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Geomorphologic Recovery of North Captiva Island from the Landfall of Hurricane Charley in 2004

Emma Wilson Kelly and Felix Jose *

Department of Marine & Earth Sciences, The Water School, Florida Gulf Coast University,
Fort Myers, FL 33965, USA; ewkelly8615@eagle.fgcu.edu
* Correspondence: fjose@fgcu.edu

Abstract: Hurricane Charley made landfall on the Gulf Coast of Florida on 13 August 2004 as a category 4 hurricane, devastating North Captiva Island. The hurricane caused a breach to occur to the southern end of the island, which naturally healed itself over the course of three years. By 2008, the cut was completely repaired geomorphologically. LiDAR data analysis shows the northern half of the island has been subjected to persistent erosion from 1998–2018, while the southern half experienced accretion since 2004, including the complete closure of the "Charley cut". The maximum volume of sediment erosion in the northern sector of the island (R71–R73) from 2004–2018 was −85,710.1 m^3, which was the source of southern accretion. The breached area of the island (R78b–R79a) obtained 500,163.9 m^3 of sediments from 2004–2018 to heal the cut made by Hurricane Charley. Along with LiDAR data analysis, Google Earth Pro historical imageries and SANDS volumetric analysis confirmed the longshore transport of sediments from the northern to the southern end of the island. Winter storms are mainly responsible for this southerly longshore transport and are hypothesized to be the main factor driving the coastal dynamics that restored the breach and helps in widening the southern end of North Captiva Island.

Keywords: North Captiva Island; barrier island; Hurricane Charley; sediment transport

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1. Introduction

North Captiva is a low-lying barrier island located along the Gulf coast of Florida and is highly susceptible to morphological changes. During the hurricane season and winter storms, natural erosion of frontal beaches and transport of sediments is increased due to higher wave energy, a phenomenon that is also often observed and documented throughout the Caribbean and in tropical and subtropical regions around the world [1,2]. When Hurricane Charley made landfall near the island as a Category 4 hurricane on 13 August 2004, it caused a significant breach of approximately 0.5 km towards the southern end [3]. Interestingly, this breach naturally healed itself over the course of only about three years, without the help of any artificial nourishment. Since 1998, the National Oceanic and Atmospheric Administration (NOAA) along with the US Army Corps of Engineers (USACE) have conducted a series of LiDAR mapping surveys for the study area, along with the rest of the coastal United States [4]. These data sets are available in the public domain and have been proven to be an effective tool in monitoring long-term evolution of barrier islands and frontal beaches. This study sought to further examine the shoreline evolution, beach erosion characteristics and winter-storm induced longshore sediment transport that could have led to North Captiva Island's rapid and natural recovery, including the healing of the "Charley cut"; the breach that occurred from the landfall of Hurricane Charley. In order to do this, an Arc GIS-based modeling approach was used to quantify the morphological changes of the island from the landfall of Hurricane Charley and subsequent years until 2018, when the latest LiDAR survey was conducted for the region.

Hurricane Charley

On 9 August 2004, a tropical depression developed south-southeast of Barbados, and approaching Jamaica two days later, became Hurricane Charley, reaching a Category 4 status on 13 August 2004, when it made landfall on the southwest coast of Florida [5]. Landing near Cayo Costa just north of Captiva Island, Charley had maximum sustained winds nearing 150 mph [6]. This is where the hurricane reached peak intensity, and as it traversed across the state of Florida, it left destruction in its wake. Moving into the Atlantic shortly after its initial landfall, Charley re-strengthened and then weakened to a lesser hurricane when it hit South Carolina, lessening still to a tropical storm by the time it reached southeastern North Carolina [5]. Across the state of Florida, maximum rainfall was measured to be just above 5 inches from gauges, although radar-estimated precipitation was as high as 8 inches [7]. In total, Hurricane Charley was responsible for ten deaths in the United States along with twenty-five indirect deaths, and an additional five in Cuba and Jamaica. The total damage across Florida and the Carolinas is estimated to be 6.8 billion dollars in insured losses [5].

The 2004 hurricane season was extraordinary for the state of Florida. Of the 9 hurricanes named in the season, 5 of them made landfall, and 4 of them (Charley, Frances, Jeanne, and Ivan) battered the state [7]. The higher hurricane activity in the time period of 1995–2004 has been attributed to warmer sea surface temperatures in the Atlantic along with reduced wind shear over the deep tropics [7].

2. Materials and Methods

2.1. LiDAR Data and GIS

Beginning in 1998, the National Oceanic and Atmospheric Administration (NOAA) in partnership with the US Army Corps of Engineers (USACE) have conducted light detection and ranging, also known as LiDAR mapping surveys of beaches and nearshore areas on a national scale [8,9]. The data from these surveys have been shown to be effective tools for monitoring the long-term evolution of barrier islands and coastal environments. These datasets are available in the public domain at https://coast.noaa.gov/dataviewer/#/ (accessed on 25 January 2021).

Using NOAA Digital Coast archives, classified LiDAR data were extracted for the years of 1998, 2007, 2010, 2015 and 2018, as well as two additional LiDAR sets for 2004; post-Hurricane Charley and post-Hurricane Ivan [10]. As the data from 1998 were not classified and having low spatial resolution, it has been removed from further processing and analysis. The LiDAR data from each consecutive year were filtered for ground elevation and bathymetry, representing reasonable elevation points down the coastal environment. Using LiDAR data processing tools in ArcGIS, terrain models for each year were generated with a spatial resolution of 2 m and 5 levels of pyramid structure for optimal zooming [11]. From these terrain models, raster DEMs were generated using the 3D Analyst tool in ArcGIS.

To create the DEMs (see Figure 1), LAS datasets for each of the subsequent years were needed [9]. LAS files were extracted from the LiDAR datasets, and the statistics of the LAS datasets were calculated. Next, the dataset was added to ArcMap and the classification codes were edited and filtered so that only the ground and bathymetric elevation data would be incorporated. This was done to exclude data points that may have shown tree canopies, vegetation, and building elevations that would interfere and skew the results.

The next step in this mapping process was to create a terrain model from the LiDAR data. This terrain model is a multiresolution TIN-based surface stored as features, created by importing the ground and bathymetry LiDAR data points to a multipoint feature class. “LAS to Multipoint”, a 3D Analyst tool, was used to create this feature. Next, the multipoint feature class was combined with a 2D shapefile of the study area [11].

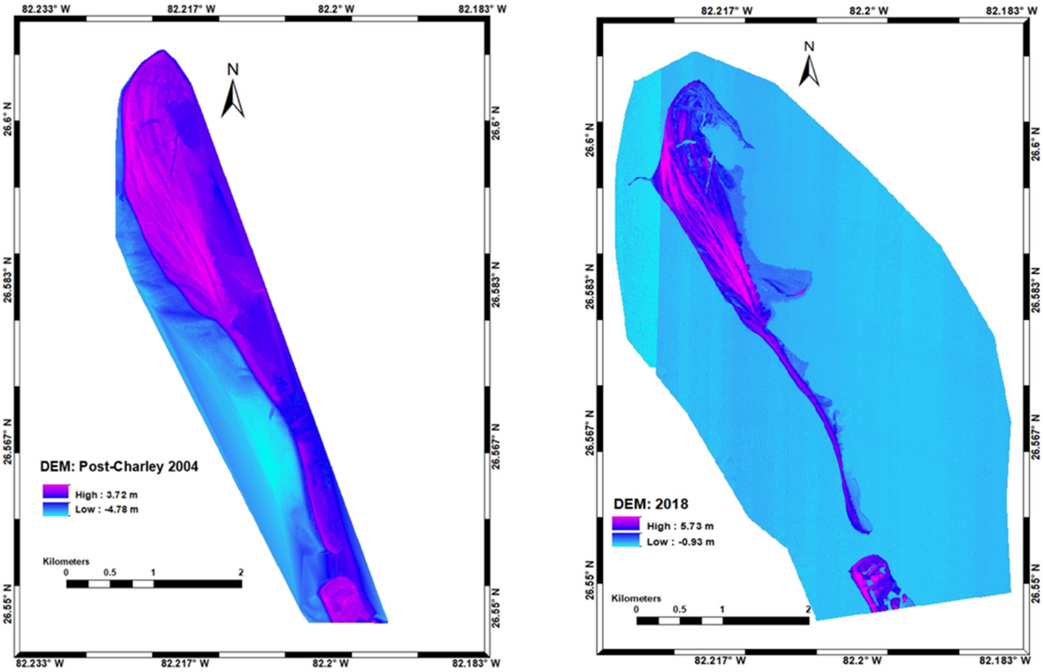

Figure 1. Digital Elevation Models (DEMs) for the North Captiva island using LiDAR data from 2004 and 2018.

Florida Department of Environmental Protection (FDEP) has been collecting shoreline data for the entire state since the early 1970s and they established R-monuments along the coast at an interval of 304.8 m (1000 ft) for periodically measuring the beach topography to assess the long-term erosional/accretional trends.

2.2. DEM Skill Assessment

To verify the accuracy of the DEMs generated from the terrain dataset, the DEMs from the study area were compared to those already generated by NOAA and provided in the public domain. Specifically, the datasets from 2015 were compared by extracting beach profiles from each R-monument and plotting them into Excel, where profile graphs could be generated and overlaid with one another to compare the accuracy of the data to that of DEM's generated by NOAA. The two datasets showed very good agreement across all of the R-monuments down the study area, confirming the reliability of the approach and the accuracy of the DEM development [11].

2.3. Beach Elevation Profiles

From the elevation model rasters of the study area generated for each year, beach profiles were extracted. By overlaying a shapefile of the R-monuments located on the North Captiva coastline, markers for intervals along the coast were able to be displayed and served as guides for profile extraction for each year studied. Lines extending from east to west were interpolated, and from this, a point profile and point graph were displayed showing the data points along the path. These data points were exported into Excel, where scatterplots were produced based on the data from each R-monument and year in the study. Compiling data from each year in the study and along each R-monument provided information on the beach elevation changes across the study area.

2.4. Google Earth Pro Historical Imagery

An additional aspect of this study was representing changes to the coastline of North Captiva Island and observing the different erosional and accretion patterns using Google Earth Pro. Beginning in 1994 and using historical satellite imagery base maps from Google Earth Pro archives, it was possible to outline the coastline of North Captiva Island up until 2019. Using the path and polygon features, and designating each year with a different colored outline, it is possible to see the changes to the geomorphology of the study area, specifically the areas of sediment erosion and accretion throughout the years. As the bay side of the barrier islands are fringed with mangroves and/or marsh vegetation, shoreline change analysis using historical imageries has been limited to the Gulf side of the island only.

2.5. Sediment Volume

To analyze the shoreline transformational behavior, SANDS Assessment Management software can be used to quantify the volume of sediments eroded and accreted from shorelines [12]. In the volumetric analysis of the North Captiva coastline, SANDS was used to quantify these sediment changes. This analysis was carried out from 2004 Post Hurricane Charley through 2018. The beach volume change, measured in cubic meters, was estimated for the island segment delimited by transects referenced by neighboring R-monuments between the years in the study area [11]. For the breached location, towards the southern end, additional transects were established for an increased resolution in volumetric analysis.

3. Results

3.1. North Captiva Historic Imagery

Considering the Google Earth Pro historical coastline mapping, erosion on the northern portion of the island and a comparable sediment accretion on the southern end of the island can be observed consistently from 1994–2019. In 1994, North Captiva Island had a very narrow northern coastline (Figure 2) that widened moving south towards the mid-section of the island, narrowing again towards the very southern tip of the island. Since then, the northern portion of the island has experienced steadily increased erosion, with the southern portion after the landfall of Hurricane Charley has experienced steady accretion. While Hurricane Charley has had the greatest physical impact on the shoreline of North Captiva, other factors also have contributed to the changes in its morphology. Additional storms that hit the southwest Florida region such as Ivan in 2004, and more frequent winter storms also played a significant role in the shoreline evolution of this barrier island [13,14].

Figure 2. *Cont.*

Figure 2. Google Earth image of North Captiva Island, depicting coastline from 1994–2019, denoted by different colored paths. R-monuments are overlaid on map, R67–R82.

Sediment transport since the landfall and resulting damage of Hurricane Charley in 2004 is evident in the evolving coastline of North Captiva island, specifically the healing of the southern cut and overall widening of the southern tip. By 2008, the southern portion of the coastline was consistently widening, showing the greatest width post-Charley by 2019. The modern coastline of North Captiva Island fits into this sediment transport pattern as well, as the island continues to erode in the north and widen in the south from sediment transport via longshore currents where the breach once was [7].

3.2. Beach Elevation Profiles

Elevation profiles of North Captiva's coastline from 2004–2018 are grouped based on their corresponding R-monuments, as well as approximate location on the island based on the section of island it is found in. Profiles are displayed from the northern-most region, mid-region, the breached area, and the southern tip. Figures 3–6 show the changes in elevation between 2004 post-Charley and 2018.

Figure 3 shows profiles extracted from the northernmost sector of the study area, including R-monuments 67 and 69. These profiles show a relatively stable beach with little geomorphological changes occurring from 2004–2018, aside from slight sediment accretion following Hurricane Charley and greater erosion in 2018. The orientation of this shoreline from north northeast to south southwest helps to maintain the coastal stability for this region.

Figure 4 shows profiles from the mid region of the study area including R72 and 74, which show significant erosional behavior for the region. After a slight sediment accretion post-Charley, since 2010 the shoreline has been subjected to significant erosion. In some areas along R72, specifically 75 m and 150 m onshore, the height of the beach has been eroded by about 1 m. Along R74, similar patterns are observed at 300 m and 440 m onshore where the height of the coast decreased by about 1 m since 2007 and 2010. High erosion from this area could be explained by greater exposure of this section of the island to northwesterly waves during winter storms.

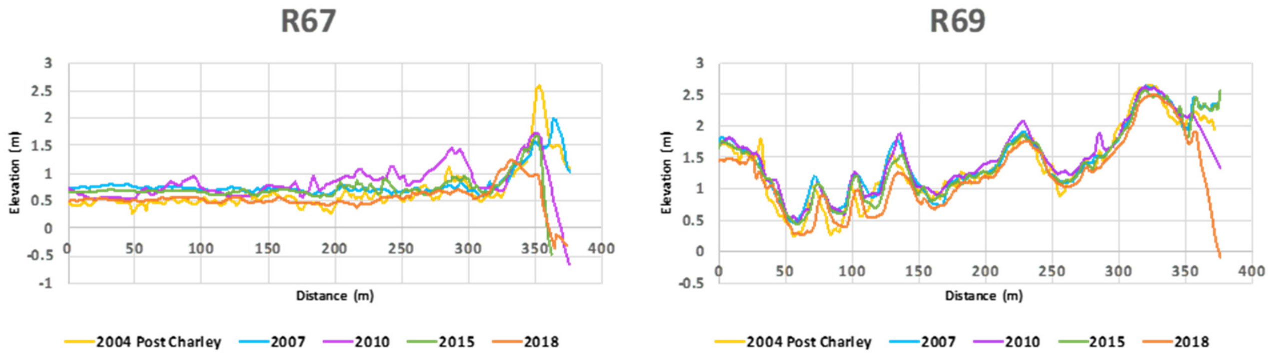

Figure 3. R67 and R79 elevation profiles with respect to NAVD88 of North Captiva Island for 2004 post-Charley through 2018.

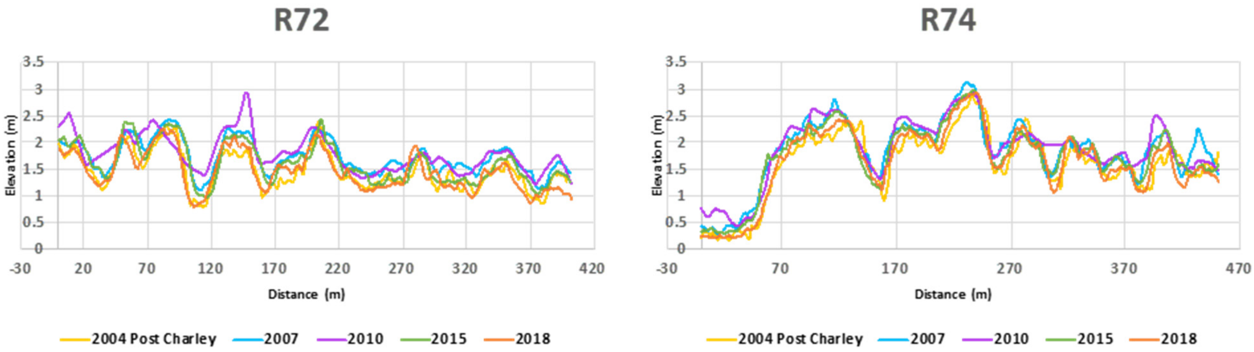

Figure 4. R72 and R74 elevation profiles with respect to NAVD88 of North Captiva Island for 2004 post-Charley through 2018.

Figure 5 depicts profiles R78a and 78c, representing the area on the island that was breached during Hurricane Charley made landfall. Data from 2004 shows evidence of the cut, as can be seen where the elevation of the island in 2004 falls below sea level on both the profiles from R-78a and for R-78c. Evidence of island recovery can be seen as the elevation increases from about −1 m to almost 2 m since 2004 post-Charley. Both of these peaks can be seen from 200–250 m. Evidence of sediment accretion from the elevation profiles began as early as 2007, showing the natural healing of the island that occurred. Sediment eroded from the beach section just north has been transported southward and helped in rebuilding this section.

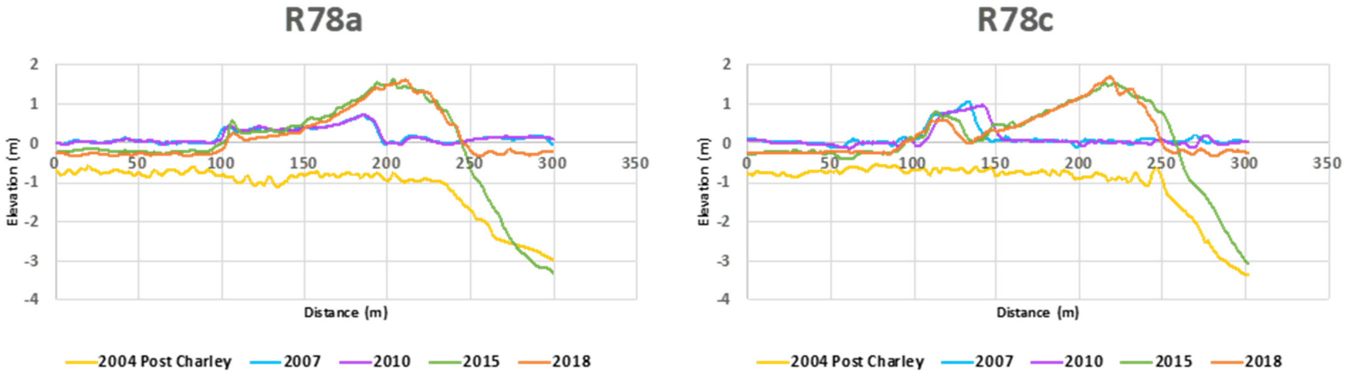

Figure 5. R78a and R78c elevation profiles with respect to NAVD88 of North Captiva Island for 2004 post-Charley.

Figure 6 shows the southern end of the study area denoted by R-monuments 79a and 80. The southern end of the island is the recipient of materials eroded from the north and transported southward. Sediment accretion can be seen in the increase in elevation of the study area since 2004. This elevation increase spikes in 2015 and 2018.

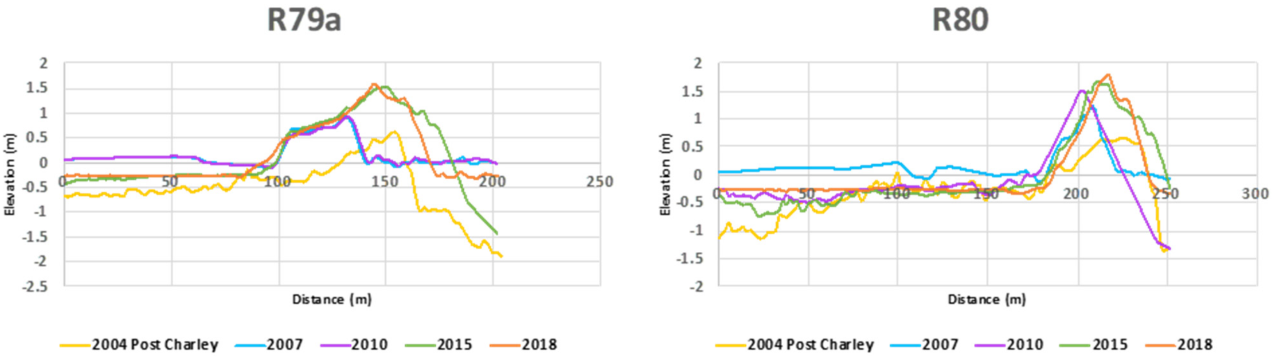

Figure 6. R79a and R80 elevation profiles with respect to NAVD88 of North Captiva Island for 2004 post-Charley through 2018.

Hurricane Charley had the most notable impact on the region denoted by R-monuments 78–79. This is the area that was breached when Hurricane Charley made landfall. Additionally, it is also the region that was most impacted by sediment transport since 2004, recovering in some areas approximately 2.5 m of elevation without the influence of artificial beach recovery.

3.3. Volumetric Changes

The calculated sediment volume changes for the northern and the mid sections of the North Captiva Island, between R67–R76 (north), from 2004–2018 are provided in Table 1. The extremely low and negative values of percentage change show the magnitude of erosion from the northern stations. The northernmost section of the barrier island has remained relatively stable since 2004, whereas from R-monuments 71–74, persistent erosion has been observed, as can be seen by the negative percentage change in sediment volume.

Table 1. Sediment volume calculations between R-monuments in the northern portion of North Captiva Island for 2004 to 2018. Beach volume change is estimated using a master profile (MP) kept at 2 m below NAVD88 datum.

Change between Locations		**2004PC-2018—Volume Changes above MP**	
		30 August 2004 to 15 August 2018	
Location 1	**Location 2**	**Vol Diff (m^3)**	**% Change**
R-67	R-68	28,221.73	6.27
R-68	R-69	16,785.05	2.44
R-69	R-70	67,938.88	10.98
R-70	R-71	61,228.89	7.4
R-71	R-72	−34,835.72	−3.31
R-72	R-73	−50,874.36	−5.44
R-73	R-74	−17,488.78	−2.19
R-74	R-75	−2676.5	−0.31
R-75	R-76	76,413.59	8.07
		144,712.78	Av = 2.66%
			Min = −5.44%
			Max = 10.98%

Percentage change shown in Table 2 shows the large-scale sediment accretion in the southern end of North Captiva island since 2004 (R76–R81). The magnitude of this accretion increases more towards the south, excluding the southernmost station R81.

Cumulatively, the breached area received 1,151,899.11 m^3 of sediments since the damage it sustained after Hurricane Charley; during 2004–2018. This massive transport of sediments from the north both helped to heal the cut created by Hurricane Charley, along with allowing for the overall expansion of the southern section of the barrier island.

Table 2. Sediment volume calculations between R-monuments in the southern portion of North Captiva Island for 2004 to 2018. See Table 1 caption for the master profile (MP) description.

Changes between Locations		**2004PC-2018—Volume Changes above MP**	
		30 August 2004 to 15 August 2018	
Location 1	**Location 2**	**Vol Diff (m^3)**	**% Change**
R-76	R-77	166,533.26	26.46
R-77	R-78	485,428.17	68.43
R-78	R-78b	166,307.04	105.69
R-78b	R-78c	106,824.82	113.81
R-78c	R-79	94,069.20	133.45
R-79	R-79a	299,269.88	129.89
R-79a	R-80	152,641.70	110.83
R-80	R-81		
		1,471,074.07	Av = 86.07%
			Min = 26.46%
			Max = 133.45%

4. Discussion

The geomorphology of beaches and barrier islands along southwest Florida can be significantly altered by hurricanes and winter storms by means of frontal beach erosion, overwash deposits, migration of foredunes, and the transport of sediments. Persistent transport of beach sediments can cause either erosion or accretion. The landfall of Hurricane Charley on North Captiva Island in 2004 created a cut to the southern end of the island, and since then, both localized sediment erosion and accretion have been observed on the barrier island when surveying the island until 2018 using LiDAR. Sediments were removed from the northern portion of the island after the hurricane in 2004 (R67–R76) and transported to the south to heal the island breach and build back up the width of the southern portion of the island (R76–R82). Most of this sediment redistribution can be attributed to strong southerly long-shore transport during the winter storms and the passage of tropical storms and hurricanes. Another study on barrier island erosional patterns, conducted on the Chandeleur Islands, Louisiana, supports the analysis that shoreline erosion and sediment transport are greatly influenced by changing wind and wave energy as a result of hurricanes and winter storms [15]. Additionally, a study conducted on a Dutch barrier island further backs this analysis that sediment transport on barrier islands is highly impacted by storm frequency [16].

As a low-lying barrier island, North Captiva is a coastal environment that is very susceptible to geomorphological changes. Alterations to the physical outline of the coast, elevation changes of the beach and fordunes, and percentage changes of sediments are all pieces of evidence that support the argument that the northern portion of North Captiva Island has experienced greater erosion of sediments since 2004, sediments which were naturally transported down the longshore current and used to heal the cut inflicted on the southern part of the island when Hurricane Charley made landfall.

Recovery of North Captiva is most evident in the southern portion of the island where Hurricane Charley inflicted the most damage in 2004. LiDAR mapping immediately after the hurricane shows that at the southern breach, a section of the island is underwater.

Only three years after Hurricane Charley, at the area of the southern breach, the island sat above sea level once again, and by 2018, it had gained over 2 m of height. The sediment loads that likely supplied renourishment to the southern end of the island likely came from the northern part of North Captiva Island, the coastline of which has been eroding consistently for almost two decades. Winter storms likely played a significant role in the redistribution of these eroded sediments along the study area. Overall, the damage inflicted to the island in Hurricane Charley was significant, but the subsequent erosion of the northern beaches and longshore transport of sediments to the damaged area was able to naturally heal the cut.

Similar patterns in erosion and accretion as a result of tropical cyclones and winter storms have been frequently observed and documented across the Caribbean Sea also [17,18]. In several small islands across the Eastern Caribbean, significant erosion of accretionary features such as spits and tombolas has been reported over the past several decades, especially on islands impacted by recent hurricanes [5]. A study conducted on Colombian Caribbean beaches found that storms with cold front characteristics were equally, and in most cases, more damaging than hurricanes. The erosional effect of these winter storms was found to have greater magnitude and additionally, remain for longer periods of time. As a result, coastal environments were often unable to fully recover from sediment loss before the next storm season [19]. Another study was conducted to compare the damage inflicted by Hurricane Wilma in 2005 to an exposed beach in Cancun and a beach fronted by a fringing reef in Puerto Morelos. Widespread erosion was observed at Cancun after the hurricane, whereas Puerto Morelos experienced substantial accretion of about 30 m on this beach [17,20]. Similar to the accretion of sand in the southern portion of North Captiva Island, accretion at Puerto Morelos is thought to be the contribution of sand from the northern beaches transported during storms [17].

Chronic erosion occurred to majority of the coastal environments mentioned can also be attributed to other anthropogenic factors such as coastal development, sand mining, coastal construction, and land clearing. Beach erosion in those cases were further exacerbated by increased wave energy from storms [5,16,18,21]. However, practices such as those mentioned above could prove to be detrimental to coastal environments that are most impacted by winter storms and hurricanes because of the way that they can potentially degrade natural barriers. Additional studies bring to light the importance of preserving natural protective barriers in coastal regions, such as coral reefs, mangroves, sand dunes and spits. All of these natural structures provide coastal environments with the valuable ecosystem service of coastal buffering and protection. In many cases, these structures may disperse wave energy and prevent sediment erosion. In Puerto Morelos, the presence of fringing coral reefs not only protected the beach from Hurricane Wilma, but also contributed to inducing coastal growth [20].

5. Conclusions

Over the decades, North Captiva Island has evolved significantly as a result of tropical storms, hurricanes, and frequently occurring winter storms, as well as seasonal changes to the wave energy experienced in the Gulf of Mexico. Specifically, after the impact of Hurricane Charley, North Captiva Island experienced significant morphological changes and has sustained remarkable shoreline evolution. North Captiva was split apart in the southern end, but the cut was healed naturally by sediment nourishment. The breached section received 1,151,899.11 m^3 of sediments delivered from the northern portion of the island from 2004–2018. Additionally, the breached area of the island saw a notable increase in elevation of approximately 2.5 m since 2004. Since Hurricane Charley, a summary of the observed and measured changes to the island includes increased volume of sediments in the southern end of the island, heightened elevation, and stabilization of the island where the breach occurred, and overall widening of the southern shoreline.

Future studies of sediment transport on North Captiva Island should further explore where alternative sources of sediment may come from, and the role that sediments in the Gulf of Mexico, or on neighboring islands, may play in island re-nourishment. The effects of rising sea level should also be monitored closely in relation to island reshaping and the ability to recover from storms [13]. Additionally, future studies detailing sediment transport should consider aspects of land usage and the alteration of natural land barriers where applicable.

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