Post-2017 Hurricane Season Assessment of Civil Infrastructure Impacts on Beach and Near-Beach Environments

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ABSTRACT: *This paper presents an overview of observations and preliminary measurements of coastal infrastructure in the aftermath of Hurricanes Harvey and Irma in 2017. Two teams mobilized by the Geotechnical Extreme Events Reconnaissance (GEER) Association were sent to document perishable data along the Texas coastline (Port Aransas, Holiday Beach, East Matagorda Peninsula, and Follets Island) and Florida Keys (Simonton Beach, Sombrero Beach, and Coco Plum Beach). Significant damage from sediment overwash and road undercutting was observed at beach access paths and roads that transect dune fields. It was also observed that beach access points weaken the line of coastal defense provided by dunes, vegetation, and structures. The lessons learned from these field reconnaissance missions indicate that longshore non-uniformity in the dune system should be well-documented. Measurements of the geometry of beach access pathways and dunes, including the height, width, length, and vegetation coverage, should be collected prior to recovery of the system post-storm.*

KEYWORDS: Hurricane Harvey, Hurricane Irma, beach access point, geomorphology, storm damage, inundation

SITE LOCATION: **Geo-Database**

INTRODUCTION

The 2017 hurricane season was characterized by a record-breaking series of hurricanes making landfall in the United States. At the forefront of this series was Hurricane Harvey, a late-August storm that rapidly intensified to a Category 4 on the Saffir-Simpson Hurricane Wind Scale and made landfall on August 24, 2017, near Rockport, Texas. During Hurricane Harvey, more than 60 inches of rain fell in the Houston and Beaumont areas, causing catastrophic flooding and nearly $125 billion (USD) in damage, ranking it second to only Hurricane Katrina (2005) in terms of economic losses (Blake and Zelinsky, 2018; Blake and Gibney, 2011; NHC, 2018). Storm surge, waves, and runoff resulted in water levels up to 2.04 m (6.71 ft) and wind speeds were measured up to 58.1 m/s (130 mph) along coastal Texas (Stark et al., 2017a).

Less than three weeks later, Hurricane Irma (Category 5 at maximum intensity) made initial landfall on September 10, 2017, in the U.S. near Cudjoe Key, Florida, as a Category 4 storm and then made a second landfall near Marco Island that same day as a Category 3 storm (Cangialosi et al., 2017). Hurricane Irma impacted most of Florida, including the Florida Keys,

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Naples area, and Miami, causing $50 billion (USD) in damages (Blake and Gibney, 2011; NHC, 2018). It presently holds the rank of the fifth costliest U.S. hurricane (NHC, 2018). High water mark measurements, which indicate the total water level including storm surge and waves, reached 2.04 m (6.72 ft) and wind speeds up to 57.6 m/s (129 mph) were measured in south Florida (Stark et al., 2017b; Cangialosi et al., 2017). The maximum high water marks and wind speeds of Hurricane Irma were very similar to those measured during Hurricane Harvey.

In response to Hurricanes Harvey and Irma, multiple reconnaissance teams funded by the National Science Foundation (NSF) Geotechnical Extreme Events Reconnaissance (GEER) Association (geerassociation.org) rapidly deployed to Texas and Florida with the purpose of collecting measurements of perishable geotechnical data and assessing damage to coastal infrastructure. In this paper, observed hurricane-induced morphological changes associated with coastal infrastructure along the Gulf coasts of Texas and Florida are analyzed, and potential increases in damage vulnerabilities of surveyed infrastructure are estimated.

SITE LOCATIONS

In this study, the geotechnical damage at seven locations featuring varying types of civil infrastructure is assessed. Locations include four sites in Texas impacted by Hurricane Harvey and three sites in Florida impacted by Hurricane Irma (Table 1). These sites are of interest because they vary in terms of location relative to storm landfall position, dune configuration prior to storm impact, surrounding infrastructure, and geomorphological responses. The four Texas locations include: (1) a beach access point near the Port Aransas Pass jetties that protect the passageway to the Port of Corpus Christi; (2) a bayfront bulkhead in Holiday Beach on Copano Bay that experienced backside scouring; (3) a cut through East Matagorda Peninsula, connecting East Matagorda Bay and the Gulf of Mexico (GoM) during elevated water level conditions; and (4) a site on Follets Island, one of the narrowest and lowest barrier islands along the upper Texas coast, where engineered dunes have been constructed along an eroding coastline directly fronting the island's main roadway and evacuation route. In Florida, each site is located on the Florida Keys and developed with no pre-existing dune structures and narrow patches of sandy beaches. These three sites are: (1) Simonton Beach, a small pocket beach located between two hotel structures in Key West; (2) Sombrero Beach, a beach park located near the southwestern tip of Marathon, FL; and (3) Coco Plum Beach, a narrow, sandy seashore backed by dense vegetation, a shore-parallel road, and engineered canals that are used by residents to access open water. Each site is described in more detail in the following subsections.

Table 1. Site locations visited in Texas and Florida after Hurricanes Harvey and Irma.

Texas	Coordinates	Site Characteristics	Post-Hurricane Observations
Port Aransas	27°50'6.39"N 97°2'50.56"W	Natural dune system; nearby jetties and beach access pathway	Road undercutting; scarps at dune toe along beach access pathway
Holiday Beach	28°10'10.50"N 97°1'1.73"W	No dunes; fronted with retaining wall; residential development	Erosion behind retaining wall; scour around trees and fixed objects
East Matagorda	28°36'44.15"N 95°56'23.87"W	Natural dunes; natural cut transected dunes	Sediment transported through cut and deposited on back-barrier region
Follets Island	29°1'27.74"N 95°11'25.25"W	Longshore uniform nourished dunes; nearby beach access pathway	Sediment transported through cut and deposited on roadway

Florida	Coordinates	Site Characteristics	Post-Hurricane Observations
Simonton Beach	24°33'42.87"N 81°48'19.63"W	Pocket beach; surrounded by mostly impervious surfaces; no dunes	Sediment deposited in beach parking lot; walkway/groin undermined
Sombrero Beach	24°41'33.00"N 81° 5'5.56"W	Beach park with nourished beach; surrounded by residential buildings	House foundation undermined; large sediment deposits in park
Coco Plum Beach	24°43'48.52"N 81° 0'5.80"W	Narrow sandy beach; dense vegetation; nearby beach access pathway	Sediment trapped by vegetation; sediment channelized through pathway

Texas

In response to Hurricane Harvey, reconnaissance was conducted September 2-5, 2017, along a wide coastal zone in Texas (Figure 1). After initial landfall only miles north of Port Aransas, Hurricane Harvey passed over Copano Bay and briefly stalled over land before returning back to the Gulf of Mexico (GoM), crossing less than 25 km southwest of the Matagorda site. It then traveled northeast along the Texas coast, producing minor surge (on the order of 1.5 m) and moderate wave impact to coastlines along the way. Sites on Matagorda Peninsula and Follets Island are located along this latter stretch of the hurricane's path. During this phase, Hurricane Harvey continued to gather moisture over the GoM, which led to historic rainfall over the Greater Houston Metropolitan and Beaumont areas and hence caused widespread flooding. The four Texas study sites described here are ordered by landfall proximity.

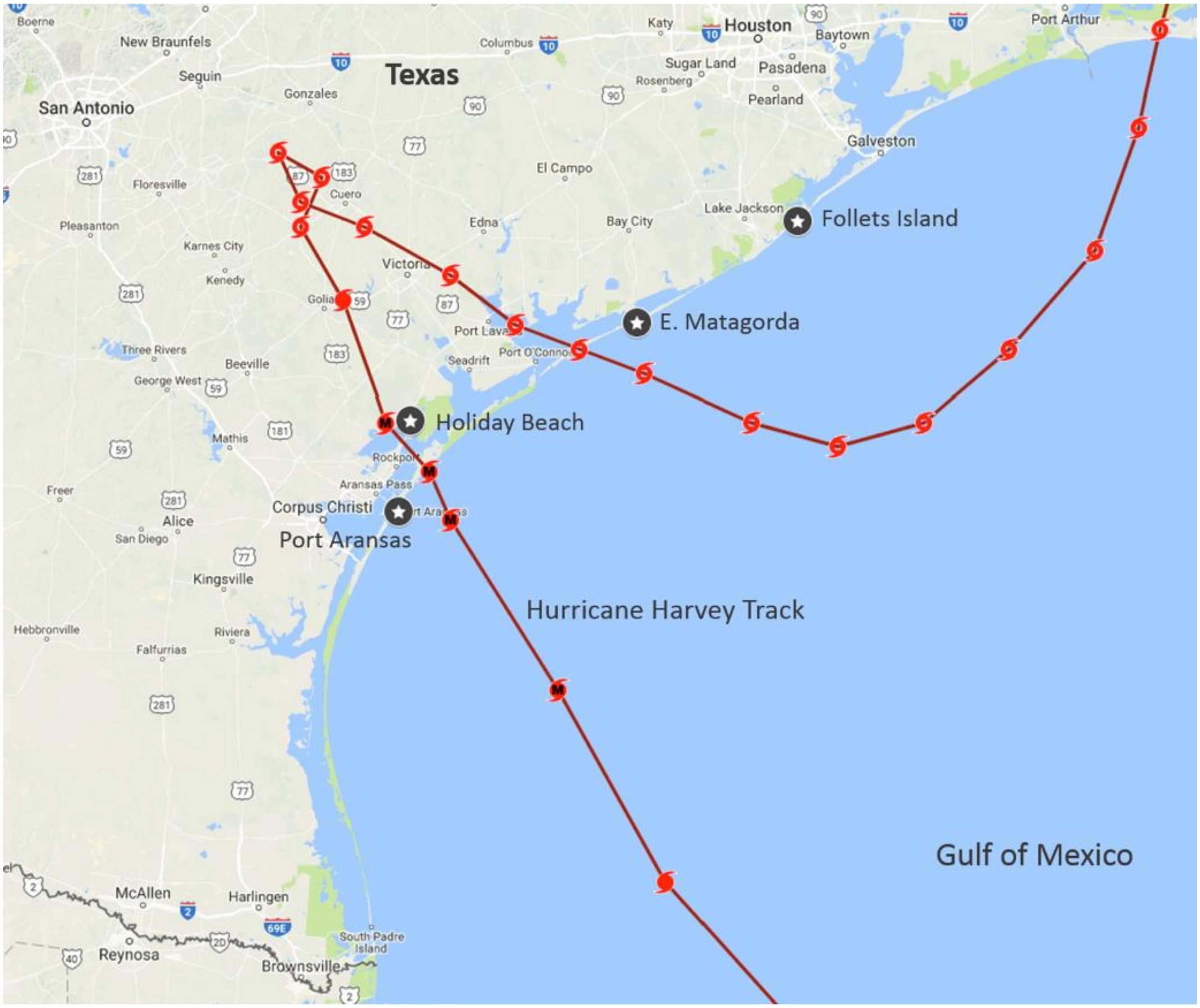

Figure 1. Map of the four Texas study sites (gray circled stars) relative to Hurricane Harvey's track (red hurricane symbols – M represents Major hurricane). Map data: Google (2018). Storm track information: Blake and Zelinsky (2018).

Port Aransas

Port Aransas is located northeast of Corpus Christi, TX, on Mustang Island (27°50'6.39"N, 97°2'50.56"W) and has over 4,000 permanent residents in the tourism-driven city. Aransas Pass, located north of the city center, provides passage to the Port of Corpus Christi and is protected from wave action by concrete and rock jetties. In 1919, a major hurricane devastated Port Aransas, sparing only a few buildings in the town (Port Aransas and Mustang Island, 2018). Nearly a century later, Hurricane Harvey made direct landfall in Port Aransas with wind gusts of up to 132 mph (59.3 m/s; NDBC, 2017) and at least 1.5 ft (0.5 m) of storm surge at Port Aransas Pass (NOAA tide gauge 8775241 failed during the peak of the storm; Tides and Currents, 2017). Most of the city's infrastructure and residential areas are located on its northeastern end closest to Port Aransas Pass, on the widest part of the Mustang Island barrier system behind natural, vegetated dunes. The pass serves as the northern border of Port Aransas and is protected by concrete and rock jetties. Here, the investigations focus on the effects of a beach access pathway on surrounding vegetated dunes and the southwestern flank of the rock jetty on the adjacent sandy beach.

Holiday Beach

Holiday Beach is a small residential bayfront community located on the east side of Copano Bay and Highway 35 N near Port Aransas, TX, at 28°10'10.50"N, 97°1'1.73"W. The community serves as a bird refuge during winter months and is also a popular fishing site (Holiday Beach Property Owners' Association, 2018). Canals parallel several streets, including a bayfront roadway and other small streets that are oriented perpendicular to the bay. Other than the residential homes that line the streets along the canals, the peninsula-type landform is mostly vegetated with marsh grasses and patchy forests. Located between Holiday Beach and the GoM are San Jose Island, Aransas Bay, and the Highway 35 Bridge. The bridge spans a 3,000 m-long opening that separates Aransas Bay from Copano Bay. Tide gauges located near the entrance of Copano Bay recorded water levels up to 1.8 m (5.8 ft); in Holiday Beach, water levels of 2.1 m (7 ft) above ground level were measured (Blake and Zelinsky, 2018). Wind data was not collected near Holiday Beach due to instrument failure during the storm. Although this site is unique among the other Texas sites because it is located on Copano Bay rather than the GoM and it has no dunes, it is similar to other sites in Florida that also have no dunes and are surrounded by infrastructure.

East Matagorda Peninsula

The Matagorda Peninsula is a thin (width: 300 – 1,300 m) barrier strip separating Matagorda Bay and East Matagorda Bay from the GoM. East Matagorda Bay stretches from Baytown on its northeastern end to the city of Matagorda on its western end (length: 30 km, width: 7 km). Matagorda Bay and East Matagorda Bay are separated by an isthmus formed by Egret Island and the extended banks of the Colorado River connecting the mainland to Matagorda Peninsula. The field site is located at 28°36'44.15"N, 95°56'23.87"W close to the southeastern corner of the bay, and is comprised of an elevated, non-vegetated cut through the barrier peninsula that connects the bay and the ocean only during storm water levels. Matagorda Peninsula is a popular beach, birding site, and commercial and recreational fishing destination and it can be accessed by a road across the isthmus from the town of Matagorda. The cut is specifically used by fishermen to access the backbarrier areas by car. The cut is 15 m wide at its throat, 330 m wide at the dune line, and acts as a discontinuity in the dune line separating the backshore from the backbarrier. Dunes surrounding the cut are approximately 3 m high and 15 m wide. The beach fronting the dunes functions as the alongshore roadway and the whole barrier system protects not only the ecological assets of the backbarrier (e.g. wetlands and salt marshes) but also the bay ecosystem and the Gulf Intracoastal Waterway hugging the bay along its northern border. The area does not exhibit any built infrastructure; the cut acts similarly to an access road through the dunes, however, which makes it relevant for this study.

Follets Island

Follets Island is located along the upper Texas coast (UTC) and is part of a series of long, narrow barrier islands and barrier peninsulas comprised of fine sand facing a microtidal, wave-dominated, hydrodynamic environment (Carlin et al., 2015). The field site is situated 80 km up the coast from the East Matagorda Peninsula site along an island transect at 29°1'27.74"N, 95°11'25.25"W in the vicinity of a previous overwash fan. Follets Island is approximately 25 km long, less than 500 m wide, and 2.06 m in elevation (NAVD88). It is one of the most vulnerable stretches of the UTC due to its lack of a major sediment source and high background erosion rates. It is separated from adjacent barrier islands by the Freeport jetties and ship channel in the southwest and by the San Luis Pass inlet in the northeast. Its eastern half fronts Christmas Bay, whereas the western half is separated from the mainland only by the Gulf Intracoastal Waterway. The island contains a series of beach communities, including Treasure Island and Surfside.

In addition, Follets Island protects important economic and ecological assets like Christmas Bay, the Brazoria National Wildlife Refuge, the CR-257 Blue Water Highway, the Gulf Intracoastal Waterway, and parts of the Port of Freeport (including the Naval Petroleum Reserve and an LNG de-liquefaction plant). Specifically, the situation of CR-257 is relevant for this study since it is the only hurricane evacuation route for the area and is, along some parts of Follets Island, located directly behind the dune line, making it vulnerable to damaging erosion and overwash during storms. The dunes at this stretch of Follets Island are part of an engineered template with a height of approximately 2 m and had been installed about a year prior to Hurricane Harvey's landfall. This site represents a nourished beach with relatively longshore uniform dune fields except at beach access pathways, allowing an assessment of the damage caused by man-made transects through the dune system.

Florida

In response to Hurricane Irma, reconnaissance was conducted from September 24-28, 2017, in southern and western Florida, including the cities along the Florida Keys (Figure 2). Hurricane Irma made initial landfall on Cudjoe Key, approximately 35 km east of Simonton Beach and 45 km west of Coco Plum and Sombrero Beaches, passing between the study sites discussed in the following subsections. These sites are ordered by their proximity to hurricane landfall location.

Figure 2. Map of the three Florida study sites (gray circled stars) relative to Hurricane Irma's track (red hurricane symbols – M represents Major hurricane). Map data: Google (2018). Storm track information: Cangialosi et al. (2017).

Simonton Beach

Simonton Beach (24°33'42.87"N, 81°48'19.63"W) is a north-facing pocket beach located between two hotels in northwest Key West. The sandy beach is approximately 18 m wide and only 23 m long. It is protected by a rock seawall on its west side and a concrete groin/walkway on its east side. A tide gauge recorded water levels up to 0.8 m (2.7 ft) Maximum higher high water (MHHW) and wind speeds were measured up to 58 m/s (132 mph) in Key West (Cangialosi et al., 2017). This pocket beach is of interest because it is a small beach with no pre-existing dune system and is surrounded by commercial buildings and the concrete groin/walkway.

Sombrero Beach

Sombrero Beach is located in south Marathon (24°41'33.00"N, 81° 5'5.56"W), which is a city spanning seven islands in the Florida Keys (Knight's, Boot, Vaca, Fat Deer, Long Point, Crawl, and Grassy). Marathon has a population of about 8,000 and is heavily engineered with navigation canals, marinas, harbors, and seawalls. During Hurricane Irma, water levels were measured to be 1.1 m (3.7 ft) above ground level (Cangialosi et al., 2017). Located on the southwestern tip of Vaca Key, Sombrero Beach, like the other Florida beaches discussed herein, is a popular tourist destination. Established in 1973 and renovated in 2002-2003, Sombrero Beach Park is outfitted with a playground, walking paths, and picnic areas. It is fronted by a narrow (less than 15 meters) nourished beach with lowlying vegetated areas positioned between the beach and the main road (Sombrero Beach Road) and street parking. This critically eroded beach underwent a 813 m^3 (1,064 cy) beach nourishment and vegetation placement in 2014 (Florida DEP, 2018). Behind the shore-parallel Sombrero Beach Road, a variety of houses line the streets, including houses that are elevated, built slab-on-grade, or fronted with short walls (similar to garden walls). Compared to Simonton Beach, Sombrero Beach is longer and wider with vegetation extending from the beach to Sombrero Beach Road except at access pathways which are made of sand. Infrastructure exists behind this roadway and on Sombrero Beach's east end.

Coco Plum Beach

Coco Plum Beach is located in east Marathon (24°43'48.52"N, 81° 0'5.80"W) and consists of a 1.4 mile-long beach that is both residential and a public park. It is backed by several manmade canals and residential development. The beach is very narrow (less than 5 m), with dense vegetation covering the area between the beach and the roadway located about 100 m landward. Coco Plum Beach was initially constructed in the 1950s from dredge and fill development, and has since received two beach nourishments. The first nourishment was completed in 2006 and consisted of 3,135 m^3 (4,100 cy) of sand placement. The second nourishment of 854 m^3 (1,117 cy) of sand and vegetation placement was completed in 2013 to repair damages from Hurricane Isaac (Florida DEP, 2018). Although very little infrastructure exists at this location, it is of interest because of a single beach access pathway and parking area that transects the vegetation.

METHODOLOGY

Due to the urgency of collecting perishable data and travel constraints during a natural disaster, data collection methods were limited to easily transportable instruments and devices. Not all data collection methods were able to be employed at every location. Despite these constraints, valuable measurements of extremely perishable geomorphological data were collected at the seven sites in Texas and Florida. In total, data were collected using free fall penetrometers, mini-torvanes, Shelby tubes, grab samples, push and vibra cores, pressure sensors, cameras, handheld GPS devices, and measuring tapes. Where employed, these instruments were used to determine soil compaction, shear strength, sediment grain size distributions, substrate characteristics, water level changes and waves, photographs, videos, high water marks, and depths of erosion or deposit. For further analysis and site characterizations, Google Earth satellite imagery was utilized (Google, 2018). In this study, the morphological changes of beaches and near-beach environments due to two major hurricanes in 2017 are assessed using photographs, videos, and Google Earth satellite imagery. These data are chosen because they were consistently available at all seven sites. In particular, the effects of civil infrastructure on morphological change are analyzed and compared to locations without surrounding infrastructure.

RESULTS AND DISCUSSION

At Texas locations, observations show beaches and barrier islands near the initial landfall location (i.e., Rockport, TX) experienced severe erosion and overwash. Locations further up the coast transitioned to different impact regimes such as collision and deposition. Surrounding the landfall location, erosion was greater near beach access points through which storm surge appeared to be channelized, scarping dunes and undercutting roadways. At other sites, particularly those along Copano Bay, inundation and structural damage was documented, including an overtopped bulkhead and scour on its backside, exposing supporting tie rods and much of the wall. On the East Matagorda Peninsula, sedimentation was explicitly recorded through a low-lying cut. It is suspected that infra-gravity wave (waves with periods of 25 to 250 s formed by the interaction of smaller wind-formed wave groups) influence and wave triad interactions are the main drivers of the observed laminae deposition through the entire cut (beach to bay). This is an example of other processes that can occur at low points in the coastal dune line similar to cuts from beach access roads. In Florida, where the beaches are nourished, surrounded by a built environment, and little to no dune system exists, the sediment was observed to be eroded from the beach and freely deposited inland on roadways and around buildings. Scour and undermining of structures were also observed both at shore-perpendicular and shore-parallel structures. These observations, collected in Texas and Florida, are described in the following subsections.

Texas Site Locations

The locations and a brief description of the geomorphological structure of the area are as follows (in order of storm landfall proximity): Port Aransas had a natural dune system with nearby jetties and a beach access cut through the dunes, Holiday Beach had no dunes and substantial existing infrastructure, the East Matagorda Peninsula site had a more natural dune shape and a cut that acts like a natural transect through the dunes, and the Follets Island site had relatively longshore uniform dunes as a result from the recent nourishment. This allows a cross-comparison of morphological response to hurricane waves and surge between sites of varying levels of infrastructure and dune system uniformity.

Port Aransas

Southwest of the jetties that protect Port Aransas Pass, several paths transect the dune system to provide beach access to Port Aransas. The closest of these beach access points at the end of East Cotter Avenue experienced severe undercutting and paralleled a newly-formed eroded runnel that extended from the road, around a large dune, to the beach (Figure 3). This breach was observed to start at a small culvert under East Cotter Avenue, extend northwest toward the jetty, follow the jetty for approximately 120 m (394 ft), then turn southwest toward the GoM. At the beginning of the breach, a maximum undercut depth of 0.4 m (1.2 ft) was measured on the west side of East Cotter Avenue (Figure 4). The toe of the large dunes between the jetty and East Cotter Avenue and at the end of the beach access road were severely eroded (Figure 5). A scarp measuring approximately 0.9 m (3 ft) was observed and a thick wrack line of debris was deposited at the toe of the scarped dune. This location, along with several other beach access points in Port Aransas, provides evidence that these transects through the dune system provide a pathway for flow channelization, resulting in increased erosion.

Between beach access roadways, dunes containing uniform longshore vegetation were not overtopped in this study area in Port Aransas. Observations indicate that the vegetated dune system remained relatively intact at further proximity from the beach access points, with only small volumes of sediment deposition measured at the toe of the dunes. However, at beach access points, increased storm surge inundation in backbarrier regions and sediment transport were observed. As a result, the damage to roadways and buildings behind the dunes appeared to be exacerbated near the beach access pathways. Because the pathways at this location are very narrow and surrounded by dunes, the pathway provided only a single channel for storm surge retreat after the storm passed, and likely caused a delay in flooding relief. Therefore, observations suggested that the beach access points in Port Aransas likely increase the vulnerability of communities located behind the dunes near the beach access points.

Figure 3. (a) Pre-storm satellite imagery (imagery date February 22, 2017) and (b) post-storm satellite imagery (imagery date August 29, 2017) show the eroded runnel created during Hurricane Harvey near Port Aransas Pass (location 27°50'6.39"N, 97°2'50.56"W). Map data: Google Earth, Digital Globe.

Figure 4. (a) Road undermining due to erosion and scour was observed on both sides of East Cotter Avenue, and (b) a 0.4 m undercut was measured at the beginning of a newly formed breach (collected September 3, 2017; location 27°50'8.53"N, 97°2'55.00"W).

Figure 5. The dune near East Cotter Avenue was eroded and a thick wrack line of debris was deposited at the toe of the scarped dune (collected September 3, 2017; location 27°50'6.60"N, 97°2'51.64"W).

Holiday Beach

During the reconnassaince survey, houses in Holiday Beach were found heavily damaged by wind and bay surge, particularly those located on the bayfront street that parallels the canals. Anchored bulkhead retaining walls constructed along the bayfront property line were overtopped during Hurricane Harvey and severely eroded on their backsides, exposing supporting steel rods (Figure 6a). Scouring around trees and other fixed obstacles was also observed (Figure 6b). Although Holiday Beach is located on Copano Bay and is not subject to GoM wave action, the damage due to hydrodynamic forces in this region was extensive. Observations show the bulkhead was overtopped during Hurricane Harvey, leaving fish and other debris on land. As the water levels retreated, sediment appeared to be transported from the backside of the bulkhead and around the base of fixed objects, leaving these structures damaged and in need of repair. The condition of the bulkheads and service life maintenance prior to Hurricane Harvey remain unknown, and it is unclear if it affected the damage observed during the survey.

Figure 6. (a) Supporting steel rods were exposed after storm surge retreat scoured the backside of a bulkhead, and (b) scour was also observed around other fixed objects (collected September 3, 2017; location 28°10'11.24"N, 97°1'2.03"W).

East Matagorda Peninsula

The infilled storm cut through East Matagorda Peninsula hydraulically connects GoM and bay surface waters only during elevated storm water levels. During Hurricane Harvey, the maximum water surface elevation at the backshore (GoM side of the cut) was 1.8 m above Mean Sea Level (MSL) and 1.0 m above MSL at the back-barrier location (bay side of the cut) as measured by rapid response field measurement units containing pressure transducers. The dunes at this site were not overtopped. Surface hydraulic connection through the cut lasted for approximately six hours. During this time, up to 0.50 m (1.6 ft) of GoM sediment was deposited in the backshore (back-barrier) region of the cut as a result of onshore-directed transport of sediment eroded from the shoreface by hurricane wave action. Figure 7 shows before and after photos of the backshore area on the GoM side of the cut, clearly indicating the accretion that occurred at this location. The cut serves as a roadway to access the back-barrier areas and is an example of what can happen to shore-perpendicular gaps in the dune line during hurricane impact.

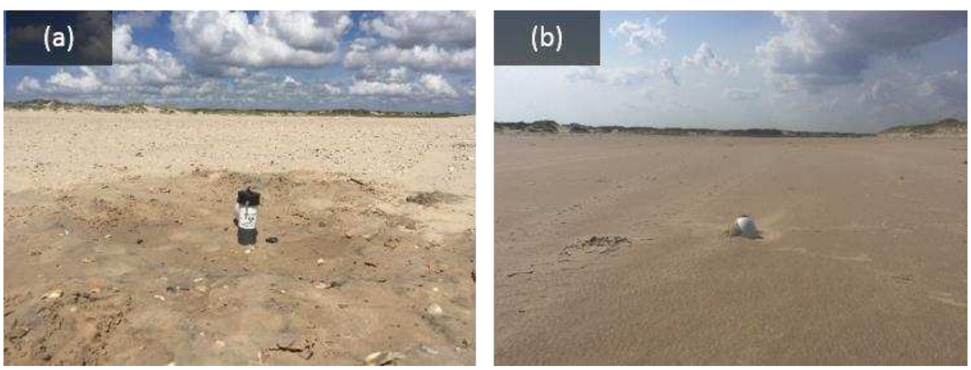

Figure 7. (a) Pre-storm (collected August 23, 2017) and (b) post-storm observations (collected August 30, 2017) of the backshore area fronting the East Matagorda cut where 0.5 m of sediment accretion was observed (location 28°36'43.57"N, 95°56'24.88"W).

Follets Island

The recently nourished, relatively longshore uniform beach on Follets Island experienced dune collision and re-grading of the beach profile by storm surge and waves, but was not overtopped or severely overwashed as observed in other study locations discussed herein (Figure 8). Significant erosion of the dune line was observed due to heavy rainfall. A shore-parallel ridge-runnel system was observed in the foreshore (Figure 9a). At the beach access point from Bluewater Highway, sediment deposits were observed on the road (257R) and a channel was formed connecting the flooded backbarrier region to the beach along the eastern and western flanks of the dunes (Figure 9b). This study location on Follets Island shows the protection afforded by dunes against storm flooding, but it also demonstrates damaging erosion along the sides of roadways. It also highlights that beach access points can serve as a funnel as rainwater and storm surge retreat, allowing the channelization of sediment transport.

Figure 8. (a) Pre-storm (collected August 24, 2017) and (b) post-storm observations (collected August 31, 2017) of the dune show regrading of the beach profile and washout from heavy rainfall on the dune peak (location 29°1'27.93"N, 95°11'24.93"W).

Figure 9. (a) A ridge-runnel system formed parallel to the shore, and (b) a channel was eroded from the beach access point to the GoM (location 29°1'27.93"N, 95°11'24.93"W).

Florida Site Locations

A similar correlation between beach access points and increased damage was observed in south and west Florida. These locations had little to no pre-existing dune structure to absorb wave energy and deform. According to observations, sediment transport caused by Hurricane Irma was affected by a shore-perpendicular groin/walkway, residential and commercial buildings, shore-parallel roadways, and beach park equipment. These impacts are further discussed in the following sections.

Simonton Beach

According to a representative of the Engineering Division for the City of Key West, Simonton Beach experienced some of the greatest beach impacts within the City of Key West due to Hurricane Irma. This very small beach was severely eroded, causing sand to be transported either offshore or deposited in the parking lot behind the beach. The beach width was reduced by nearly 4 m and the beach face was noticeably steepened due to the erosion (Figure 10). Additionally, the concrete groin/walkway located on the east side of the beach was damaged by scour and undermining, causing the structure to drop slightly in elevation (Figure 11). Simonton Beach provides evidence that beaches with small sediment volumes can be particularly impacted by storm surge and waves. Also, the lack of a dune system and the beach's location in an area characterized by mostly impervious surfaces and little natural vegetation are both factors that cause sediment to be eroded from the beach and transported further inland. Because the concrete structure is impermeable, the flow is funneled along its length, focusing flow energy and leading to larger erosion potential.

Figure 10. (a) Simonton Beach was severely eroded and (b) sediment was deposited in the parking lot backing the beach (collected September 27, 2017; location 24°33'42.85"N, 81°48'19.64"W).

Figure 11. A concrete structure located on the eastern edge of Simonton Beach was undermined due to scour around the structure (collected September 27, 2017; location 24°33'43.32"N, 81°48'20.22"W).

Sombrero Beach

At the time of reconnaissance, sections of Sombrero Beach Road were still covered with sand deposits (Figure 12) that were transported from the small nourished beach in Sombrero Beach Park. Homeowners were removing sand from inside their houses (Figure 13), which were buried with up to about 1 m (3 ft) of sediment. Additional evidence of damage by storm surge and waves was observed as structural and flood damage to houses, including the collapse of a wall located in front of an oceanfront home (Figure 14). Undermining of another home was observed to expose the foundation, likely causing structural damage in the form of large cracks in the floor slab to the beach house (Figure 15).

At Sombrero Beach Park, most of the park structures, such as fences, walking paths, and a beach access ramp, were damaged, and playground equipment was buried by about 0.6 m (2 ft) of sediment (Figure 16). Observations at this location further indicate that geotechnical impacts resulting from storm surge and waves are magnified by the surrounding infrastructure. At the park locations, sediment freely moved and deposited around park structures and on the roadway. However, at the walls and foundations of homes, which are impermeable fixed structures, sediment was eroded from around and beneath the structures. Sombrero Beach is another example that civil infrastructure can direct sediment erosion by interferring with the flow and natural sediment transport paths. Furthermore, it also highlights that small sediment-volume beaches, particularly those with no pre-existing dune structure, can be heavily damaged during extreme events.

Figure 12. (a) Large volumes of sediment were deposited on Sombrero Beach Road (facing east) and (b) a concrete bench was overturned, trapping debris on its side (collected September 26, 2017; location 24°41'33.01"N, 81°5'5.57"W).

Figure 13. (a) Large volumes of sediment were deposited around houses and other structures and (b) buried them with approximately 1 m of sand, reaching the bottom of window sills (collected September 26, 2017; location 24°41'31.52"N, 81°4'56.31"W).

Figure 14. (a) A wall located in front of a home on Sombrero Beach Road collapsed during Hurricane Irma (collected September 26, 2017; location 24°41'34.26"N, 81°5'0.93"W); (b) the pre-existing structure appeared to be intact prior to the storm. Map Data: Google (2018).

Figure 15. (a) The foundation of an elevated home was undermined due to scouring around the structure; (b) a close-up view shows damage to the structural integrity of the home (collected September 26, 2017; location 24°41'31.86"N, 81°4'57.29"W).

Figure 16. (a) Concrete park benches were nearly buried with sand (approximately 2 m), (b) some park structures were only mildly damaged and buried with sediment, (c) while others were severely damaged and in need of repair (collected September 26, 2017; location 24°41'32.20"N, 81°5'4.09"W).

Coco Plum Beach

On Coco Plum Drive, evidence of wind and inundation by storm surge was observed from the debris deposited onto the roadway (Figure 17). At Coco Plum Beach Park, large volumes of sediment were transported from the beach, narrowing its width, and deposited in the parking area (Figure 18). From the observations, the densely vegetated regions of the island trapped much of the sediment in a 20 m to 25 m zone, except at the beach access point where the transect in the vegetation served as a transport pathway through which sediment was channelized.

Figure 17. Sand and debris were deposited on Coco Plum Drive (collected September 26, 2017; location 24°43'34.52"N, 81°0'36.53"W).

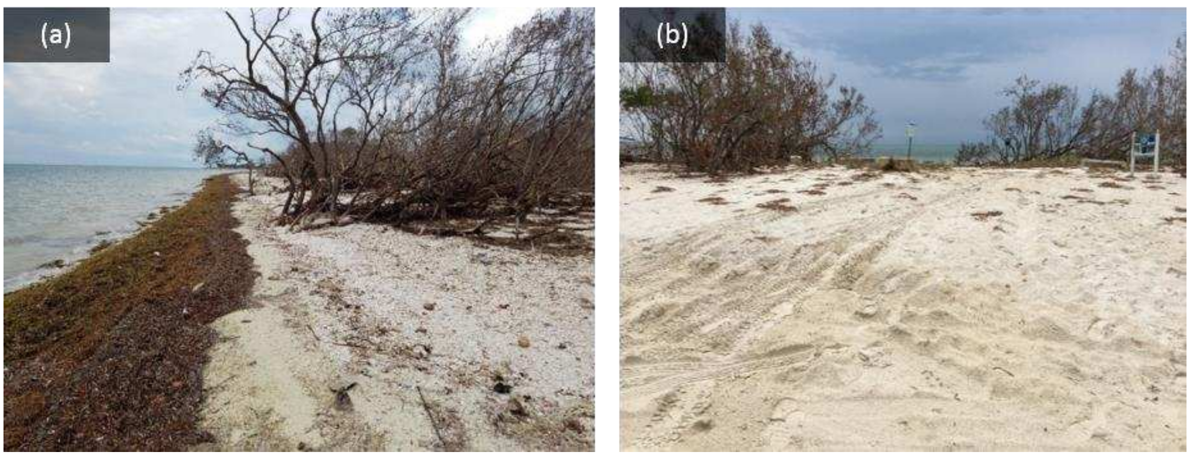

Figure 18. (a) The beach width was narrowed due to erosion and algae washed up on the beach, and (b) sediment approximately 0.3 m in depth was deposited in the beach access area (collected September 26, 2017; location 24°43'48.42"N, 81°0'5.81"W).

CONCLUSIONS

Observations indicate that coastal infrastructure, such as beach access pathways, buildings, and recreational park features, can greatly increase natural sediment transport during storms by channelizing flow and focusing energy. In low-lying regions surrounded by infrastructure, as is the case for Holiday Beach (TX), Simonton Beach (FL), and Sombrero Beach (FL), storm surge is able to freely inundate coastal areas, erode sediment from the shoreface, and deposit sediment further inland. In locations with shore-perpendicular impermeable infrastructure, such as Simonton Beach, the flow appears to be funneled along the length of the structure, focusing flow energy and increasing erosion. Similar morphological responses are observed at beach access pathways that transect dune systems. At Port Aransas (TX), Follets Island (TX), and Coco Plum Beach (FL), observations indicate flow channelization near the pathway and result in increased sediment transport. Areas located further from the beach access pathway experience a more longshore-uniform morphological response to storm surge and waves. Even in the absence of infrastructure, erosion can be increased by longshore nonuniformity in the dune or beach. East Matagorda Peninsula (TX) provides an example of how a pre-existing overwash fan can allow an increase in sediment transport, although the sediment at these locations is channelized along a wider conduit as compared to a beach access pathway.

Therefore, the protection provided by dunes against storm surge and waves can be substantially weakened by infrastructure or natural cuts that transect the dune field because these features provide a pathway for sediment to be transported. Sites where infrastructure creates a pathway for storm surge inundation and channelization of sediment transport appear to experience an increase in vulnerability (damage potential) from increased erosion and associated damage. In general, observations show significant damage from sediment overwash and road undercutting at beach access paths and roads that transect dune fields. Beach access points weakened the line of coastal defense provided by dunes, vegetation, and structures. Because the disturbance in the dune system (or other protection mechanisms such as vegetation and structures) caused by the access points are relatively small in size compared to typical dune systems, these transects are currently often ignored during risk assessment of coastal zones. The results of this study highlight that detailed knowledge of spatial distribution of storm hydrodynamics (water levels, waves, etc.), morphological features (e.g. dune and beach widths, heights, and vegetation coverage), and coastal infrastructure (beach access pathways, fixed objects, impermeable structures, etc.) is important to predict impacts to local infrastructure, beaches, and near-beach environments.

A lesson learned from these post-2017 field reconnaissance missions, similarly to previous hurricane observations, is the need to monitor and evaluate any longshore non-uniformity in the dune system and infrastructure. Furthermore, observations and data associated with sediment transport and erosion need to be collected as quickly as possible to maintain the integrity of the failure conditions. Measurements of the geometry of beach access pathways and dunes, including the height, width, length, and vegetation coverage, are necessary prior to recovery of the system post-storm to allow for a quantitative comparison. The immediate collection of data before and after the extreme event is of critical importance in order to accurately assess storm damages and develop accurate results that will be used to increase the scientific knowledge and resiliency of coastal communities.

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