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SURVEY REPORT

Impacts of Hurricane Dorian on the Bahamas: field observations of hazard intensity and performance of the built environment

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ABSTRACT
On September 1 2019, Hurricane Dorian made landfall in Elbow Cay in the Bahamas with sustained winds of 295 km/h and a central pressure of 910 mb, with subsequent landfalls in Marsh Harbour and Grand Bahama Island, where it stalled for two days. This paper presents field observations of Dorian's coastal hazards and impacts on the built environment in these locales, collected by the Structural Extreme Events Reconnaissance (StEER) Network. Data were collected using a mixed methodological approach: (1) surveying high-water marks and inundation extent, including an approximately 8 m high water mark in Marsh Harbour, (2) conducting surface-level forensic assessments of damage to 358 structures, and (3) rapidly imaging 475 km of routes using street-level panoramas. Field observations are complemented by a debris field analysis using high-resolution satellite imagery. Observed performance reiterates the potential for well-confined, elevated construction to perform well under major hurricanes, but with the need to codify such practices through the addition of storm surge design provisions and an increase in the design wind speeds in the Bahamas Building Code. This study further demonstrates the value of robust reconnaissance infrastructure for capturing perishable data following hurricanes and making such data rapidly available using publicly accessible platforms.

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KEYWORDS
Hurricane; Dorian; Bahamas; storm surge; wind; damage assessment

1. Introduction

On September 1 2019, Hurricane Dorian made landfall in Elbow Cay in the Bahamas at 16:40 UTC with sustained winds of 295 km/h (185 mph), wind gusts up to 360 km/h (225 mph), and a central pressure of 910 mb (Avila et al. 2020). Dorian is regarded as the strongest hurricane (by various measures) to impact the Bahamas and tied the 1935 Labor Day hurricane (which struck the Florida Keys) for the strongest sustained winds observed in a landfall in the Atlantic Basin. Shortly thereafter, Dorian made a second landfall in the Bahamas at Marsh Harbour on Great Abaco Island before continuing westward across Grand Bahama Island. After nearly two days over Grand Bahama Island, setting records for the longest duration over land at a Category 5 intensity, Dorian approached the US in a weakened state with its most notable impacts confined to flooding and tornadoes in the Carolinas (Kijewski-Correa et al. 2019a). Some of the most extensive damage in the Bahamas was driven by storm surge, in excess of 8 m above mean sea level at some locations of high water marks (HWM) documented by the authors. This storm surge was a major driver in the official death toll of 74 (63 in Abaco, 11 in Grand Bahama) with over 200 more missing (Avila et al. 2020), though notably the undocumented migrants killed in the catastrophic destruction of informal settlements in Central Abaco were not included in these totals (Deopersad et al. 2020). The Inter-American Development Bank (IDB) estimated the losses in the Bahamas at $3.4 billion, over a quarter of the gross domestic product (GDP) for this small archipelago nation of 386,000 people (Deopersad et al. 2020), and only 38% of these losses were insured.

This paper presents the geospatial characterization of wind and coastal hazards driving these losses in the Bahamas, correlating these hazards with the authors' observed performance of the built environment. The analyses herein are informed by data captured using a mixed-methodological approach to survey coastal

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hazards and resulting damage to a wide class of buildings and other infrastructure. Data were collected in two missions within five weeks of Hurricane Dorian, as part of the coordinated response of the Structural Extreme Event Reconnaissance (StEER) network operating under the Natural Hazards Engineering Research Infrastructure (NHERI) (Kijewski-Correa et al. 2019a; Marshall et al. 2019). The field observations focused on the islands most impacted by Dorian: the Abaco Islands and Grand Bahama Island. In Great Abaco, two rounds of field investigations documented the area around Marsh Harbour, which is the island's largest population center and experienced the worst impacts with direct landfalling wind, waves, and surge. Meanwhile, rapid end-to-end data collection covered the populated areas on Grand Bahama, including the Freeport metro area, where the population is similarly concentrated. In these investigations, the teams (1) surveyed high-water marks and inundation extent, (2) conducted surface-level forensic assessments of damage to buildings and other infrastructure, and (3) rapidly imaged a wide cross-section of impacted regions along major routes using street-level panoramas.

The paper will first introduce the construction norms and regulatory environment in the Bahamas followed by the data collection methods engaged, after which the hazards generated by Dorian are characterized. The second half of the paper details the resulting impacts to the built environment, and the correlations with this geospatial distribution of hazard intensity, as well as implications for reducing future hurricane risk.

Table 1. Typical features of three classes of residential construction in the Bahamas.

	Class 1 (Figure 1a)	Class 2 (Figure 1b)	Class 3 (Figure 1c-d)
Foundation	Slab-on-grade	Mostly slab-on-grade; isolated use of CMU piers in coastal areas	Slab-on-grade, masonry walls, or reinforced concrete piers
Structural System	Mix of galvanized metal sheets, unreinforced masonry, wood	Lightly confined, lightly reinforced masonry walls with wood-frame roofs	Wood-framed or confined masonry walls; wood roof framing and roof sheathing
Roof Cover	Plastics, sheet metal, asphalt shingles	Mostly asphalt shingles; some standing seam metal panels	Asphalt shingles, standing seam metal panels, or Bermuda roof
Mitigation Features	None	Some hipped roofs, short roof overhangs, metal straps connect roof framing to walls	Hipped roofs, shutter systems to protect openings, secondary water barriers, hurricane straps/clips

2. Construction practices and regulatory environment

2.1. Prevailing construction practices

As damage to the housing sector was estimated at $1.48 billion, a dominant (43%) share of the losses in this event (Deopersad et al. 2020), housing will receive significant emphasis in Section 6, Impacts to the Built Environment. Bahamian residential construction is

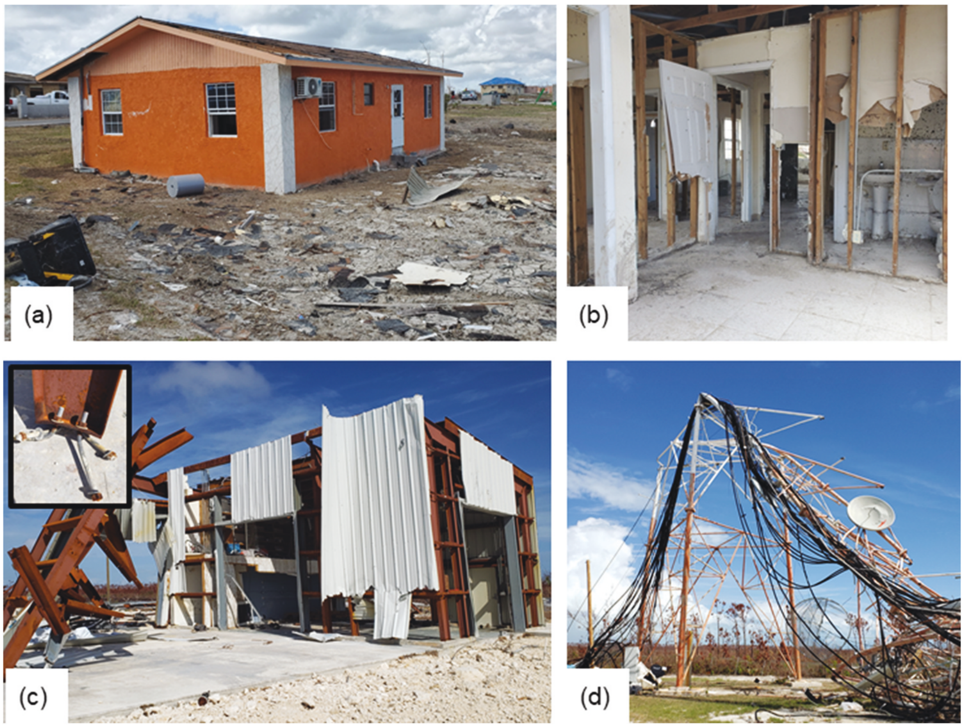


Figure 1. (a) Example of Class 1 home in Sweeting's Cay employing a mixture of lightly framed construction with a variety of sheathing materials and an annex of unreinforced masonry; (b) Example of Class 2 home near the West End; (c-d) Examples of Class 3 homes in Marsh Harbour with progressively higher levels of elevation of the primary living space.

generally implemented using one of three material typologies: load bearing masonry (76%), wood-frame (15%), and reinforced concrete (9%) (Karamlou and Ramanathan 2019). Akin to the three-level home-valuation categorization adopted by de Bruijn et al. (2020), the authors specifically organize the residential building inventory into three major classes, as summarized in Table 1 and illustrated in Figure 1, whose quality of construction and material choices are shaped by economic capacity.

2.2. Regulatory environment

The Out Islands (or Family Islands) that comprise the Bahamas have been frequently exposed to Hurricanes, with 55 documented impacts by tropical storms since the start of the 20th century, 13 of which were major hurricanes (Zegarra et al. 2020). However, construction was not regulated until the adoption of the Bahamas Building Code (BBC) in the early 1970s. Notably there are features of the Family Islands, including settlements with small populations dispersed across the islands, that make enforcement and compliance with building codes challenging (Deopersad et al. 2020). As noted by Karamlou and Ramanathan (2019), the Ministry of Works, the BBC oversight body, lacks the capacity to strictly enforce code requirements, leading to deficiencies and unregulated construction.

The BBC was updated in 1987 to follow the South Florida Building Code (SFBC), but was not updated to reflect the changes to the Florida Building code following Hurricane Andrew, which impacted both the Bahamas and Florida. The latest edition of the BBC (3rd Edition) is based upon ASCE 7–88 and designs buildings within 1500 feet of the coast for Exposure Category D and Importance Category I (GoB, 2003). The BBC further increased its design wind speeds from 120 mph to 150 mph (3-second gust at 10 m height in open terrain) and mandated the design of hurricane shutters. However, it has been noted that the BBC Code lacks thorough detailing requirements and specifications for critical elements of the load path and roof system (Karamlou and Ramanathan 2019).

Although Great Abaco Island had recently been impacted by Hurricanes Floyd (1999) and Matthew (2016), with damage from the latter storm still yet to be repaired on Grand Bahama Island at the time Dorian struck, wind-resistant design in the Bahamas at the time of landfall was still regulated by the 2003 edition of the BBC. Notably, as demonstrated later in Section 4.1, Dorian's wind speeds readily exceeded the BBC's design-level event. Further, BBC makes no explicit considerations for storm surge in coastal areas, despite recent hurricanes (Wilma in 2005, Joaquin in 2015) highlighting the potential for damaging storm surge, as was the case in Hurricane Dorian (see Section 4.2).

3. Field survey strategy and methods

The StEER response began with formation of a Virtual Assessment Structural Team (VAST), which subsequently used publicly available sources (e.g. curated on social media platforms) to characterize and contextualize the unfolding disaster, and to establish priorities for an on-site deployment. This information was summarized in a Preliminary Virtual Reconnaissance Report (Kijewski-Correa et al. 2019a). Informed by the PVRR, and in consideration of the logistical challenges, a subset of the authors deployed in a phased investigation, initiating with a small scout team (termed Field Assessment Structural Team 1, or FAST-1) followed by a larger interdisciplinary team (termed FAST-2). Logistical details of each FAST deployment are available in the Data Report on DesignSafe (see Data Availability Statement in Section 9).

FAST-1 collected building performance and approximate high-water mark data from 24-26 September, 2019 on Great Abaco Island, and specifically Marsh Harbour and Treasure Cay. Attention was centered on these two regions since they: (i) were impacted by significant wind and storm surge, (ii) encompassed diverse building typologies, and (iii) had sufficient density to generate robust sample sets over compact areas. Based on targets of opportunity from FAST-1 as well as ongoing analysis of satellite imagery, a second Field Assessment Structural Team (FAST-2), including experts in both structural and coastal engineering, was deployed 5-9 October, 2019 with a more expansive range of targets that included Great Abaco Island, Man-o-War Cay, and Grand Bahama Island. In total, these FASTs were able to conduct a coastal survey and assess a representative sample of engineered construction such as hospitals, government buildings, airport/port facilities, commercial buildings, and hotels, as well as numerous residential buildings. Notably the team's use of a mixed methodological approach, geospatially summarized in Figure 2, enabled the swift collection of perishable data over a large geographic area to minimize the demands in challenging field conditions. Partitioning the data generation between the on-site investigators and VASTs enabled ongoing remote data enrichment and quality control well beyond the field deployment, improving the efficiency of data collection and the quality of the final dataset (Roueche et al. 2019). The methodologies employed by FAST-1 and FAST-2 are now introduced. See the Data Availability Statement to access both the data generated by these methodologies and appropriate metadata.

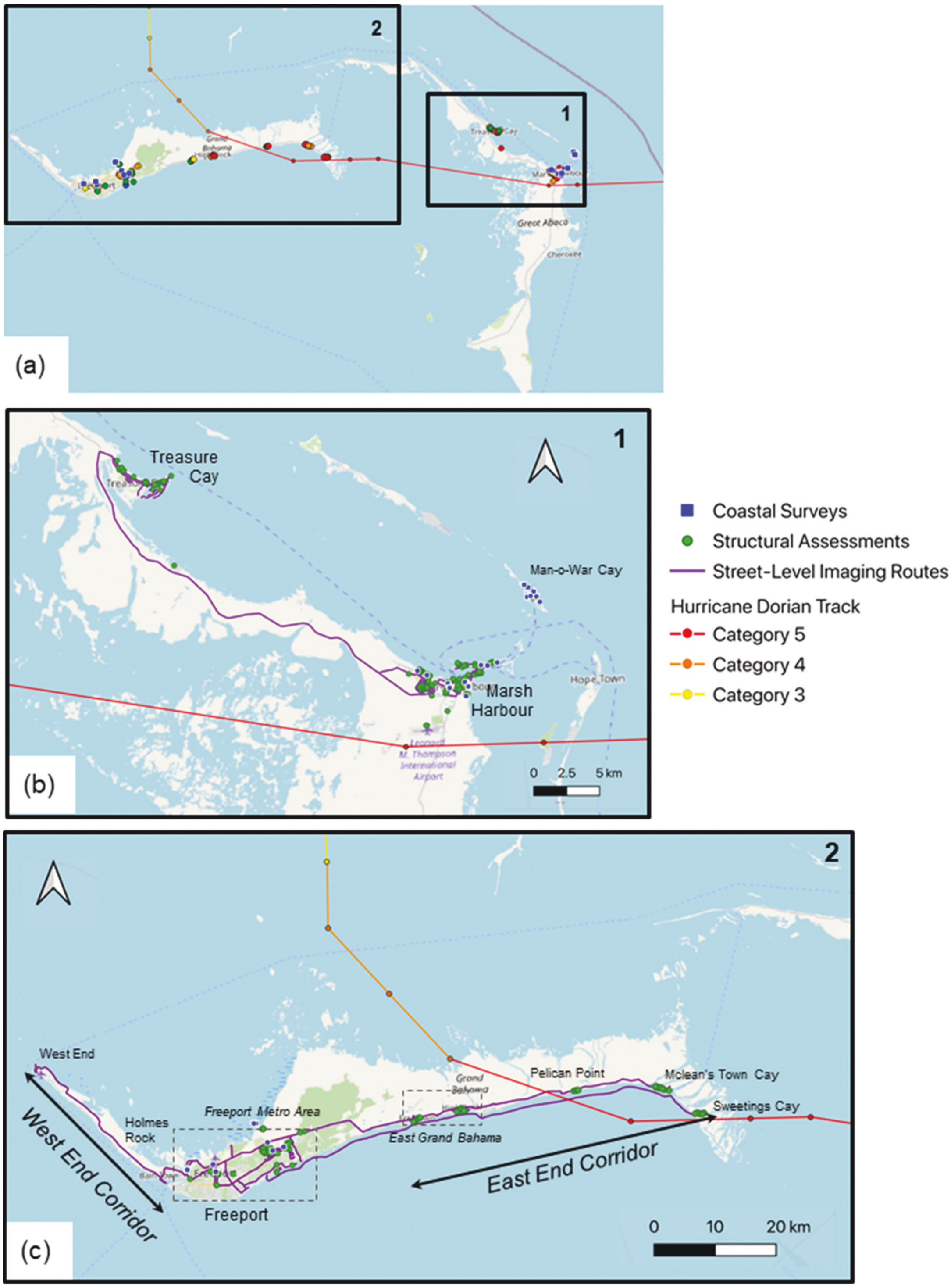


Figure 2. (a) Overview of data collection sites relative to Hurricane Dorian's Track with two inset maps: (b) Inset 1 – surveyed region of the Abaco Islands; (c) Inset 2 – surveyed regions of Grand Bahama Island. Maps depict locations of structural assessments, street-level imaging, and coastal surveys.

3.1. Coastal survey

A documentation of coastal hazard intensity was achieved through both processing of satellite imagery and field surveys by FAST-2. Satellite reconnaissance employed pre- and post-storm imagery on Great Abaco Island near Marsh Harbour, taken from various sources including images purchased from commercial satellite providers and freely available imagery on Google Earth. Two aspects were considered: movement of shipping containers during the storm and debris fields generated by the storm. Both could only consider features clearly visible on approximately 0.5 m resolution imagery, which was sufficient for large objects. Where possible, but not always, confirmation was obtained from other sources to ensure that, for example, a presumed shipping container was not actually a mobile home. In cases where such confirmation was

Figure 3. Representative high water marks. (a) Looking downward from approximately 8.1 m HWM in Marsh Harbour, Great Abaco; (b) Interior watermark in bathroom; (c) Looking seaward from 6.2 m elevation near top of large debris pile/watermark on the side of a hill in Marsh Harbour.

not possible, these objects were noted as uncertain. Although field observations confirmed some of the shipping containers, it was not possible to visit all of the sites. Debris fields were evaluated by eye, with additional ground-level confirmation and guidance where possible. Only debris fields with linear dimensions of at least 5 m were considered.

At each of the coastal survey sites in Figure 2, FAST-2's primary focus was on obtaining evidence of high-water mark (HWM) elevations above sea level, with a secondary goal of finding inland limits of inundation. HWM evidence was usually established based on floating debris stranded at the water's edge or interior watermarks on structures (Figure 3). In a few cases, eyewitnesses described the extent or depth of inundation during the storm. Where possible, the elevation above mean sea level was determined using a rod and optical level, or laser rangefinder transect to the ocean, with corrections from tidal databases. Horizontal locations were determined using handheld GPS on cellular phones and corrected if needed from satellite maps after the survey. Photographs were taken at all locations.

3.2. App-based structural assessments

Structural assessments were collected by both FAST-1 and FAST-2 using a suite of Fulcrum mobile smartphone applications standardized for use in StEER missions. As detailed in Kijewski-Correa et al. (2021), these apps support the acquisition of geo-tagged photos, recorded audio dictations, and investigator-supplied inputs to over 100 standard assessment fields enabling a component-level damage quantification for diverse typologies. Assessments adopted standardized damage ratings (Kijewski-Correa et al. 2019b). Owing to the mixed-methodological approach employed, emphasis was placed on using these apps to: 1) collect clear photographs from multiple perspectives, 2) accurately geo-locate the site, 3) populate any fields that require on-site forensic investigation and structural engineering expertise, and 4) note unique features that would affect windstorm performance and not be otherwise visible when processing data remotely (generally captured through an embedded audio dictation). Remaining fields could then be populated afterward using the other acquired and supplemental data. Structural assessments focused on pre-identified clusters of structures, selected based on typology, year of construction (as inferred from time-evolving satellite imagery), post-Dorian performance (as indicated by satellite imagery), and hazard exposure/intensity. Assessments within pre-identified clusters of buildings were conducted at regular intervals (e.g. every third structure) to provide detailed evaluation of building performance without biasing toward damaged structures. Beyond sampled clusters, individual case study buildings of notable successes and targets of opportunity were also assessed. Figure 2 visualizes the locations of the 358 structural assessments generated by FAST-1 and FAST-2 across the surveyed islands.

3.3. Street-level panoramic imaging

FAST-1 and FAST-2 deployed 360-degree-imaging platforms to capture near continuous surface imagery of building exteriors and other aspects of the built and natural environment sufficient to infer exterior structural performance patterns through manual or automated tagging. Specific hardware included the Insta360 One camera (producing 6912 × 3456 pixel panoramas), Applied StreetView system (producing 8192 × 4096 pixel panoramas), and an NCTech iStar Pulsar system (producing 11,000 × 5500 pixel panoramas), each of which produced equirectangular panoramas geotagged with ~2.5 m accuracy. These 360-degree-imaging platforms were deployed in the Bahamas using vehicular, handheld, backpack-mounted and boat-mounted implementations to generate panoramas in a range of areas with varying degrees of accessibility. Frames were captured every 5 m or less along the approximately 475 km of routes visualized in

Figure 2. FAST-1 focused on Marsh Harbour and Treasure Cay, while FAST-2 imaged the full length of Grand Bahama, from the West End all the way to the first landfall site at Sweetings Cay.

4. Hazard characterization

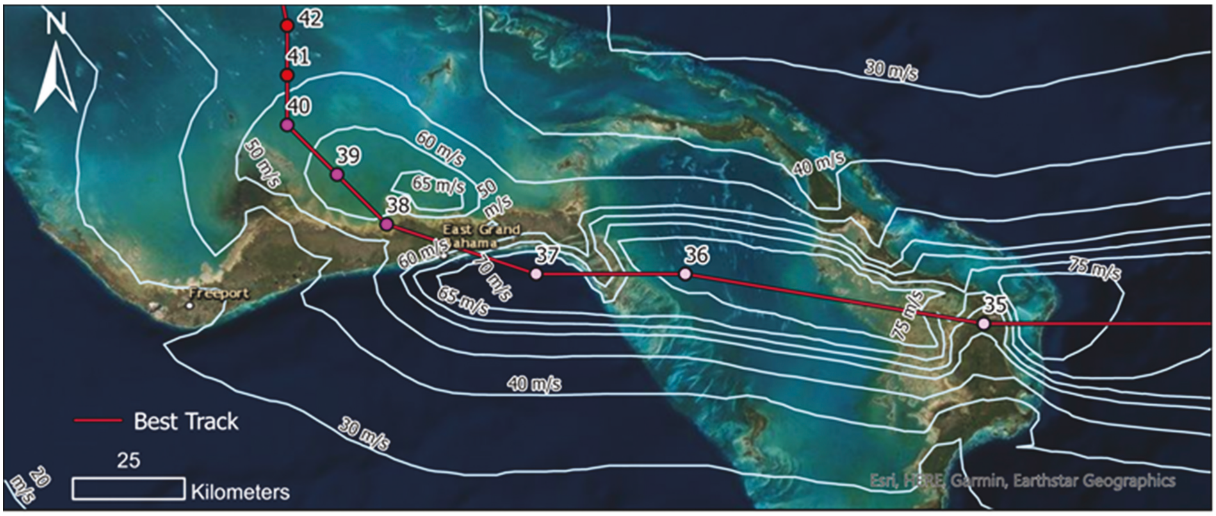
4.1. Wind field

A description of the complete track for Hurricane Dorian, including landfalls in the Bahamas and the US, is provided in Kijewski-Correa et al. (2019a) and Avila et al. (2020). Hurricane Dorian approached the Bahamas as a Category 5 hurricane with maximum sustained wind speeds near 82 m/s (295 km/h; 184 mph) and a minimum sea-level pressure of 910 mb (Avila et al. 2020) when it made landfall in Elbow Cay and Marsh Harbour on Great Abaco Island. All told, Hurricane Dorian produced hurricane force winds, with associated rain and storm surge, over portions of the Bahamas continuously for approximately 48 hours (Figure 4).

Using aircraft-based observations of the center location, minimum pressure, RMW, and sustained winds, Done et al. (2020) developed an estimated wind field for Dorian (Figure 4). The surface wind field was modeled using a parametric wind field model at the top of the hurricane boundary layer (approximately 1 km above the surface), bringing winds down to the surface using a numerical boundary layer model that responds to local changes in surface roughness and topography (Kepert and Wang 2001). The wind field as presented thus represents sustained wind speeds, averaged over 1-minute windows, under local terrain conditions. All references to estimated wind speeds in subsequent sections of this paper represent these conditions.

4.2. Inundation extent and high water marks

Figures 5–7 show HWM elevations plotted in geographical space for Man-o-War Cay, Marsh Harbour (Great Abaco Island), and Western Grand Bahama Island, respectively, with the HWMs and inundation limits tabularized in the Appendix. In these figures, reference datums are to mean sea level (MSL) in most cases (red circles or blue triangles) or to local ground elevations (yellow diamonds). As Man-o-War Cay and Marsh Harbour (Great Abaco Island) are in close proximity, they show similar damage patterns. In Man-o-War Cay (Figure 5), which was exposed to the open Atlantic Ocean, inundation on the seaward, eastern shore was driven by wave runup, with HWM up to 7.1 m, measured at the top of an erosional scarp. Many other HWMs slightly lower than this were measured at different locations along the Atlantic shoreline. In contrast, the sheltered western side had much smaller



Advisory	Month	Day	Time (UTC)	Saffir-Simpson	Max Intensity (m/s)	Min Pressure (mbar)
35	09	1	1800	5	71.5	910
36	09	2	0000	5	69.3	914
37	09	2	0600	5	64.8	916
38	09	2	1200	4	60.3	927
39	09	2	1800	4	55.9	938
40	09	3	0000	4	51.4	944
41	09	3	0600	3	46.9	950
42	09	3	1200	3	44.7	954

Figure 4. Maximum 1-min sustained wind speed at 10 m height, adjusted for local terrain with a table of storm parameters at ID points shown along the best track. Wind field analysis conducted by James Done at the University Corporation for Atmospheric Research (UCAR) (1 m/s = 1.94 knots = 2.24 mph = 3.6 km/h).

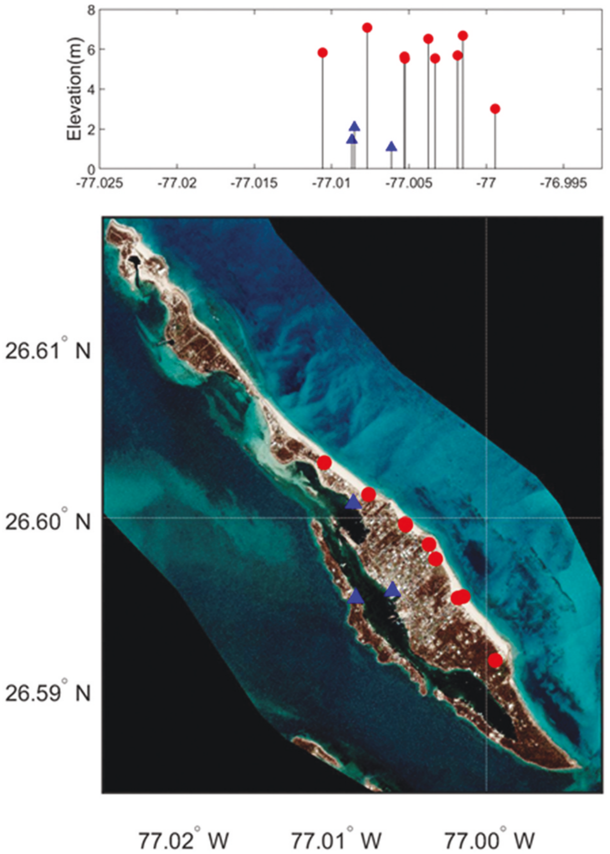


Figure 5. Measured high water marks on Man-o-War Cay, referenced to mean sea level. Red circles show observations on the exposed side, while blue triangles are on the sheltered side.

waves, and maximum water levels around 2 m, measured from the elevation of a grounded boat. This difference is entirely due to the lower wave runup and/or setup because the strong hydraulic connection around the island means that the "surge" component can have only little change in this short distance. In contrast, low wave runup and little evidence of direct wave damage or erosion were seen on the sheltered west side of Man-o-War, as compared to the exposed eastern side.

A similar difference was observed in Marsh Harbour on Great Abaco Island (Figure 6) between the exposed (northern) and sheltered (eastern) coastlines. High-water marks on the exposed coast are up to approximately 8 m, with many in the 5–6 m range. These were again driven by wave runup and left both small debris lines and much larger debris fields on the coast. The eastern coast (sheltered) had far fewer measurements, but only around 2 m water levels were observed around a marina, and relatively small inland inundation limits were seen at other locations. The impacts of the wave runup in Marsh Harbour were in part mitigated by the local topography (Figure 7), as a pronounced 2D ridge runs along the northern coast (along Pelican Shores Dr.) approximately 18 m above mean sea level. However, this feature is not present in the heavily impacted regions of Marsh Harbour known as the Mudd and Pigeon Peas. These notably more low-lying areas of Marsh Harbour were home to large settlements of Class 1 residential structures. The elevated topographical features also do not extend up to Treasure Cay, which features a flatter and more homogeneous terrain.

On western Grand Bahama Island near Freeport (Figure 8), the largest inundation evidence was documented on the northern (exposed) shore from small chunks of asphalt that were deposited at around 7.7 m elevation. These were likely generated from wave runup

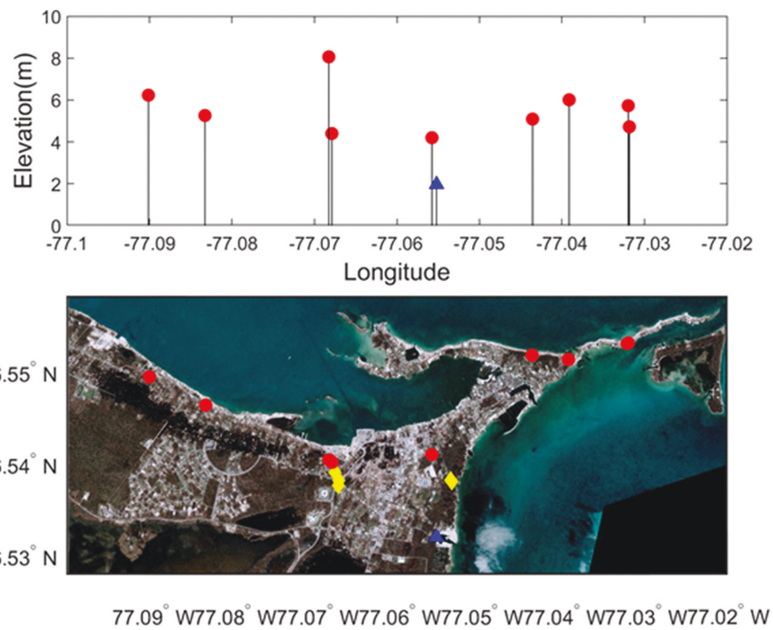


Figure 6. Measured High Water Marks in Marsh Harbour, Great Abaco Island. Observations at red circles (exposed) and blue triangle (sheltered) are referenced to mean sea level, while yellow diamonds are relative to local ground elevations.

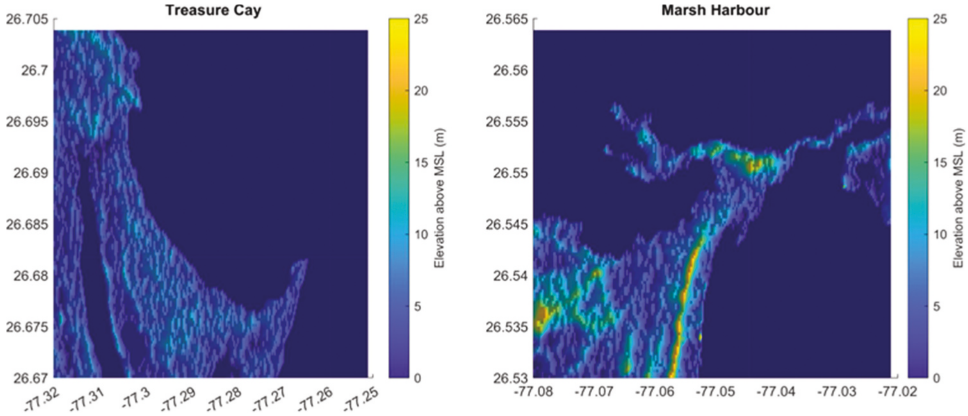


Figure 7. Topography in Treasure Cay and Marsh Harbour using the USGS EROS Shuttle Radar Topography Mission 1 Arc-Second Global Digital Elevation Model (Data Source: USGS, 2020).

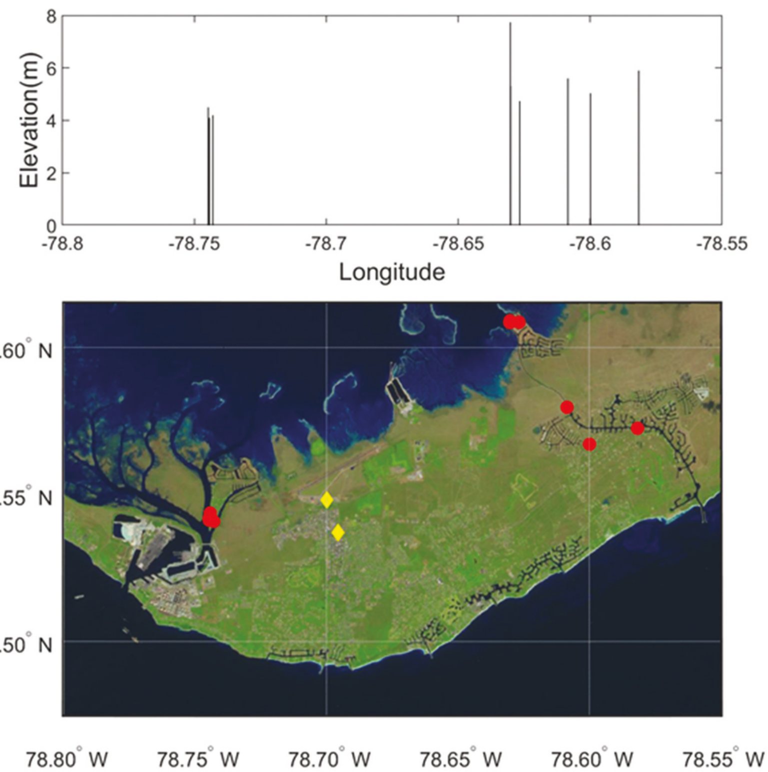


Figure 8. Measured High Water Marks on Grand Bahama Island; observations at red circles are referenced to mean sea level, while observations at yellow diamonds are relative to local ground elevations.

onto the coastal road below and splashup to a higher elevation, as it does not appear that large waves reached this higher elevation. HWMs not influenced by large wave runup were lower, with numerous measurements to 4.5 m in Queen's Cove west of Freeport. Further east, on and near the Grand Lucayan Waterway, large quantities of floating debris suggested inland HWMs from 5.4–5.9 m. Although the waterway is normally at sea level, these elevations may have resulted from a combination of inland runoff and storm surge. No elevations were taken within the city of Freeport, but water levels 2.9 m above ground were noted at Grand Bahama International Airport, and 1.7 m water levels above ground at the Freeport Police Headquarters approximately 2.7 km from the closest coast.

While direct measurements were not recorded on the east end of Grand Bahama Island, considerable wave and surge damage were noted, with eyewitness reports and post-storm reconnaissance discussed later in Section 6.2.1. Note that ADCIRC simulations and satellite imagery presented in Kijewski-Correa et al. (2019a) affirms that storm surge was highest along the north coast of Grand Bahama Island effectively submerging most of the island.

5. Debris generation and transport

A debris analysis was conducted as a further indication of coastal hazard intensity in Hurricane Dorian. The analysis focused on Abaco Islands, using post-Dorian imagery that was acquired on September 5, 2019 from the Pleiades 1B satellite with 50 cm resolution. Three types of debris were classified: visible debris fields, probable shipping containers displaced by Dorian, and sunken or stranded boats visible in satellite images. Figure 9a shows debris fields in the area of Marsh Harbour. Waterborne debris tends to be close to the coastline, and extensive debris fields were found all along the northern Marsh Harbour coastline. Low areas, such as the informal settlement known as the Mudd, collected floating and other debris in very deep piles. The debris locations given here are in no way exhaustive, as the manual identification and delineation were time-consuming and uncertain, and only the portion of the coastline in the vicinity of the port was covered. Additionally, visibility was poor in some locations and distinguishing between storm debris and other items was sometimes not possible. Nevertheless, floating and other light debris was observed to be concentrated in the coastal areas up to the inland limits of inundation in some areas.

Storm-surge-transported shipping containers have very distinctive shapes in satellite imagery and tend to originate from coastal shipping yards for which pre-disaster satellite imagery is generally available to confirm debris sources. Figure 9b visualizes the locations of potential storm-transported shipping containers visible in the satellite images in Marsh Harbour post-Dorian. Although containers were seen everywhere in pre-storm images, the port area was likely the source of many containers, and the largest concentrations of post-storm containers were found just inland of this area with other debris.

Sunken and stranded boats mapped in Figure 10 offered another indicator of storm intensity and could be either a navigational hazard or another costly cleanup. These were visible around almost all marinas and areas with small craft; from the little that could be determined, although a few small boats seemed to be transported long distances, possible original locations seemed near final resting places in almost all instances examined here. Because boats are anchored in what are normally sheltered locations, i.e. on the southwestern side of Man-o-War Cay, the waves and surge may have been lower than in some other locations but damage was still substantial.

6. Impacts to the built environment

A summary of structural performance is organized by island, focusing first on the Abaco Islands and then Grand Bahama Island. For the analysis in the Abacos, performance summaries will focus on specific communities where targeted sampling resulted in clusters of app-based assessments. In Grand Bahama, street-level panoramas along the full length of the island were

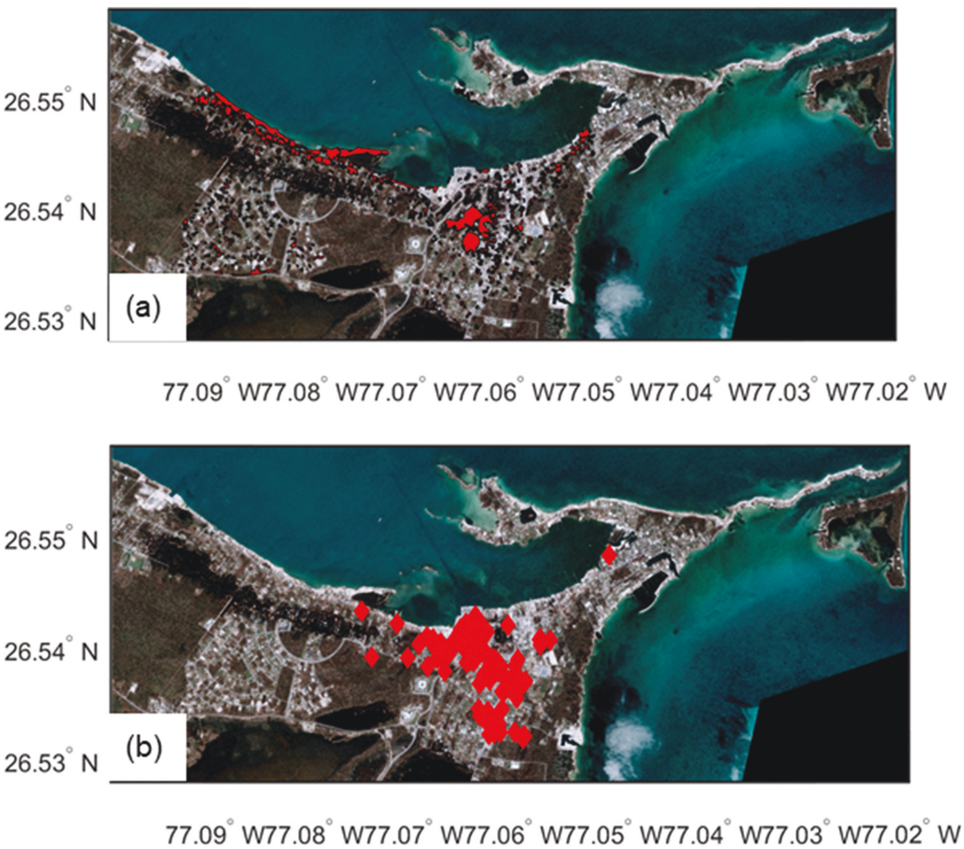


Figure 9. (a) Areas of debris concentration observed from satellite images; (b) Locations of apparent shipping containers post-Dorian, without confirmation of source.

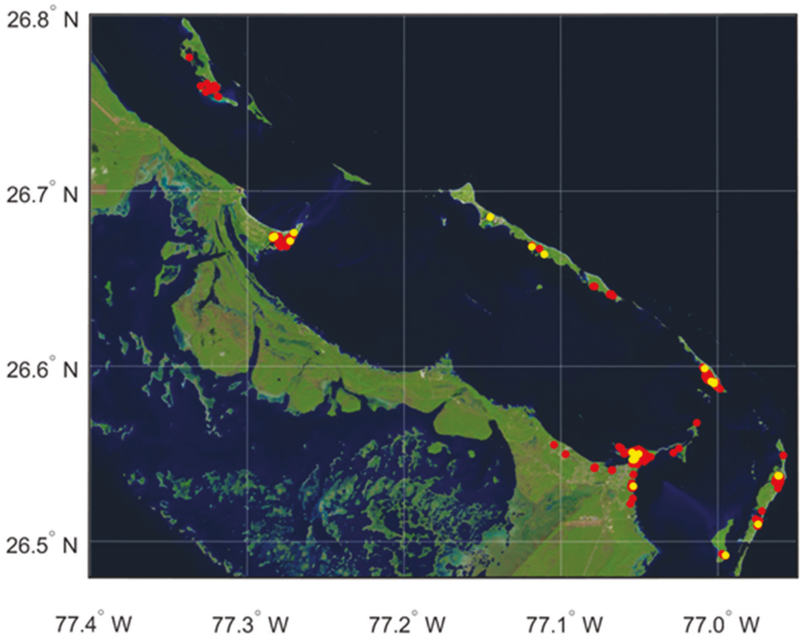


Figure 10. Locations of observed sunken (yellow) and stranded (red) boats post-Dorian on the Abaco Islands.

evaluated to summarize representative performance, geospatially, with additional details provided by isolated clusters of app-based assessments.

6.1. The Abaco Islands

On Great Abaco Island, more than 75% of the dwellings were impacted and approximately 57% of the houses were severely damaged, particularly in Central Abaco (Marsh Harbour), Treasure Cay, and Hope Town (Deopersad et al. 2020). The former two settlements, as well as Man-o-War Cay, were investigated by the authors. The affected building inventory in the Abacos included single and multi-family homes, resorts/hotels/rental properties, light industrial/marina facilities, and commercial construction serving retail and tourism industries. Nearly 90% of Dorian's housing damage was concentrated in the Abaco Islands (Deopersad et al. 2020), which have a relatively high proportion of the building stock serving the tourist or vacation home industry (Class 3 construction), as well as a large migrant community (de Bruijn et al. 2020) occupying informal settlements (Class 1 construction).

6.1.1. Treasure Cay, Great Abaco Island

Treasure Cay experienced peak wind speeds estimated at 50 m/s (180 km/h; 112 mph) as Dorian tracked approximately 15 km south at its nearest point. FAST-1 measured a HWM of 1.8 m above ground level (~3 m above mean sea level) inside a home at (26.687, −77.302), located approximately 275 m inland. Widespread high-water marks or other estimates of surge inundation or wave heights were not captured by field teams in the area, but from the observed structural damage it did not appear that wave action was a significant contributor. The majority of structures (which in Treasure Cay are almost entirely Class 2 and Class 3 residential) remained standing, though damage was still widespread and variable. The majority of observed exterior structural damage was due to wind action, although surge inundation flooded many structures and damaged interior contents.

6.1.2. Marsh Harbour, Great Abaco Island

Performance assessments in Marsh Harbour centered around the port and surrounding areas, encompassing single-family and multi-family residential construction, as well as health centers, essential facilities, government buildings, religious institutions, schools, and businesses. A synthesis of FAST-1 and FAST-2 observations across these building classes are provided herein, with additional details of FAST-1 findings available in Marshall et al. (2019). Maximum wind speeds in this region were 70–75 m/s (252–270 km/h; 157–168 mph) (per Figure 4) with most observed HWMs ranging between 4 m and 6 m (per Figure 6).

Throughout the port area, evidence of significant wave runup was observed, resulting in failures of multiple metal frame and CMU masonry warehouses/industrial buildings. As noted in Figure 6, a HWM of approximately 8 m was documented in this area. Steel frame buildings experienced wash-throughs, stripping the metal envelope or punching through the masonry infill (Figure 11a), as well as system-level failures due to insufficient foundation anchorage (both with respect to embedment length and edge distance).

Surveys of the residential areas east of the port (along East Bay Street and along Eastern Shores Road and Pelican Shores Drive on the cape where HWMs of 5–6 m were documented in Figure 6) were inhibited

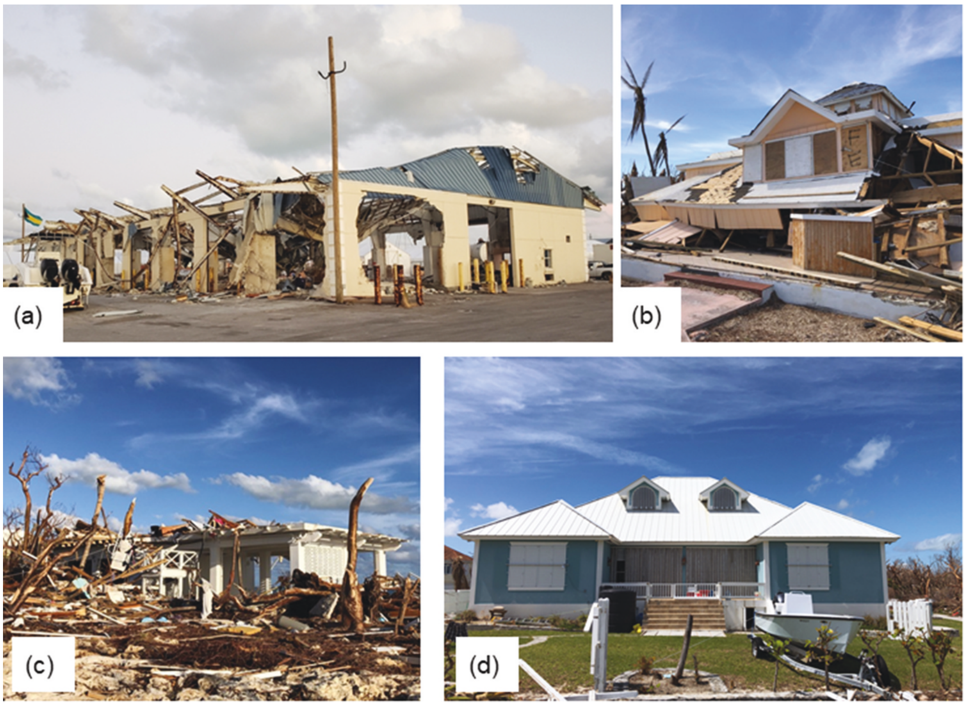


Figure 11. Illustrative performances in the Marsh Harbour (Great Abaco Island) region: (a) failure of masonry infill on steel moment frame port warehouse at (26.542944, −77.064664); (b) example of surge-induced "soft story" failure in wood framed Class 2 residence at (26.545954, −77.046597); (c) complete destruction under storm surge leaving only the elevated foundation of an assumed Class 3 home at (26.551910, −77.037554); and (d) minor/no structural damage in a coastal Class 3 masonry home at (26.552433, −77.060514).

due to debris/road wash out, though those accessible were severely damaged if not completely destroyed by storm surge (Figure 11b), with failures of even elevated Class 3 homes as a result of insufficient freeboard (Figure 11c). Documented wall-to-foundation failures in Class 3 wood-framed residential construction were characterized by limited to no visible evidence of metal straps to connect wood stud walls to sill plates.

Similar trends were observed among Class 2 and 3 residential construction (single and multi-family) west of the port, where comparable HWMs were observed (see Figure 6) and notable shoreline erosion was documented. Progressing along George Albury Boulevard to the northwest of the port, significant inundation and wave runup led to severe damage or destruction of most oceanfront buildings. While the few instances of well-confined masonry construction were exceptions (Figure 11d), most CMU buildings lacked the steel reinforcement in masonry walls, confinement (e.g. insufficient lap lengths in ring/bond beams), and/or foundation anchorage necessary to sustain the demands of storm surge and breaking waves. Furthermore, surviving masonry homes with minor damage often sustained extensive interior losses due to surge-induced flooding.

The primary commercial district, along Don Mackay Boulevard south of the port, sustained damage due to wind and inland storm surge with a number of displaced boats on-site: 75% of the commercial construction surveyed sustained severe damage or total destruction. Finally, government buildings in the region were typically inland at a higher elevation and constructed of concrete and/or reinforced masonry, with prevalent use of storm shutters and other window coverings. Fenestration protection (where employed) performed well, with most government buildings sustaining only minor damage to exterior finishes. Government buildings with damaged roof cover experienced little to no interior water damage due to secondary water barriers.

6.1.3. Man-o-War Cay

Limited structural and coastal assessments were conducted on Man-o-War Cay during a brief survey there. The majority of buildings were wood-framed Class 3 structures, with slab on grade or reinforced concrete pier foundations. Notably, relatively few buildings were exposed to storm surge due to the higher elevations near the coast, though significant erosion was documented along all oceanfront sandy shorelines (Figure 12a). HWMs on the order of 6 m were measured on the oceanfront, three times that observed on the harbor-side of the island (see Figure 5). Peak wind speeds are estimated at 70–75 m/s (252 km/h; 157 mph) (per Figure 4), causing

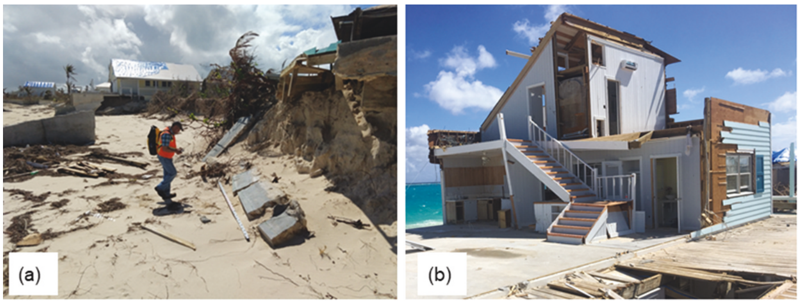


Figure 12. Man-o-War Cay (The Abacos): (a) erosional scarp to approximately 6 m elevation at (26.599536, −77.005361); (b) example of destroyed Class 3 residence at (26.601322, −77.008317) with poor anchorage at base of wall.

failures due to insufficient anchorage of the superstructure to the foundation in several homes (e.g. Figure 12b) and widespread damage to roof cover elements.

6.2. Grand Bahama Island

Grand Bahama is a primarily residential island also supporting a considerable share of the total industrial production in The Bahamas (Zegarra et al. 2020). This section overviews the damage observed here across three regions: (1) working east to west from Sweetings Cay toward Freeport through the East End Corridor (along Grand Bahama Highway) on the south coast (see Figure 2c); (2) working northwest to southwest from West End toward Freeport through the West End Corridor (along Queens Highway) (see Figure 2c), and then (3) the Freeport metro area. Note that fenestration protection was widely used on structures in these areas.

Figure 13. Sweetings Cay (Grand Bahama Island) overview: (a) panoramic image of collapsed Class 2 building; (b) St. Michael's Church at (26.609564, −77.878146); (c) complete destruction of Class 2 home at (26.609161, −77.891425); (d) well-confined Class 2 home at (26.609926, −77.877274) with (e) displaced vehicle impacting front porch column indicative of storm surge on site resulting in (f) significant interior flood losses.

6.2.1. East end corridor

Sweetings Cay, near the first landfall point on Grand Bahama Island (Figure 2c), is a small community of primarily Class 2 residential construction, with some instances of Class 1 homes.

Wind speeds in Sweetings Cay were estimated to be 65 m/s (234 km/h; 145 mph), with evidence of significant storm surge inducing partial or full collapse of approximately 75% of the buildings investigated. In most cases, the individual contributions of wind and surge hazards to the collapses could not be discerned.

Local construction practices failed to consistently implement sound detailing, such as lap splices in rebar, stirrups in tie columns, and proper load transfer from masonry walls to foundation. The use of coral stone in concrete structural elements was also observed. With few exceptions, these homes were severely damaged to completely destroyed (down to bare slabs) with significant debris fields remaining even weeks after landfall. Masonry wall failures were instigated by both roof uplift tensioning unreinforced walls and lateral pressure from storm surge (Figure 13c), both of which often propagated to complete collapse (Figure 13a).

Even for structures that performed well structurally, storm surge caused considerable interior contents damage, rendering the buildings uninhabitable. Notable examples include St. Michael's Church (Figure 13b), which was one of three churches in the community that performed well under Dorian's wind loads. St. Michael's was exposed to an estimated 5.5 m of interior flooding due to storm surge. Figure 13d provides another positive outlier, a well-confined Class 2 residence whose reinforced concrete elements used a local aggregate that is stronger than the coral stone used for concrete elements in surrounding homes. The confinement proved effective in resisting the propagation of wind-induced uplift failures (Figure 13d) and the effects of storm surge evidenced by a displaced vehicle that impacted the concrete front porch column (Figure 13e), consistent with eyewitness reports of 3.5–4.5 m of storm surge at this site. This resulted in 1.0–1.5 m of standing water inside the property, leading to significant interior losses (Figure 13f).

Moving along Grand Bahama Highway (GBHW) westward to McLean's Town Cay (Figure 2c), Class 2 structures east of Dorian's track remained uninhabitable, with few exceptions. Wind speeds here were estimated at approximately 65 m/s (234 km/h; 145 mph) and storm surge depths, while not formally documented by the Coastal Survey team, were reported by eyewitnesses to be 6 m at some sites. There was consistent evidence of sediment and debris deposition (Figure 14a) coupled with interior damage (Figure 14b) in surviving Class 2 structures that had sufficient wind resistance. In many cases, structures destroyed down to bare slab had debris swept away with the retreating surge. Engineered structures also exhibited severe damage, including a steel-frame marine facility with evidence of surge wash-through (Figure 14c) and a collapsed lattice communication tower (Figure 14d). The observed damage gradient, progressing from moderate roof damage to complete destruction (bare slab), increased north of GBHW, away from the south coast of Grand Bahama Island consistent with the direction of increasing depth of storm surge overland.

Figure 14. McLean's Town Cay (Grand Bahama Island) overview: (a) surviving Class 2 structure at (26.648639, −77.947904) with good wind resistance but (b) extensive interior damage due to storm surge; Examples of failures in other structural classes: (c) steel marine facility at (26.646725, −77.952984) with inset of anchor failure and (d) lattice communication tower at (26.648297, −77.947030).

Figure 15. Examples of varying damage levels observed in Class 2 wood-framed homes on elevated CMU piers in Pelican Point (Grand Bahama Island), including (a) surge wash-through of a single-story wood-frame home at (26.649183, −78.092826); note that a deck present on the coast-side of the home was removed but could not be found in nearby debris piles; and (b) complete destruction of the superstructure of a wood-frame home built atop a wood floor platform supported by CMU piers (26.649183, −78.092826).

At Pelican Point, a small community of about 30 buildings located just east of the second landfall point (Figure 2c), properties north of GBHW show higher incidence of structural wall damage to complete collapse (see Figure 15b for example of bare slab), though the trend was not as pronounced as in areas further east. A limited number of performance assessments and review of the street-level panoramas reveals variable performance, with four structures destroyed down to the slab, nine experiencing only roof cover damage, and two with no visible exterior damage. Wind speeds in this region were estimated to be 55 m/s (198 km/h; 123 mph) with eyewitness reports of significant storm surge. Note that while most buildings are Class 2, some may be interpreted as Class 1 construction with respect to quality and details, thus translating into higher rates of collapse. There was also a greater prevalence of wood-framed Class 2 construction in this region, in some cases elevated above grade on CMU piers (Figure 15a).

To the west of the second point of landfall on Grand Bahama Island, significant roof losses were documented through the East Grand Bahama Cluster (see Figure 2c) including the community of High Rock, though instances of complete destruction and bare slabs were less frequent. Wind speeds varied from 55 m/s (198 km/h; 123 mph) near High Rock to 45 m/s (162 km/h; 100 mph) closer to Freetown, while the amount of interior contents debris outside of surviving structures suggests flooding due to storm surge. Regarding the spatial distribution of damage within the region, the pattern of greater surge-induced damage including bare slabs to the north of GBHW continued through Freetown, though the levels of wind-induced damage notably diminish moving westward, with most structures experiencing minor to moderate roof damage. A number of assessed structures in this area were new construction yet to be occupied by owners (Figure 16a).

At Golden Grove while newer Class 3 construction performed exceptionally well, significant coastal erosion resulted in severe foundation scour, drift, and/or complete collapse of multiple Class 2 and 3 beachfront homes (Figure 16b-d). While the roof and superstructure of the pair of homes in Figure 16c performed well, substantial scouring of the foundations was observed in the surviving home, with complete foundation failure at a neighboring elevated home, unseating the

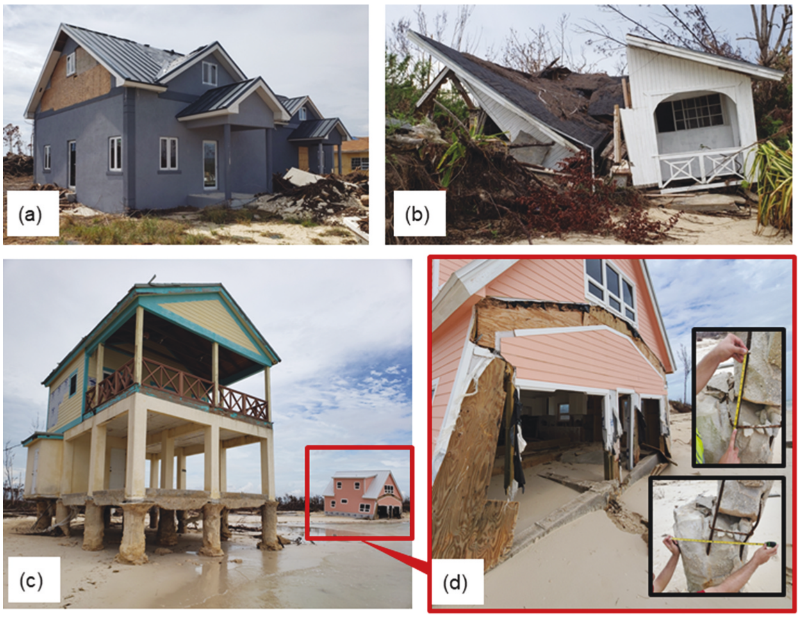


Figure 16. Varying performance levels in East Grand Bahama (Grand Bahama Island), including (a) brand new Class 2 masonry home at (26.611846, −78.354843) with minor cladding damage; (b) complete destruction of a beachfront Class 3 home in Golden Grove at (26.606874, −78.361771); Additional examples of (c) scour and (d) resulting foundation failure of beachfront Class 3 homes at (26.606950, −78.360959) and (26.614456, −78.346353), respectively.

house. The failed concrete piers were approximately 30 cm square with four longitudinal bars and #3 stirrups at 30.5 cm spacing (Figure 16d). Scour depths of 2.0–3.0 m were documented across the sites at this location.

6.2.2. West End corridor

The West End Corridor from West End toward Freeport along Bayshore Road and eventually Queen's Highway is typified by Class 2 construction, with the less frequent use of metal roofs outperforming their more prevalent asphalt counterparts. Class 2 properties increased in size and quality of construction closer to Freeport. Near West End, on Bayshore Road, exterior damage was limited to minor roof cover and flashing loss, though substantive debris piles suggest considerable interior water damage. Peak wind speeds in these regions were estimated to have varied between 20 and 30 m/s (72–108 km/h; 45–67 mph), so the lack of substantial wind-induced damage is not surprising. Continuing southeast along Queens Highway, the level of damage remains confined to minor roof damage, with less interior contents debris. Moving southeast toward Freeport, visible roof damage markedly increases from minor to moderate, with some outliers showing disproportionately severe damage. However, it is important to note that communities in the vicinity of Holmes Rock sustained significant damage in Hurricane Matthew (2016). Some of the more severely damaged properties were yet to be repaired when Dorian struck, making it difficult to distinguish damage from the respective storms and likely explaining the observed outliers.

6.2.3. Freeport metro area

The University of the Bahamas-North Campus, on the east side of Freeport, had extensive damage to two of its buildings due to storm surge. The more severely damaged building was a unique modular system of shipping container units, stacked, studded, and stucco finished (Figure 17a). The exterior cladding was completely stripped off from the first floor (note a standard container is 2.6 m high), ground-floor windows were blown out, and some container units themselves were damaged (Figure 17b). A second more conventionally constructed reinforced concrete and masonry building showed similar evidence of first story damage due to storm surge, with most windows blown out. Note the concrete cover on a pair of steel columns supporting the entryway roof was completely spalled off by the storm surge (see arrow in Figure 17c). Interior losses in both buildings were substantial, destroying the metal-studded partitions, false ceilings, and other finishes.

Strong storm surge damage gradients, increasing to the north, were documented in areas just south of GBHW moving from the east toward downtown Freeport. Panoramic imagery of commercial construction in downtown Freeport, showed no evidence of significant wind damage, though interior content

Figure 17. Freeport Metro Area (Grand Bahama Island) overview: Storm surge damage at University of the Bahamas-North campus to (a) stacked shipping container building at (26.583368, −78.570521) including (b) damage to container walls; (c) a more conventional concrete and masonry structure also sustained flood damage to its ground floor with arrow indicating spalling of concrete cover under storm surge; (d) Class 3 home with minor exterior damage but extensive interior water damage at (26.578872, −78.573360); (e) complete destruction of Class 3 home at (26.573176, −78.606356); (f) surge-induced spalling (red arrows) to concrete columns of Class 3 residence south of GBHW at (26.577974, −78.572962), with high-water mark (yellow arrow) evidencing surge inundation levels; (g) undamaged precast elevated Class 3 home at north shore of island (26.548214, −78.700064); (h) evidence of wash through at hangar at Grand Bahama International Airport (26.600281, −78.615322); (i) elevated Class 3 home in Queen's Cove, site of eyewitness surge evolution account (26.541744, −78.744403).

losses due to surge-induced flooding were documented in areas northwest of downtown along Queen's Highway/GBHW. The structural assessments particularly focused on residential areas such as Pine Bay, north of Garden of the Groves (bounded to the south by E. Sunrise Highway and to the north by GBHW). These properties were of higher quality (Class 3) than homes along the East or West Corridors. Outside of the surge-exposed parcels, Class 3 buildings had little evidence of wind damage, at worst minor loss of asphalt shingles. Wind speeds in these areas were estimated to be between 30 and 40 m/s (108–144 km/h; 67–89 mph). However, surge-induced damage increased sharply moving north toward Grand Bahama Highway, with HWM of 5.0–6.0 m measured in this area (see Figure 8). Significant content losses were documented even in undamaged structures (Figure 17d) and visible damage was observed to the top of the first floor (elevation of 2.0–2.5 m above grade) in some residences, at times resulting in partial collapses (Figure 17e). Figure 17f shows an example of the observed high-water marks just above the first story of a Class 3 home (yellow arrow) as well as spalling of reinforced concrete columns at the base of the house (red arrows).

Notably, to the northwest of this neighborhood, on the northern coast of the island, a HWM of nearly 8 m was measured (see Figure 8). Just inland of that point is a small community where a cluster of five newly constructed precast concrete elevated Class 3 houses (Figure 17g), detailed by a Clearwater, FL designer, were also assessed as having negligible damage (e.g. minor vinyl soffit loss). The houses featured precast concrete walls tied by a continuous concrete ring beam supported on HSS columns anchored to the concrete floor system. Topped with standing seam metal hip roofs, the houses were elevated 3.6 m above grade on precast concrete columns (with joints grouted) tied into 75 cm-deep footings. The storm surge reached the elevated story but did not enter the home.

Just north of Queen's Highway, at the Grand Bahama Airport, hangar buildings displayed characteristic wash-through patterns suggesting flow depths of 2.5 to 3.0 m (Figure 17h). Due west of the airport, a survey of Class 2 and 3 properties in Queen's Cove (on Victoria Lane) similarly documented extensive surge-induced damage, with measured HWMs of 4 m (see Figure 8) and fairly high velocity leading to major damage to lower elevation structures. Elevated structures performed well, though some unreinforced/ungrouted break-away walls did not fail as intended.

One notable eyewitness account was recorded at 38 Victoria Lane (Figure 17i), site of an amateur video from the elevated living space showing the rising storm surge during one of the high tide events (see Video). The eye witness benchmarked the evolution of storm surge from mean sea level as follows: September 1 rose from 1.5 m (5 pm) to 2 m (9 pm), then on September 2 reached 3 m (12 am), then 3.5 m (9 am) and eventually 4.5 m (5 pm), at which point the water had filled the entire lower level and waves were pounding the elevated living space, as depicted in the video. The waters did not recede until September 4.

7. Discussion

With 82 m/s winds at landfall, Hurricane Dorian was the strongest historical storm by a significant margin out of 8 total storms in the HURDAT 2 database of Category 4 or higher within 110 km (60 nm) of Marsh Harbour (NOAA, 2020); the next strongest being an unnamed 1932 storm with 72 m/s winds. Dorian is also the only Category 5 storm ever recorded near Freeport on Grand Bahama, with eight Category 4 storms or higher within a 110 km (60 nm) radius, including Hurricane Matthew in 2016. As such, effects on Abaco and Grand Bahama were unprecedented on each island but may be compared to other recent severe hurricanes in the area: here we consider Hurricanes Irma and Maria (2017) in the US Virgin Islands (USVI), Hurricane Matthew (2016) in Haiti, and Hurricane Michael (2018) in Florida.

Both Hurricanes Irma and Maria (2017) were Category 5 strength as they passed by the USVI in 2017, but did not make direct landfall on St Thomas, St. John, or St. Croix (Cox et al. 2019). Furthermore, the path of Irma resulted in a short open ocean fetch that could not generate extreme damaging waves in the USVI. Hurricane Maria passed south of the less developed (with the notable exception of the shuttered Hovensa Refinery) and relatively steep St. Croix southern coastline, and well away from St. Thomas and St. John. As such, USVI damage from Maria and Irma, while severe, did not approach the levels seen in Marsh Harbour during Dorian, where large sections of the town were completely destroyed. If winds, waves, and water levels similar to Dorian had impacted Christiansted, St. Croix, or Charlotte Amalie, St. Thomas, both of which have broadly similar construction to the Bahamas, wave destruction would have greatly increased, as would wind damage from a direct landfall. Although existing USVI damage was significant, it could have been much worse under this scenario.

Hurricane Matthew (2016) (which also clipped the extreme western tip of Grand Bahama with winds of 59 m/s) was a strong Category 4 with 67 m/s winds when it made landfall on the Tiburon Peninsula of Haiti, far from the population center of Port-au-Prince (Kijewski-Correa et al. 2018). Waves and runup were extreme on the less-populated southwestern coast, reaching 7.5 m above sea level on an exposed hillside, very similar to the 8.1 m runup observed in Marsh Harbour. Damage patterns were also similar, although the Haitian building stock was generally more vulnerable than the structures documented in the Bahamas, with more instances of what would be Class 1 residential construction or more weakly confined versions of the Class 2 construction defined in Section 2.1. Wind damage in Matthew was very similar to that in Marsh Harbour, with almost all structures near landfall experiencing major or total roof loss, and sometimes out-of-plane wall failure. It was noted in Matthew, similar to the observations in the Bahamas, that the isolated instances of well-confined masonry construction in Haiti were capable of withstanding the combined effects of strong wind and storm surge (Kijewski-Correa et al. 2018).

Hurricane Michael (2018) made landfall in the Florida Panhandle near the town of Mexico Beach with sustained 72 m/s winds, causing great destruction (Kennedy et al. 2020). The low-lying parts of Mexico Beach saw damage very similar to that observed in Marsh Harbour, with numerous structures completely destroyed (bare slabs), resulting in very large quantities of debris. Wind damage was also severe, particularly for older homes, but newer Florida Building codes and notable examples of construction exceeding minimum code requirements led to some structures at landfall surviving with relatively low damage. Runup on steep hillsides by the beach reached 7.2 m, similar to that documented in Marsh Harbour.

Overall, while comparable in some aspects, Hurricane Dorian's waves, surge, winds, and duration exceeded the strongest recent storms in the region, resulting in the significant destruction observed on Great Abaco and Grand Bahama Islands. The confluence of such highly damaging storms over a few years in the same region reiterates the importance of promoting and expanding access to the construction technologies and design principles proven to deliver the required capacity against strong winds and storm surge, though acknowledging that contexts with less formal construction regulations like Haiti would achieve this through different mechanisms than highly regulated settings like the United States.

8. Conclusions and recommendations

This paper demonstrates the application of the Structural Extreme Events Reconnaissance (StEER) network's data collection workflow to document the effects of Hurricane Dorian on the Bahamas. This workflow promotes the use of (1) preliminary damage assessment reports swiftly issued based on virtual reconnaissance; (2) centralized target selection and logistical support; (3) partitioning data collection activities between on-site and virtual team members; and (4) rapid sharing of data on public platforms for use by diverse stakeholders. Field data was captured by two teams of investigators that surveyed coastal hazards and the damage to a wide class of buildings and other infrastructure on Great Abaco Island, Grand Bahama Island, and Man-o-War Cay.

Field-documented high-water marks were measured as high as 7 m above mean sea level on Man-o-War Cay, 8.1 m in Marsh Harbour, and 7.7 m near Freeport in western Grand Bahama Island. Each of these was generated by wave runup on the exposed shores, with HWMs on sheltered coastlines considerably lower. These coastal hazards occurred simultaneously with wind speeds (1-minute sustained over open terrain) in excess of 75 m/s (270 km/h; 168 mph) and 70 m/s (252 km/h; 157 mph) at the points of landfall on Great Abaco Island and Grand Bahama Island, respectively.

Both the intensity and sustained duration of the hurricane accrued significant and even catastrophic losses to communities across the surveyed islands, as demonstrated by the damage reported in this study. In stark contrast, a cross-section of residential, institutional, and commercial buildings performed well structurally, providing critical learning opportunities for enhancing resilience in coastal communities exposed to hurricanes. Specifically,

- Elevated structures with sufficient freeboard performed well provided that the foundation was appropriately tied to the superstructure. While unconfined masonry unsurprisingly performed poorly under both wind and storm surge hazards, well-confined masonry, with adequate transfers to the foundation, proved effective in withstanding strong winds and even low-velocity storm surge, despite not being elevated. Providing adequate confinement and connection between the superstructure and foundation further ensures that this style of construction delivers sufficient wind-resistance.

- While wood-framed construction was not as prevalent, particularly outside of Class 3 residences, recently constructed wood-framed residences also performed well. This provides a lightweight typology that is well-suited for elevated construction, which warrants greater promotion in the Bahamas.
- Buildings that survived structurally were often damaged internally by storm surge that destroyed interior finishes/partitioning and contents. Most of those buildings were uninsured and again reiterates the need to promote greater use of elevated construction in the Bahamas given the potential for damaging storm surge now documented in multiple recent hurricanes.

- Breakaway walls were observed to not fail as intended, imparting additional hydrodynamic loads to the foundation elements of elevated structures.

Moving forward, updating the Bahamas building code will be an important first step. The Bahamian Building Code (BBC) is based on US building codes that are over 30 years old and thus fails to capture the latest guidance regarding resistance to wind and coastal hazards. Some recommended changes include: (1) adding storm surge design provisions in the BBC, specifying minimum base flood elevations and providing hazard maps for the islands and (2) updating the design wind speeds to 700-year MRI wind speeds of 260 km/hr (Vickery and Wadhera 2008). While the latter recommendation would be risk-consistent with the US, it is important to evaluate whether a more risk-averse approach is warranted, considering that a single hurricane can result in losses that are a sizable percentage (in this case over a quarter) of the annual GDP of the country. However, these recommendations will not fully address the challenges observed by the authors, without equal emphasis on redoubling the training of building technicians, contractors, and inspectors to raise the quality of private-sector Bahamian building construction for all its people.

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Data Availability Statement

- Data is curated under project ID PRJ-2555 in DesignSafe: https://www.designsafe-ci.org/
- StEER's Fulcrum Community page
- Mapillary website for street-level panoramas: Mapillary - Street-level imagery, powered by collaboration and computer vision
- Marsh Harbour and Treasure Cay StreetView Scans (September 24-25, 2019): http://streetview.rapidfacility.org/Projects/Bahamas-Fast-1/player/
- Marsh Harbour and Treasure Cay StreetView Scans hosted on Google: https://goo.gl/maps/yLrBt52uP2tjsqPs5
- Grand Bahama StreetView Scans (October 5-8, 2019): http://streetview.rapidfacility.org/Projects/Bahamas-Fast-2/player/
- Grand Bahama StreetView Scans hosted on Google: https://goo.gl/maps/vaqeunYGFSG1QdFy5
    - Specific sites:
        - Sweeting's Cay
        - Golden Grove Road - washed away
        - Golden Grove Rd - ocean front
        - Neighborhood near Golden Grove
        - Grand Bahama University
        - Jack Hayward Bridge

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Appendix Observed High Water Marks

Elevation from MSL (m)	Tide Level (m)	Depth above ground (m)	Uncorrected Elevation (m)	Latitude	Longitude
–	–	2.2	–	26.53898	−77.0676
4.4	−0.4	–	4.8	26.54006	−77.0679
8.06	−0.44	–	8.5	26.54032	−77.0683
4.2	−0.41	2.06	4.61	26.5409	−77.0558
6.01	−0.19	–	6.2	26.55129	−77.0391
5.09	−0.01	–	5.1	26.55175	−77.0436
–	–	2.75	–	26.53809	−77.0671
–	0.16	0	–	26.53757	−77.0671
1.97	0.27	–	1.7	26.53191	−77.0552
–	–	0	–	26.53815	−77.0535
–	–	0	–	26.53799	−77.0534
5.73	−0.27	–	6	26.553	−77.032
4.72	−0.28	0.7	5	26.55307	−77.0318
5.63	−0.47	–	6.1	26.59966	−77.0053
5.53	−0.47	–	6	26.59958	−77.0053
1.46	−0.44	0.2	1.9	26.60084	−77.0087
7.08	−0.42	–	7.5	26.60137	−77.0077
2.09	0.09	–	2	26.59532	−77.0085
5.54	−0.46	–	6	26.5976	−77.0033
6.52	−0.48	–	7	26.59845	−77.0037
5.83	−0.37	–	6.2	26.60323	−77.0106
3.02	−0.18	–	3.2	26.59167	−76.9994
6.68	−0.02	–	6.7	26.5954	−77.0015
5.69	−0.01	–	5.7	26.59532	−77.0019
1.08	0.08	–	1	26.59573	−77.0061
5.26	−0.24	–	5.5	26.54631	−77.0833
6.23	−0.47	–	6.7	26.54938	−77.0901
5.6	0	–	5.6	26.57967	−78.6084
5.31	−0.19	–	5.5	26.60909	−78.6301
4.74	−0.26	–	5	26.60858	−78.6267
7.74	−0.16	–	7.9	26.60848	−78.6302
5.04	−0.36	–	5.4	26.5671	−78.5999
5.9	0	–	5.9	26.57251	−78.5816
4	0	–	4	26.54127	−78.7447
4.1	0	–	4.1	26.54371	−78.7443
4.5	0	–	4.5	26.54182	−78.7448
4.2	0	–	4.2	26.54088	−78.743
–	–	1.7	–	26.53708	−78.6957
–	–	2.9	–	26.54812	−78.6999