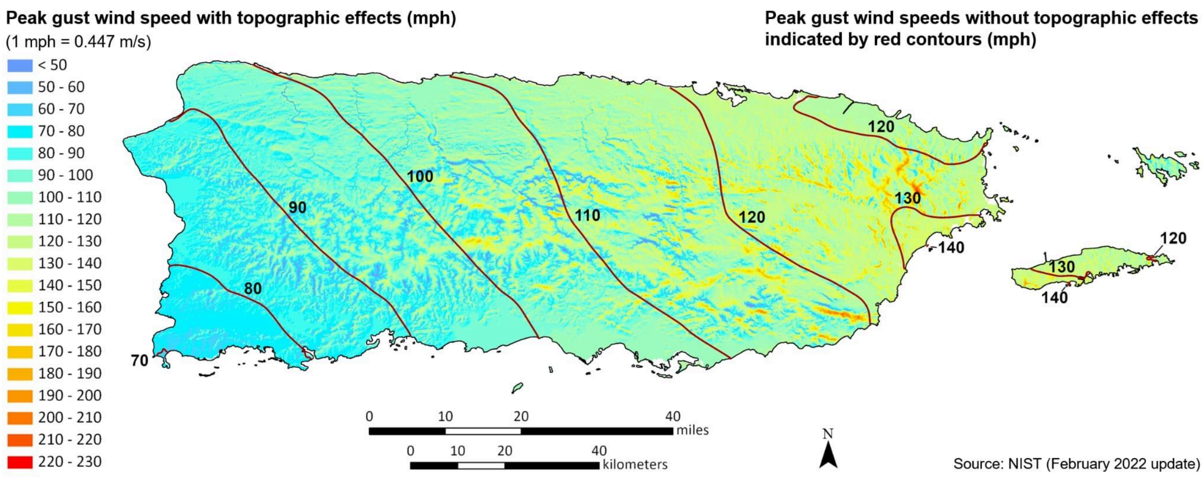

Figure 17: The sustained winds from Hurricane Maria in the study area indicate that the hurricane's impact was experienced at the intensity of a tropical storm (NIST, 2022).

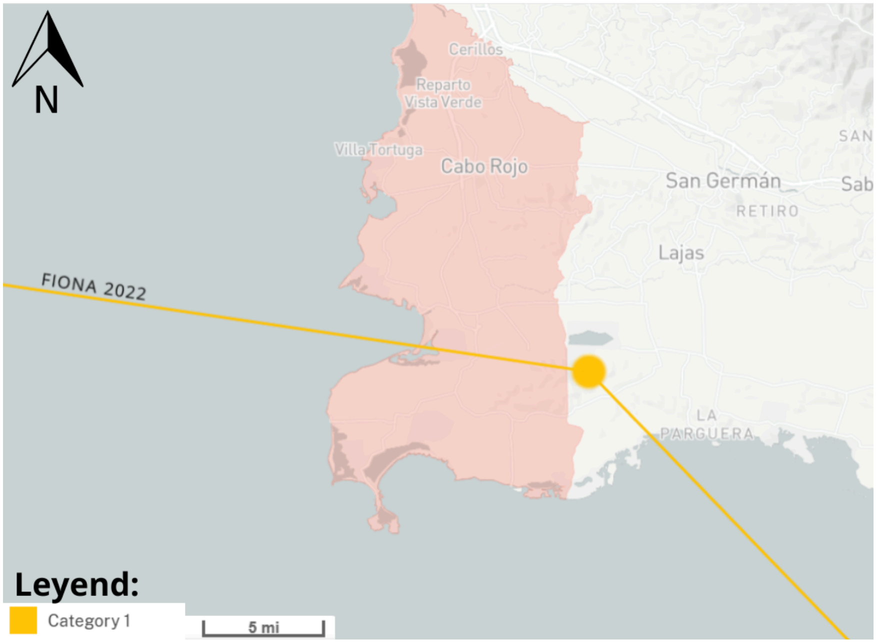

Figure 18: On September 18, 2022, Hurricane Fiona (a Category 1 hurricane) passed through the study area.

Given the minor damage from Hurricane Maria, ocean water intrusion into the study area was observed, as seen in the NDVI (**Figure 19**).

Playa Salinas proved particularly vulnerable with Hurricane Fiona causing further damage to an already weakened shoreline. NDVI analysis from October 2022 (**Figure 20**) revealed a reduction in mangrove cover in the southern portion of the study area, as shown in Figure 1. This loss exacerbated shoreline fragility, leaving it more susceptible to wave and tidal events, resulting in a significant net loss of shoreline during this period. This loss of shoreline fragility revealed with the NSM analysis an average shoreline retreat of -33.63 meters across 96 of the 99 transects, with 96.97% of the transects showing signs of erosion. The EPR further supports this, showing an average erosion rate of -4.77 m/yr, with a maximum erosion of -16.01 m/yr being in transect ID 26, with a retreat calculated by NSM in -112.90 m (**Figure 21**). While some accretion occurred, it was minimal, with only 3.03% of transects exhibiting positive movement and an average accretion rate of 0.08 m/yr.

The loss of sediment in the area may be linked to the decline in mangrove cover, which has historically served as a crucial protective barrier against shoreline erosion. Mangroves play an essential role in stabilizing coastlines by dissipating wave energy and reducing the impact of tidal currents, which otherwise contribute to erosion (Lugo and Snedaker, 1974). Their complex root systems help anchor sediments, preventing them from being washed away, while also facilitating sediment deposition, which supports the growth and stability of the shoreline over time (Lugo and Snedaker, 1974). According to a study by Escalera (2019), mangrove loss in the region became evident as early as 2004. Key factors contributing to this decline include rising sea levels, as well as anthropogenic activities both in the study area and throughout the southwest of Puerto Rico.

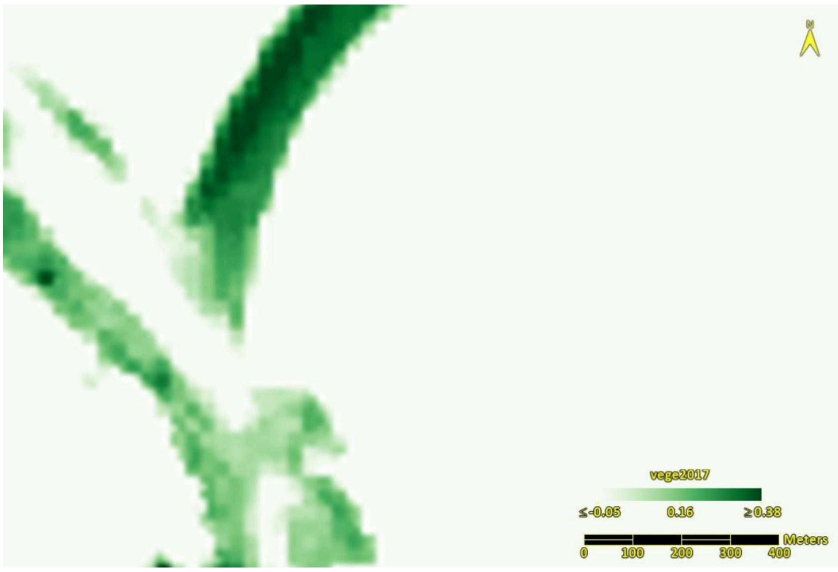

Figure 19: The NDVI analysis indicated ocean intrusion into the salt flats of Hurricane Maria, as values from and less of -0.05, corresponding to water, were detected in Playa Salinas study area. This intrusion is clearly visible in the imagery.

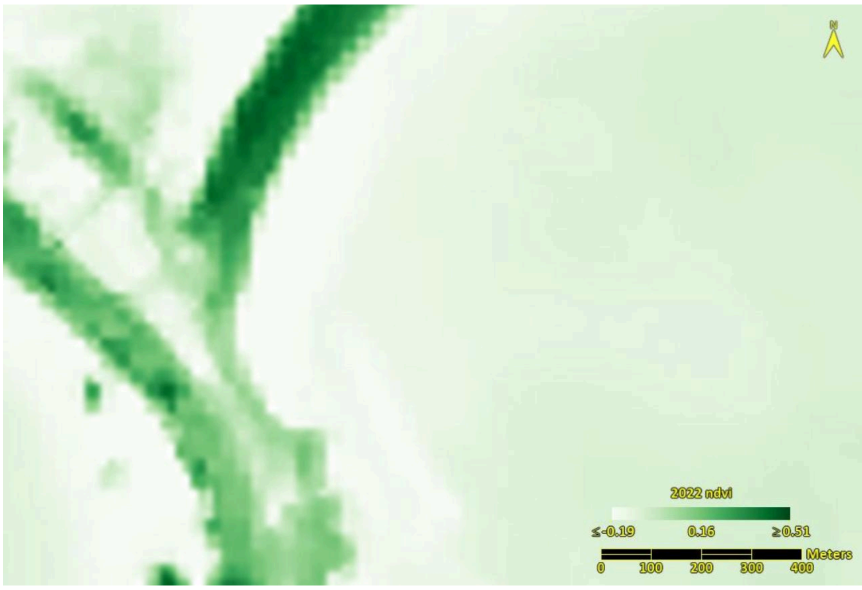

Figure 20: The 2022 NDVI analysis revealed a reduction in mangrove density in the southern part, shown in Figure #1, of the study area following Hurricane Fiona. Areas previously covered by mangroves showed values of less -0.19, indicative of water, highlighting significant mangrove loss in the Playa Salinas study area.

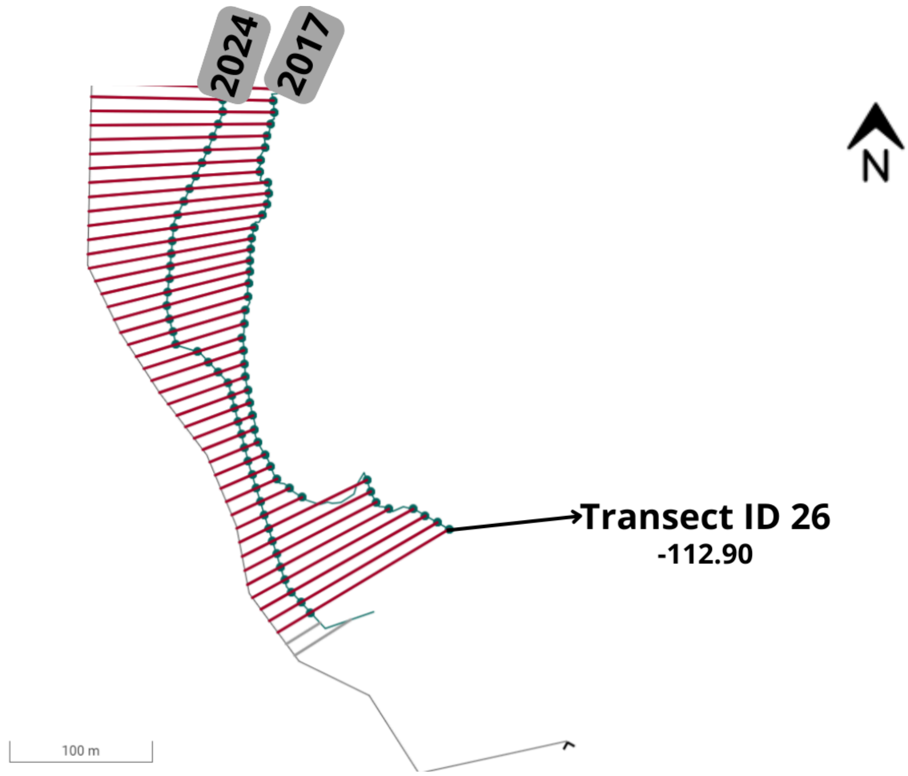

Figure 21: The transect ID 26 had a maximum erosion of -16 m/yr, with a retreat calculated -112.90m.

The longshore current transports sediments from different rivers and creeks mouths to the study area, but that longshore current does not only transport sediment. A significant amount of trash generated in the southwest region of Puerto Rico, as well as from other unknown sources, becomes trapped in the roots of mangroves, as seen in Figure 11 of the capacity to act as carbon sinks, but also causes physical damage to the roots of red mangrove, altering the ecosystem (Yuniar et al., 2023). They also indicate that accumulation of waste can degrade water quality, harm local fauna that rely on mangroves for habitat, and increase the risk of invasive species proliferation.

In the three years after Hurricane Maria, the area showed minimum recovery as the NDVI 2020 analysis showed (**Figure 22**). Recovery in such areas can take decades, but predicting this with certainty is difficult, as the vegetation that once stabilized the sediment and supported natural restoration processes has died. While mangrove die-off was already occurring in 2009 (**Figure 23**), it was not as extensive as the widespread loss observed today (**Figure 24**). These findings emphasize the critical role of vegetation in shoreline stability and the long-term challenges posed by climate events and environmental degradation. Without targeted restoration efforts, the natural recovery of Playa Salinas may remain unattainable, further exposing the area to more coastal erosion, shoreline reduction and habitat loss.

Conclusion

This study analyzed 94 years of shoreline changes in Playa Salinas, revealing an average erosion rate of −0.68 m/yr and a maximum accretion rate of +0.10 m/yr. While the analysis spans a long temporal range, potentially masking short-term variations, additional physical observations and subsequent short-term analyses confirmed the identified trends. The NDVI analysis indicated higher vegetation values in 2009; however, significant mangrove loss was evident following Hurricane Fiona

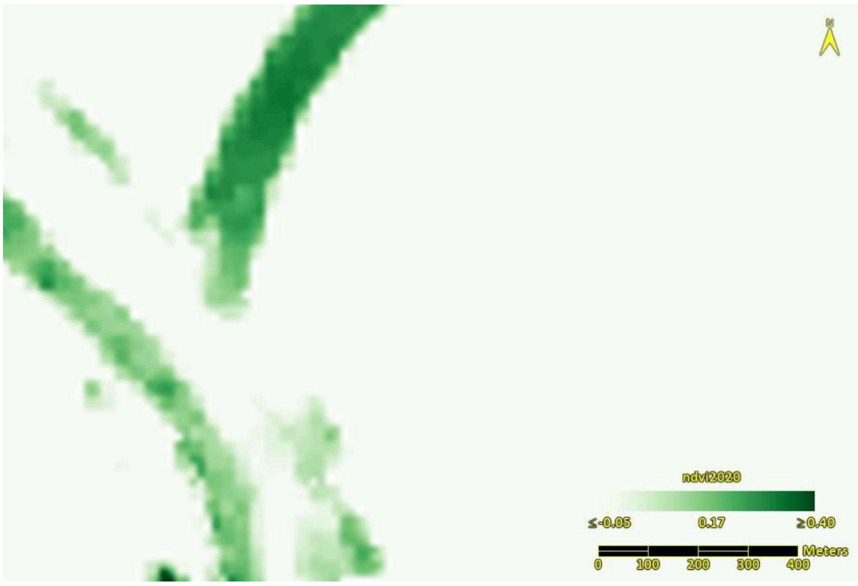

Figure 23: The NDVI analysis in Playa Salinas indicated ocean intrusion after three years of Hurricane Maria (2020), as values are near or less than -0.05, corresponding to water.

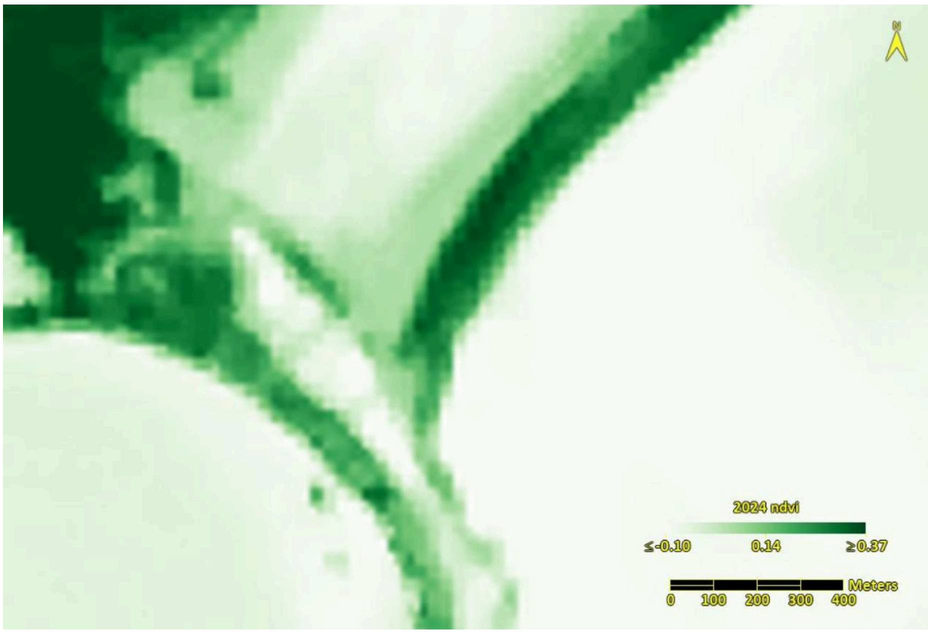

Figure 24: The 2024 NDVI analysis indicated vegetation and shoreline reduction on the south of the study area after two years of Hurricane Fiona. The values are near or less than -0.10 corresponding to water.

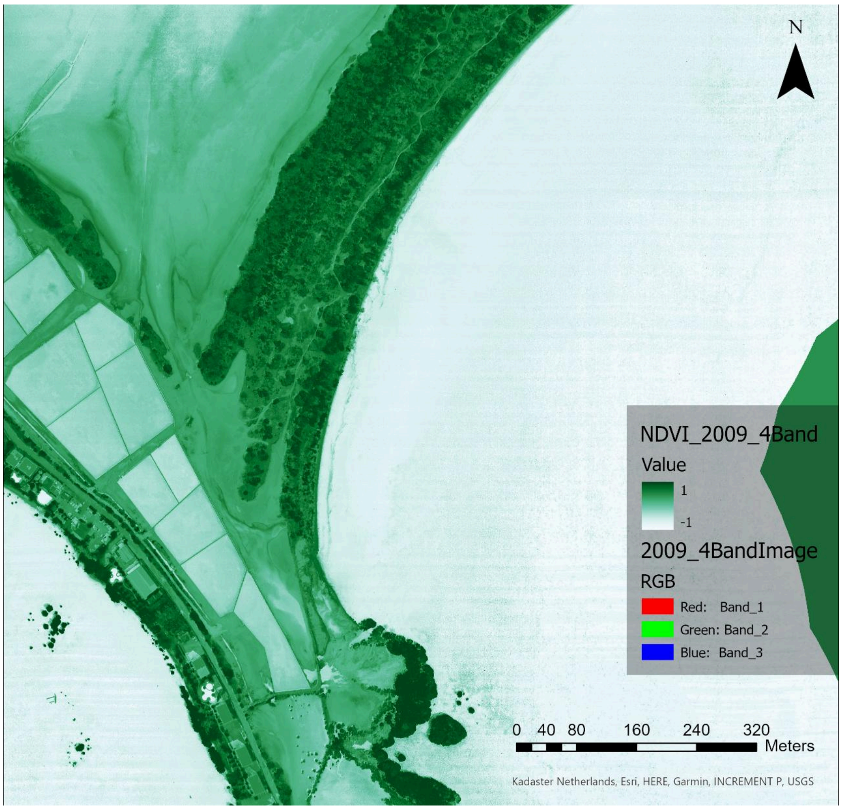

Figure 25: The 2009 NDVI analysis showed a higher density of vegetation, although some loss was evident. However, the decline was not as severe as the massive losses observed after 2017.

Shoreline erosion data from 2017 to 2024 is linked to extensive mangrove loss. These findings reveal an accelerated erosion rate of -16.01 m/yr, supporting the hypothesis that mangroves play a crucial role in stabilizing coastal areas. This underscores the importance of conservation efforts to mitigate erosion in vulnerable regions like Playa Salinas.

Recommendations

Future research related to this topic and within the same study area should focus on two main themes. One should emphasize on quantifying vegetation changes, particularly mangrove density in the region over time. This would provide more precise insights into the ongoing changes at the beach. Additionally, another study should investigate the dynamics of sediments that are supposed to be deposited in Playa Salinas. These complementary studies would provide valuable data to support and strengthen the hypotheses and objectives of this research. Additionally, future studies could build upon the results of this study and develop new hypotheses and objectives.

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