


Mitigation Assessment Team Report

Hurricanes Irma and Maria in Puerto Rico

Building Performance, Observations, Recommendations, and Technical Guidance

FEMA P-2020 / October 2018

FEMA

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Map imagery sources (unless otherwise noted in the report):

CariCOOS https://www.caricoos.org/

USGS https://www.usgs.gov/

Weather Flow http://weatherflow.com

NSF RAPID https://nsf.gov

NOAA https://storms.ngs.noaa.gov/

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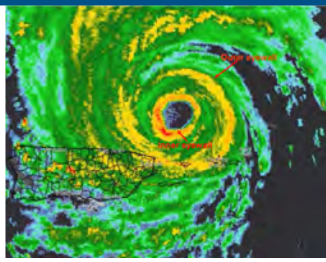
MITIGATION ASSESSMENT TEAM REPORT

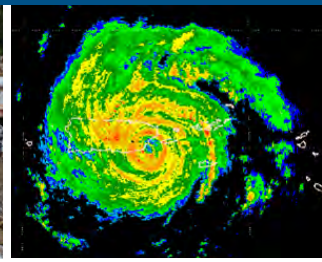
In response to Hurricanes Irma and Maria, the Federal Emergency Management Agency (FEMA) deployed a Mitigation Assessment Team (MAT) to evaluate damage, document observations, and, based on these, offer conclusions and recommendations on the performance of buildings and other structures affected by wind forces, flooding, and other hazards due to the hurricanes. The MAT included FEMA Headquarters and Regional Office engineers, representatives from other Federal agencies, government officials from the Commonwealth of Puerto Rico, and experts from academia and the design and construction industries. The conclusions and recommendations in this report are intended to provide decision makers, designers, contractors, planners, code officials, industry groups, government officials, academia, homeowners, and business owners and operators with information and technical guidance that can be used to reduce future hurricane damage.

DEDICATION

The Puerto Rico Mitigation Assessment Team dedicates this report to the memory of the victims of Hurricanes Irma and Maria, and the families, friends, and communities suffering from their loss. The Mitigation Assessment Team hopes this report will help others avoid similar losses in the future.

MITIGATION ASSESSMENT TEAM REPORT




HURRICANES

IRMA AND MARIA

IN PUERTO RICO

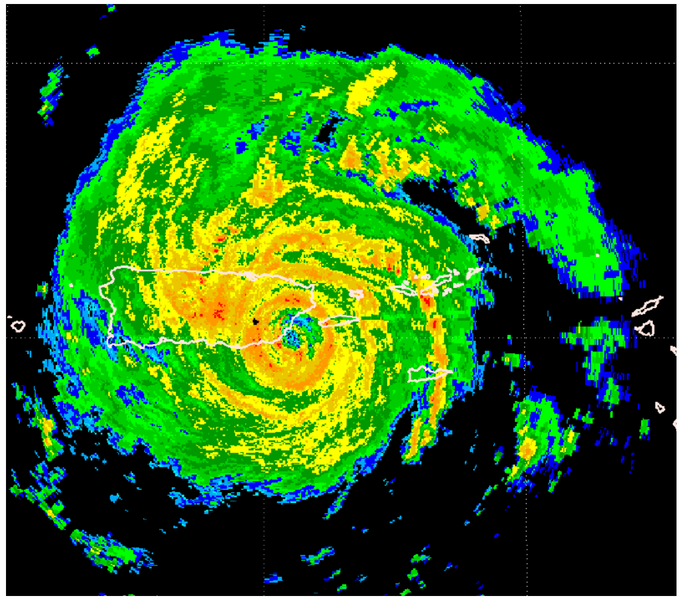
Executive Summary

In September 2017, Hurricanes Irma and Maria significantly impacted Puerto Rico.

Irma was a Category 5 hurricane when its eye passed within 30 miles (48 kilometers) of the Puerto Rican island of Culebra on September 6, 2017. Peak wind gust speeds in the Commonwealth of Puerto Rico were over 120 miles per hour (mph) (193 kilometers per hour [kph]) and over 10 inches (25 centimeters) of rainfall was recorded. Thousands of buildings were damaged and over a million residents lost power. Just two weeks later, on September 20, while much of Puerto Rico was still recovering, Maria made landfall as a Category 4 hurricane. Preliminary peak wind gusts in Puerto Rico were over 140 mph (225 kph), over 35 inches (89 centimeters) of rainfall was recorded, and storm surge of over 6 feet (2 meters) was estimated. The hurricanes caused numerous deaths. Hundreds of thousands of buildings were damaged and the power grid failed, causing long-lasting interruptions to essential services. Most of the 3.7 million residents were left without power for months, and 95 percent of cellular sites were out of service, leading to complicated and protracted recovery efforts.

Puerto Rico experienced high wind speeds throughout the Commonwealth during both storms, particularly on the islands of Culebra and Vieques and along the northeastern coast of the island of Puerto Rico. In some areas of the Commonwealth, wind speeds approached or exceeded the prescribed design wind speed requirements of 145 mph (233 kph) of the American Society of Civil Engineers (ASCE) standard, Minimum Design Loads and for Buildings and Other Structures (ASCE 7-05). This standard is referenced by the 2009 International Building Code (IBC©) and the 2009 International Residential Code (IRC©), which are the model codes legally adopted in the effective building code at the time of both storms, the 2011 Puerto Rico Building Code (PRBC).

Damage from storm surge and flooding was severe in some areas, while wind damage was widespread throughout the Commonwealth. Damage from wind-driven rain and other sources of water intrusion was significant across many building types, including critical facilities. High winds caused severe damage, particularly to informally constructed buildings (broadly defined as those not permitted or not built to current building standards) and improperly anchored rooftop equipment.



Radar image of Hurricane Maria at 0950 UTC, September 20, 2017, just before landfall in Puerto Rico. Source: Pasch, Penny, and Berg (2018).

Past Disasters and Mitigation

Puerto Rico has a history of reacting to the impact of severe previous hurricanes by adopting hazard mitigation techniques to minimize future damage. Previous mitigation actions have included establishing or improving building codes and building code enforcement. This was a key recommendation of the Federal Emergency Management Agency (FEMA) Hurricane Georges Building Performance and Assessment Team (BPAT) Report and is recommended again in this report.

On September 18, 1989, Hurricane Hugo made landfall in Puerto Rico as a Category 2 hurricane. Hugo caused severe damage to the infrastructure of Puerto Rico, with over thirty thousand people losing their homes. Eighty percent of wooden structures on Culebra and Vieques were destroyed. Property damage is estimated to have exceeded $1 billion in 1989 dollars[1]. Evidence of mitigation carried out in response to Hurricane Hugo, including the installation of frame connection hardware (hurricane clips) and other wind retrofits was later cited in the Hurricane Georges FEMA report.

On September 21, 1998, the Category 2 Hurricane Georges made landfall in Puerto Rico. Georges had devastating effects on an array of building types and infrastructure. In the aftermath of Georges, FEMA made observations and recommendations. Observations included a prevalence of informally constructed buildings. Poor implementation and enforcement of existing codes were cited as a major contributor to the heavy losses. Because Hurricane Georges's winds were below design speeds for modern building codes, code-compliant construction would likely have proved much more hurricane-resistant than what was observed. Noting deficiencies in the building code, Puerto Rico adopted the 1997 Uniform Building Code (UBC) with local amendments following Georges. The 1997 UBC served as Puerto Rico's Building Code until the 2009 IBC© was adopted in 2011.

Additional mitigation efforts beyond the building code included a major reconstruction and hazard mitigation program after Hurricane Georges called the New Secure Housing Project (NSHP). This project, established in October 1998 by order of then-Governor Pedro Rosselló, had an "on-site component" that replaced vulnerable buildings at existing sites. Its "off-site component" involved

[1]This is roughly $2 billion in inflation-adjusted September 2017 dollars.

acquiring and removing damaged or destroyed homes in highly flood-, seismic-, and landslide-prone sites, and replacing them at new sites. The NSHP built 1,647 housing units that were designed to the 1997 UBC, and these performed well during the recent hurricanes.

Mitigation Assessment Team

For over 30 years, FEMA has been conducting studies and assessments of the performance of the built environment after disasters of national significance. In these instances, FEMA deploys Mitigation Assessment Teams (MATs) to observe building performance and provide design and construction guidance to improve disaster resistance of the built environment in the affected area. MATs are composed of national and regional experts including academics, design professionals, FEMA engineers, representatives from standards development organizations, and other subject matter experts as needed for the event.

HURRICANE METRICS

Hurricane Irma

- Several deaths
- Skirted Puerto Rico as a Category 5 hurricane, approaching within 30 miles (48 kilometers)
- Sustained winds in Puerto Rico 58 mph (93 kph)
- Maximum rainfall 10–15 inches (25–38 centimeters) in 36 hours
- With $50 billion in damage, the fifth-costliest hurricane in U.S. history

Hurricane Maria

- Numerous deaths
- Strong Category 4 hurricane at landfall in Puerto Rico
- Sustained winds in Puerto Rico 155 mph (249 kph)
- Maximum rainfall 38 inches (96 centimeters) in 48 hours
- With $90 billion in damage, the third-costliest hurricane in U.S. history

Following Hurricanes Irma and Maria, FEMA's Building Science Branch, in coordination with Region II office and the Puerto Rico Joint Field Office (JFO), deployed a Preliminary MAT in October 2017. Observations from that team led to a full MAT deployment in December. The MAT consulted frequently with Commonwealth and municipal officials and resident subject matter experts during both deployments. Areas of focused observations included: building codes, standards and regulations; residential and low-rise buildings; schools, critical facilities, photovoltaic (PV) arrays, and solar water heaters.

Assessment Observations

The MAT visited affected locations throughout Puerto Rico, including the islands of Culebra and Vieques, making observations on building performance. Initial mitigation topics from the MAT observations included rooftop equipment attachment, Coastal A Zone (CAZ) construction techniques, topographic wind-speed up effects, and hurricane sheltering considerations. These and other important topics were communicated to Commonwealth and municipal stakeholders, JFO staff, and the public in the form of six Recovery Advisories (Appendix D) and this MAT report. The key purpose of this report is to aid communities in rebuilding resiliently and improving the hazard resistance of existing and new buildings in Puerto Rico and throughout the rest of the United States and its territories.

Recommendations

The MAT observed severe damage to residential and public buildings. Many homes in Puerto Rico are of informal construction, and the residential building stock is aging. The rate of flood insurance participation in the Commonwealth is limited. All these factors have negatively impacted many residents. Hurricanes Irma and Maria destroyed several hundred thousand homes and, with many homeowners not carrying flood insurance policies from the National Flood Insurance Program (NFIP), these residents' ability to rebuild is uncertain.

This report provides many recommendations to assist in rebuilding a more resilient Puerto Rico, addressed respectively to the public, private, and nonprofit sectors. Three key recommendations follow:

> Recommendation PR-3a. **The Permits Management Office (OGPe[2]) should finalize adoption of the latest hazard-resistant building codes and standards.** To enable new buildings and those that have been substantially damaged or will be substantially improved to better resist the impacts of hurricanes, floods, and seismic events, the latest edition of the building code and reference standards should be considered for adoption. OGPe should review the entire International Codes series (I-Codes) and adopt those that are relevant for the Commonwealth. In addition, Puerto Rico should consider local amendments to ensure that the hazard-resistant provisions are not weakened and that local conditions are accounted for.
>
> Recommendation PR-9a. **FEMA should consider working with the Insurance Institute for Business & Home Safety to conduct a review of private flood insurance policies for equivalency and effectiveness.** Private flood insurance can offer different protections than NFIP policies. Because Puerto Rico's reliance on private insurance is unique in the U.S., a study is warranted after this event to assess the efficacy of private insurance on homeowners' ability to rebuild more quickly while reducing the burden on U.S. taxpayers.
>
> Recommendation PR-35a. **Puerto Rico should require storm shelters to be provided in all new Group E Occupancy buildings.** Storm shelters provide buildings or portions with life-safety protection from high wind events such as hurricanes. Puerto Rico should create a local amendment to the PRBC to require that any new facilities constructed for Educational Group E Occupancies with an aggregate occupant load of 50 or more (including public and private schools, but excluding Group E day-care facilities or Group E occupancies[3] accessory to places of religious worship), 911 call stations, emergency operations centers and fire, rescue, ambulance and police stations comply with IBC© table 1604.5 as a Risk Category IV structure and be provided with a storm shelter constructed in accordance with ICC 500©. In addition, OGPe and PRDOH should keep a record of all ICC©-compliant community shelters in the Commonwealth.

[2]The Permits Management Office (Oficina de Gerencia de Permisos) is commonly referred to by its Spanish acronym, OGPe.

[3]The 2018 IBC defines eight classifications of occupancy and use, with varying levels of hazard and risk. The 2018 IBC© defines an Educational Group E occupancy as including "among others, the use of a building or structure, or a portion thereof, by six or more persons at any one time for educational purposes through the 12^{th} grade (ICC© 2018, 305.1).

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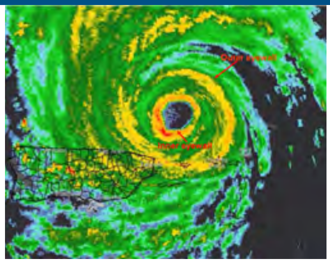
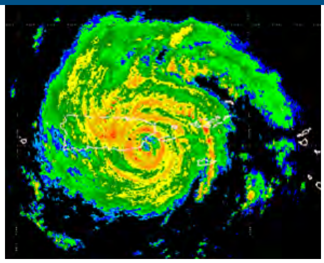





HURRICANES

IRMA AND MARIA

IN PUERTO RICO

1 Introduction

In September of 2017, Puerto Rico was impacted by two major hurricanes, Irma and Maria.

Hurricane Irma passed directly to the northeast of Puerto Rico on September 6, 2017, resulting in hurricane-force winds and island-wide power outages. On September 20, 2017, Hurricane Maria made landfall on the southeast coast of Puerto Rico as a Category 4 storm, resulting in widespread damage throughout the islands. In response to the two hurricanes, the Federal Emergency Management Agency (FEMA) authorized a Mitigation Assessment Team (MAT) to deploy to Puerto Rico. A preliminary field team deployed in October and a full MAT in December 2017.

The MAT Report's primary purpose is to provide recommendations to improve building resistance to natural hazards, especially hurricane winds and flooding. It describes observations made during the MAT deployment, draws conclusions about drivers of building damage, and presents actionable solutions to the underlying causes of damage. This report also discusses several topics not emphasized in previous MAT reports:

- Successes of prior mitigation actions
- Formal and informal construction
- The effect of topographic features on building performance
- The performance of rooftop and ground-mounted solar photovoltaic (PV) systems

1.1 Organization of the Report

This report discusses Hurricanes Irma and Maria, regulatory issues, and the performance of various building types, and presents conclusions and recommendations, as follows:

Chapter 1: Summarizes the meteorological history of Hurricanes Irma and Maria, the deployment of the MAT, the history of previous MAT efforts in Puerto Rico, and the MAT's damage observations.

Chapter 2: Discusses historical and current codes and standards; the adoption of, implementation of, and exceptions made to the building codes within various government municipalities; prescriptive allowances in the building code; standards for PV systems; and the National Flood Insurance Program (NFIP) in Puerto Rico.

Chapter 3: Reviews the performance of residential and low-rise buildings.

Chapter 4: Reviews the performance of schools and sheltering facilities.

Chapter 5: Reviews the performance of hospitals, police and fire stations, and other mid-rise buildings.

Chapter 6: Reviews the performance of solar water heaters and rooftop and ground-mounted PV arrays.

Chapter 7: Presents conclusions and recommendations for mitigation efforts.

The appendices provide supplementary information:

Appendix A: Acknowledgements

Appendix B: Bibliography

Appendix C: Abbreviations

Appendix D: Recovery Advisories for Hurricanes Irma and Maria in Puerto Rico

1.2 Overview of Recent Hurricanes

This section provides a meteorological and hazards overview of Hurricanes Irma and Maria in Puerto Rico. A discussion of observed flooding and wind speeds with respect to the building code may be found in Sections 1.5.4 and 2.4, respectively.

1.2.1 Hurricane Irma

Hurricane Irma was a long-lasting hurricane that reached Category 5 on the Saffir-Simpson hurricane wind scale (Table 1-1). In total, Irma made seven landfalls, including four as a Category 5 hurricane, across the northern Caribbean islands. Hurricane Irma brought strong winds, heavy rains, and in some areas, high storm surge. The storm caused several deaths and widespread devastation across the Caribbean islands and southeastern continental United States.

Irma formed near Cape Verde on August 30, 2017, and moved south and west, fluctuating between Categories 2 and 3 from September 1 to September 4, 2017 (Figure 1-1, top). The hurricane reached its maximum intensity of 178 miles per hour (mph) (287 kilometers per hour [kph]) sustained winds on September 5 about 80 miles (130 kilometers) east-southeast of Barbuda. On September 6, 2017, Irma made its first landfall on Barbuda as a Category 5 hurricane with maximum wind speeds of 178 mph (287 kph), making landfall next on St. Martin and Virgin Gorda. Irma's eye passed 58 miles (93 kilometers) north of Puerto Rico's capital, San Juan (and less than 30 miles [48 kilometers]) from Culebra) over September 6-7, 2017, before temporarily weakening to Category 4. Irma made landfall on Little Inagua in the Bahamas on September 8, 2017, and in Cuba on September 9, 2017, as a Category 5 hurricane with 167 mph (269 kph) winds, after which its interaction with land caused it to quickly weaken to Category 2. Over the warm waters of the Straits of Florida, the storm re-intensified to a Category 4 before making its sixth landfall on Cudjoe Key with winds of 130 mph (215 kph) on September 10. Later that day, Irma made its seventh landfall on Marco Island in Florida as a Category 3 hurricane. Finally, the system degraded into a remnant low over Alabama and dissipated over Missouri on September 13, 2017, (Cangialosi, Latto and Berg 2018).

Table 1-1: The Saffir-Simpson Hurricane Wind Scale

Category	Wind Speed mph	Wind Speed kph
1	74–95	119–153
2	96–110	154–177
3	111–129	178–208
4	130–156	209–251
5	≥ 157	≥ 252

The Saffir-Simpson hurricane wind scale classifies hurricanes according to their peak 1-minute wind speed at 33 feet (10 meters) above ground level over unobstructed terrain.

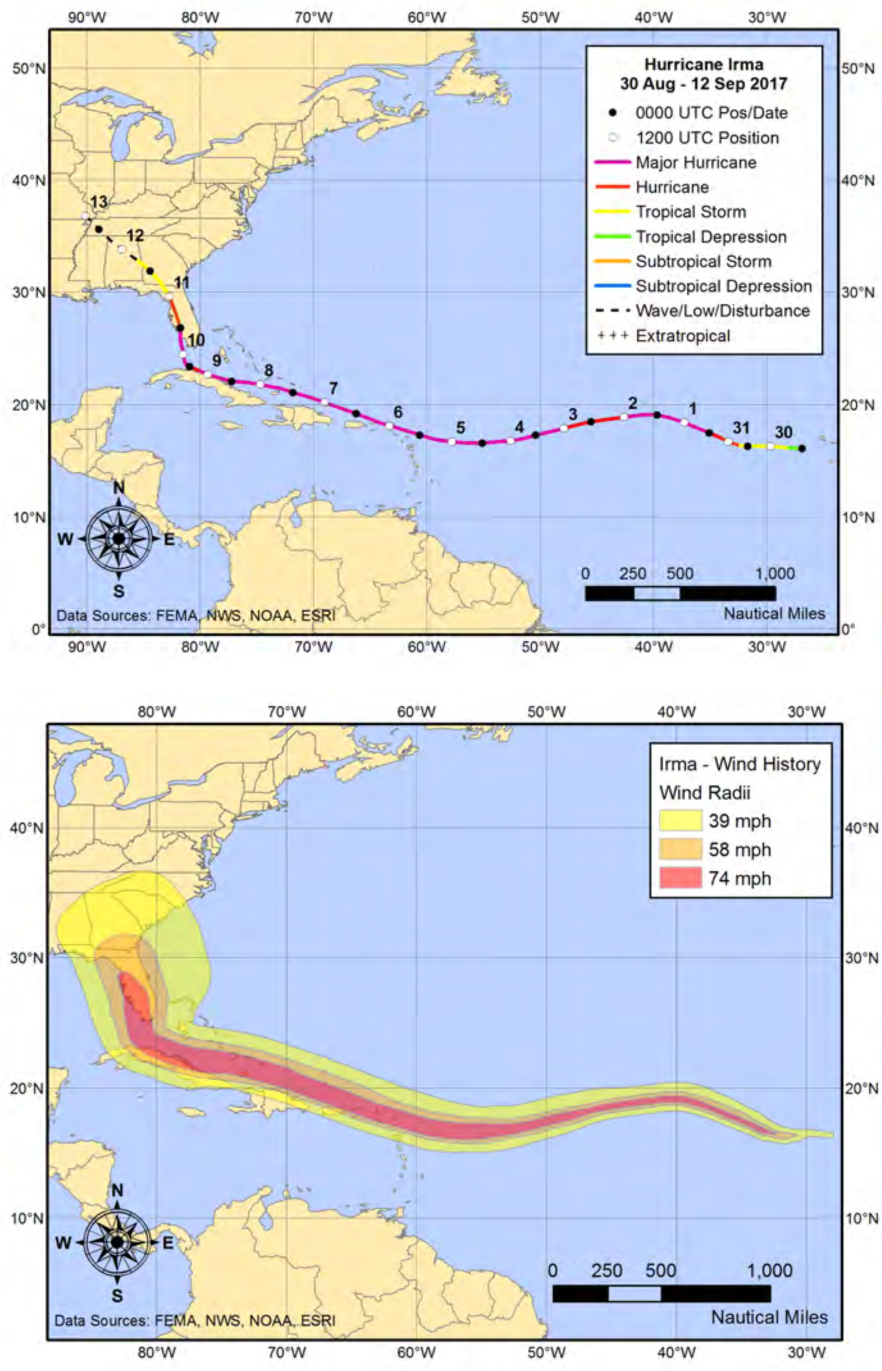
Hurricane Irma passed less than 30 miles (48 kilometers) from Culebra as a Category 5 hurricane with wind speeds estimated to be greater than 160 mph (257 kph). The highest wind speed recorded in the Commonwealth was 58 mph (93 kph) sustained, with a gust of 89 mph (143 kph), on the island of Culebrita. On the island of Puerto Rico, the highest recorded sustained wind speed was 55 mph (89 kph), with a gust of 74 mph (118 kph), in San Juan Bay. Irma's eye passed about 57 miles (92 kilometers) north of San Juan on September 6 (Cangialosi, Latto and Berg 2018).

The peak wind gust map (Figure 1-2) depicts the high winds experienced in eastern Puerto Rico during Irma, with the highest wind speeds on the islands of Culebra and Vieques and along the northeastern coast of the island of Puerto Rico. Figure 1-2 shows estimated 3-second wind gust speeds at 33 feet (10 meters) above ground level for open terrain (ASCE Exposure Category C) for comparison with ASCE 7 design wind speeds. In contrast, Figure 1-3 shows maximum measured sustained and gust wind speeds. Note that these observations may have been made at exposure conditions or elevations above ground that differ from those modeled in Figure 1-2.

Irma also caused storm surge flooding in a few areas on the north coast (Figure 1-4). The deepest inundation was 1–3 feet (0.3–0.9 meters) above ground level near Arecibo and west of San Juan in Bayamón and Dorado.

Irma produced heavy rainfall in the central and eastern portions of the island, with some higher-elevation areas in the interior of the island of Puerto Rico experiencing 10–15 inches (25–38 centimeters) of rain[1] (Figure 1-5).

Figure 1-1: Top, Hurricane Irma's track; bottom, Hurricane Irma wind speed radii for 39, 58, 74 mph (63, 93, 119 kph) winds. Modified from Cangialosi, Latto, and Berg (2018).



[1]For Southern Canóvanas, where Irma's rainfall was greatest, 10–15 inches (25–38 centimeters) corresponds to a recurrence interval of roughly 5–25-years, according to NOAA Atlas 14 frequency estimates (National Weather Service Hydrometeorological Design Studies Center 2008).

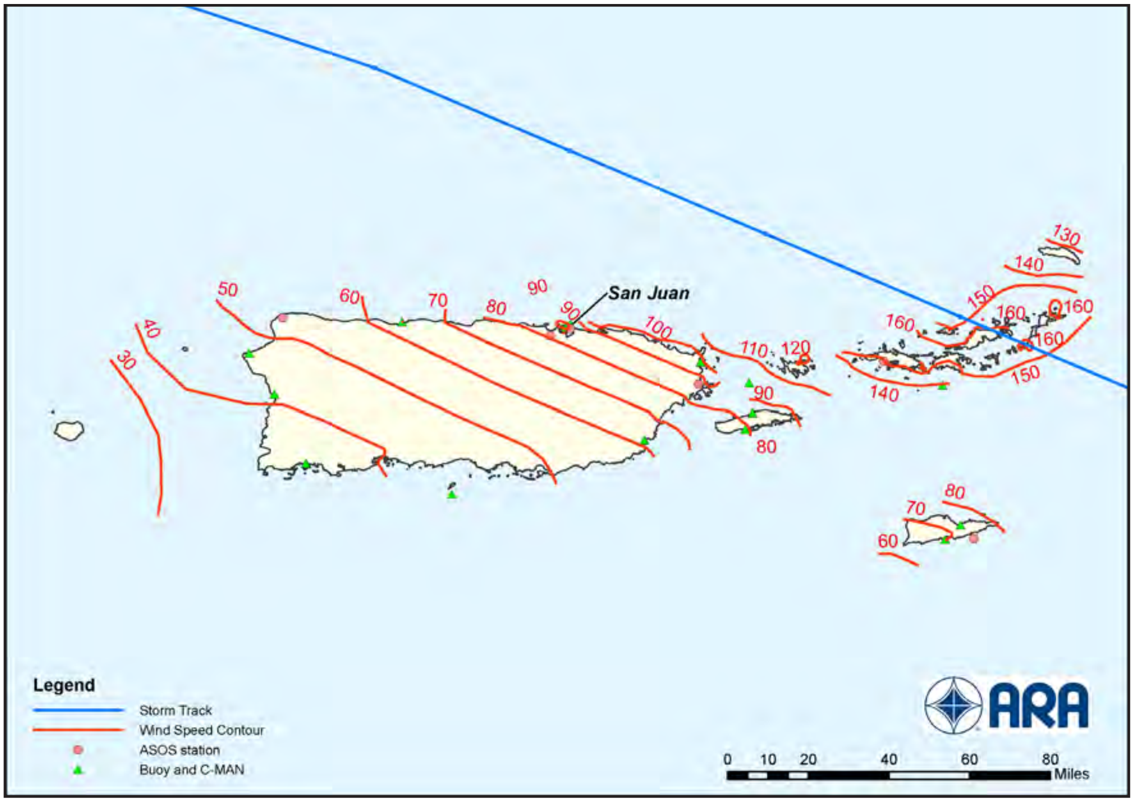


Figure 1-2: Preliminary peak wind gust map for Hurricane Irma with track (blue line). Estimated 3-second gust wind speeds (mph) at 33 feet (10 meters) above ground for flat open terrain from ARA model fit to surface level observations. The model used smoothed National Hurricane Center storm track and central pressure data through Forecast/Advisory 52 at 03:00 UTC on September 12, 2017.

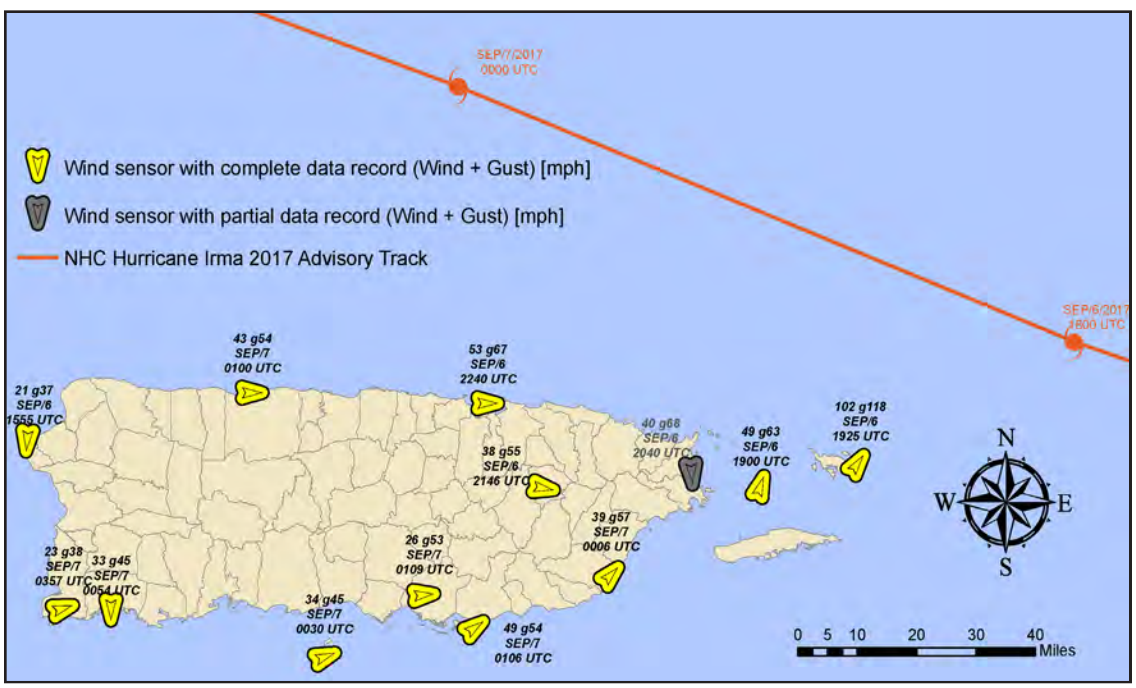


Figure 1-3: Peak sustained and gust wind speeds measured during Hurricane Irma. Data source: Cangialosi, Latto, and Berg (2018).

Figure 1-4: Estimated storm surge inundation (feet above mean sea level) for Hurricane Irma. Data source: Coastal Emergency Risks Assessment (2017).

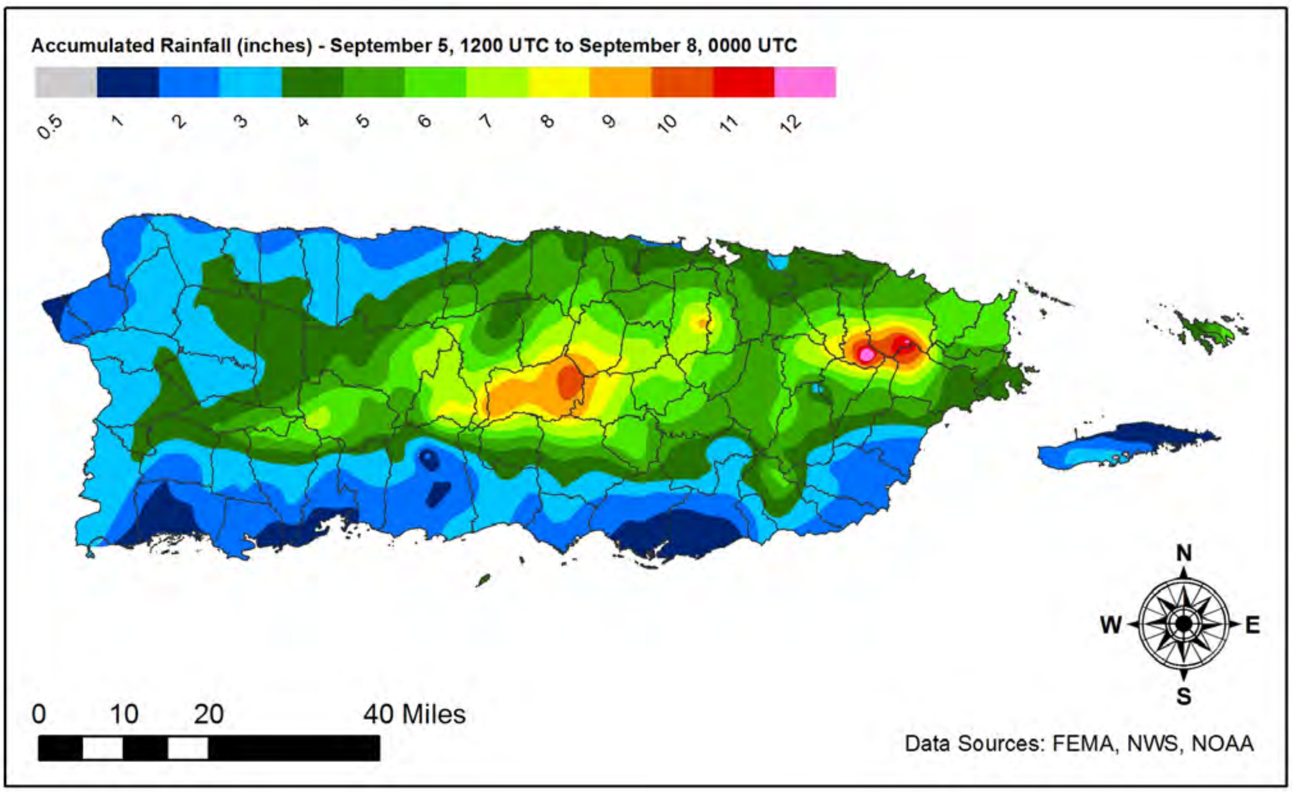


Figure 1-5: Estimated rainfall total from Hurricane Irma.

Table 1-2: Costliest U.S. Hurricanes in 2017 Dollars

Rank	Hurricane	Season	Damage	Rank	Hurricane	Season	Damage
1	Katrina	2005	$160 billion	6	Andrew	1992	$48 billion
2	Harvey	2017	$125 billion	7	Ike	2008	$35 billion
3	Maria	2017	$90 billion	8	Ivan	2004	$27 billion
4	Sandy	2012	$70 billion	9	Wilma	2005	$24 billion
5	Irma	2017	$50 billion	10	Rita	2005	$24 billion

Source: National Hurricane Center (2018).

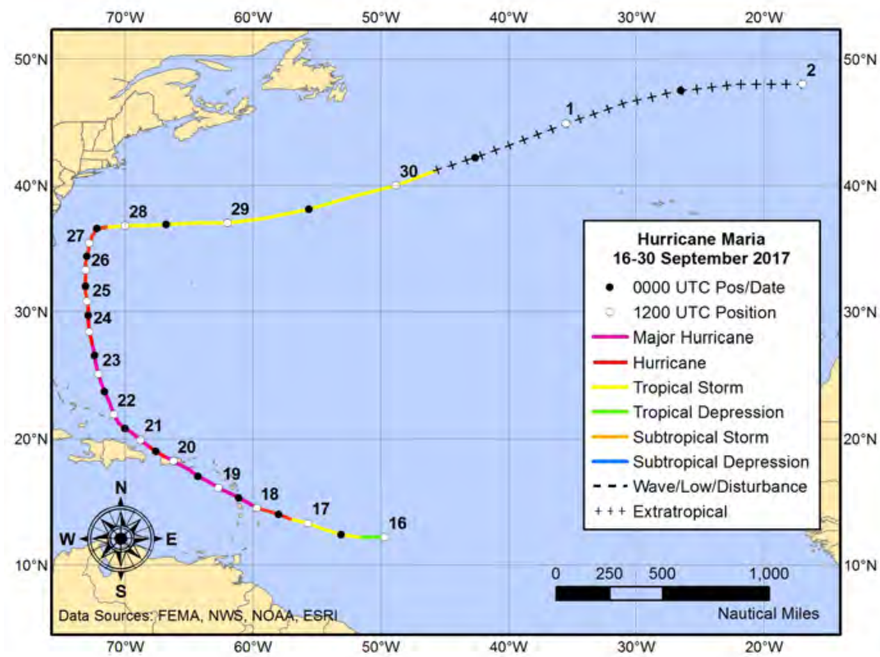
In addition to housing damage, more than a million residents lost power (U.S. Department of Energy 2017). Total economic losses from Hurricane Irma are estimated as $50 billion, making it the second-costliest Caribbean hurricane on record, behind only Hurricane Maria, and fifth-costliest in the U.S., in 2017 inflation-adjusted dollars (Table 1-2). However, much of Irma's United States-based damage totals occurred in the U.S. Virgin Islands (USVI) and the continental U.S. including Florida and Georgia.

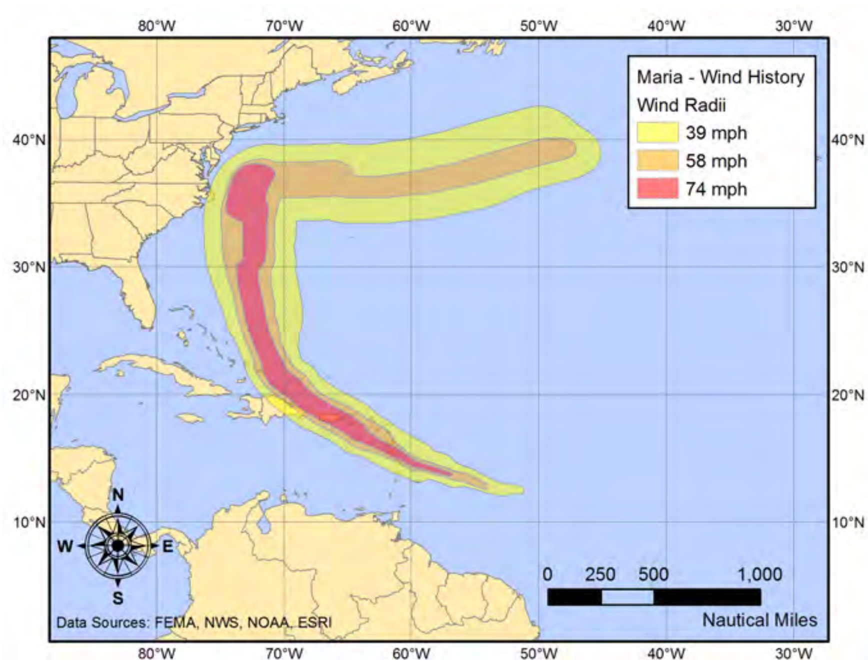
1.2.2 Hurricane Maria

Three weeks after Hurricane Irma, Hurricane Maria was a Category 4 hurricane when it made landfall in Puerto Rico on September 20, 2017. The hurricane caused numerous deaths and extensive damage to the power grid.

Maria originated east of the Lesser Antilles and became a tropical storm on September 16, proceeding west (Figure 1-6). As it approached the Caribbean islands, Maria intensified rapidly, with highly favorable environmental conditions; it became a Category 5 hurricane before making landfall on Dominica on September 18. Land interaction while crossing Dominica caused Maria to weaken, but it achieved its peak intensity over the eastern Caribbean with maximum sustained winds of 175 mph (280 kph). Maria weakened to Category 4, but increased in size, before making landfall in Puerto Rico on September 20 with maximum sustained winds of 155 mph (249 kph). The hurricane weakened gradually, becoming a tropical storm on September 28 as it moved north. Maria later accelerated eastward over the open Atlantic and dissipated by October 3.

Figure 1-6: Top, Hurricane Maria's track, bottom, Hurricane Maria wind speed radii for 39, 58, 75 mph (63, 93, 118 kph) winds. Modified from Pasch, Penny, and Berg (2018).





The peak wind gust map (Figure 1-7) depicts the estimated high winds experienced throughout the Commonwealth during Maria, with the highest winds on the island of Vieques and to the east of the center of the storm track through the island of Puerto Rico, including near San Juan. Figure 1-7 shows estimated 3-second wind gust speeds at 33 feet (10 meters) above ground level for open terrain (ASCE Exposure Category C) for comparison with ASCE 7 design wind speeds. In contrast, Figure 1-8 shows maximum measured sustained and gust wind speeds. Note that these observations may have been made at exposure conditions or elevations above ground that differ from those modeled in Figure 1-7.

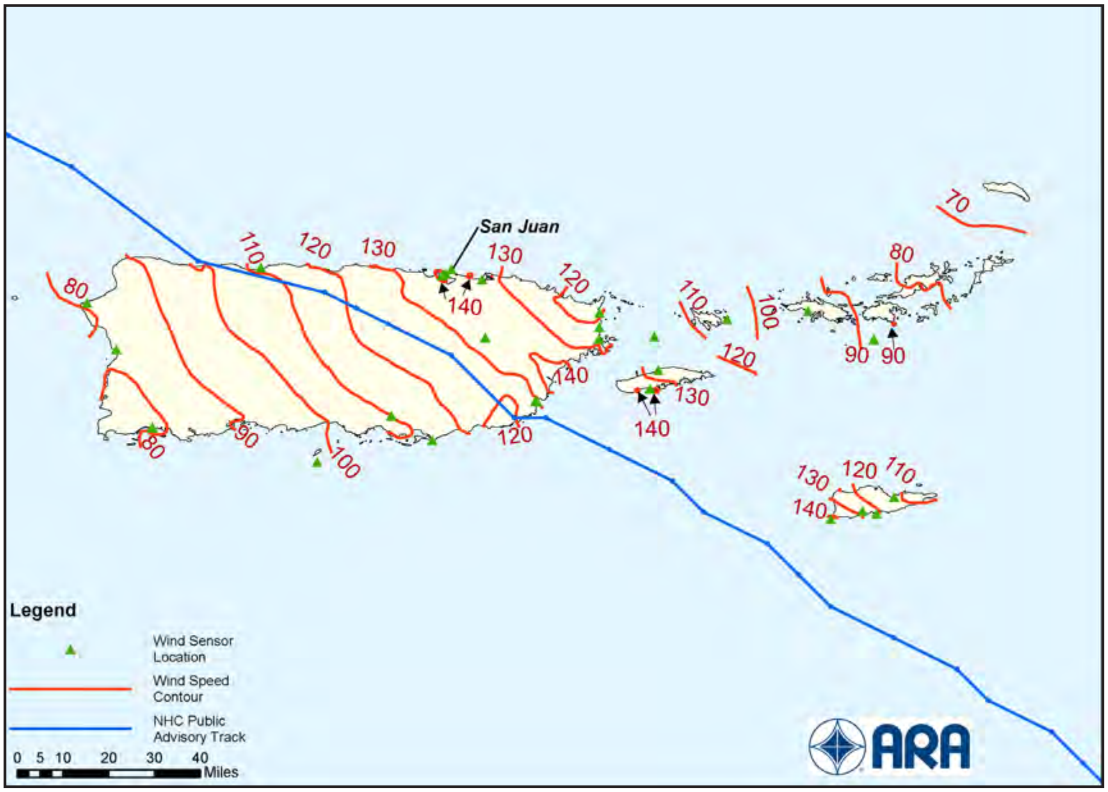


Figure 1-7: Preliminary peak wind gust map for Hurricane Maria with track (blue line). Estimated 3-second gust wind speeds (mph) at 33 feet (10 meters) above ground for flat open terrain from ARA model fit to surface level observations. The model used smoothed National Hurricane Center storm track and central pressure data through Intermediate Advisory 41A at 12:00 UTC on September 26, 2017.

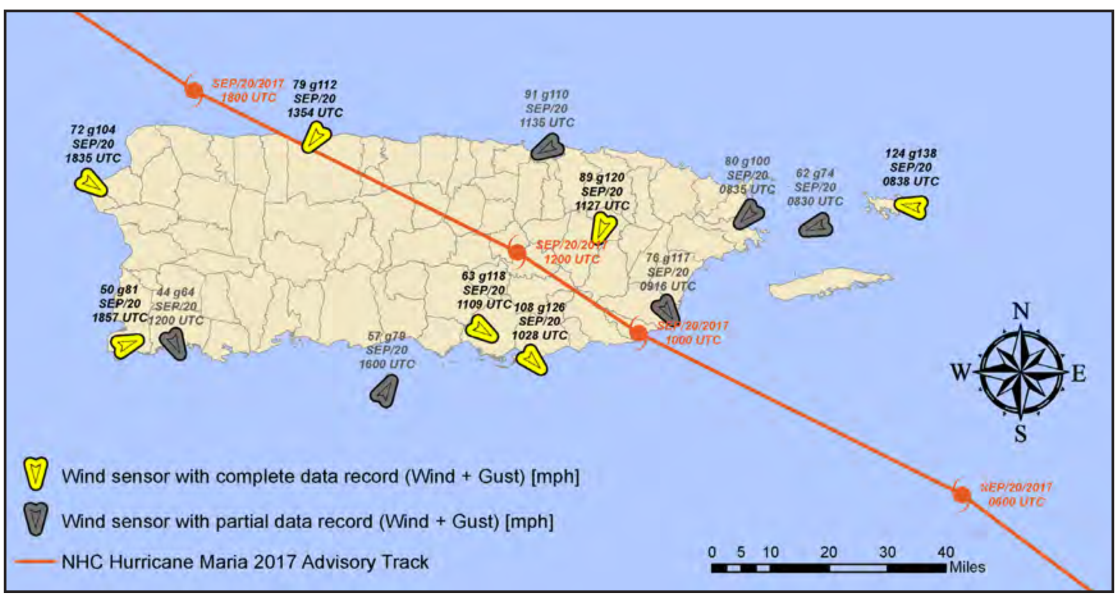


Figure 1-8: Peak sustained and gust wind speeds measured during Hurricane Maria. Data source: Pasch, Penny, and Berg (2018).

Hurricane Maria caused maximum storm surge inundation of 6–10 feet (1.8–2.7 meters) above ground level to the east of Maria's landfall along the coasts of Humacao, Naguabo, and Ceiba, as well as the north central municipality of Arecibo. To the southeast, in Yabucoa, Maunabo, Patillas, and Arroyo, maximum storm surge inundation was approximately 4–7 feet (1.2–2.1 meters). Along the remaining southern and northeastern coastline, maximum inundation of 3–5 feet (0.9–1.5 meters) occurred from the municipality of Ponce eastwards. The remaining coastline generally experienced inundations ranging from 1 to 4 feet (0.3 to 1.2 meters). Additionally, the island of Vieques experienced 3–5 feet (0.9–1.5 meters) of maximum storm surge inundation. Figure 1-9 depicts the storm surge along the Puerto Rico coastline caused by Hurricane Maria.

Figure 1-9: Estimated storm surge inundation (feet above mean sea level) for Hurricane Maria. Data source: Coastal Emergency Risks Assessment (2017).

Heavy rainfall occurred throughout the Commonwealth during Maria, peaking at 37.9 inches (96.3 centimeters) in Caguas (Figure 1-10). Severe flash flooding occurred in many locations. Thirty rivers reached major flood stage, and 13 of those were at or above record stages. Many bridges were destroyed. Communities along the Guajataca River were displaced when flooding compromised the stability of the dam at Guajataca Lake. Some of the most significant riverine flooding was associated with the La Plata River on the northern part of the island west of San Juan, including the municipality of Toa Baja, where hundreds were rescued from rooftops. Landslides associated with the high rainfall occurred throughout Puerto Rico, blocking thousands of roads (Martinez-Sánchez 2018).

High winds from Hurricanes Irma and Maria contributed to the extensive damage to buildings across Puerto Rico, with hundreds of thousands of homes damaged (Rosselló Nevares 2017). The combined effects of storm surge and wave action produced extensive damage to buildings and roads throughout the eastern and southeast coast. Significant damage also occurred along the north coast (Pasch, Penny and Berg 2018).

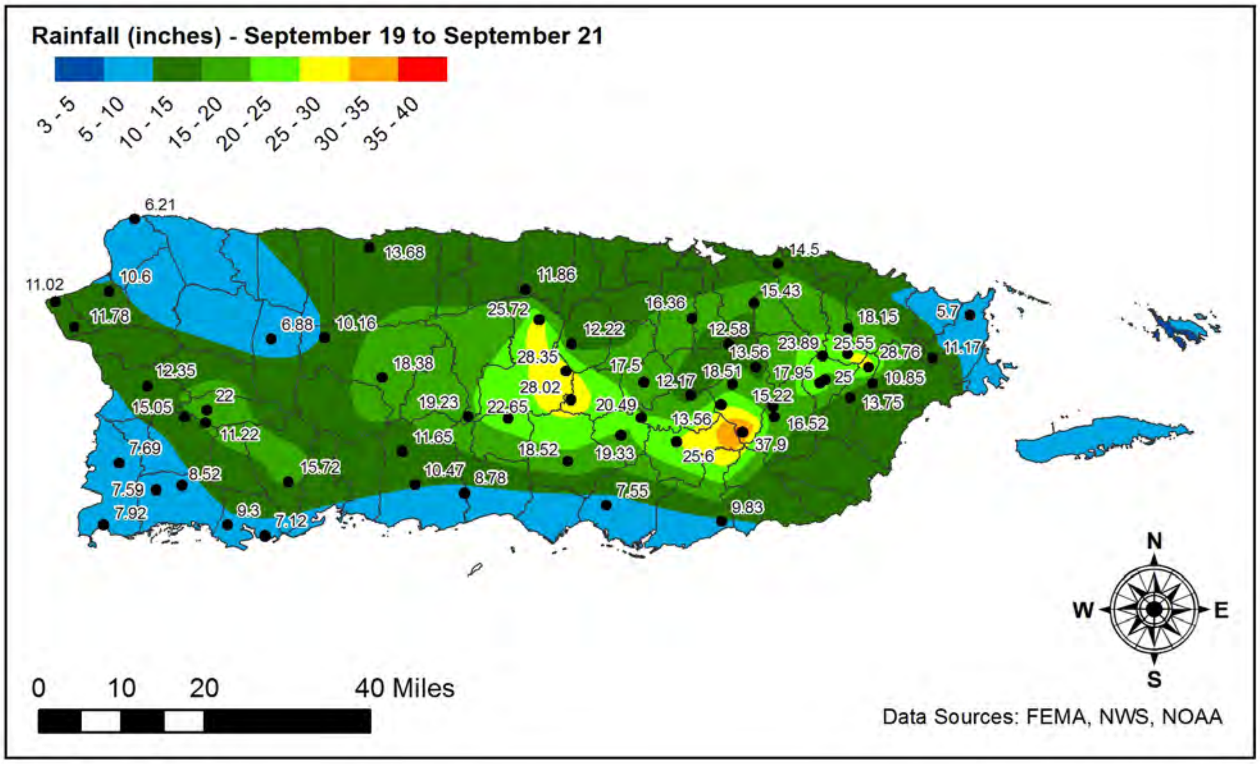


Figure 1-10: Estimated rainfall total from Hurricane Maria (National Weather Service 2017).

Maria caused lasting interruptions to essential services and severe damage to housing and infrastructure. A month after Maria, fewer than 8 percent of Puerto Rico's roads were open and usable (Martinez-Sánchez 2018). Total losses from the hurricane are estimated at upwards of $90 billion, mostly in Puerto Rico, making Maria the costliest U.S. Caribbean hurricane and third-costliest on record for the U.S. in 2017 inflation-adjusted dollars (Table 1-2).

HURRICANE MARIA'S DEATH TOLL

Hurricane Maria had a devastating impact on Puerto Rico that not only damaged and destroyed the built environment but resulted in the tragic loss of life. Various reports have been undertaken by the Federal Government and the Government of Puerto Rico. These include the National Hurricane Center Tropical Cyclone Report for Hurricane Maria, which stated that sixty-five people are known to have been killed directly or indirectly by Hurricane Maria (Pasch, Penny, and Berg 2018) and three indirectly by Irma (Cangialosi, Latto, and Berg 2018). On August 28, 2018, the Government of Puerto Rico adopted an official death toll for Hurricane Maria of 2,975 (Santiago, Schoichet and Kravarik 2018) based on a study conducted by researchers at George Washington University (Santos-Burgoa, et al. 2018). The MAT did not investigate the loss of life associated with the hurricanes but has provided the above information as the best available at the time of the release of this report.

1.3 History of Previous Hurricanes and Mitigation

Hurricanes Irma and Maria were only the most recent significant storms to have affected Puerto Rico in the past 100 years. According to the USGS, other notable hurricanes that impacted Puerto Rico include Hurricanes San Ciriaco (1899), San Felipe (1928), San Nicolas (1931), San Ciprian (1932), Santa Clara (1956), Federico (1979), Hugo (1989), Georges (1998), and Irene (2011). Figure 1-11 represents the tracks of historical hurricanes impacting Puerto Rico. The figure shows 28 hurricanes in 166 years, for an average of more than one hurricane every six years.

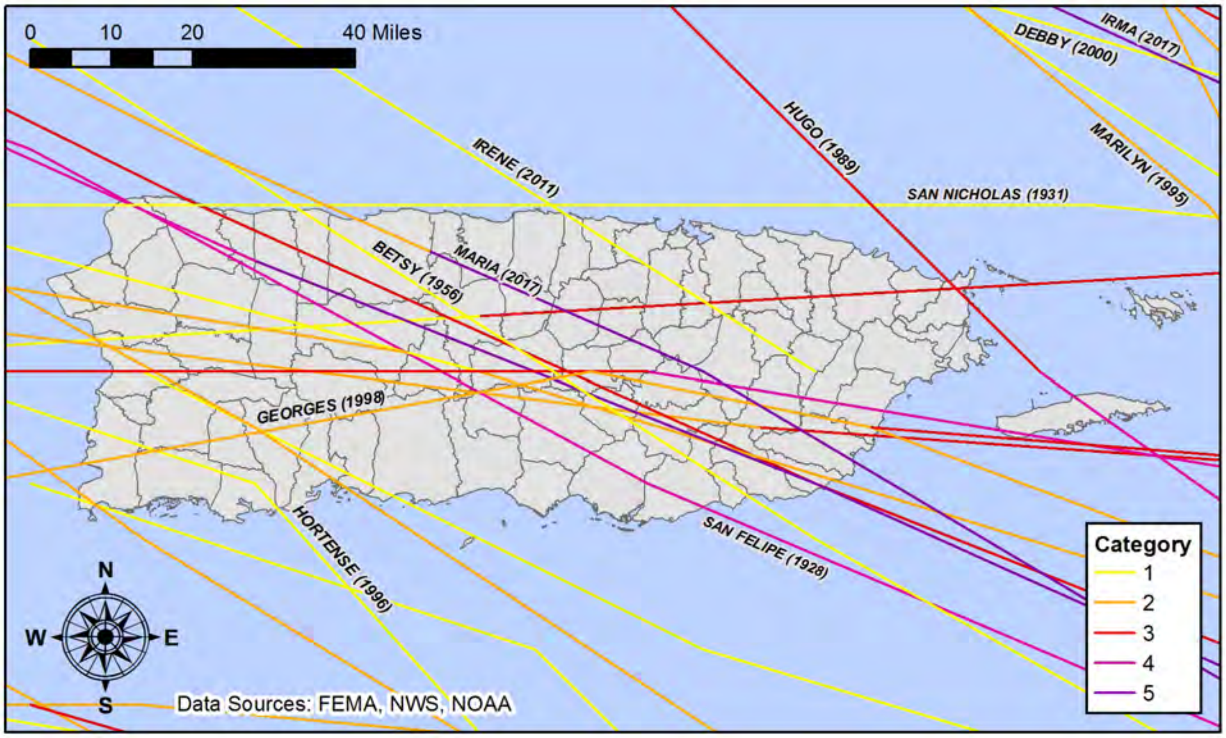


Figure 1-11: Hurricanes in Puerto Rico since 1851, color-coded by Saffir-Simpson hurricane wind speed category. Data source: NOAA (2018).

1.3.1 Hurricane Hugo

On September 18, 1989, Hurricane Hugo crossed the Puerto Rican islands of Vieques and Culebra as a Category 4 hurricane, impacting the municipalities of Fajardo and Luquillo at the easternmost tip of Puerto Rico (Figure 1-10). Maximum winds over Vieques were estimated at 132 mph (212 kph), with a gust of 170 mph (273 kph) measured from a ship in Culebra's harbor and sustained winds of 98 mph (158 kph) measured at Roosevelt Roads Naval Station in Ceiba (National Weather Service 1990). At that time, Hugo was the strongest hurricane to hit Puerto Rico since the 1960s.

Hurricane Hugo caused loss of life and great damage to the infrastructure of eastern Puerto Rico, including a large amount of damage to San Juan. Thirty thousand people were made homeless. Eighty percent of wooden buildings on Culebra and Vieques were destroyed. Damage to property is estimated to have been roughly $1 billion in Puerto Rico, not adjusted for inflation (Bureau of Labor Statistics 2018, National Weather Service 1990, Schwab 1994). Electrical distribution lines, telephone systems, water supplies, and transportation systems all were hard hit (Bush and Marshall 1994).

A 1991 American Society of Civil Engineers (ASCE) symposium paper stated that many of the repairs and reconstruction performed in Puerto Rico after Hugo were executed according to preexisting practice, repeating mistakes in design and construction that had been made before the hurricane (Rodriguez, Pesquera, and López 1991).

1.3.2 Hurricane Georges

Hurricane Georges made landfall in Puerto Rico on the evening of September 21, 1998, as a Category 2 hurricane with maximum sustained wind speeds of 115 mph (185 kph) (Guiney 1999) and traveled directly over Puerto Rico in an east-west direction (Figure 1-11). Though Georges did not match the intensity of Maria at landfall, it had devastating effects on an array of building types and infrastructure. Over 30,000 homes were destroyed, and an additional 100,000 experienced major or minor damage. Approximately 80 percent of the 3.8 million residents were left without power and water. Damage in Puerto Rico exceeded $2 billion, not adjusted for inflation[2] (DHSOIG 2015, NOAA 1999).

Following Hurricane Georges, FEMA deployed a Building Performance Assessment Team (BPAT), a precursor of the MATs, to evaluate damage and compile lessons learned for future mitigation (Figure 1-12). This team of architects, engineers, planners, insurance specialists, and floodplain management specialists traveled to Puerto Rico for field investigations focusing on facilities ranging from single-family homes to critical facilities. The resulting BPAT Report (FEMA 1999) detailed recommendations for updated building codes and regulations, training and continuing education, and mitigation techniques for critical facilities and residential buildings. The report also recommended a study on electrical power distribution.

As with the current MAT process, the goals of the Hurricane Georges BPAT were to observe damage and provide conclusions and recommendations to help in recovery operations, reducing building vulnerabilities and increasing community resilience.

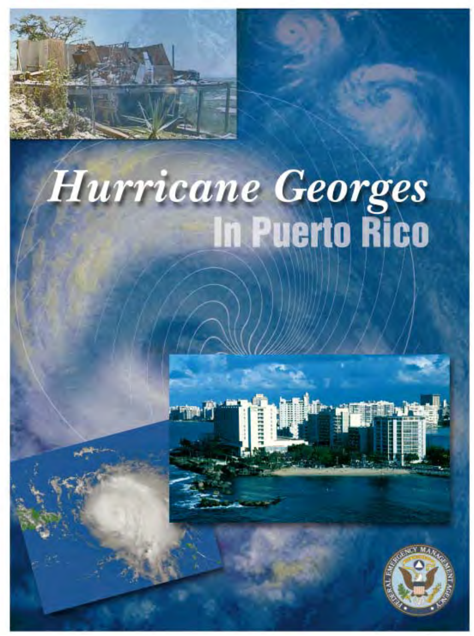


Figure 1-12: FEMA BPAT Report for Hurricane Georges (FEMA 339 1999).

[2]This represents approximately $3 billion in inflation-adjusted September 2017 dollars (Bureau of Labor Statistics 2018).

Most structural damage observed by the BPAT after Georges was to low-rise residential buildings (Figure 1-13). Many of these were informally constructed homes[3] not designed or constructed to current building standards. Wood-framed buildings in general were found to perform poorly and made up a significant portion of damage caused by severe winds. The lack of proper wood-framed construction techniques did not provide adequate load path connections and lowered building survival odds. Failures often occurred at connection points, often near the roofline. Code-compliant houses typically sustained limited structural damage from Georges's winds, which were below design speeds.

Figure 1-13: Examples of observed damage by the BPAT after Hurricane Georges in 1998. Source: (FEMA, 1999a).

In general, reinforced concrete and concrete masonry unit (CMU) buildings, which have strong continuous load path connections between the roof, wall system, and foundation, sustained limited structural damage from Georges. These buildings typically have flat roofs and significant steel reinforcement, helping them resist wind and flood loads. When damage was observed to concrete and CMU buildings, it was usually roof damage to those buildings with wood-framed roof structures and not damage to the concrete itself.

Some concrete houses with CMU infill panels were found susceptible to future seismic activity. These buildings had first floors supported by narrow concrete or CMU columns. Such instability posed a significant risk of collapse in the event of an earthquake. The BPAT recommended

[3]Following local usage in Puerto Rico, this report uses the term "informal" to refer to buildings not permitted or built to contemporary building codes and standards (Section 2.3.4). The Hurricane Georges BPAT Report uses the term "self-built" for these buildings.

addressing seismic vulnerability along with hurricane-related hazards. Unfortunately, informal construction practices remain a concern in the Commonwealth.

Roof covering damage was a common occurrence following Hurricane Georges. Corrugated roofing systems frequently blew off their framing, though in some instances the framing failed first. The level and location of damage depended upon the type of connections and specific construction pattern of the roof covering. Exposed concrete roof types performed well against winds but suffered occasional leaks during the storm. Liquid-applied membranes over concrete roof decks performed well and suffered little wind or water damage; this was generally the best-performing option. Built-up membranes were observed to have lifted and peeled near the corners but to have generally stayed intact. Most built-up membranes were in low-wind-speed areas, so the overall performance could not be assessed. Both tile and built-up aggregate roof coverings sustained damage, either from uplift or missile impact. This damage was particularly concerning, as aggregate debris could become projectiles, causing injury or damaging other buildings.

BPAT investigators noted several instances of mitigation for wind hazard, primarily frame connection hardware (hurricane clips) installed by some residents after hurricanes in 1995 and 1996 (Figure 1-14). Such mitigation measures were only partially implemented in the observed buildings.

Figure 1-14: Frame connection hardware (hurricane clips) installed in a wood-framed house on Culebra. Source: FEMA (1999a, 52).

Flooding from Georges damaged buildings of all types. Flooding typically caused wetting of the building and its contents but little structural damage. Reinforced concrete and CMU homes could be dried out and cleaned off easily and made habitable in a relatively short period of time. Occasional foundation damage was observed, particularly where buildings were sited close to coastlines or riverbanks (Figure 1-15).

Figure 1-15: Example of damage to floodplain development observed by BPAT after Hurricane Georges in 1998. Source: FEMA (1999a, 30).

Damage observed to mid- and high-rise commercial buildings was limited. These buildings were usually steel-framed or reinforced concrete construction and engineered by design professionals. Generally, the damage that did occur was to non-structural elements, such as glazing, curtain walls, interior walls, and finishes, and in many cases involved wind-driven rain.

Most of the residential buildings damaged during Georges were built without proper construction practices, siting, building permits, or design services. These informally constructed houses were not constructed to the guidelines prescribed in Puerto Rico's Planning Regulation 7, which was amended in 1987 to reference the 1982 Uniform Building Code (UBC), more than ten years before Georges. The BPAT found code violations and unregulated construction due to overlooked provisions in existing statutes, regulations, policies, and practices governing development. These deviances accounted for significant failures in wind-damaged houses. Informal construction in Puerto Rico is discussed further in section 2.3.4 of this report.

Additional damage resulted from a lack of adherence to Planning Regulation 13, which enacted NFIP-compliant standards of floodplain management, but which was inconsistently implemented. Buildings were built in the floodplain with limited oversight and frequently without having been designed for relevant floodplain requirements. The BPAT notes that a 1998 Community Assessment Visit conducted by FEMA Region II, Caribbean Area Division, concluded that many buildings within the floodplain were at risk of flooding due to these violations and alterations without permits. Many buildings within the floodplain were inundated during Georges and sustained significant damage.

1.3.2.1 BPAT Mitigation Recommendations

The Government of Puerto Rico took swift action in the aftermath of Georges to address identified flaws in the building sector. The Regulations and Permits Administration (Administración de Reglamentos y Permisos [ARPE]), the permitting body at that time, repealed Planning Regulation 7 and adopted regulations based on the 1997 UBC as an emergency action. The previously adopted 1982 UBC was found to significantly under-predict loads and new provisions of the 1997 UBC provided for wind speedup due to topography and new loads for windows, doors, and roofs. The

BPAT noted that while recommended, an updated code was only part of an effective mitigation strategy. Much of the observed damage could have been avoided had buildings initially complied with the older code. To help address those concerns, the government of Puerto Rico worked with FEMA to develop a strategic plan to offer training on the new provisions.

The BPAT Report outlined a series of recommendations to advance mitigation priorities. These recommendations included the following overarching goals:

- Design buildings to new building regulations.
- Permit, build, and inspect new buildings to meet the new regulations.
- Retrofit existing buildings to make their envelopes more resistant to breaching in future windstorms.
- Take precautions in areas with known hazards, such as floods and landslides.

These guiding principles were further detailed for practical action. For example, for wind hazards, mitigation efforts prior to Georges encouraged metal framing connectors between rafters and bearing walls. Where implemented, however, similar reinforcement had not been provided for connections between the metal roof panels and wood nailers, or between the nailers and rafters. The result was homes with only partially connected load paths. These houses typically sustained significant roof covering damage, which led to further damage to the interiors and contents. Mitigation recommendations by the BPAT suggested a total load path strategy and prioritizing the most vulnerable components of the load path first. If a complete load path was not possible, the roof covering typically fails first and should be strengthened to reduce losses to the interior.

The bulk of BPAT recommendations were related to training, code adoption, and code enforcement. The emergency adoption of the 1997 UBC was an important first step, but further work was needed to ensure that it would be effective and comprehensively implemented. The BPAT recommended several local amendments to the 1997 UBC: provisions for roofing uplift testing, prescriptive design of metal roofing, requirements for non-structural envelope repairs, the adoption of the Uniform Code for the Abatement of Dangerous Buildings (ICC© 1997), requirements for re-roofing, requirements for wood preservative treatments, and provisions for wind-resistance and missile impact testing for glazing. It also recommended aggressive enforcement of the new code throughout permitting and inspection to encourage a culture of regulatory compliance.

For buildings within the floodplain, the BPAT recommended renewed enforcement of the NFIP standards found in Planning Regulation 13. As adopted by Puerto Rico, these standards applied to residents in the floodplain both with and without flood insurance. Yet, it was common for residents to enclose ground-floor areas of buildings or otherwise add improvements that did not comply with NFIP regulations. The BPAT recommended continued efforts to encourage participation in the NFIP to increase compliance and reduce risk. At the time of the BPAT, about 25 percent of the population in the Special Flood Hazard Area (SFHA) had flood insurance.

Finally, the BPAT stressed the importance of education and implementation to support the adoption of the new provisions. This was to include hiring and training additional ARPE staff. Multiple training needs were identified for ARPE staff, design professionals, technicians, builders, contractors, and public policy decision-makers. ARPE, the Colegio de Ingenieros y Agrimensores, the Colegio de Arquitectos, the International Conference of Building Officials (ICBO), and FEMA worked together to develop a training schedule to explain the new provisions to such audiences.

FEMA-funded mitigation programs enacted after Hurricane Georges included retrofitting of existing buildings by Project Impact and replacement of vulnerable buildings by the New Secure Housing Program (NSHP; Nuevo Hogar Seguro).

1.3.2.2 Project Impact Culebra

Project Impact was a FEMA program in existence from 1997-2001 that supported and facilitated community preparations for natural disasters. The Puerto Rican island of Culebra was nominated by FEMA to participate in Project Impact in June of 1998, three months before Hurricane Georges, and Project Impact Culebra was actively participating later that year. In March 1999, Culebra was designated a Disaster-Resistant Community under Project Impact. As a result, FEMA provided $500,000[4] for mitigation including the installation of hurricane clips and straps in existing wood buildings and waterfront restaurants and the installation of hurricane shutters and hurricane resistant windows for several community facilities: the Culebra Community Health Center, Municipal Building, Municipal Library, the Elderly Center, and the Multiple Use Center (FEMA 1999b). The Hurricanes Irma and Maria MAT visited the Municipal Building and Culebra Community Health Center. Some mitigation measures were observed, and structural and opening performance at these facilities was generally good (Chapter 5).

1.3.2.3 New Secure Housing Program

The New Secure Housing Program (NSHP; Nuevo Hogar Seguro) was established on October 15, 1998, by executive order of then Governor of Puerto Rico Pedro Rosselló. Its purpose was "to replace or rebuild low-income housing stock the disaster damaged while undertaking permanent measures to mitigate against damage from similar future events" (DHSOIG 2015 p2). Hurricane Georges had damaged 100,000 homes and left more than 30,000 families homeless. The NSHP received funding from two FEMA programs, the FEMA Hazard Mitigation Grant Program and FEMA Disaster Assistance for Unmet Needs (DHSOIG 2015, FEMA 2000). The total cost claimed by the Puerto Rico Department of Housing (PRDOH; Departamento de Vivienda) was $184 million[5] (DHSOIG 2015).

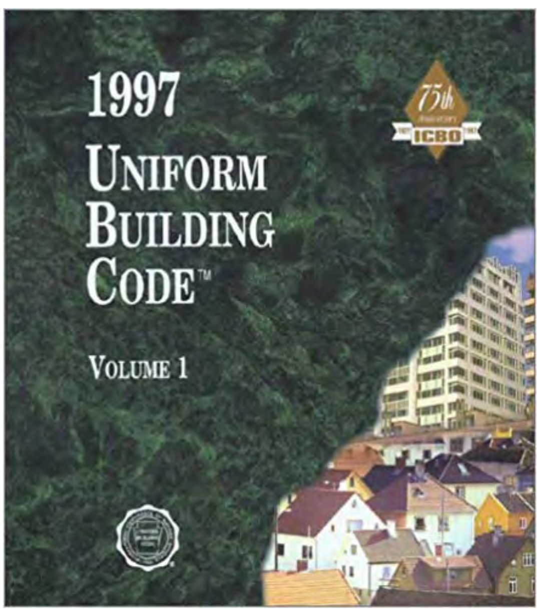


Figure 1-16: Cover of the 1997 UBC, adopted by Puerto Rico after Hurricane Georges.

The program had two parts. The "on-site component" involved replacing vulnerable buildings at existing sites. The "off-site component" involved acquiring and removing damaged or destroyed homes in highly flood-,

[4]This is approximately $750,000 in inflation-adjusted September 2017 dollars.

[5]This is approximately $277 million in inflation-adjusted September 2017 dollars.

seismic-, and landslide-prone sites, and replacing them at new sites. New homes were constructed in accordance with the 1997 Uniform Building Code (UBC) (Figure 1-16).

Work to replace homes began in 2003 and finished in 2011. In total, the program built 1,647 housing units, 66 on-site and 1,581 off-site (as defined above), in a total of 15 municipalities in Puerto Rico. The municipalities were Arroyo, Caguas, Canóvanas, Coama, Dorado, Guayama, Jayuya, Juana Diaz, Juncos, Morovis, Ponce, Santa Isabel, Toa Baja, Vega Alta, and Villalba (Figure 1-17). The flagship site was Campanilla Farm in Toa Baja, where 223 concrete homes were built (DHSOIG 2014, FEMA 2000a).

The MAT visited several NSHP homes throughout Puerto Rico. Performance of these code-compliant concrete buildings (Chapter 3) in Irma and Maria was generally very good.

Figure 1-17: Locations of New Secure Housing Program Communities.

1.3.3 Other FEMA Hazard Mitigation

On August 22, 2011, Tropical Storm Irene became Hurricane Irene while passing over Puerto Rico (Figure 1-10). The hurricane continued away from the island to the northwest. Sustained winds of 51 mph (82 kph) (66 mph [106 kph] 3-second gust) were recorded in Vieques. Irene produced heavy rain in Puerto Rico, with a maximum rainfall of 22 inches (56 centimeters) in Gurabo Abajo, Juncos. The northeast portion of the island experienced major flooding (Avila and Cangialosi 2011).

Following Irene, several hazard mitigation projects were carried out in Puerto Rico. Fifteen public buildings received wind retrofits including storm shutters, mostly in San Juan. Properties were acquired to mitigate riverine flooding and erosion hazards in Cayey and San Sebastián, respectively.

In response to severe storms, flooding, and mudslides in May 2001 (FEMA DR-1372) (FEMA 2012), a FEMA HMA grant was awarded for the installation of storm shutters on fire stations throughout Puerto Rico. Forty-five stations were equipped with impact-resistant shutters at a total program cost of $237,838[6] (FEMA 2018a, FEMA 2018b). Following severe storms and flooding in 2009 (FEMA DR-1798), 23 additional fire stations, largely in southern municipalities, were equipped with storm shutters at a total program cost of $124,093[7] (FEMA 2008b, FEMA 2018a, FEMA 2018b). Performance of fire station shutters in Irma and Maria was generally good. Detailed observations are presented in chapter 5.

1.4 FEMA Mitigation Assessment Team

FEMA conducts building performance studies after unique or nationally significant disasters to better understand how natural and manmade events affect the built environment. A MAT is deployed when FEMA believes the findings and recommendations derived from field observations will provide design and construction guidance that will improve the disaster resistance of the built environment in the affected State or region and will be of national significance to other disaster-prone regions. FEMA bases its decision to deploy a MAT on preliminary information such as the following:

- Magnitude of the expected hazards
- Potential type and severity of damage in the affected areas
- Pre-storm site conditions, such as the presence of older housing stock and aging infrastructure
- Potential value of study results to the rebuilding effort
- Potential to gain strategic knowledge related to improving building codes, standards, and industry guidance, potentially on a national level;
- Potential to gain feedback on the effectiveness of previous FEMA grants

[6]This is approximately $330,000 in inflation-adjusted September 2017 dollars.

[7]This is approximately $140,000 in inflation-adjusted September 2017 dollars.

- Potential to gain pertinent information on key engineering principles and practices that FEMA promotes in published guidance and best practices documents

The MAT studies the adequacy of current building codes, local construction requirements, building practices, and building materials based on the damage observed after a disaster. Lessons learned from the MAT process are communicated to policy makers, stakeholders, and the public; for this event, the work products include six Recovery Advisories (Appendix D) and the following comprehensive MAT Report. This report is intended to aid communities in improving the disaster resilience of buildings through repairs, improvements, and new construction.

1.4.1 MAT Composition

The MAT for Hurricanes Irma and Maria in Puerto Rico was composed of engineers, architects, floodplain managers, and other experts with diverse training and experience from a range of institutions:

- FEMA Headquarters and Regional Office staff
- Housing and Urban Development staff
- National Institute of Standards and Technology staff
- Construction and building code industry experts
- Local and national design professionals, including engineers and architects
- FEMA specialists deployed to the Puerto Rico Joint Field Office (JFO)

Team members included structural and civil engineers; coastal engineers; architects; floodplain managers; building code, wind design, and critical facilities experts; an aerial drone operator; and FEMA specialists. Members of the MAT are listed at the front of this document.

The MAT report is divided into these main study areas:

- Building codes, standards, and regulations
- Residential and low-rise buildings
- Schools and shelters
- Hospitals and other critical facilities
- PV systems and solar water heaters

Each specific study area included field visits to numerous locations throughout Puerto Rico, including the islands of Culebra and Vieques.

1.4.2 Involvement of Commonwealth and Local Agencies

FEMA encouraged the participation of Commonwealth and municipal officials, as well as resident experts in the assessment process. The MAT met with various Commonwealth and municipal officials, as well as facility managers and engineers at critical facilities. These officials were able to provide insight into damage within their communities as well as recommending specific geographic areas to be visited by the MAT. The MAT also coordinated with specialists at the Puerto Rico JFO. The involvement of local agencies was key to the effectiveness of the MAT and offered several significant advantages:

- Improving the MAT's understanding of local building processes, including permitting and construction practices.
- Assisting the MAT in developing recommendations that are economically and technically feasible and can be readily implemented by communities and stakeholders.
- Facilitating communication among Federal and Commonwealth government entities and the private sector.
- Improving the Commonwealth's understanding of the MAT's observations and recommendations so it can implement them for improved building and community resilience.

1.4.3 Pre-MAT

FEMA deployed a Pre-MAT consisting of two sub-teams to Puerto Rico on October 24-October 26, 2017. The purpose of the Pre-MAT was to perform initial reconnaissance and determine areas of focus for further investigation by the MAT. Following the Pre-MAT, an outbrief was provided to FEMA, Commonwealth officials, and other stakeholders summarizing preliminary observations and proposing areas of study for the MAT. Pre-MAT damage observations were supplemented by desktop analyses including a review of aerial imagery taken by NOAA and the U.S. Civil Air Patrol. Review of this imagery gave additional insight about damage in areas that the Pre-MAT was unable to visit due to time constraints.

Key areas of focus by the Pre-MAT included the performance of residential buildings, commercial buildings, critical facilities, and buildings built following Hurricane Georges. The Pre-MAT also considered the effectiveness of mitigation programs and recommendations provided in the Hurricane Georges BPAT (FEMA 1999a) as well as the performance of power and communication systems, specifically PV systems.

1.4.4 Structure Types Assessed

The structures selected by the MAT for damage assessment included single-family, multifamily, low-rise, and mid-rise buildings, as well as schools, shelters, hospitals, public buildings, police and fire stations, PV arrays, and solar water heaters. The MAT visited coastal and riverine floodplains and urban, suburban, coastal, and mountainous areas.

1.4.5 MAT Field Deployment

The MAT deployed to Puerto Rico in four sub-teams, with the first group deployed December 5, 2017, and the rest deployed December 11. Each MAT sub-team consisted of 5-6 members, and each focused on specific items:

- **The Building Code, Permitting, and Residential Sub-Team (Dec. 5–9)** met with Commonwealth and municipal officials involved with the building codes, floodplain ordinances, and local policies governing construction in various municipalities on the main island of Puerto Rico.
- **The Coastal and Riverine Flooding Sub-Team (Dec. 11–15)** met with municipal officials and observed coastal, riverine, and critical facility sites on the main island of Puerto Rico.
- **The Wind Sub-Team (Dec. 11–15)** met with Commonwealth and municipal officials, and reviewed wind performance of residences, schools, critical facilities, and PV systems on the main island and Vieques.
- **The Support and Drone Sub-Team (Dec. 11-15)** provided support for the flood and wind groups. It also provided drone reconnaissance to access sites and perspectives that were either unsafe or impractical to physically access.

As the MAT sub-teams performed site visits, additional or alternative sites were added after reviewing on-the-ground conditions or based on information from Commonwealth and municipal officials. Officials, facility operators, building owners, and residents were interviewed regarding specific local conditions experienced during the storms, performance of buildings, knowledge of mitigation actions, and progress of recovery.

1.5 Summary of MAT Observations

Hurricane Irma resulted in damage to residential buildings and utility infrastructure throughout Puerto Rico, even though Irma did not make landfall in the Commonwealth. Two weeks later, Hurricane Maria made landfall, causing significant damage throughout Puerto Rico. The combination of high winds, heavy rainfall, and storm surge resulted in damage across a wide variety of building types. Levels of damage varied widely by building type, building construction quality, and geographical location.

1.5.1 Residential and Low-Rise Buildings

A wide range of construction quality was seen in residential buildings. In general, permitted wood and concrete homes with properly-detailed connections performed well. Informally constructed homes often performed poorly due to a combination of materials used, poor or nonexistent connections, and location.

Many buildings, formal and informal, experienced large amounts of water infiltration due to damaged roof coverings, damaged openings (windows and doors), or wind-driven rain entering through unsealed openings. It was noted that many opening protection systems failed due to being in poor condition and being at the end of their useful life.

The MAT also noted wind damage related to topography. There were groupings of failures in larger residential settings where damage was likely caused or intensified by wind speed-up over topographic features. Failures due to rainfall and flooding were also noted. Buildings adjacent to channels or ridges experienced failures due to stream bank erosion or landslides. There was damage noted from both inundation and velocity flooding. Buildings on the coast were damaged from both storm surge inundation and collapse due to coastal erosion.

1.5.2 Schools and Critical Facilities

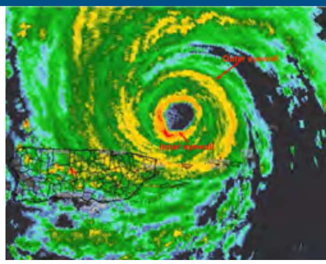
Schools and critical facilities, including hospitals, generally performed well structurally during Hurricanes Irma and Maria. However, several common failures were observed and collectively these buildings performed no better than commercial buildings overall. Water intrusion into buildings from roof covering or rooftop equipment failures was a common observation. Additional water intrusion occurred due to failures of unprotected or inadequately protected openings and at unsealed openings. Water intrusion for these buildings was especially problematic, as it resulted in loss of use of portions of the buildings.

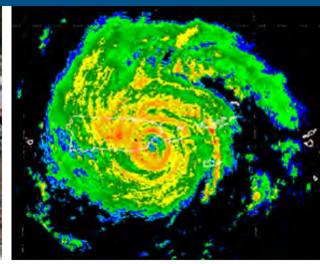
1.5.3 Photovoltaic Arrays and Solar Water Heaters

PV arrays and solar water heaters have become very common in Puerto Rico and play an important role in providing electrical service and hot water. Solar water heaters are required through the building code in new residential construction in the Commonwealth. The performance of solar equipment including ground-mounted and rooftop systems varied widely based on factors including type, attachment, and location.

1.5.4 Flood Zones

Flood risk in Puerto Rico varies widely with geographic location. Coastal areas are subject to storm surge flooding. These include VE Zones, which are coastal areas subject to high-velocity wave action; AE Zones, which are coastal areas subject to wave action that is less severe than in VE Zones; and Coastal A Zones (CAZs), which are portions of the AE Zone landward of the VE Zone and seaward of the inland limit of the 1.5-foot (0.5-meter) breaking wave height during the base flood event. For the first time in Puerto Rico, the CAZs have been depicted on post-storm Advisory Mapping, adopted on an emergency basis in April 2018. In addition to AE and VE Zones along the coast of Puerto Rico, there are inland riverine A and AE Zones. There are many areas not located in a designated flood zone that are nevertheless at high risk of localized flooding. These locations, which may be as small as a single property, may flood due to runoff from local terrain, poor building siting, or poor local drainage. Additionally, many buildings in mountainous regions are at risk from landslides in heavy rains. Many buildings sited on steep slopes were observed to be at risk of collapse from landslides.




HURRICANES
IRMA AND MARIA
IN PUERTO RICO

2 Building Codes, Standards, and Regulations

A combination of building codes and floodplain management ordinances determine the requirements that govern construction in the Commonwealth.

2.1 History of Building Codes in Puerto Rico

Planning Regulation 7 was adopted by the Governor as Puerto Rico's building code in 1968 (Figure 2-1) under the authority of Law No. 168 of 1949. In 1975, a new agency, the Regulation and Permitting Administration (Adminstración de Reglamentos y Permisos), commonly referred to by its Spanish acronym, ARPE[1], was created to regulate permitting in the Commonwealth. In 1987, ARPE amended Planning Regulation 7 to include provisions on requirements for minimum design loads acting on structures based on the 1982 Uniform Building Code (UBC), requirements for all new construction to be seismic-resistant, and a new basic design wind speed of 110 mph (177 kph) fastest-mile (125 mph [201 kph] 3-second gust).

[1]Puerto Rico's building code is currently administered by the successor entity to ARPE, the Permits Management Office (Oficina de Gerencia de Permisos [OGPe]).

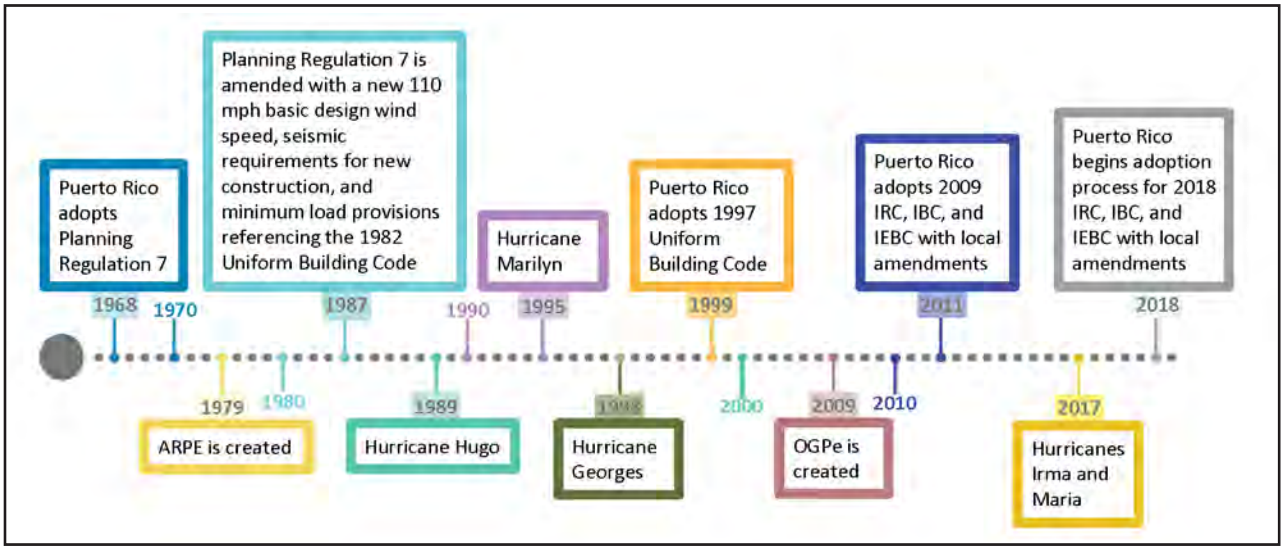


Figure 2-1: Timeline for the Puerto Rico Building Code.

After Hurricane Hugo in 1989, much of the reconstruction did not follow hazard-resistant practices, posing additional risk to structures in future storms (Rodriguez, Pesquera, and López 1991). Nine years later, after Hurricane Georges in 1998, although mandatory practices for different principal construction types were required by Planning Regulation 7, the guidelines for new construction, accounting for wind and seismic loads, had not been consistently followed or enforced. The BPAT concluded that a majority of the damage caused by Hurricane Georges was directly related to design inadequacies and deficient enforcement of Planning Regulation 7 and poor construction quality of informally constructed homes.

Immediately following Hurricane Georges, ARPE initiated changes to increase public safety and reduce property damage. The first step took place in December 1998 when the Government of Puerto Rico passed an emergency regulation that repealed Planning Regulation 7 and replaced it with the 1997 UBC with local amendments. The 1997 UBC would serve as the Puerto Rico Building Code (PRBC) until 2011.

In January 1999, ICBO conducted a peer review of ARPE to assess the needs of the Commonwealth. ARPE requested the peer review to help respond effectively to post-storm reconstruction activity in the wake of Hurricane Georges, as well as anticipated future construction. The ICBO review provided recommendations for improved policies, procedures, and training.

Following the peer review, ARPE and FEMA established a comprehensive plan to provide necessary training and briefings for ARPE staff, design and construction groups, the banking and mortgage industries, and policymakers. The goal of the plan was to provide a smooth transition to updated building codes. ARPE prepared improved building and enforcement regulations for the Certification and Building Board of Puerto Rico which was under proposed legislation at the time. One of the Board’s projected responsibilities was to adopt updated building regulations, including the formal adoption of the 1997 UBC. The Board was never created, but in December 1999, Puerto Rico did adopt the 1997 UBC formally, with amendments revised by ARPE (FEMA 1999).

In 2007, Puerto Rico attempted to develop a process to update its building codes; however, the effort was unsuccessful, with no updates taking place. Two years later, a Construction Codes Committee, established by the Permits Office, reviewed and implemented a transition from the existing 1997 UBC to a subset of the International Code series (I-Codes) published by the International Code Council (ICC©). The Committee was comprised of representatives from the construction industry, architects, engineers, and representatives of regulatory government agencies, who attended several seminars to become familiar with the 2009 I-Codes. The committee evaluated proposed amendments for three days with the goal of revising the PRBC based on the 2009 I-Codes.

In 2009, the Permits Management Office (Oficina de Gerencia de Permisos), commonly referred to by its Spanish acronym, OGPe, was created as the successor to ARPE to enforce regulations including those on land use planning, licensing, inspections, certification, and permitting. Besides assuming the duties of ARPE, OGPe took on a unifying, coordinating role to enforce permitting regulations developed by PRPB (PRPB Audit and Compliance Bureau 2017).

2.2 Puerto Rico Building Code

The 2011 PRBC is a compilation of I-Codes adopted with local amendments. The I-Codes adopted include the 2009 editions of nine of the I-Codes:

1) International Building Code
2) International Energy Conservation Code
3) International Existing Building Code
4) International Fire Code
5) International Fuel and Gas Code
6) International Mechanical Code
7) International Plumbing Code
8) International Private Sewage Disposal Code
9) International Residential Code

The PRBC is implemented to "provide minimum requirements to safeguard the public health, safety and general welfare of the occupants of new and existing buildings and structures" (PRBC 2011, 3). Local amendments included a municipality-based map for IBC© "1613.5 Seismic Ground Motion" that used the most conservative ground acceleration within the municipality. For the IRC©, a local amendment to "R301.2.12 Protection of Openings" expanded the design wind speed allowance for prescriptive-based wood structural panels for wind-borne debris region opening protection from 130 mph (209 kph) to 145 mph (233 kph). This is a significant amendment, as all of Puerto Rico is within the 145 mph design wind speed for the 2011 PRBC. The 2011 PRBC became available for adoption and use in March of that year.

According to the PRBC, the building codes are updated, and a new edition issued, every three years to incorporate new construction methods. However, no new edition of the building code has been adopted since the initial implementation of the code in March 2011, and it has only been amended once, in June 2012. Due to many advances since the 2009 I-Codes, the 2018 I-Codes incorporate the most up-to-date hazard-resistant provisions. In addition, Puerto Rico does not participate in The International Organization for Standardization's (ISO's) Building Code Effectiveness Grading Schedule (BCEGS) program, which tracks the adoption and enforcement of building codes, with emphasis on hazard resistance.

After the destruction of Hurricanes Irma and Maria, OGPe issued Administrative Order 2017-10 (OGPe 2017) on December 26, which orders the establishment of a committee to revise and adopt the PRBC based on the 2018 I-Codes. The Committee's focal responsibility is to "study, evaluate, and make recommendations regarding adopted building codes" (OGPe 2017, 2). The order allows for a maximum of 180 days from the Administrative Order's issue date to establish the Committee and for the Committee to make the necessary recommendations.

On May 30, 2018, the Commonwealth enacted Law 2018-109 (Law 2018-109 2018). This law directed the Construction Codes Review Committee to revise Puerto Rico building codes on a three-year cycle.

The final publication of the new PRBC is expected to occur on November 15, 2018, according to communications with the Puerto Rico Construction Code Adoption and Revision Committee (Comité para la Adopción y Revisión del Códigos de Construcción de Puerto Rico) in September 2018. The codes proposed for adoption are the 2018 editions of 10 of the I-Codes (Planning Department 2018):

1) International Building Code
2) International Energy Conservation Code
3) International Existing Building Code
4) International Fire Code
5) International Fuel and Gas Code
6) International Mechanical Code
7) International Plumbing Code
8) International Private Sewage Disposal Code
9) International Residential Code
10) International Swimming Pool and Spa Code

2.3 Planning, Permitting, and Code Enforcement

Development in Puerto Rico is governed by several different bodies. The Puerto Rico Planning Board (PRPB; Junta de Planificación de Puerto Rico) guides development, and building permits are administered by OGPe. Code enforcement is governed by the PRPB and some autonomous municipalities.

Law 19-2017, the Permitting Reform Act, was enacted in Puerto Rico (Permitting Reform Act of 2017). This Act consolidated Commonwealth and municipal permits in one online system to allow design professionals and contractors to follow a consistent set of procedures (Federal Affairs Administration 2017).

Puerto Rico's floodplain management ordinance is Puerto Rico Special Flood Hazard Areas Regulation (Planning Regulation 13) effective January 7, 2010. Planning Regulation 13 enacted NFIP-compliant standards for floodplain management. Additional floodplain regulations were proposed by the PRPB in 2016 but not adopted; these included requiring 2 feet of freeboard for residential buildings and 1 foot for non-residential buildings, requiring compensatory runoff storage to offset losses in flood storage capacity due to development, and regulating the siting of critical infrastructure within the 500-year floodplain. Local floodplain management regulation in Puerto Rico requires a minimum of 1 foot of freeboard for residential structures. Per Planning Regulation 13, Section 7.03(b), non-residential structures currently have no freeboard requirement.

The 2018 I-Codes include a number of floodplain management provisions that have changed since Regulation 13 was issued in 2010. The two documents are currently not consistent. For example, Planning Regulation 13 has no freeboard requirement for commercial structures; however, 2018 IBC© which references ASCE 24-14, requires a minimum of 1 foot of freeboard for commercial structures; more than 1 foot may be required, depending on the building's Flood Design Class. Refer to *Highlights of ASCE 24 Flood Resistant Design and Construction* (FEMA 2015b) https://www.fema.gov/media-library/assets/documents/14983 for more information.

2.3.1 Planning Board

The PRPB was created by Law No. 213 on May 12, 1942, during the governorship of Rexford G. Tugwell, to regulate development in the Commonwealth (PRPB Audit and Compliance Bureau 2017). Originally known as "Puerto Rico Planning, Urbanization, and Zoning Board", it established the means to systematize and organize planning. Today, the PRPB continues to guide development to meet current and future needs (PRPB 2010). It acts as an extension of the Governor "to design and formulate the short, medium and long term public policy of economic development, and the use of the resources of the Island" (PRPB 2017). The PRPB regulates construction, prepares maps of geographic limits of Puerto Rico municipalities and neighborhoods, and declares slum areas. Its authority allows it to address urban renewal and the elimination of slums.

Members of the PRPB are appointed by the governor of Puerto Rico and work in conjunction with OGPe, which issues construction permits throughout the Commonwealth. While the PRPB evaluates projects, including public and regional impact works, and changes in zoning classifications, OGPe evaluates variations in construction and use. The PRPB also serves as the lead for the NFIP State Coordinating Agency.

Beginning in April 2017, the PRPB has had authority to "carry out compliance inspections and audits of permits granted by [OGPe] and the 17 permits office[s] of the [autonomous] municipalities" (PRPB Audit and Compliance Bureau 2017).

2.3.2 Permits Management Office (OGPe)

In December 2009, the Puerto Rico Government created Act No. 161, the "Puerto Rico Permit Process Reform Act" as a response to the economic and fiscal crisis in Puerto Rico. The Act created OGPe to implement a new and efficient permit system that would boost the Puerto Rican economy by creating jobs in the construction industry and other sectors. OGPe replaced ARPE, which had governed the permitting process in Puerto Rico since its establishment in 1975.

OGPe is responsible for defining and enforcing Division I of the PRBC. This includes establishing the applicability of codes, defining the enforcement agencies, and processing construction documents. OGPe maintains the PRBC by reviewing proposed changes submitted by code enforcement officials, design professionals, industry representatives, and other interested parties. OGPe considers changes through an open code development process with updates to be promulgated every three years according to the PRBC.

OGPe handles permitting and inspections from a main office in San Juan and regional offices in Aguadilla, Arecibo, Humacao, and Ponce. Municipal officials have identified this as problematic, because staffing and office locations limit OGPe's ability to inspect every project.

2.3.3 Permitting and Enforcement at the Local Level

While much of the permitting in Puerto Rico is done at the Commonwealth level by the PRPB and OGPe, municipalities may be granted a transfer of some powers to regulate construction. The Autonomous Municipalities Act of 1991 ("Autonomous Municipalities Act of the Commonwealth of Puerto Rico of 1991" 1991), since amended, defines the mechanisms by which municipalities may have degrees of fiscal autonomy and self-government. Section 13.012 of this Act defines five categories or tiers of delegation of authority. The autonomous municipalities are those at the highest tier, Tier 5, which have a Land Ordination Plan in effect; they may acquire powers for regulating construction that are otherwise reserved for the PRPB and OGPe (Puerto Rico Permit Process Reform Act 2009). Delegation of planning authority to a municipality requires that the municipality establish a Permits Office and have a territorial plan in effect, among other requirements. The agreement may set limitations to the delegated powers according to the municipality's capacity. As of the time of preparation of this report, 18 municipalities have delegation agreements in place with permit offices (PRPB 2017), with some municipalities having consolidated permit offices (Table 2-1).

Table 2-1: Municipalities with Delegated Permitting Authority and Permit Offices

Aibonito *	Carolina	Guaynabo
Aguadilla	Cayey**	Humacao
Barranquitas*	Cidra	Ponce
Bayamón	Comerío*	San Juan
Cabo Rojo	Coamo**	Salinas**
Caguas	Fajardo	Villalba**

*Aibonito, Barranquitas, Comerío (ABC) Consortium, permit office in Barranquitas
** Cayey, Coamo, Villalba, Salinas (CCVS) Consortium, permit office in Cayey
Source: PRPB (2017), http://jp.pr.gov/Municipios-Tabla

The transfer of powers to a municipality grants the power to handle, resolve, and process complaints and violations related to that power. It also grants the municipal agencies powers to promote compliance and implementation of regulations. However, the PRPB may determine that a project that has been referred to a municipality must be referred back to the PRPB due to possible regional impacts not accounted for in the plan.

As of December 2017, there were 11 Compliance Inspectors at the PRPB. These inspectors are responsible for compliance inspections throughout Puerto Rico. At that time, OGPe had 13 inspectors and technicians assigned to Construction Permits and 12 to Uses Permits (PRPB Audit and Compliance Bureau 2017). The ICC© lists three ICC©-certified individuals in Puerto Rico on its website (ICC 2018), and the Association of State Floodplain Managers lists seven Certified Floodplain Managers (CFMs) for Puerto Rico. Most States have dozens to hundreds of CFMs (Association of State Floodplain Managers 2018), and more CFMs and ICC©-certified inspectors and technicians would be beneficial for Puerto Rico. As of the publication of this report, increasing the number and training of permitting staff is the goal of ongoing HMA-funded efforts in Puerto Rico.

2.3.4 Formal and Informal Construction

Construction in Puerto Rico is commonly described as either formal or informal. Formal construction typically follows adopted building codes and standardized practices. It is officially permitted either by OGPe or by an autonomous municipality. Formal construction is overseen by, and requires final approval from, a professional engineer or registered architect. In contrast, informal construction is often “self-built” without proper permitting and without design professional supervision during the construction process. Nearly half of Puerto Rican homes were built or renovated through informal construction (PRDV 2018). In general, the prevalence of informal construction is a major challenge to the effective implementation and enforcement of building codes.

Based on data from the PRDOH, there are currently 1.4 million housing units in Puerto Rico, with 1.1 million of these units occupied. A report for the PRDOH cited an estimate that 45–55 percent of all housing in Puerto Rico is informal (PRDV 2018). Only 1 percent of housing stock was built after 2010, compared to a national average of 4.2 percent.

Reasons for the existence of informal construction prior to Hurricanes Irma and Maria included a lack of adequate resources to enforce and remediate unpermitted construction and OGPe’s current exemption from design professional certification requirements for certain projects less than $6,000 (PRPB not dated).

Administrative Order 2017-07, issued on October 5, 2017 (OGPe 2017) enabled certain aspects of reconstruction, replacement, or repairs following Hurricanes Irma and Maria to commence without the requirement of a government-issued permit. The order was valid for 120 days from its issuance. While issued with the intent of encouraging rapid reconstruction and helping individuals reoccupy their homes and businesses after Irma and Maria, the order allowed unpermitted work to be performed and may have contributed to the continued prevalence of informal construction in Puerto Rico.

Informal construction may be non-compliant with some or all of the building code, zoning, or title requirements. Aspects of informal construction practices may be additive; for example, a home with no title may have been built in a high-risk location in a manner not compliant with the building code. The discussion below is provided to clarify the use of the terms.

2.3.4.1 Informal Construction: Building Codes, Floodplain Management Ordinance, and Permitting

The building code provides the minimum design criteria for buildings and structures. The 2011 PRBC requires that a building be designed by a qualified design professional to meet criteria set out in the code, be permitted, be built to the design, and be inspected. Informal construction with respect to building codes, floodplain management ordinance, and permitting does not meet the requirements of the PRBC and/or Planning Regulation 13 for design, permitting, construction, and/or inspection. Informal construction may have some code-compliant design features when builders have previous construction experience. However, building codes are amended and changed over time; therefore, building according to techniques learned by example is unlikely to produce buildings meeting modern standards for hazard resistance. Experience has shown such construction to vary widely in construction quality.

2.3.4.2 Informal Construction: Zoning

Informal construction that does not meet zoning requirements for the municipality will require either a variance to the zoning code or some form of remediation if it is to be brought into compliance. For example, residential buildings built too closely according to the code may be granted a variance if the spacing is determined to be acceptable or if some measure is taken to protect the two buildings. The municipality may require some adjustment in the buildings to maintain fire resistance, ensure privacy, or satisfy other requirements.

In the event a home has been built in an area where the risks of landslides or flooding is too great, issuing a variance may not be possible, as continued occupancy of a home in those areas places the residents at risk. In those cases, the municipality could condemn[2] the property.

Effectively implementing zoning and land use requirements in a municipality requires the development and enforcement of a land use plan. Such an effort requires technically skilled planners as well as political support for enforcement of zoning, planning, permitting, design, and construction requirements.

2.3.4.3 Informal Construction: Title

Informal construction that lacks title is possibly the most difficult issue to resolve, as the building owner may not have the legal right to occupy the underlying land. In those cases, the owner of the home would need to secure title to the land. This may require some type of subdivision of the land as there is little chance a single, platted lot was developed without title. In the case of land owned by

[2]Condemnation is a process in which a structure is deemed unsafe for habitation. Residents are required to relocate from a condemned structure.

the municipality or Commonwealth, there might be additional procedural requirements associated with transferring publicly owned land to private ownership.

Municipal officials told the MAT that Puerto Rico's banking industry incentivizes homeowner compliance with the building code by requiring permit information for mortgages and mortgage-backed transactions, including home equity loans and reverse mortgages. These officials stated that the PRPB and OGPe have considered developing programs based on these industry practices to work with homeowners to retrofit existing informally constructed buildings and issue permits retroactively for those now in compliance with the building code. A building code inspector could inspect the property to identify the issues requiring correction and determine whether it would be feasible to bring the building into compliance.

2.4 Design Wind Speeds

In some areas of the Commonwealth, Maria's wind speeds approached the prescribed wind speed design requirements of the 2018 International Building Code (IBC©) and 2018 International Residential Code (IRC©), which reference design wind speeds found in the ASCE standard *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* (ASCE 7-16).

Design winds speeds for Puerto Rico can be found on maps in ASCE 7. It should be noted that comparing design wind speeds used in building codes and standards with observed or estimated wind speeds from a hurricane is not straightforward. For a direct comparison of one wind speed to another, they must both have the same basis in terms of averaging time, height, and terrain. Because the wind speed definitions and related criteria used in the building codes and standards have undergone two major changes in recent decades, design wind speeds from older codes and standards cannot be directly compared to those in newer versions.

Hurricane wind speeds are often reported using the maximum sustained surface wind speed (peak 1-minute sustained wind) at the standard meteorological observation height of 33 feet (10 meters) above ground over open water, although peak gusts and wind speeds at other heights are also reported. Prior to the publication of ASCE 7-95 (ASCE 1995), the ASCE load standard (referenced in the model building codes) and its predecessors used a fastest-mile wind speed at 33 feet (10 meters) over flat, open terrain. In ASCE 7-95, the standard switched from the fastest-mile wind speed with its variable averaging time to a 3-second peak gust. Additionally, ASCE 7 editions prior to 2010 used a service level wind speed, but also included an importance factor and a load factor, which together had the effect of adjusting the return period of the design wind speed from a service level to a strength level. In ASCE 7-10 and subsequent editions, the standard has moved to a strength-level design wind speed (a simplification that eliminated the importance factor and reduced the load factor on wind from 1.6 to 1.0). In addition to other advantages, this change made it easier to compare design wind speeds given in the standard (referred to by ASCE 7 as Basic Wind Speeds) with observed or forecast hurricane wind speeds[3] .

[3]A detailed description of the relationship between wind speeds as defined by ASCE 7 and those in the Saffir Simpson hurricane wind scale used by the National Hurricane Center is provided in section C26.5.1 of the ASCE 7-16 Commentary (ASCE 2017).

Design wind speeds for buildings and other structures in the ASCE 7 standard are also a function of the assigned Risk Category, "based on the risk to human life, health, and welfare associated with damage or failure by nature of their occupancy or use" (ASCE 2017). Risk Categories range from I to IV, where Risk Category I buildings and structures represent low risk to human life in the event of failure. Risk Category III represents buildings and other structures that could pose a substantial risk to human life, and Risk Category IV includes buildings designated as critical facilities, such as hospitals and emergency operations centers. Risk Category II buildings are those not meeting the definition of the other three categories, which include most residential and commercial facilities. Prior to the ASCE 7-16 edition, there was no differentiation between Risk Category III and IV for determination of wind speeds.

The code currently in force in Puerto Rico at the time of preparation of this report references ASCE 7-05, which designates a basic wind speed of 145 mph (233 kph) island-wide. Wind speeds for different Risk Categories are accounted for indirectly through the importance factor. In later editions of ASCE 7, contoured wind speed maps are used, showing the variation of design wind speeds with location. The design wind speeds for Puerto Rico in ASCE 7-05, 7-10, and 7-16 are compared in Table 2-2 for the four Risk Categories. In ASCE 7-05, the basic (service-level) wind speed of 145 mph for the entire Commonwealth is shown in the second column. The third column provides equivalent strength-level wind speeds for ASCE 7-05, which can be directly compared with the wind speeds in ASCE 7-10 and 7-16. The strength-level wind speeds in Puerto Rico (and on the U.S. mainland) decreased in ASCE 7-10 compared to ASCE 7-05, resulting from advances in hurricane modeling[4].

Table 2-2: Design Wind Speeds for Puerto Rico, in mph (kph)

Risk Category	ASCE 7-05 Basic Wind Speed (Service Level)	ASCE 7-05 Equivalent Wind Speed (Strength Level)*	ASCE 7-10 Basic Wind Speed (Strength Level)	ASCE 7-16 Basic Wind Speed (Strength Level)
I	145 (233)	161 (259)	140-160 (225-257)	140-160 (225-227)
II	145 (233)	183 (295)	150-170 (241-273)	150-170 (241-273)
III	145 (233)	197 (317)	160-180 (257-290)	160-180 (257-290)
IV	145 (233)	197 (317)	160-180 (257-290)	160-190 (257-306)

* Equivalent strength level wind speed = basic wind speed × square root (importance factor × load factor)

Speeds given represent 3-second-gust wind speeds at 33 feet (10.0 meters) above ground level for Exposure Category C (flat, open terrain), as described in ASCE 7.

Sources: ASCE 7-05 (ASCE 2005), ASCE 7-10 (ASCE 2010), ASCE 7-16 (ASCE 2017)

[4] References documenting the hurricane model improvements are provided in Commentary section C26.5.1 of ASCE 7-10 (ASCE 2010).

Increasing wind speeds correspond to increasingly rare events; for example, all wind speeds for Risk Category II have an approximate mean recurrence interval of 700 years, equivalent to a seven percent probability of exceedance in any 50-year period. In contrast, speeds for Risk Category in ASCE 7-16 represent a mean recurrence interval of 3,000 years, equivalent to 1.6 percent probability of exceedance in a 50-year period (Table 2-3).

Table 2-3: Probability of Design Wind Speed Exceedance at Least Once in 50 years.

Risk Category	ASCE 7-10 and Prior Editions	ASCE 7-16
I	15%	15%
II	7%	7%
III	3%	3%
IV	3%	1.6%

Lastly, it should be noted that wind speeds are but one factor of many in determination of wind loads. For example, although the design wind speeds in ASCE 7-16 are slightly lower than the equivalent speeds in ASCE 7-05 for Puerto Rico, net uplift loads for the design of components and cladding on building roofs will often be greater under ASCE 7-16 than ASCE 7-05. This is due to a significant increase in roof pressure coefficients in ASCE 7-16 that resulted from extensive wind tunnel testing and was validated through wind load data collected from real buildings under straight-line and hurricane wind conditions. Many other changes to the ASCE 7 wind loading provisions have occurred between the 2005 and 2016 editions, based on improved understanding of the wind hazard and wind-structure interaction. Significant changes are typically described in the commentary to each edition of ASCE 7.

2.5 National Flood Insurance Program

Puerto Rico has participated in the National Flood Insurance Program (NFIP) since 1978. Development is governed by Puerto Rico's floodplain management ordinance, Planning Regulation 13. Building permits within the floodplain are the responsibility of OGPe. Puerto Rico has five NFIP communities that may adopt and enforce floodplain management regulations. These five NFIP communities encompass all 78 of the municipalities of Puerto Rico. The largest community is the Commonwealth of Puerto Rico, which includes 74 municipalities. The additional NFIP communities are the municipalities of Bayamón, Carolina, Guaynabo, and Ponce.

Only one community in Puerto Rico, Ponce, participates in the Community Rating System (CRS). CRS is an incentive program that encourages communities to develop more hazard-resistant building practices. Ponce is a Class 9 community under the CRS rating system, entitling residents in SFHAs to a 5 percent discount on their flood insurance premiums. The MAT observed interest in the CRS from municipal officials who wished to lower the cost of flood insurance.

The current effective Flood Insurance Rate Maps (FIRMs) for all municipalities in Puerto Rico are dated November 2009. Following Hurricanes Irma and Maria, these maps were reviewed to determine if the 1-percent-annual-chance flood event (the base flood or 100-year flood) shown on the maps is accurate. Where appropriate, Advisory Base Flood Elevations (ABFEs), Advisory Flood Zones, and other Advisory Data were developed to update the flood hazard maps. On April 13, 2018 Puerto Rico adopted on an emergency basis the ABFEs developed in the aftermath of Irma and Maria. The ABFEs were permanently adopted for new construction and substantially improved or substantially damaged buildings on July 11, 2018. The effective 2009 FIRMs shall be used to determine NFIP policy premiums until the ABFEs is formally adopted as the effective FIRMs.

The percentage of NFIP-insured households in Puerto Rico is very low compared to the United States as a whole. As of the end of 2017, there were approximately 44,200 flood insurance policies in effect in the Commonwealth. Of these, only 4,200 were NFIP policies, the remainder being private insurer policies (Kousky and Lingle 2018). In contrast, as recently as 2009, roughly 60,000 NFIP policies were in effect. The sharp decline in NFIP policies can be attributed to a few potential causes. From 2011 to 2012, private companies began offering flood coverage in Puerto Rico. These policies could potentially offer improved value compared to NFIP policies by bundling flood coverage with other coverage, such as vandalism. Additionally, only homes with a mortgage, and that are located within the 100-year floodplain, are required to carry flood insurance. As the Puerto Rican economy has weakened, many households voluntarily carrying coverage may have opted to drop their flood policies for financial reasons. Of total occupied housing units, approximately 58 percent are in mapped floodplains, underscoring the importance of flood insurance participation in Puerto Rico (Government of Puerto Rico 2017).

PRIVATE FLOOD INSURANCE IN PUERTO RICO

A recent study by the Risk Center at the Wharton School of the University of Pennsylvania (Kousky and Lingle 2018) highlighted the unique nature of private flood insurance in Puerto Rico.

Overall, fewer than 5 percent of the homes in Puerto Rico have NFIP or private flood insurance. Approximately 90 percent of the flood insurance policies in Puerto Rico are private, compared to only 2 percent nationwide.

Private insurance tends to be less expensive than NFIP insurance in Puerto Rico. Different construction practices are one reason the private sector can offer less expensive flood policies.

The availability of private flood insurance in Puerto Rico has not led to greater demand. One contributing factor could be affordability challenges for roughly half of residents currently estimated to be living in poverty.

2.6 Standards for Solar Equipment

In Puerto Rico, the permitting of PV panels is managed by OGPe rather than the municipalities. Approval by the Puerto Rico Electric Power Authority (Autoridad de Energía Eléctrica), commonly known by its English acronym, PREPA, is also required for the system to be connected to the electric grid. Permitting of solar power and heating systems is covered under general building requirements, which call for a permit certified by a design professional for projects over $6,000. However, PV systems typically go through the permitting process regardless of cost according to municipal officials, because PREPA requires a permit showing the installation is code-compliant. Conversely, installation of a solar water heater on existing buildings typically falls under the $6,000 threshold for a certified permit and does not need PREPA review; therefore, solar water heater installations are typically unpermitted according to municipal officials.

The only specific design guidance for solar equipment wind speeds or pressures given in the 2011 PRBC and its reference standards, including ASCE 7-05, is an amendment added to the IBC© that includes design pressures for components and cladding where solar water heaters and PV panels are mentioned. Other references appear in the PRBC for installation processes; however, these references are broad and primarily focus on the condition of the installation components. Another amendment included in the 2011 PRBC includes a requirement that all new houses and townhouses use only solar water heaters. Specific design guidelines are not provided. This lack of guidance is especially noteworthy given that local permitting does not review or inspect PV panels or solar heating system installations. Chapter 6 details the performance of ground-mounted PV systems and residential and non-residential rooftop solar equipment.

OGPe has begun a process of adopting the 2018 I- Codes (OGPe 2018), which reference ASCE 7-16. The biggest improvement from ASCE 7-05 to ASCE 7-16, regarding solar equipment, is the addition of design wind loads for rooftop PV panels. Although ground-mount solar equipment has not been included in ASCE design standards yet, the addition of rooftop solar equipment design guidance will aid in a more complete design standard. With the growing use of solar water heaters and PV systems, the importance of appropriate design standards continues to increase, especially for locations exposed to extreme wind conditions.

2.7 Safe Rooms and Storm Shelters

Safe rooms and storm shelters are purpose-built structures that provide life-safety protection for people during hurricanes and tornadoes. Safe rooms provide near-absolute life-safety protection for their occupants against both wind pressures and wind-borne debris impacts associated with tornadoes and hurricanes. Design and construction criteria for storm shelters are detailed in the ICC© *Standard for the Design and Construction of Storm Shelters* (ICC 500© 2008), which has been adopted by reference by the IBC since 2009. (The 2009 IBC© is incorporated by reference into the 2011 PRBC[5].) Design and construction criteria for safe rooms are found in *Safe Rooms for Tornadoes and Hurricanes: Guidance for Community and Residential Safe Rooms,* 3rd Edition (FEMA 2015a).

ICC 500© and FEMA P-361 provide the design and construction criteria for storm shelters and safe rooms,

SAFE ROOMS AND STORM SHELTERS

FEMA defines "safe rooms" as buildings or portions thereof that comply with the criteria described in FEMA P-361, *Safe Rooms for Tornadoes and Hurricanes: Guidance for Community and Residential Safe Rooms*, 3rd Edition (FEMA 2015a) for providing near-absolute life-safety protection from extreme wind events. The ICC© defines "storm shelters" as buildings or portions thereof that comply with the ICC and National Storm Shelter Association (NSSA) ICC/NSSA Standard for the Design and Construction of Storm Shelters (ICC 500©, 2014). All safe room criteria in FEMA P-361 meet or exceed the storm shelter requirements of ICC 500©.

The MAT was not made aware of and did not observe any storm shelters or safe rooms in Puerto Rico that met the ICC© or FEMA standard.

[5]The most recent version of ICC 500© is ICC 500-14©.

respectively. However, neither document requires the construction of purpose-built structures for life-safety protection from wind events. Currently, the IBC has a requirement for some new buildings to include an ICC 500© storm shelter in tornado-prone regions of the country where the tornado hazard design wind speed is 250 mph (3-second gust) or greater. This information is presented in IBC 2018 423.3 and 423.4 for specific building uses identified within Risk Category IV and selected buildings under the Category E occupancy designation. Several states and local jurisdictions also have requirements for the design and construction of storm shelters in tornado-prone regions of the country. Florida is the only hurricane-prone state that has a shelter program with triggers that require some new facilities to include hurricane storm shelters (through the Enhanced Hurricane Protection Area provisions of the Florida Building Code).

While the 2011 PRBC does not mandate the construction of storm shelters or safe rooms, Puerto Rico has approved an amendment to the proposed 2018 PRBC that would require schools and critical facilities meeting certain criteria to provide storm shelters. The amendments modify IBC© 2018 Sections 423.3 and 423.4 as follows:

> *423.3 Critical Emergency Operations. In areas where the shelter design wind speed for hurricanes is 190 mph or greater on island states or territories where vehicle access to the continental US by roadway is not available, 911 call stations, emergency operations center and fire, rescue, ambulance and police stations shall comply with Table 1604.5 as a Risk Category IV structure and shall be provided with a storm shelter constructed in accordance with ICC 500©.*
>
> *423.4 Group E Occupancies. In accordance with Figure 304.2 (2) of ICC 500©, all Group E occupancies with occupant load of 50 or more shall have a storm shelter constructed in accordance with ICC 500©.*

2.7.1 Design Criteria for Safe Rooms and Storm Shelters

Safe rooms are planned with one primary purpose: protecting the occupants from hurricanes and tornadoes. However, designers and decision-makers must plan for multiple hazards: FEMA P-361 and ICC 500© criteria address wind as well as other hazards associated with hurricanes, such as storm surge, flooding, siting issues, collapse hazards, laydown hazards, and fire.

Storm shelters are buildings or portions thereof that comply with the ICC 500© standard. All safe room criteria in FEMA P-361 meet the ICC 500© storm shelter standard, but FEMA P-361 includes recommended guidance that is more conservative than that in ICC 500©. These differences are outlined in a table at the beginning of each chapter in Part B of FEMA P-361, and summarized in Appendix D. For safe room projects built using FEMA HMA grants, the recommendations in Appendix D of FEMA P-361 become requirements.

The level of protection provided by a safe room or storm shelter is a function of design wind speed (and resulting wind pressures) and wind-borne debris impact criteria. The FEMA safe room criteria and ICC 500© storm shelter standards are similar, with a few differences, such as siting with respect to flood hazards and using FEMA's recommended guidance to use the 250 mph (402 kph) design wind speed for all residential safe rooms (regardless of their location). FEMA P-361 references ICC 500 for much of the design and construction criteria of a safe room; it also has additional guidance on conducting risk assessments, benefit-cost analyses for constructing safe rooms, and guidance on the operations and maintenance of safe rooms.

RESIDENTIAL SAFE ROOMS

A residential safe room is defined in FEMA P-320 *Taking Shelter from the Storm: Building a Safe Room for Your Home or Small Business* (FEMA 2014) as a safe room serving occupants of a dwelling unit and having an occupant load of no more than 16. FEMA P-320 provides prescriptive safe room plans that comply with the criteria of FEMA P-361 and ICC 500©. These plans are intended for residential safe room use but can be used for small community safe rooms if the community safe room requirements are also met.

ICC 500© DESIGN WIND SPEEDS

ICC 500-14© provides design wind speeds for tornado and hurricane shelters in Figures 304.2(1) and 304.2(2), respectively. The minimum design wind speed for hurricane and tornado shelters in Puerto Rico is 200 mph (322 kph) per ICC 500©.

Traditional buildings are designed to withstand a design wind speed, which determines the wind pressures the structure is designed to withstand. In Puerto Rico, the 2018 IBC© is in a process of being adopted by OGPe in response to the recent hurricanes. ASCE 7-16 provides wind speed maps used for the design of buildings and other structures. This standard is referenced by the 2018 IBC©. It defines the design wind speeds for Puerto Rico in a range from 140 to 190 mph (225 to 306 kph), depending upon the building use and risk categorization.

Design wind speeds for storm shelters in hurricane-prone regions in ICC 500© (referenced by the 2018 IBC©) are 190–235 mph (306–378 kph) along the Atlantic Coast and 200–250 mph (322–402 kph) for the Gulf Coast. ICC 500©-2014 gives design wind speeds of 200 mph (322 kph) for hurricanes and tornadoes in Puerto Rico. Structures designed to these higher wind pressures provide much greater resistance to wind loads than typical buildings and are less likely to be damaged or collapse from wind forces experienced during hurricanes.

Besides having a higher design wind speed, a safe room or storm shelter must also be resistant to wind-borne debris and falling debris from laydown and collapse hazards. Flood, landslide, and seismic hazards must also be considered when siting, designing, and constructing safe rooms and storm shelters. Consequently, the structural systems and envelope (building exterior) of a safe room or storm shelter, as well as the connections between the building elements, are very robust.

2.7.2 Operations and Planning for Safe Rooms and Storm Shelters

When developing plans for hurricane community safe rooms, designers and other stakeholders should consider hazard-specific constraints that may be governed by local emergency management or law enforcement requirements, mandatory evacuations, and other emergency plans that affect the movement of at-risk populations. For some communities, given sufficient warning of an impending hurricane, a large proportion of the population could be expected to evacuate and seek shelter outside the at-risk area. Only first responders and a small number of residents would not evacuate. In Puerto Rico, in contrast, it is not practical for residents to evacuate the islands, although it may be possible to travel within the main island when smaller storms threaten. The difficulty of evacuation emphasizes the importance of having purpose-built safe rooms and storm shelters to provide life-safety protection for residents of Puerto Rico during hurricanes.

FEMA SAFE ROOM GUIDANCE AND INFORMATION

For information on FEMA safe room guidance and programs, see the FEMA Safe Room Resources web page:

https://www.fema.gov/safe-room-resources

Specifically, the following information may be of most assistance to municipalities and entities considering a safe room:

- FEMA P-388*, Safe Room Resources CD* (FEMA 2015)

https://www.fema.gov/media-library/assets/documents/23315

- ICC 500©, *ICC©/NSSA Standard for the Design and Construction of Storm Shelters* (ICC© 2014)

https://codes.iccsafe.org/public/document/toc/565/

- FEMA P-361, *Safe Rooms for Tornadoes and Hurricanes: Guidance for Community and Residential Safe Rooms*, 3rd Edition (FEMA 2015)

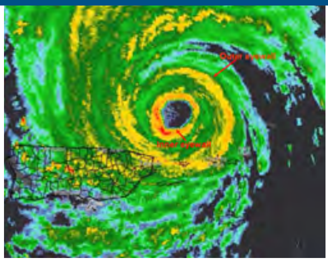
https://www.fema.gov/media-library/assets/documents/3140

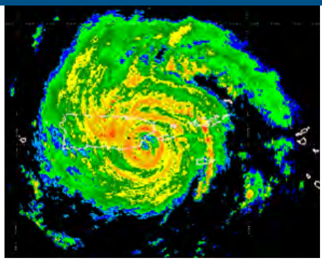
- FEMA P-320, *Taking Shelter from the Storm: Building a Safe Room for Your Home or Small Business* (FEMA 2014)

https://www.fema.gov/media-library/assets/documents/2009

- FEMA P-341*, Tornado Protection: Selecting Refuge Areas in Buildings*, 2nd Edition (FEMA 2009)

https://www.fema.gov/media-library/assets/documents/2246




HURRICANES
IRMA AND MARIA
IN PUERTO RICO

3 Performance of Low-Rise Buildings

This chapter describes MAT observations of residential and other low-rise buildings, defined as those up to four stories high.

A description of general types and vulnerabilities of residential and low-rise buildings in Puerto Rico is followed by consideration of specific hazards. Finally, the performance of residential and low-rise buildings is considered with respect to previous mitigation programs.

In Puerto Rico, the most devastating impacts of Hurricane Irma and especially Hurricane Maria can be seen in the damage to residential and low-rise construction, because these are the most common type of building. According to a letter dated October 29, 2017, from Governor of Puerto Rico Ricardo Rosselló Nevares to Federal Coordinating Officer Michael Byrne, over 300,000 homes are estimated to have been destroyed and many more damaged across the Commonwealth (Rosselló Nevares 2017). Other estimates have included 166,000 residential buildings damaged or destroyed (Puerto Rico Central Office for Recovery, Reconstruction, and Resiliency 2018) and 472,000 housing units having received major damage or having been destroyed. By November 2017, there had been more than a million applications for FEMA Individual Assistance. (Government of Puerto Rico 2017). Of the homes damaged in Hurricanes Irma and Maria, an estimated 85,000-90,000 were informally constructed (PRPB Audit and Compliance Bureau 2017).

Most housing in Puerto Rico is 40–50 years old. As noted in Chapter 2, only 1 percent of housing stock was built after 2010, compared to a national average of 4.2 percent. (Resilient Puerto Rico Advisory Commission 2018).

3.1 Summary of Building Performance

Unlike most parts of the United States, in which the vast majority of residential units are of wood-framed construction, Puerto Rico has a broad range of low-rise and residential construction types ranging from one-story, single-family wood-framed buildings with wood-framed metal roofs to two- to four-story, multi-family reinforced cast-in-place concrete-framed buildings with concrete roof decks.

The choice of residential construction materials is often driven by economic considerations and market availability. Residents with greater financial means tend to choose concrete buildings in developed neighborhoods that have been designed and built by professionals following the building code. Concrete buildings are more expensive to construct than wood; however, concrete buildings are often more flood- and wind-resistant, easier to permit, and less expensive to insure against fire and other hazards than wood buildings. Unfortunately, Puerto Rico's ongoing economic difficulties have left 40-50 percent of the Commonwealth's residents living in poverty (Kousky and Lingle 2018), and many residents live in wood-framed buildings.

In addition to the choice of materials, the level of design found in residential construction is also often driven by economic considerations. Residents with greater financial means tend to choose code-compliant buildings over those built informally. Code-compliant residences are more expensive to design and construct; they must be designed by a professional engineer or registered architect to comply with current building codes and standards, and construction permits must be acquired to ensure buildings comply with Commonwealth requirements. An advantage of code-compliant construction is that code-compliant residences are engineered and constructed to resist design flood, wind, earthquake, and other hazards. Because they are permitted and more likely to be properly connected to utilities, they are ultimately easier for homeowners to sell and insure.

Concrete buildings typically withstood the combined impacts of flood, wind, and wind-driven rain better than wood-framed buildings. The house shown in Figure 3-1 is an example of a type of construction that performed well in the hurricanes: Set on an open foundation, it is elevated on concrete columns and constructed of concrete, including its roof.

The majority of residential and low-rise buildings observed by the MAT that were destroyed by the storms were wood-framed buildings that collapsed from high-velocity flood forces or high wind pressures. The MAT observed that these buildings typically lacked a continuous load path to support all loads (lateral and vertical). Many wood-framed roofs were also damaged due to inadequate roof covering or attachment. Wood-framed buildings and buildings with wood-framed roofs that were observed to have proper load paths performed well in high winds. Concrete buildings with concrete roofs were generally observed to perform well in high winds; however, the MAT was unable to determine the load path connection details. Observations of proper load paths were used to distinguish informal from code-compliant construction. This was typically possible for wood-framed buildings but not possible with only visual observations for most concrete and concrete masonry unit (CMU) buildings.

Figure 3-1: Elevated concrete house in Punta Santiago that performed well.

Most residential and low-rise buildings that were damaged, but not destroyed, were inundated by low-velocity flooding or experienced water intrusion through damaged roofs. Concrete buildings that were inundated or subjected to water intrusion performed better than wood-framed buildings. When buildings were inundated by water, the building performance was highly dependent upon the ability to rapidly dry the home. Where homes were flooded, they could be cleaned and reoccupied as many did not experience structural damage. Observations in this chapter are not intended to reject or endorse specific construction materials for residential and low-rise buildings in Puerto Rico, but rather to identify and highlight where construction methods (use of load path) or use of some materials with specific qualities (such as flood resistance) performed well in a variety of conditions.

Table 3-1 provides a summary of the major types of residential and low-rise building construction found in Puerto Rico. The table includes sample photos, typical features, and vulnerabilities observed by the MAT. Recommended improvements associated with each construction type are covered later in the report. In addition to the major types of residential and low-rise buildings listed in Table 3-1, Puerto Rico also has some historic buildings and other construction types. Historic buildings were typically located in historic urban centers or districts and constructed of wood or a combination of wood and concrete with good quality design and construction. Historic buildings have typically resisted multiple hurricanes for over 100 years, and most withstood Hurricanes Irma and Maria with little or no damage. Other construction types in Puerto Rico include some pre-engineered metal buildings and a small amount of manufactured housing. Several older pre-engineered buildings observed by the MAT were damaged or destroyed by high winds caused by key connections that failed due to improper construction detailing or corrosion. The MAT did not assess any manufactured housing.

Table 3-1: Summary of Major Types of Residential and Low-Rise Construction in Puerto Rico

Construction Type	Typical Features	Vulnerabilities Observed
Wood-Framed on Piers and Posts	 • Structural system consisting of lumber wall, roof, and floor framing • Elevated foundation on timber or concrete piers and posts • Wood panel exterior wall covering and galvanized metal (zinc) panel roof covering	  • Predominantly poor-quality construction subject to heavy damage due to poor-quality framing connections, materials, and structural systems • Typical 28-guage metal roof covering has virtually no diaphragm strength (red circle) with high failure rates of gable style roofs
Wood-Framed on Slab on Grade	 • Structural system consisting of lumber wall and roof framing. Slab-on-grade foundation. • Wood panel exterior wall covering and galvanized metal (zinc) panel roof covering	  • Subject to roof damage or loss due to poor quality construction and lack of proper connections to the roof and walls • Slab foundations undermined due to storm surge

Construction Type	Typical Features	Vulnerabilities Observed
Concrete with Wood Roof	 • Concrete block walls and wood framed roof with plywood deck • Slab-on-grade or elevated concrete pier and beam, or pile foundations • Stucco exterior wall covering, galvanized metal (zinc) panel or synthetic roof covering	  • Roof deck and covering subject to wind damage to roof due to lack of proper anchor connectors • Newer structures with hipped roofs sustained less damage than observed with gable roofs
All Concrete	 • Concrete walls; concrete roof deck • Slab-on-grade or elevated concrete pier and beam and pile foundations • Stucco exterior wall covering with synthetic roof covering	  • Many concrete houses in rural areas are informal construction and may lack seismic capacity • Damage can occur when concrete walls are not reinforced, or openings are breached, or when subject to coastal storm surges forces • Damage to awnings, clay tile roof accents (red oval) and jalousie windows observed

Construction Type	Typical Features	Vulnerabilities Observed
Wood-Framed over Concrete	 • First-floor concrete wall structure with concrete roof deck • Second floor wood-framed walls and wood roof built on top of concrete ground floor • Stucco exterior wall covering and synthetic roof covering on concrete structures; wood panel siding and galvanized metal roof panels on wood framed structure	  • Wood-framed second stories atop concrete ground floor structures are typically informal construction built without analyzing the additional structural loads imposed on the first-floor house • This typically results in an elevated light wood roof structure that cannot resist hurricane winds • Loss of the wood-framed second floor can lead to water infiltration through first-floor roof and create wind-borne debris damage to the ground floor and surrounding buildings
Concrete or Wood-Framed, Supported by Columns	 • Concrete or wood-framed structure over column/pier foundation • Foundations and column/pier materials vary between wood and concrete (often matching frame construction materials) • Sizes and lengths of columns/piers depend on site topography	  • Observed many foundation failures due to column slenderness and poor-quality materials without adequate lateral reinforcement • Columns are in danger of failure during flood/erosion/earthquake events, leading to structural collapse

Construction Type	Typical Features	Vulnerabilities Observed
Low-Rise Construction	 • Concrete or wood-framed structures with high-end wall and roof covering materials, like stucco and clay tile roofing • Foundations types include slab-on-grade and pier • Designed and constructed in accordance with building codes and permitting process	  • Severe damage to glass windows, glass sliding doors, interior gypsum board walls and the exterior wall finishes • Wind damage to clay roof tile coverings (red circle) and rooftop waterproofing systems allowed for rainwater intrusion • Buildings built in coastal zones subject to erosion, storm surge, and corrosion damage

3.2 Performance Relative to Flood

MAT observations related to residential and low-rise building performance relative to flooding may be grouped broadly by whether they occurred along the coast or in inland areas with heavy rainfall. Along the coast, impacts on buildings were primarily caused by forces from coastal flood hazards such as inundation, waves, and coastal erosion. Inland flood and rainfall impacts on buildings were primarily related to the building type and elements or systems exposed to flooding and rainfall.

FEMA FLOOD RISK TERMINOLOGY

Flood Insurance Rate Maps (FIRMs) delineate flood hazard areas using zone designations that reflect the conditions expected during the base flood. Some flood hazard terms are defined below:

Base Flood. The flood with a 1-percent-annual-chance of occurrence. It is sometimes referred to as the 100-year flood. (Likewise, the 0.2-percent-annual-chance flood is sometimes called the 500-year flood.)

Base Flood Elevation (BFE). The elevation of the base flood, usually rounded to the nearest foot. The “E” in a zone designation such as “AE” means that a BFE has been established for this zone.

Special Flood Hazard Area (SFHA). The area subject to inundation from the 1-percent-annual-chance flood. The SFHA also encompasses areas that are prone to more frequent flooding, for example, flooding from the 2-percent- or 10-percent-annual-chance event. Subsurface building areas such as basements are subject to flooding at a water surface elevation less than the BFE.

VE Zone. The portion of the SFHA that extends from offshore to the inland limit of a primary frontal dune along an open coast, and any other area subject to high-velocity wave action (3 feet or higher) from storms or seismic sources. The VE Zone is sometimes called the Coastal High Hazard Area.

AE Zone. The portion of the SFHA not mapped as a VE Zone. Although FIRMs depict AE Zones in both riverine and coastal floodplains (as Zones A, AE, and AO), the flood hazards and flood forces acting on buildings in those different floodplains can be quite different. In coastal areas, the AE Zone is subject to wave heights less than 3 feet and wave run-up depths less than 3 feet.

Coastal A Zone (CAZ). Shown on newer FIRMs and the Puerto Rico Advisory Data, CAZs are referenced in ASCE 24-14 and ASCE 7-16. These are portions of an AE Zone where breaking wave heights are 1.5–3 feet during base flood conditions. Flood forces are not as severe as in VE Zones but are still capable of damaging or destroying buildings on shallow foundations.

Limit of Moderate Wave Action (LiMWA). The inland limit of the CAZ, shown as a line on newer FIRMs. For more information about the CAZ and LiMWA, see the LIMWA and Higher Construction Standards Fact Sheet (FEMA 2018c), https://www.fema.gov/media-library/assets/documents/96413

B, X, and C Zones. These zones identify areas outside of the SFHA. The B Zone and shaded X Zone identify areas subject to inundation by the 0.2-percent-annual-chance flood (the 500-year flood). The C Zone and unshaded X Zone identify areas of areas unknown flood risk that are above the level of the 0.2-percent-annual-chance flood. The NFIP has no minimum requirements for buildings in these zones.

For a listing of NFIP flood zone designations, refer to 44 CFR 59.1. For more on the flood zones, see *Answers to Questions about the NFIP* (FEMA 2011a), https://www.fema.gov/media-library/assets/documents/272

3.2.1 Coastal Flood Impacts

The MAT observed direct coastal flood impacts to buildings by inundation and waves as well as damage from erosion that undermined foundations.

3.2.1.1 Coastal Flood Forces

The MAT observed many low-lying areas along the coast of Puerto Rico that were subjected to inundation by coastal storm surge. These areas saw approximately 2-6 feet (0.6-1.8 meters) of flooding depth. The buildings in coastal areas are predominantly concrete, which usually survived inundation well. However, structural damage was observed when the storm surge also brought waves inland and caused coastal erosion.

The MAT observed that there were few buildings elevated in areas subjected to coastal flooding. In northern Mayaguez, one home (Figure 3-2, left) was elevated on piles and did not get inundated, while the surrounding homes that were not elevated had approximately 4 inches (10 centimeters) of storm surge flooding from Hurricane Maria, damaging belongings and utilities. Because the walls of the non-elevated buildings were concrete (Figure 3-2, right), no visible flood damage was done to the buildings themselves However, submergence of concrete structures in salt water can expose internal rebar to chloride intrusion, causing long-term weakening of the structure.

Figure 3-2: Elevated house (left) and non-elevated house (right) in northern Mayaguez, Zone AE.

Punta Santiago took a direct hit from Hurricane Maria, experiencing high winds, storm surge, and large waves. Much of Punta Santiago had been mapped in the high-risk flood hazard area on the 2009 effective FIRM as well as previous FIRMs. In one area of Punta Santiago, where the storm surge from Maria was 7-9 feet (2.1-2.7 meters), a multi-story apartment building (Figure 3-3) had been built to the most recent FIRM (2009) by elevating on fill to the BFE and did not flood. In contrast, many pre-FIRM buildings built at ground level did flood.

Figure 3-3: Apartment building in Punta Santiago, Humacao, elevated on fill. Adjacent buildings experienced significant damage from coastal storm surge. Effective FIRM: Zone AE. Advisory Data: CAZ.

On the previous FIRM, dated 2005 (Figure 3-4, top), the area containing the apartment building was shown in a VE Zone. As a result, many buildings in the area were elevated on piles. On the 2009 current effective FIRM, the area is an AE Zone (Figure 3-4, bottom); however, the BFE is higher on the current effective FIRM than on the 2005 FIRM. Therefore, buildings may now be built on fill, but they must be elevated to a higher elevation. Due to the higher BFE on the 2009 FIRM compared to the 2005 FIRM, the homes elevated on piles to the 2005 FIRM may not have been elevated high enough to avoid damage.

Since the location is in an AE Zone on the current effective FIRM, and the Coastal A was not previously identified and adopted for VE Zone building requirements, the apartment building shown in Figure 3-3 could be elevated on fill for structural support. Because the building was elevated on fill to the effective FIRM BFE, 11.1 feet (3.4 meters), and flooding during Hurricanes Irma and Maria did not reach the level of the 1-percent-annual-chance flood event shown on the FIRM, the building was not inundated. The building is included in the recently developed CAZ in the Advisory Data (Figure 3-5); therefore, structural fill will no longer be allowed due to the potential for erosion and damaging waves during the 1-percent-annual-chance event. In this neighborhood, many of the first row of homes from the shoreline, which were elevated on piles, did not flood and were not damaged. However, some buildings elevated on piles were poorly constructed and may not have been elevated high enough when built to the 2005 FIRM or older FIRMs (Figure 3-6). Buildings not elevated on piles or fill experienced inundation and may have been impacted by damaging waves.

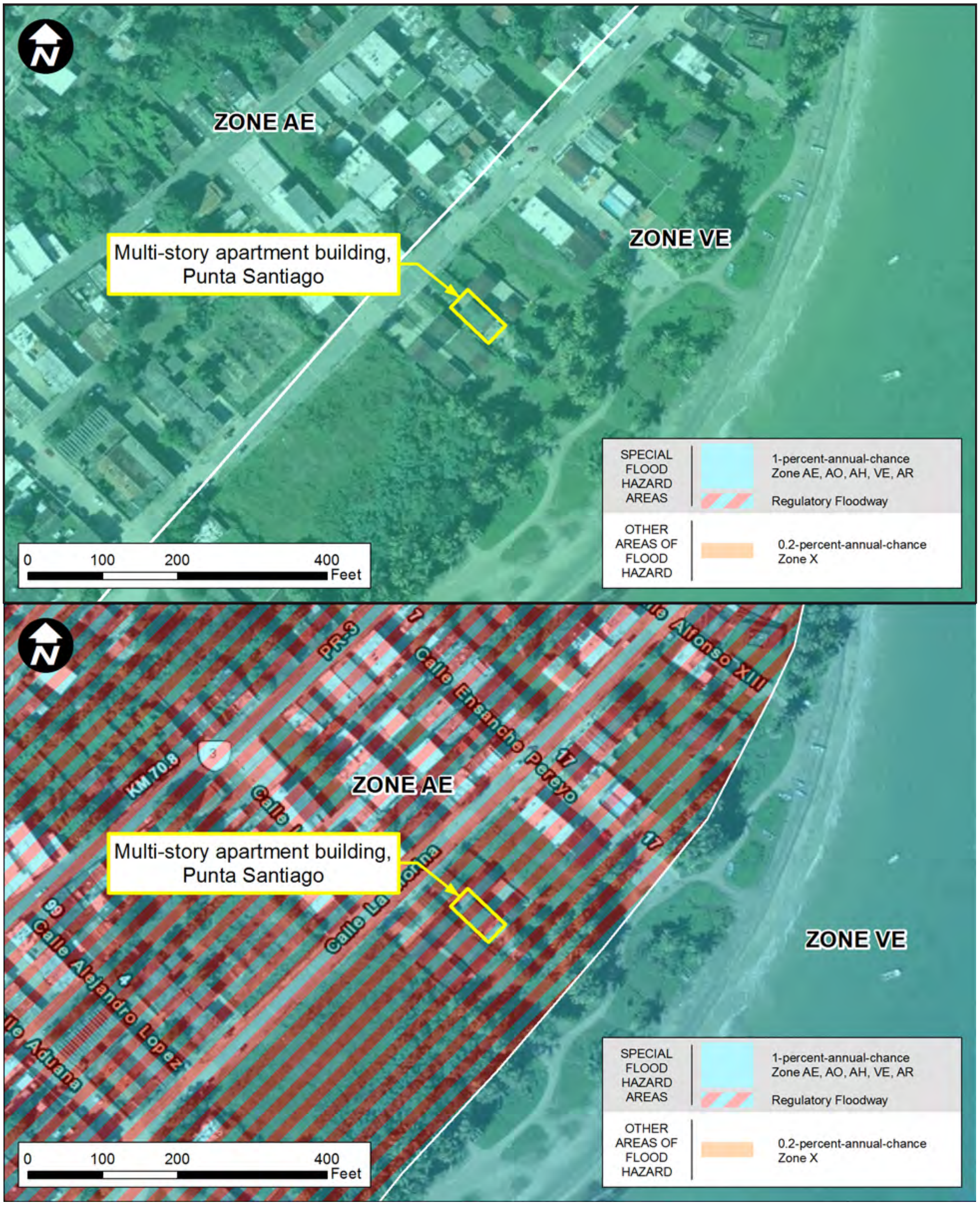


Figure 3-4: Top, 2005 superseded FIRM for an area in Punta Santiago; bottom, a portion of the 2009 effective FIRM. The apartment building shown in Figure 3-2 is in the VE Zone on the 2005 FIRM and AE Zone on the 2009 effective FIRM.

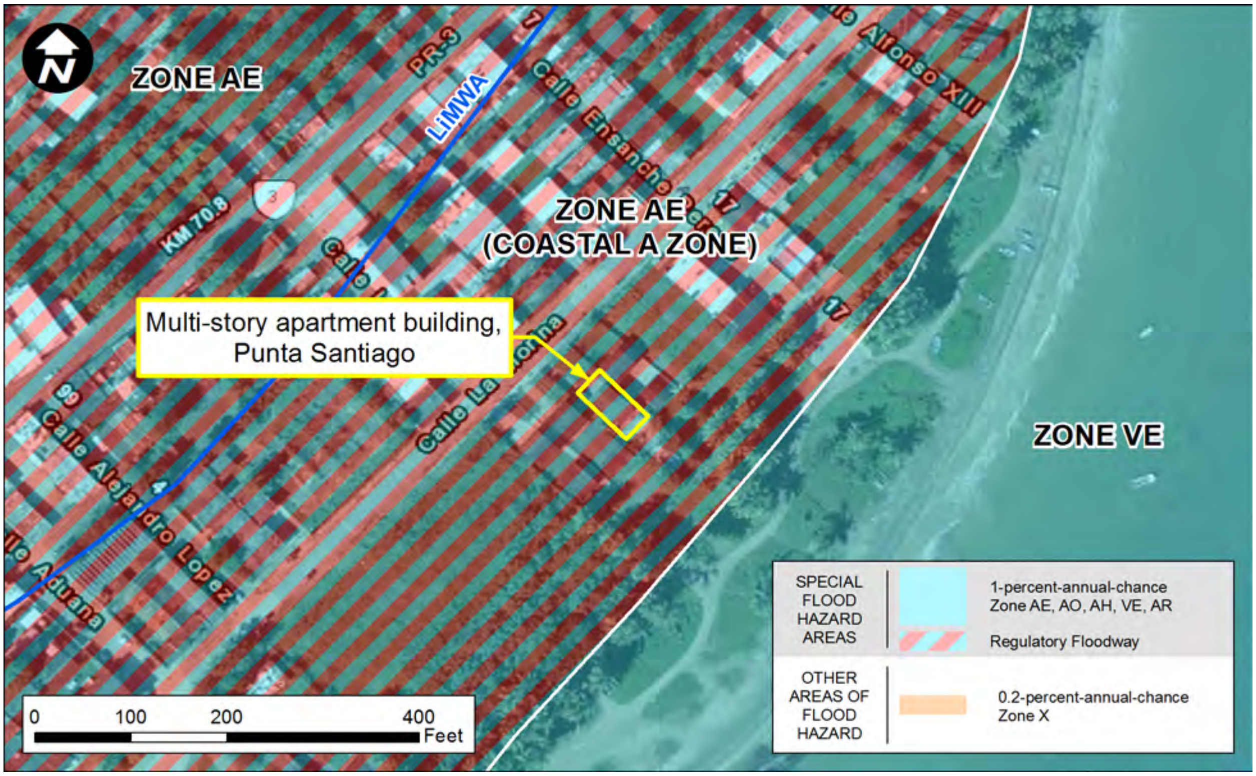


Figure 3-5: A portion of the Advisory Data for an area in Punta Santiago. The apartment building shown in Figure 3-3 is shown in the CAZ in the Advisory Data.

Figure 3-6: Poorly constructed elevated buildings in Punta Santiago.

Before Hurricanes Irma and Maria, Punta Santiago had a wide and heavily vegetated beach that was stable without a history of shoreline recession. During Hurricane Maria, the area's beaches experienced significant erosion. The Advisory Data highlights this area as one that is at risk from storm-induced erosion, and reconstruction or new construction in this area should consider the impact of storm-induced erosion to properties (Figure 3-7). Also, because the Advisory Data now includes the CAZ, buildings within the CAZ will have to build to V Zone standards with the adoption of the 2018 IBC and IRC in Puerto Rico.

Figure 3-7: Left, storm-induced beach erosion in Punta Santiago. Right, the location (red box) of the apartment building shown in Figure 3-3 overlaps a region of Hurricane Maria beach erosion (yellow shading) identified in the Advisory Data.

Overall, concrete construction in coastal areas resisted minor coastal forces, and elevated coastal concrete buildings withstood wave impacts. Wood construction in coastal areas subject to waves was observed to sustain major damage or complete destruction. Areas observed in which flood depths and conditions from Hurricane Maria could have supported damaging 1.5-foot (0.5-meter) waves were limited to the first several rows of buildings from the coastline. In most of these areas, these first rows were not elevated, but many had concrete walls. Most buildings sustained only minor damage. Figure 3-8 (left) shows a house in Fajardo built at grade with concrete walls. Based on estimated Maria flooding depths and the house's location along the first row of buildings, it would have been subject to wave heights 1.5 feet (0.5 meters) or greater, implying that the house is in a CAZ. This house had minor damage from waves. By contrast, Figure 3-8 (right) shows an area in Punta Santiago where there is an eroded beach and lower ground elevations. This area was subject to larger storm surge and wave heights, and more evidence of wave damage can be seen; wood homes built on piles, while not inundated by storm surge, appear to have been impacted by waves and wind and were destroyed, however, the concrete buildings built at ground level or on piles and impacted by the same wind, depth of flooding, and wave heights performed well (Figure 3-9).

Figure 3-8: Left, concrete house in Fajardo subject to 1.5-foot (0.5-meter) wave heights. Current FIRM and Advisory Data: VE Zone. Right, elevated beachfront house in Punta Santiago, Humacao subjected to wave heights greater than 1.5 feet (0.5 meters). Current FIRM: AE Zone. Advisory Data: CAZ.

Figure 3-9: Left, an elevated wood-framed house in Punta Santiago was destroyed, right, an elevated concrete house withstood wind and coastal wave forces. Current FIRM: VE Zone.

I-CODE REQUIREMENTS FOR COASTAL A ZONES

The current PRBC incorporates the 2009 IBC and 2009 IRC, which reference ASCE 24. Under the IBC, buildings in a Coastal A Zone (CAZ) must be designed to V Zone standards; however, CAZ buildings subject to the IRC, including detached one- and two-family dwellings, among others, can be designed to less stringent requirements that comply with ASCE 24 while not meeting V Zone standards. The 2018 IBC and IRC, which are expected to be adopted by Puerto Rico in 2018, both require all CAZ buildings to be designed to V Zone standards.

To reduce vulnerability to future flood damage and increase disaster resilience, FEMA recommends that all structures in a CAZ be designed to V Zone standards regardless of whether this is required by code.

There were some elevated buildings in the area that were destroyed, but these were wood-framed buildings damaged by the high winds when Hurricane Maria made landfall. Property owners in low-lying coastal areas with homes severely damaged by Hurricanes Irma and Maria should consider determining whether they are in a CAZ and rebuilding appropriately to help minimize future damage.

At Playa Cortada, Santa Isabel, storm surge and waves battered the shoreline. Storm surge in this area ranged from 4-6 feet (1.2–1.8 meters), inundating the coastal community and allowing damaging waves to impact the buildings along the shoreline. Several homes built at grade along the shoreline at Playa Cortada suffered major damage from the storm surge and waves. The building shown in Figure 3-10 is a one-story home built at grade that experienced major damage. Based on a high-water mark, the storm surge reached a maximum depth of 26 inches (66 centimeters) in the interior of the home. The surge and waves also eroded sand and rocks from the shoreline and deposited them in and around homes along with rubble from broken-up concrete perimeter walls (Figure 3-11). This depth would have allowed at least 1.5-foot waves, the wave height criterion for a CAZ, to impact the homes in the area. A water depth of approximately 2 feet is all that is necessary to support 1.5-foot waves.

Figure 3-10: Left, house in Playa Cortada subject to damaging storm surge and waves; right, high water mark from storm surge 2.2 feet (0.66 meters) above the floor.

The 2009 current effective FIRM for the area, as well as the Advisory Data, identifies at least the first row of buildings from the shoreline in the VE Zone (Figure 3-12). Most of the homes in Playa Cortada are currently not elevated on piles. At least the first row of homes from the shoreline will be required to be rebuilt to VE Zone standards and elevated on piles for new construction or for existing homes that are substantially damaged or substantially improved[1] .

[1]NFIP regulations define substantial improvement and substantial damage in Title 44 of the Code of Federal Regulations Section 60.3. Briefly, substantial damage is damage for which the total cost of repairs is 50 percent or more of the structure's market value before the disaster occurred, regardless of the cause. Likewise, substantial improvement is any reconstruction, rehabilitation, addition, or other improvement of a structure, the cost of which equals or exceeds 50 percent of the structure's market value before the start of construction.

Figure 3-11: Shoreline at Playa Cortada where sand, rock, and broken-up debris covered the ground.

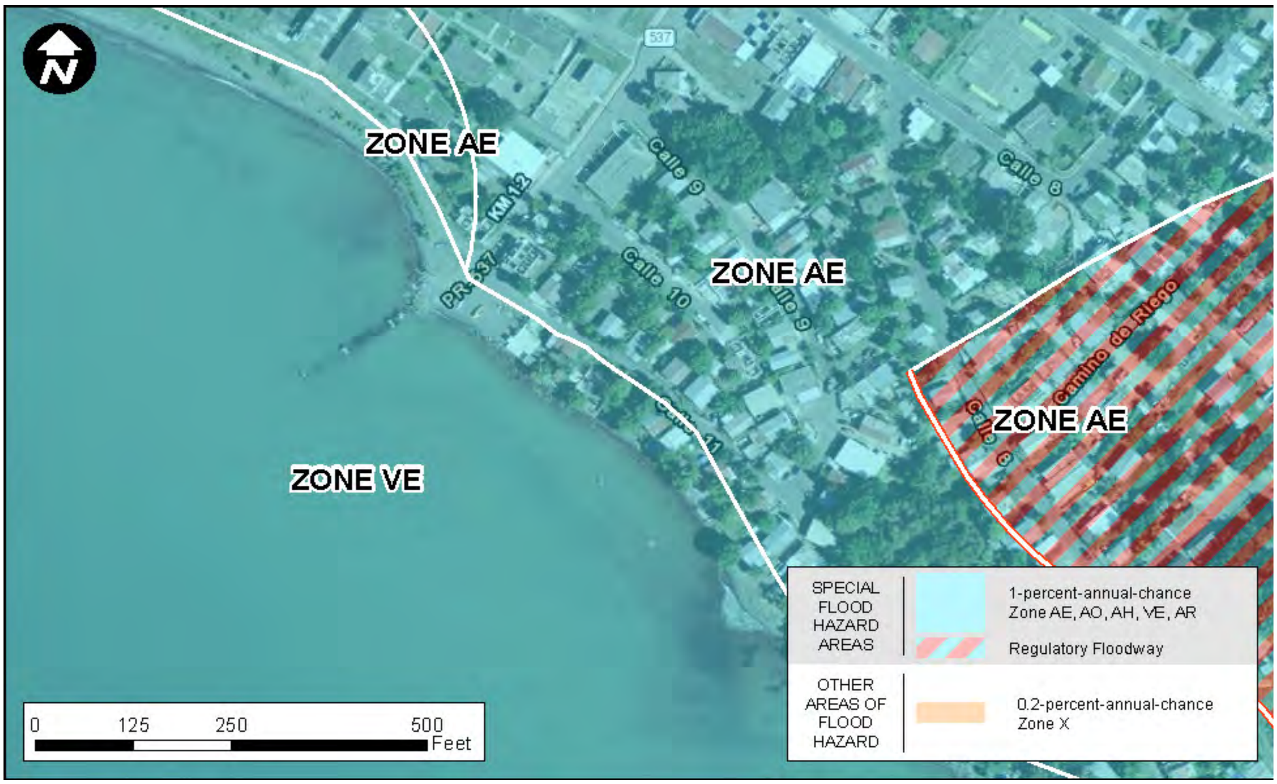


Figure 3-12: A portion of the 2009 current effective FIRM for Playa Cortada.

While Playa Cortada did not experience a large amount of storm erosion to the shoreline, it is an area subject to long term erosion and shoreline recession. For rebuilding and new construction along the shoreline, planners, developers, designers, owners, among other stakeholders, should consider the impacts of long-term erosion as presented in the Advisory Data for 30-year and 60-year shoreline positions (Figure 3-13) when siting buildings on properties and constructing homes to minimize their risk.

Figure 3-13: An example of projected future shoreline positions after long-term coastal erosion, Playa Cortada, Santa Isabel.

3.2.1.2 Coastal Erosion

Another major cause of damage to residential and low-rise coastal buildings during Hurricane Irma and Maria was erosion that undermined foundations. While many houses may have had a wide beach in front of them at one time, many years of erosion have placed them precariously close to the water line and they are now at higher risk of damage or destruction by erosion and undermining of their foundations from storm surge and waves. The MAT observed many residential buildings that were spared from significant damage during Irma and Maria but lost their ocean-facing decks because of the storm-induced erosion. The MAT also observed many protective walls and buildings that were damaged or destroyed by Irma and Maria, leaving the loose ground behind them susceptible to erosion. Because many of the houses in these areas were not identified as being in a coastal flood hazard area on the existing FIRMs, they were not required to be built to withstand coastal erosion impacts with deep/pile foundations. Owners of new construction or buildings being rebuilt in highly erosive areas should consider relocating from the coastline toward the inland edge of their property line where feasible and constructing to V Zone standards that account for erosion and scour as part of their deep foundation design. Hurricane Maria Advisory products for long-term erosion and storm erosion impacts are available and should be used to help identify areas vulnerable to erosion. Table 3-2 provides examples of many of the buildings observed by the MAT that were damaged by coastal erosion.

The home in Rincón shown in Figure 3-14 is located along Corcega Beach. This area has been known for chronic storm-induced erosion of its beaches. The building is a multi-level residence with a deck facing the water and porches on the side. Hurricanes Irma and Maria caused significant erosion in the area. Any pre-existing sandy beach fronting the building was lost, and the ground was eroded out from under the deck and building causing failure and collapse of the deck and porches.

Figure 3-14: Multi-story residence in Rincón that partially collapsed due to coastal erosion.

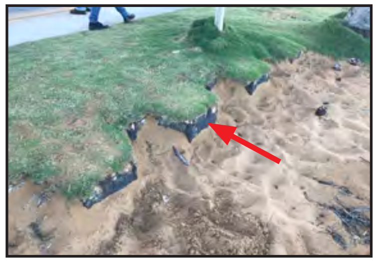
Table 3-2: Examples of Coastal Erosion Damage Observations

		
Home in Rincón undermined by long-term erosion	Protective walls and decks in Rincón damaged by erosion	Home in Rincón undermined by long-term erosion
Current FIRM VE Zone, BFE 3.4 m	**Current FIRM** Unshaded Zone X	**Current FIRM** Unshaded Zone X
Advisory Data VE Zone, BFE 3.4 m	**Advisory Data** Shaded Zone X	**Advisory Data** Shaded Zone X
		
Homes in Rincón built too close to shoreline, subject to severe wave action and erosion of pile foundations	Homes in Shacks Beach, Isabela built on top of sandy coastal dune, subject to erosion	Homes in Shacks Beach, Isabela built on top of sandy coastal dune, subject to erosion
Current FIRM VE Zone, BFE 4.6 m	**Current FIRM** Unshaded Zone X	**Current FIRM** Unshaded Zone X
Advisory Data VE Zone, BFE 4.6 m	**Advisory Data** Unshaded Zone X	**Advisory Data** Unshaded Zone X

Protective wall failure due to lack of tie-back rods to prevent seaward slumping of wall due to erosion

Current FIRM Unshaded Zone X

Advisory Data Shaded Zone X



Beach erosion in Luquillo exposing sheet pile (red arrow) protecting road.

Current FIRM AE Zone, BFE 2.4 m

Advisory Data AE Zone, BFE 2.4 m

Parking area behind house in Luquillo undermined by erosion

Current FIRM VE Zone, BFE 4 m

Advisory Data VE Zone, BFE 3 m

*Zones AE and VE are in the SFHA. Zone X is outside of the SFHA and represents an area of minimal flood hazard.

In addition to storm-induced erosion, Rincón has been experiencing long-term erosion and shoreline retreat (Thieler, Rodriguez and Himmelstoss 2007). The area also experienced significant erosion from hurricane Matthew in 2016 even though the storm tracked far to the south and west of Puerto Rico (Aponte-Bermúdez, et al. 2017). Figure 3-15 shows several aerial photographs taken over time. In the 1930s, there was a wide natural sandy beach and no development in the area. Since the 1930s, the area was developed and homes built. However, without consideration of the long-term erosion impacts, the buildings were built at an elevation and a distance from the water that were thought safe. Over time, that beach has eroded, leaving the homes at a greater risk to damage from coastal storms. Before the 2017 hurricanes, the beach in front of this building had already been eroded away, leaving the building vulnerable to undermining by storm surge and waves.

As part of the Puerto Rico Advisory Data effort, long-term erosion rates were estimated, and 30-year and 60-year future shoreline positions were estimated (Figure 3-16). These Advisory products show areas, such as in Rincón, which are potentially subject to long-term and storm-induced erosion risks to guide smarter siting and design decisions.

Figure 3-15: Aerial photographs of a beach in Rincón showing the residence pictured in Figure 3-14 (red box). Left, 1930s aerial showing wide natural beach with no development. Source: López Marrero, et al. (2017). Center, pre-Irma and -Maria aerial. Source: ESRI, Digital Globe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community. Right, post-Irma and -Maria aerial showing storm-induced erosion of the narrow beach. Source: NOAA 2017.

Figure 3-16: An example of projected future shoreline positions after long-term coastal erosion, showing the residence pictured in Figure 3-13 (red box).

The 2005 FIRM for the area did not show the beachfront houses to be in the SFHA. In 2009, a new coastal flood risk study was performed, and a new FIRM was released. The 2009 FIRM and the Advisory Data show the buildings in the area in the VE Zone (Figure 3-17) partly due to storm-induced erosion risk having been considered in the 2009 coastal study. There is no AE Zone mapped in this area, as the 100-year floodplain terminates with the limit of the VE Zone. Because this area was developed before the 2009 FIRM, the buildings would not have had to comply with VE Zone building requirements. Now that the effective FIRM and Advisory Data show the area in a VE Zone, any new construction or reconstruction for existing homes that are substantially damaged or are to be substantially improved must be built to VE Zone standards.

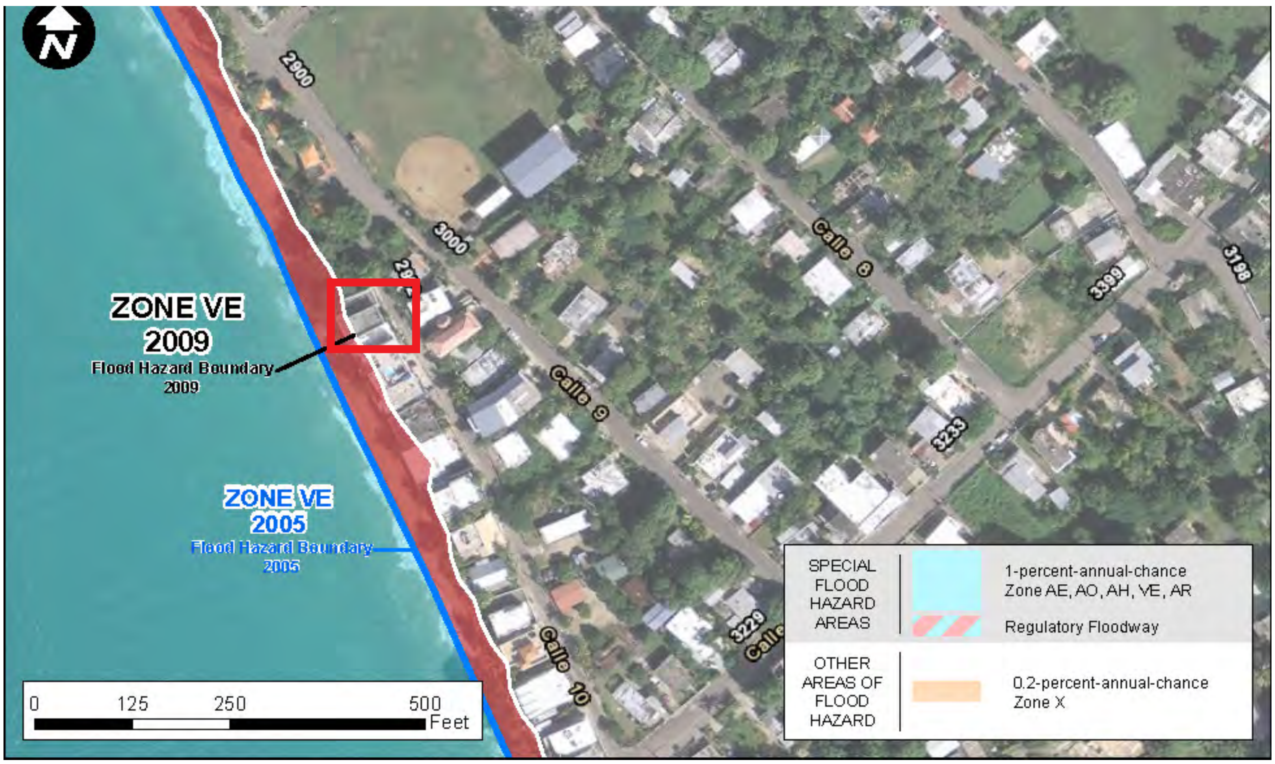


Figure 3-17: Outdated 2005 FIRM versus current effective 2009 FIRM with updated coastal analysis that includes storm erosion in Rincón around the house shown in Figure 3-14 (red box).

3.2.2 Inland Flood Impacts

Inland flood and rainfall impacts include riverine and sheet flow inundation and impacts from intrusion of wind-driven rain.

3.2.2.1 Building Performance

Concrete and concrete-framed buildings observed by the MAT performed better than wood-framed buildings under most inland flood and rainfall conditions. This was because most concrete buildings in Puerto Rico used either uninsulated concrete or CMU infill walls, both of which are classified in NFIP Technical Bulletin 2 *Flood Damage-Resistant Materials Requirements* (FEMA TB-2 2008) as flood-damage-resistant materials. The higher hydrostatic and hydrodynamic load-bearing capacity of concrete and concrete-framed buildings, especially reinforced concrete systems, contributed to their good performance.

Additionally, most concrete-roofed one- and two-family dwellings used moisture-resistant materials to manage water intrusion and damp/wet island conditions. The preferred materials included plaster, masonry, tile, and stone finishes that are less likely to absorb moisture and are generally considered flood-damage-resistant per FEMA TB-2. Figure 3-18 shows typical flood-damage-resistant interior finishes for a concrete residence under construction in Yabucoa.

Figure 3-18: Painted concrete, a typical flood-damage-resistant interior finish, in a concrete house under construction in Yabucoa.

One homeowner in Humacao showed the MAT a list with all the items needing replacement after his concrete house was inundated; the list included possessions and appliances but no supplies for rebuilding or renovating. Although the first floor was flooded, the house was still habitable, with only the contents needing to be replaced. The use of flood-damage-resistant materials greatly reduced the time and expense of reoccupying this home.

Unlike concrete buildings, most wood-framed buildings used wood panels or other cladding materials that are not considered flood-damage-resistant per FEMA TB-2, resulting in greater flood damage and cleanup costs associated with floodwater inundation and rainwater intrusion (Figure 3-19).

Figure 3-19: Wood roof in Toa Alta that failed due to insufficient design and detailing, allowing rain to enter the building. It was constructed with wood panels or other materials that were not considered flood-damage resistant.

Although concrete roofs performed much better than wood-framed roofs, the MAT observed water ponding on some flat concrete roofs of residential and low-rise commercial buildings (Figure 3-20). Most of the flat concrete roofs observed by the MAT where ponding as a result of the extreme rainfall from Hurricane Maria was observed had inadequate roof drainage with too few and undersized roof drains (1.5–2-inch [3.8–5.1-centimeter] diameter instead of 4-inch [10.2-centimeter]) and inadequate roof slope toward the drains (less than 1/8-inch per foot [1:96]) or a lack of roof maintenance, with drains clogged by debris or vegetation. Other flat concrete roofs experienced water ponding due to deformation of the roof slab leading to low spots, which tended to occur more in low quality mass-produced housing developments or informal construction.

Figure 3-20: Water ponding on flat concrete roof of a residence in San Juan.

Figure 3-21: Wood framed residence in Toa Baja neighborhood pushed off its foundation by high velocity riverine flooding.

Most inland flood and rainfall damage to residential and low-rise buildings observed by the MAT were the result of inundation from local drainage or low-velocity riverine flooding or rain intrusion from roof damage or wind-driven rain. However, the MAT did observe some inland flood damage apparently caused by sheet flow and high-velocity riverine flooding. Figure 3-21 shows a wood-framed residence in one neighborhood of Toa Baja pushed off its foundations by high-velocity flooding, and Figure 3-22 shows a concrete residence in Utuado that was impacted by sheet flow flooding, with minimal structural impact.

Figure 3-22: Concrete house in Utuado impacted by sheet flow flooding.

3.2.2.2 Foundation Performance

The MAT observed very few residences or low-rise buildings with basements, defined by the NFIP as any area of a building having its floor subgrade (below ground level) on all sides (FEMA 2014), but did observe other foundation types throughout the Commonwealth. In flood-prone areas, the MAT observed more houses elevated over columns. However, these buildings often closed the semi-open space underneath the building with CMU walls that were rigidly attached to the columns to create more living space, rather than keeping the area free of obstructions or adding hydrostatic openings. Unfortunately, this approach not only increases vulnerability to inundation from shallow flood events, it also increases the risk of the walls collapsing under hydrostatic and/or hydrodynamic forces in larger flood events, which could lead to a failure of the columns and complete structural collapse. Figure 3-23 shows a failed CMU wall attached to columns that contributed to a residential deck collapse in Isabela.

Figure 3-23: Failed CMU wall (red circle) attached to columns at a house in Isabela. The failure contributed to the collapse of a residential deck supported by the columns. Current FIRM: Unshaded Zone X. Advisory Data: Unshaded Zone X, Erosion-impacted area.

3.2.2.3 Mechanical, Electrical, and Plumbing System Performance

Protecting mechanical, electrical and plumbing (MEP) system equipment and components in residential and low-rise buildings from natural hazards is important for ensuring the speedy recovery of homes and small businesses that survived the storms. Not surprisingly, the MAT observed that elevated or rooftop building MEP equipment experienced less flood damage than MEP equipment placed at grade. This was especially true for residential and low-rise buildings with concrete roofs, where MEP equipment is easier to secure against wind and seismic hazards by anchoring into the roof deck (Figure 3-24).

Figure 3-24: Solar water heater and cistern on a residential concrete roof in Rincón.

MEP equipment located on elevated cantilever structures observed by the MAT typically performed well (Figure 3-25). However, many concrete houses in Puerto Rico have aleros, overhangs above their windows (Figure 3-26), and some homeowners may not understand that the structural capacities of the overhangs are not the same as cantilever structures. This can lead to the collapse of the overhangs and potential injuries to residents. Therefore, although locating MEP equipment over an elevated cantilever structure can be an effective flood mitigation strategy, it is important to differentiate cantilever structures from existing overhangs and carefully consider the placement and the weight of the equipment.

Figure 3-25: Typical overhangs (aleros) above the windows of a concrete residence.

Figure 3-26: Air conditioning equipment elevated on a cantilever at a concrete house in Punta Santiago, Humacao. This means of elevating equipment typically performed well, as here.

Supporting frames can also be used to elevate MEP equipment when properly designed and constructed. However, as with cantilever structures, supporting frames must consider the MEP equipment weight and bracing. Figure 3-27 shows a supporting frame for an elevated residential cistern that does not appear to have been professionally designed or inspected to ensure it can handle the weight of the tank or lateral forces on the tank or the frame. Lacking bracing in the vertical plane of the columns, it appears seismically vulnerable.

Figure 3-27: This frame supporting a residential cistern did not appear to be professionally designed.

Many low-rise residential and commercial property owners had water intrusion problems through air conditioning (AC) unit drainage lines and windows due to improper installation of rooftop or window-mounted AC units. Residential concrete buildings experienced problems related to water damage on wood doors, while commercial buildings exhibited damage and mildew on gypsum board wall partition and floor materials including tile.

3.3 Performance Relative to Wind

The MAT observed varied performance of low-rise buildings and one- and two-family dwellings. Material selection, the presence of a continuous load path, and protection for openings (windows and doors) all played a part in whether a building performed well. While building successes were observed in wood-framed, reinforced concrete and reinforced CMU homes, the MAT observed that the reinforced concrete and CMU homes with concrete roof decks exhibited the best performance resisting wind loads.

Informal construction observed by the MAT was missing critical connections to hold structural members together. As a result, many roof structure and wall failures were observed; these were the most catastrophic of the observed failures. When some load paths were present, damage was often extensive but did not result in the failures of the main wind force resisting system (MWFRS). The most common structural failures were partial failures of the MWFRS and failures of components and cladding systems.

Overall, the most common damage type observed was water intrusion. Window damage was often the cause.

MAIN WIND FORCE RESISTING SYSTEM

The MWFRS is "an assemblage of structural elements assigned to provide support and stability for the overall building or other structure. The system generally receives wind loading from more than one surface" (ASCE 7-16, 26.2).

CONTINUOUS LOAD PATH

The structural condition required to resist loads acting on a building. The continuous load path starts at the point or surface where loads are applied, moves through the building, continues through the foundation, and terminates where the loads are transferred to the soils that support the building (FEMA 2011).

3.3.1 Main Wind Force Resisting System

The MWFRS is defined in ASCE 7-16 as the "assemblage of structural elements assigned to provide support and stability of the overall building" (ASCE 7-16). The MWFRS is a critical portion of a continuous load path that carries loads acting on buildings from the building envelope into the structural elements of the MWFRS, into the foundation, and finally into the ground. If there is a break or missing element in the continuous load path in the building when lateral or uplift loads occur from a flood, wind, or seismic event, then a failure in some or all the building's structural or envelope system usually occurs. Figure 3-28 gives an example of how a continuous load path carries loads through a home.

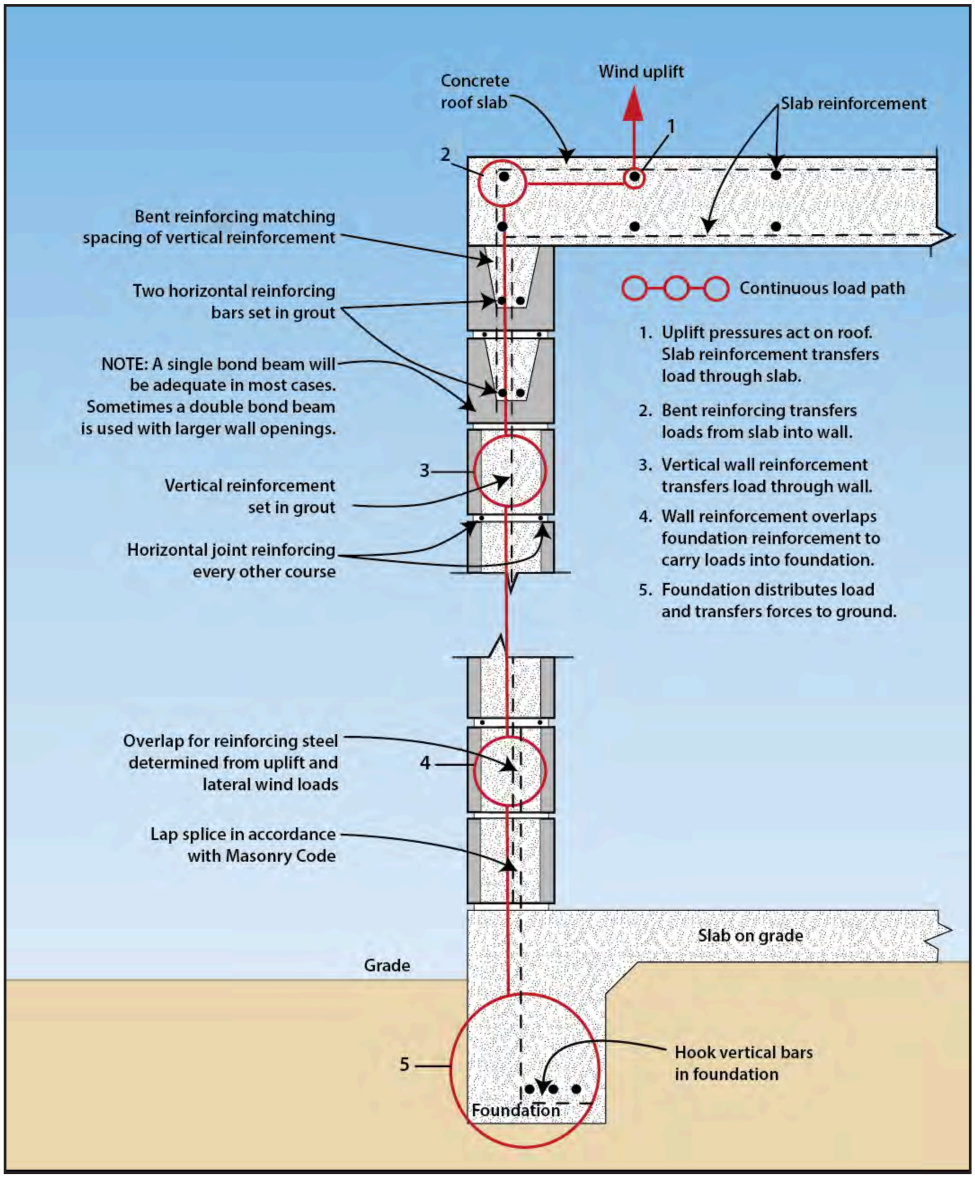


Figure 3-28: Example of a continuous load path in a concrete building with masonry infill.

Low-rise and residential buildings observed by the MAT exhibited varied performance in the winds associated with Hurricane Maria. Many of the buildings where roof deck, roof structure, and wall failures occurred were lacking the continuous load path at specific connection points. The most common failure points in the load path were observed at the following locations:

- Roof deck to roof framing or purlins (typically observed as a metal panel roof covering with no plywood or slat board decking present below the metal panels)
- Roof framing connection at the top of the wall (to wood-framed, concrete, or CMU walls)
- Lower wall to upper wall connections
- Overhangs and cantilevered or lightly supported roofs (deck roofs, carports, and other awnings)

3.3.1.1 One- and Two-Family Residential Buildings

The MAT observed some wood-framed buildings that were well-constructed and experienced only minor damage. In these houses, the load path was established throughout the buildings using a combination of metal connectors and bolted or screwed connections between wood members. While the house in Figure 3-29 was a success, many wood-framed buildings did not perform well. As noted earlier, the primary factor contributing to the poor performance of wood-framed buildings was the lack of continuous load paths. When there were not continuous load paths within the MWFRS, the building would experience partial or complete failure in the wood roof or wood wall framing. Based on field observations, the MAT observed the following key causes of failure:

- The buildings were never designed to resist high wind loads, and a continuous load path with engineered connections between structural members was not provided.
- The buildings are older and were constructed prior to the residential design criteria which specified requirements for wind resistant construction.
- The buildings were informally constructed.

Figure 3-29: Example of a wood-framed home in Vieques that performed well during Hurricane Maria.

Figure 3-30 and Figure 3-31 illustrate failures in the continuous path in one- and two-family houses with wood-framed walls and roofs or with wood-framed roofs with concrete wall framing. The common use of large metal panels as roof coverings atop lightly constructed wood-framed roof systems with no structural deck between the panels and the supporting frame exposed many homes to rain and wind, causing significant damage. Figure 3-31 shows the most frequently observed failure type in buildings with wood-framed roofs: damage to some or all of the wood-framed roof system. For both houses, wind forces removed a portion of the metal panel roof covering. With the loss of the roof covering, the roof structure became unstable, because the metal panel was the only element of the roof system providing lateral load support. As the roof lost support, some or all of the roof system failed, because there was no roof deck below the roof covering. This probably contributed to the complete destruction of the wood-framed house in Figure 3-30 and structural damage to as well as significant water intrusion into the concrete house with wood-framed roof in

Figure 3-31. Had roof decking been present and a proper load path provided, the building would have performed much better, minimizing or eliminating exposure of the interior of the home to rain or debris from its own failed elements.

Figure 3-30: Wood-framed house in Toa Baja. With the loss of the roof and wood-framed structural walls, the elevated living space was completely destroyed.

Figure 3-31: Concrete house with major damage to wood-framed roof system.

Figure 3-32 shows an example of an informally constructed wood-framed addition to a home. This addition, on the second story of the home was on top of the reinforced concrete roof of the first floor of the home. At this home, there was no structural deck below the metal panel roof covering, roof rafters were not connected to the top of the wall framing with connectors capable of resisting uplift loads, and there was no lateral support for the roof rafters.

Figure 3-32: Informally constructed second story wood-framed addition in Loíza with partial loss of metal panel roof covering and wood-framed roof system.

Additions to existing houses were frequently of wood-framed construction. These additions were second stories atop a concrete or CMU home or additions to the side of the home. Most of these additions were informally constructed, with little to no engineering design, and these structures performed poorly, with loss of roof covering, roof structure (no deck was present) and wall failures. Figure 3-33 shows a wood-framed, second story addition that lost its entire wood-framed roof structure.

Figure 3-33: Second story wood-framed addition in Canovanas which lost the entire wood-framed roof on the second story addition.

Many homes were constructed from reinforced concrete frames or walls, reinforced CMU, and reinforced concrete roof decks. These buildings exhibited the best performance and resistance to damage from high winds. Figure 3-34 shows two homes in Caguas; the beige home on the left with the reinforced concrete roof deck experienced no structural damage, while the light blue CMU home on the right lost most of its wood-framed roof and metal panel roof covering. Most of the homes with concrete roof decks visited by the MAT were observed to have little or no structural damage from the hurricanes (Figure 3-35). This was true for homes on the coast near landfall and those inland. Some of these homes experienced minor damage due to failed opening protection or roof coverings. The MAT was not able to confirm whether all the reinforced concrete and reinforced CMU homes observed during site visits had approved permits and were formally constructed.

Figure 3-34: Comparison of two homes in Caguas: Left, the beige house had a reinforced concrete roof deck and experienced no structural damage; right, the blue CMU home lost most of its wood-framed roof and metal panel roof covering.

Figure 3-35: Concrete residences in, left, Palmas del Mar; right, Loíza, that performed well with no structural damage.

Homes with reinforced concrete roof decks did experience failures and damage during the hurricanes. The home in Figure 3-36 lost a portion of its reinforced concrete roof deck. This home in Yabucoa, near where Hurricane Maria made landfall, was located on a bluff overlooking the ocean. Wind forces coming up the hillside from the water caused a failure in the concrete roof deck over the porch. The damage observed at this location appeared to be caused by a lack of adequate reinforcing steel in the connection between the roof deck and the supporting beam. As a result, the roof deck was peeled back by the wind when the reinforced concrete was not able to resist wind loads.

Figure 3-36: Failure of reinforced concrete roof deck over garage. Source: Héctor J. Cruzado, PhD, PE and Gustavo E. Pacheco-Crosetti, PhD, PE.

It is common practice in Puerto Rico to build homes with steel reinforcing bars protruding through the roof, so that the homeowner may add an upper floor in the future. The MAT observed such staged construction practices throughout Puerto Rico (Figure 3-37). However, steel rebar that is left unprotected for months or years can corrode and weaken, making it unsuitable for its intended use.

Figure 3-37: This home in Vieques had rebar exposed on the roof (red circles), indicating that the homeowner planned to add a second story sometime in the future.

3.3.1.2 Low-Rise, Multi-Family Residential Buildings

In addition to one- and two-family dwellings, the MAT visited low-rise buildings used for multi-family residential and light commercial use. These buildings were observed to be of load-bearing-wall construction or multi-story framed construction. The buildings were likely all professionally designed and engineered to resist wind, flood, seismic, and gravity loads. The MAT observed that very few of these buildings experienced structural failures of the MWFRS due to wind forces alone. In general, these larger buildings had a continuous load path that resisted wind loads without failure. Exceptions to this good performance occurred when building materials were in poor condition or where the building was impacted by falling or wind-borne debris. Figure 3-38 shows a low-rise building on the coast in Palmas del Mar, Humacao that had no damage to its structural systems. However, high winds, wind-driven rain, and wind-borne debris caused damage to roof coverings and windows, displacing residents from this building complex after the storm.

Figure 3-38: Low-rise building on the coast in Palmas del Mar that lost tile roof coverings.

3.3.2 Windows

Window damage is very common following hurricanes. The MAT observed both glazed (made of glass) and non-glazed window systems. Glass casement and glass jalousie windows were the most commonly observed glazed window systems, and metal panel jalousies were the most commonly observed non-glazed window systems. Performance of window systems varied depending on material type, quality of installation, condition of the window system, and the framing or structure supporting the window opening. Water intrusion occurred due to window systems having poor seals or seals that were never designed or intended by the manufacturer to be watertight, or when window systems were impacted and damaged by wind-borne debris impact. Water was also observed to have blown in under doors, leading to property damage.

In addition to keeping wind-driven rain and water out of a building, window systems can affect the performance of a building during a hurricane or high wind event. Window systems can be designed to resist wind pressures and prevent wind forces from entering a building, and the proper design of the building itself must consider whether the window system allows wind to enter the building (a partially-enclosed condition) or keeps wind out of the building (an enclosed condition). Older buildings and informally constructed buildings were not designed to withstand the increase of wind pressures within the buildings due to the use of window systems that allowed wind pressures to enter the buildings (the partially-enclosed condition). This contributed to increased pressures on roof systems from within the buildings, precipitating the failure of roof decking, roof framing, and entire roof systems.

3.3.2.1 Jalousie Windows

The most common window system observed in residential buildings in Puerto Rico is the jalousie window system (Spanish: ventanas de celosia). These window systems allow natural ventilation to help control the temperature inside the building while also limiting sunlight into the building and providing visual privacy. However, they are not air- or watertight and allow air to flow through the building. Jalousie window systems contain panels (louvers) made of metal, glass, or wood that are typically opened or closed by turning a handle. Figure 3-39 shows an elevated single-family residential building with metal jalousie windows. Figure 3-40 shows a close-up view of a metal jalousie window.

Figure 3-39: Elevated concrete residential building with glass jalousie windows.

Figure 3-40: Close-up of jalousie windows with metal louvers on a residential building.

Jalousie window systems are typically used because they are an affordable window option with a number of practical benefits. However, because they are inherently "open," non-sealed systems, they allow the passage of wind-driven rain, water, and air into buildings, which can lead to damage of the interior walls, interior floor, and building contents due to wetting. It also can lead to damage or failure of the building's structural systems (most commonly the roof systems) because wind pressures allowed within the building overload the roof structure; the wind loads within the building were probably never considered in the design. The common use of metal panel jalousie window systems in informally constructed homes contributed to the failure of many roof systems in the residential buildings the MAT observed.

Although the louvers of jalousie windows are commonly made of metal, or occasionally wood, they may also be made of glass; however, observations on the performance of glazed windows are presented in the next section of this report. Traditional glazed window systems, whether they are fixed or operable, are typically more air- and water-tight than jalousie window systems, which are inherently difficult or impossible to seal.

3.3.2.2 Glazed Windows

Glazed windows are a popular window type for buildings with central air conditioning, as they allow openings to be sealed, preventing airflow and moisture from entering the building under normal conditions. Glazed windows are common although not as popular in Puerto Rico as in most other parts of the United States. Glazing in many observed homes did not appear to be adequately secured to resist failure from wind pressures, regardless of the age of the home. The PRBC requires that glazing in wind-borne-debris regions and hurricane prone regions, which include all of Puerto Rico, to be either adequately rated for impact resistance or have hurricane shutters.

The most common damage observed for glazed windows was damage from wind-borne debris and water intrusion at gaps in window sills. Pressure from high winds forced water through poorly sealed openings, around window frames, and into the building, even if the glazing was closed and locked.

Windows that are not adequately attached to a building can become a hazard. Glazing, particularly those covering large openings, must be adequately anchored to the building. The structure surrounding the opening needs to be adequately designed, or strengthened if necessary, to handle the load transferred by the window or its covering.

In Figure 3-41, a large window was blown into the building, and the glazing broken, which could have injured any occupants of the building. There are no signs of anchors having been pulled out of the block or causing widespread damage to the edges of the opening, which indicates the fasteners that attached the glazing frame to the opening were inadequate.

Figure 3-41: Low-rise residential building with large glazed windows blown in (yellow arrows) and windows broken (red arrow).

The homes in Figure 3-42 and Figure 3-43 utilized impact-resistant glazed casement windows. These windows are very popular in Puerto Rico, as they can be opened wide to allow circulation and airflow. The glazed doors and windows on both homes performed well during these storms and did not suffer breakage of glazing during either hurricane. Water intrusion and damage from wind-driven rain was minimal due to excellent seals around the windows and doors. Figure 3-42 shows a close-up view of the double-glazed casement windows and seals. Seals around the glazing help to prevent water intrusion when the windows are closed and locked.

Water intrusion was also observed where glazing was broken due to wind-borne debris, often where no shutters or plywood covering were installed prior to the storm.

Figure 3-42: Concretesingle-family home with casement windows. Windows seal around opening (red arrows) and lock from inside to prevent water intrusion.

Figure 3-43: Concrete single-family home with impact-resistant glazing covering windows and doors (red arrows).

3.3.2.3 Opening Protection

Buildings with opening protection generally fared better than buildings without opening protection during Hurricane Maria. Buildings with opening protection suffered less damage from wind-borne debris and wind-driven rain. Common opening protection types observed during MAT assessments included metal panel hurricane shutters, accordion-style hurricane shutters, and plywood panels.

Hurricane shutters offer excellent protection from wind-borne debris and are designed to prevent debris from penetrating openings and entering the building. Properly specified and installed hurricane shutters reduce the likelihood of breakage to glazing or jalousie windows. The effectiveness of shutters is dependent on the quality of the shutter system, proper specification for the given application, adequate attachment to the window frame studs, and the ability of the structural wall to handle the design loads. Shutter systems can be installed either during construction of the home or as a retrofit.

In either case, it is important to evaluate the main building to ensure it can accommodate the load from the shutter system. Also, a shutter must be properly specified for its given application. It must be able to withstand the design pressure and debris impact forces, and it must have sufficient separation from the window to allow it to flex under load without breaking the window it protects.

The PRBC, and standards it references, identify the geographic areas where opening protection systems are required to protect glazed openings. Sections 1609.1.2 and R301.2.1.2, of the 2018 editions of the IBC and IRC, respectively, address the Protection of Openings. These sections state that in wind-borne-debris regions, glazing in buildings shall be impact-resistant or protected with an impact-resistant covering that meets the requirements of an approved impact-resistant standard or the American Society of Testing and Materials (ASTM) standards ASTM E 1996 and ASTM E 1886. Wood structural panels could be used as an alternative to provide protection so long as they meet local building code requirements.

Panel attachments for residential construction in Puerto Rico are required to be designed to resist the component and cladding loads determined in accordance with either the 2009 IRC Table R301.2(2) or ASCE 7-05, with permanent corrosion-resistant attachment hardware provided and anchors permanently installed on the building. An amendment to the 2011 PRBC increases the design wind speed V_{ASD}, such that attachment in accordance with the 2009 IRC Table R301.2.1.2 is permitted for buildings with a mean roof height of 33 feet (10.1 meters) or less where the design wind speed, V_{ASD}, is 145 mph (233 kph) or less, rather than 130 mph (209 kph) or less as given in the model code table.

The 2009 IRC references ASTM E 1996 and ASTM E 1886. Section R301.2.1.2 of the 2009 IRC states the following:

> *Glazed opening protection for windborne debris shall meet the requirements of the Large Missile Test of ASTM E 1996 and ASTM E 1886 referenced therein. Garage door glazed opening protection for windborne debris shall meet the requirements of an approved impact resisting standard or ANSI/DASMA 115.*

Figure 3-44 shows impact-resistant glazing at a newer low-rise restaurant in Bayamón visited by the MAT, which was impacted but performed well and likely reduced further damage. Although the restaurant has some siding failures, it was operational and serving food at the time of the MAT visit.

While shutters perform well under ideal situations, it is important to make sure systems are well maintained and components are checked regularly to ensure systems remain functional. Corroded fasteners should be replaced, damaged rails or connection should be repaired or replaced, and panels should be checked for corrosion or damage. Panels are typically replaceable and may need to be replaced following strong storms if damaged. Figure 3-45 shows a glazed window with metal panel hurricane shutters. The shutters protected the glazing; however, the window AC unit was not protected and allowed water to enter the building just below the window sill.

Figure 3-44: Newer low-rise restaurant in Bayamón with impact-resistant glazing panel (red inset) that performed well after being impacted, likely reducing further damage.

Figure 3-45: Metal hurricane shutter over glazed opening, (yellow arrow). Window unit air conditioner below window was not protected (red arrow) and became a source of water intrusion.

The residential building shown in Figure 3-46 used accordion-style shutters for the glazing on the second floor and traditional metal panel shutters for glazing on the first floor. Damage to the exterior finish of the building indicates high winds and possible debris impacts. This home was located near landfall of Hurricane Maria, yet all glazing remained intact.

Figure 3-46: Residential building with accordion-style shutters (yellow arrows) on second story over glass jalousie windows and metal panel shutters (blue arrow) on first floor. Glass was protected by shutters, and no windows were broken. Exterior finish was damaged (red arrows).

Figure 3-47 shows a residential building near the location of Hurricane Maria's landfall with hurricane shutters protecting glazed windows. Damage to exterior finish is visible, however, the shutters protected the glazed windows from wind-borne debris and water intrusion.

The MAT observed successful uses of plywood as protection for openings. Plywood panels offer considerable protection against wind-borne debris and protection for glazing or jalousie windows. Plywood panels may also reduce water intrusion through window openings from wind-driven rain.

Figure 3-47: Residential building with metal panel shutters over windows and exterior doors (blue arrows). Damage is visible on exterior finish (red arrows).

In many cases, residents attached hurricane shutters or plywood by screwing into framing studs. Attaching shutters directly to window frames is strongly discouraged, because window frames are not designed to resist these additional loads. Rather, shutters or plywood should be installed into the building's framing around window openings.

The low-rise residential building shown in Figure 3-48 has several units with different owners. The unit on the left used roll-down hurricane shutters to protect glazing. The unit on the right had no glazing protection (red arrows). Plywood was installed following Hurricane Irma. The glazing was broken during the hurricanes due to high winds and debris impact, damaging the contents of the building. This is a good example of the effectiveness of shutters to protect openings and glazing and what can happen when large glazed windows are not protected.

Figure 3-48: Residential windows, protected on the left (yellow arrow) and unprotected on the right, (red arrow) in Loíza. The unprotected windows were damaged and subsequently boarded up.

3.3.3 Roof Systems

There was widespread roof covering damage throughout Puerto Rico. The typical failure points of roof coverings were from insufficient attachment of the roof covering to the roof structure (in the absence of a roof deck) or inadequate attachment to the roof decking. It was commonly observed that there was no roof decking or sheathing installed below the roof covering. Damage to roofing systems was widespread. The roof covering is missing entirely on the concrete building in Figure 3-47.

The MAT observed that buildings with concrete roofs generally experienced less damage from wind-driven rain than buildings with wood roofs. The primary reason for this is that most buildings with concrete roofs observed by the MAT were constructed with sufficient mass and strength to withstand the wind forces, so they were less likely to be damaged or blown off. Additionally, based on discussions with local experts, the MAT understands that residential and low-rise buildings with concrete roofs in urban areas were typically professionally designed and permitted in accordance with building code requirements. By contrast, most wood houses observed by the MAT were built without input from design professionals: Wood trusses for roofs appeared to have been estimated and were mostly nailed, sheathing was rarely 3/4-inch (1.9 centimeters) thick, spacers and nailers were not used, gable ends were not braced, and any metal decking was nailed to the sheathing with no consideration of higher wind pressures at ends, ridges, or corners.

Figure 3-49: Residential building missing entire roof covering.

Figure 3-19 showed a typical wood roof observed by the MAT that was destroyed by high winds in Toa Alta, allowing wind-driven rain into the building. Wood roofs attached to concrete or CMU walls typically have an 8-inch (20.3-centimeter) concrete beam at the top of the wall with four reinforcing bars placed in the concrete beam with inadequate consideration of the loading and poor anchorage. Wood roofs attached to wood walls frequently use hurricane clips, but with little or no anchorage of the wall to the floor or foundation.

3.3.3.1 Metal Roof Covering

Many older homes in Puerto Rico have a roof covering consisting of thin corrugated metal panels with no structural deck beneath (Figure 3-50). These systems were often of an insufficient gauge (thickness) and were fastened to 2-inch-thick nailers with spans and spacing too wide to meet code requirements and best practices in hurricane-prone regions.

Figure 3-50: Metal roof covering with no structural decking.

The metal roof coverings typically performed poorly and were ripped from supporting structural members. The connection between the panels and the building below was observed to be inadequate due to several factors. Improper fasteners and thin metal coverings create weak connection points. There was also a lack of redundancy with the connections to adequately resist the uplift forces due to missing or sparse decking and framing members. It appears that edge, eave, corner, and ridge zones did not have reinforced connections. These areas experience higher wind pressures and are therefore more susceptible to damage if not adequately connected. Once these areas have sustained damage, further roof damage often progresses that may result in the entire roof cover failing.

In Figure 3-51, the metal roof covering and nailers have pulled away from the supporting roof structure. Metal roof covering panels were also often heavily corroded (Figure 3-52), resulting in connections weakening over time, thereby also reducing the roof's ability to protect the buildings and their contents from wind-driven rain. This corrosion can be due to improper coatings, inadequate material selection, and age. In addition, the majority of the damaged buildings lacked structural decking and blocking that would provide a robust connection for the metal coverings as well as lateral stability, lateral load path, and secondary protection from rain.

Figure 3-51: House with metal roof and nailers pulled from its roof structure with no structural decking.

Typically, metal roof systems that performed well were those with structural decking beneath the corrugated panels. Figure 3-53 shows a house with a metal roof covering that sustained damage, even while structural decking beneath the metal protected the integrity of the roof support structure and the house's contents. Small adjustments to the system used here could further strengthen the roof, including using a metal roof covering of sufficient gauge and using proper fasteners at a reduced spacing.

Figure 3-52: House with a corroded metal roof (red circles).

Figure 3-53: Residence with metal roof covering damage.

3.3.3.2 Tile Roof Covering

There are many types of tile roof styles, including clay, concrete, plastic, and even metal panels made to look like tile roof. Many older homes in Puerto Rico used traditional clay tile roofs. Tile roof covering performed inconsistently along the coastal areas of Puerto Rico. Some tile roofs remained in place, while other roofs experienced significant tile loss.

Tile roof covering is susceptible to damage and breakage from wind-borne debris. In high-wind regions, tiles should be mechanically fastened to the roof deck with screws; however, in many cases in Puerto Rico, tiles were glued using adhesive that weakened with time (Figure 3-54).

Figure 3-54: Clay roofing tiles inadequately attached to a roof with glue in Palmas del Mar, Humacao.

Satisfactory performance of the connections of tile roof coverage depends on using proper design edge, corner, overhang, and ridge wind pressures and designing the roof elements and their attachments to those design pressures. These areas are particularly vulnerable, and, when they have been compromised, the remaining areas of the roof become more susceptible to damage.

Clay tile roof covering was often installed on wood-framed roof structures that used a wood deck with roofing felt beneath the nailers (Figure 3-55). This roof deck is decaying due to moisture infiltration at the edges and missing or inadequate flashing.

Figure 3-55: Tiles installed on felt over a wooden roof deck. Tiles were removed, but the deck remained in place.

The presence of a roof deck helps prevent direct exposure of the building interior to water, but the roof deck itself is also susceptible to water intrusion and must be protected by waterproof barriers such as felt and flashing. While the roof deck in Figure 3-56 provided a water intrusion barrier, adequate fastening of the roof tiles would have alleviated some of the risk to the secondary barrier. Once blown off, loose tiles may themselves become debris capable of damaging other elements, including glazing.

Figure 3-56: Tile roof performance with secondary protection from decking system. Tiles were removed, but the decking remained in place.

3.3.4 Topographic Effects on Wind Forces

Many houses and other low-rise buildings constructed along hillsides and on hilltops of the mountainous terrain previously discussed also experienced increased wind forces during the hurricanes. During wind events such as hurricanes, winds associated with those storms are directed and channeled through mountainous terrain. As the wind moves over hills, ridges, bluffs, escarpments, or other topography, and up mountain valleys, the storm-induced winds often increase as the topography rises; much like the speed of water through a pipe increases when a nozzle constricts the flow. The ASCE 7 design standard provides guidance on how to account for this wind speed-up to determine wind loads acting on buildings.

The MAT observed residential building damage caused by wind speed-up effects at abrupt changes in topography. These situations occurred on the upper one-half of hills, ridges, and escarpments. ASCE 7 provides design formulas and commentary which describes the situation as one in which the speed-up effects increase with increasing topographic feature height. As the slope becomes steeper, the wind speed-up also increases until it is maximized at a rise:run of 1:2. The greatest wind speed-up exists at the crest of the topographic feature and decreases with building height above ground and distance from the crest. As stated in ASCE 7-16, “Buildings sited on the upper half of an isolated hill or escarpment may experience significantly higher wind speeds than buildings situated on level ground.” (ASCE 7-16, 744).

The MAT observed buildings with significant damage likely generated by the higher wind speeds occurring at topographic features. In Figure 3-57, the black portions of the roofs indicate areas where the wind lifted clay tile roofing off the home. The roof damage became more pronounced proceeding up the hill. Since the homes indicate similar construction types, these residential buildings likely experienced greater damage because of the wind speed-up effects.

Figure 3-57: Roof damage from wind speed-up effects in Palmas del Mar in Humacao along the eastern coastline.

In some situations, topographic wind speed-up on buildings can contribute to damage or even catastrophic failure; however, the MAT was not able to confirm the specific impacts of topographic effects and their quantitative contribution to these failures. Figure 3-58 shows images of a neighborhood atop a ridge in the mountainous region of Cayey. The strongest winds came from the bottom right of the aerial. Two adjacent homes (blue box) experienced significant damage, with one losing all four walls and the entire roof, and the other losing one wall and a good portion of its roof. Another home (red box) lost most of its roof covering and wood roof structure. A metal building system (MBS) (yellow box) was pushed over by wind forces.

Figure 3-58: Top, overhead view of neighborhood atop a mountainside in Cayey after Hurricanes Irma and Maria, showing locations of damaged buildings; below, street-level views of homes (red and blue boxes) and collapsed MBS (yellow box) shown in overhead. (Source: Aerial image taken October 4, 2017 [NOAA 2017]).

Homes with informal construction appeared to suffer more extensive damage from wind speed-up. A home set on a hillside in Camino Nuevo, Yabucoa (Figure 3-59) experienced complete failure of the upper floor structure.

Figure 3-59: Complete failure of informal construction of upper floor structure in Camino Nuevo, Yabucoa.

Some residential construction performed well despite the wind speed-up effects. A cast-in-place concrete home in Jajome Alto, Cayey (Figure 3-60) demonstrated good performance in high winds even though it is located on the side of a steep slope.

Figure 3-60: Good performance of cast-in-place concrete house set along the steep hillside of Jajome Alto, Cayey.

The main structure of other formally constructed houses in the vicinity demonstrated commendable performance in high winds. Some of these homes had informally constructed additions that did not withstand high winds as well. In Figure 3-61, the MAT observed partial failure of a metal canopy which appeared to be informally constructed.

Figure 3-61: Hillside house in Jajome Alto, Cayey. The main building demonstrates good performance under wind speed-up effects, while the informally constructed canopy suffered partial failure (canopy debris, red circles).

3.4 Performance Relative to Geology (Landslide)

The MAT observed residential and low-rise buildings located in inland areas near the center of the Commonwealth where the topography was steeper and more mountainous. Many of the buildings in areas such as Utuado and Ciales are placed along roadside developments that were either carved into the natural slope of the existing hillside or placed on fill materials used to build up the outside edge of the existing hillside (Figure 3-62), resulting in a developed slope that is steeper than the natural slope. As the developed slope naturally weathers over time, erosion gradually occurs that may ultimately impact structures or roadways. In the event of a landslide, the developed slope – particularly one that is excessively steep – experiences a partial or complete collapse, damaging the roadway and other buildings on the developed slope.

Furthermore, the MAT met with local geotechnical experts and reviewed information published by the United States Geological Survey (USGS) in the geologic map quadrangles for San Sebastian, Utuado, Florida, Jayuya, Ciales, and Corozal. Based on a review of the data collected, the MAT found that many hillsides along Puerto Rico's Cordillera Central, which extends from the west to the east-southeast on the interior of the island, tend to be formed of residual deposits from the weathering of intrusive rocks, metamorphic volcanic rocks, or sedimentary rocks.

Figure 3-62: Samplebuilding placement along hillside development, showing angles of the natural slope and the developed slope. Slope angles are exaggerated.

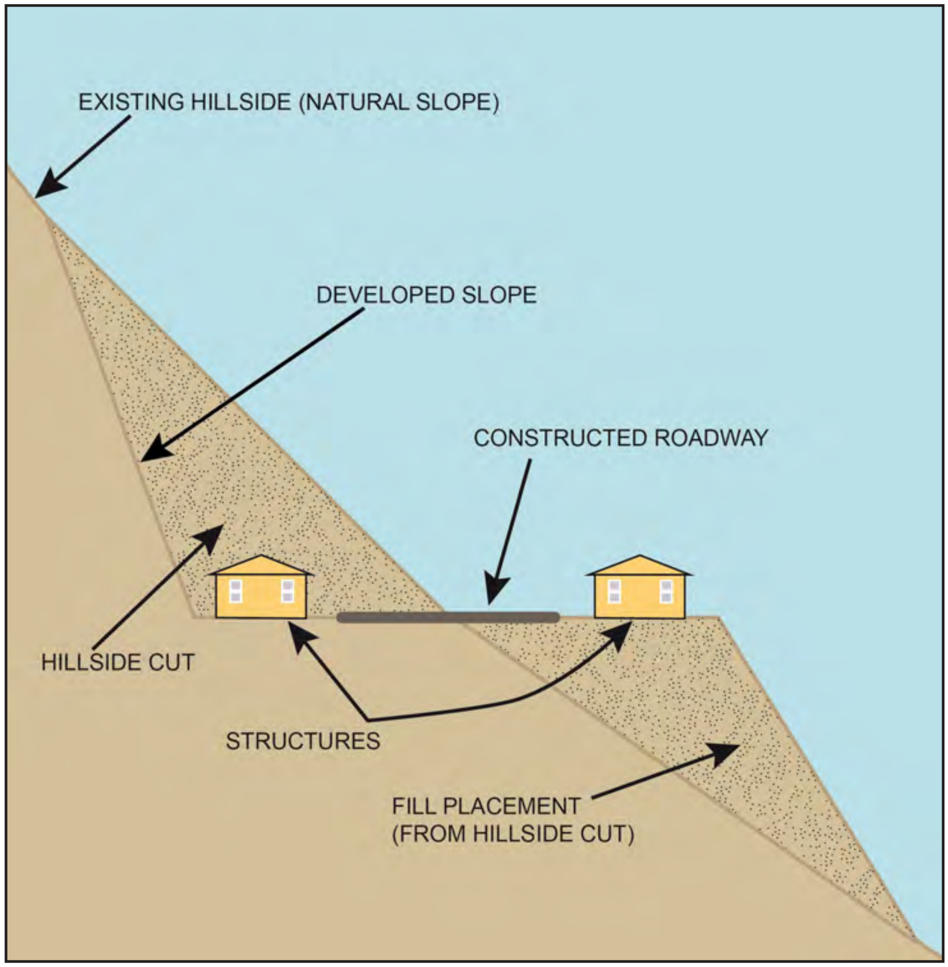


Figure 3-63 and Figure 3-64 show the USGS geologic map quadrangles for the municipalities of the Utuado and Ciales, respectively, which the MAT visited. USGS geologic maps for other municipalities of Puerto Rico can be downloaded from the National Geologic Map Database, https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html.

The intrusive rocks consist mainly of (1) rocks from the Utuado pluton, composed of massive granodiorite, including quartz diorite, quartz monzonite, diorite and gabbro; and (2) dikes of granodiorite and some diorite. These intrusive rocks can be quite hard initially, but over time these rocks weather into more erodible materials such as sand and silt.

The volcanic metamorphic rocks include, among others, sandstones, siltstones, breccias, tuffs, and lava flows. These rocks tend to weather into fine soils which lose their strength with time, becoming unable to withstand the bedrock slope angles or the slopes provided to the cuts performed for development and/or road construction.

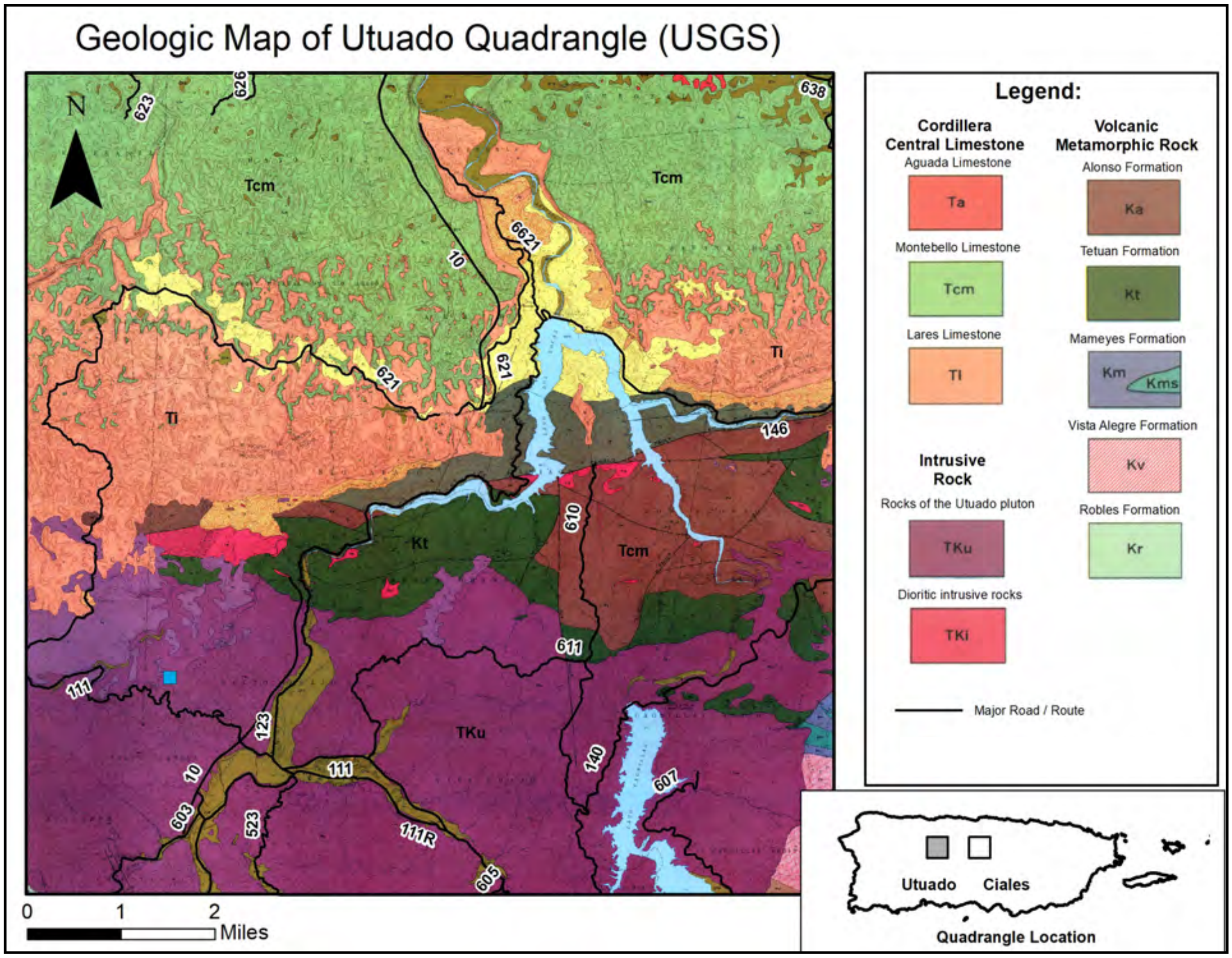


Figure 3-63: USGS geologic map of Utuado with location of hillside residence in Figure 3 65 (blue square). Modified from Nelson (1967).

Similar conditions occur with the sedimentary limestone formations prevailing alongside and north of the Cordillera Central. Because of these conditions, many hillside buildings were at risk of damage or collapse from landslides induced by heavy rainfall from Hurricanes Irma and Maria (Figure 3-67 and Figure 3-68).

Many homes built along the outside edge of hillsides that appear to be one- or two-story buildings from the road are actually two- or three-story buildings, with one or more lower levels constructed as walk-out basements facing out toward the hillside that are used for an additional residential unit. Unfortunately, this type of building is often of informal construction and does not have the proper supervision and guidance from geotechnical engineers who can assess the stability of the site or from appropriate design professionals who can provide the necessary construction details. As shown in Figure 3-65 and Figure 3-66, the resulting deficiencies can increase the vulnerability of structural failures from landslides–such as the ones that occurred during Hurricane Maria–as well as earthquakes.

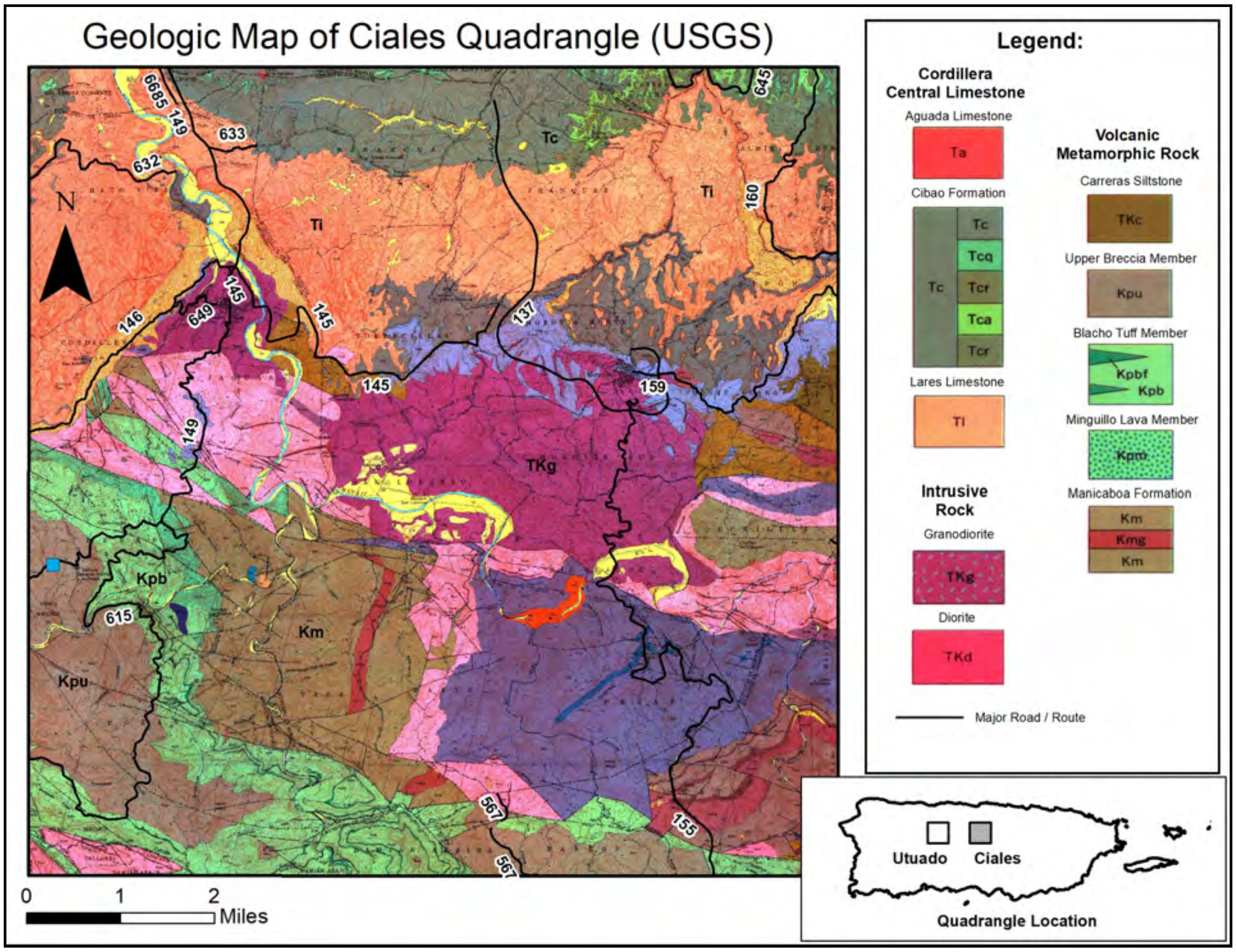


Figure 3-64: USGS geologic map of Ciales, with location of hillside residence shown in Figure 3 66 (blue square). Modified from Berryhill (1965).

Figure 3-65: Hillside residence in Cerro Gordo, Utuado that failed due to poor siting on unstable slope and poor connection of wood foundation to building.

Figure 3-66: House that failed due to landslide in Utuado. Source: NWS (2017)

Figure 3-67: Hillside house in Ciales at risk of landslide failure. The house was occupied despite the apparent risk.

Figure 3-68: Hillside mixed-use building in Ciales with extensive lower-level additions at risk of landslide failure.

As shown in Figure 3-69, The MAT did observe hillside residences that performed well when properly sited away from potentially unstable slopes and properly designed to resist potential design flood and wind forces.

Figure 3-69: Hillside residence in Utuado that was sited away from the edge of the slope and designed to resist potential flood and wind forces.

3.5 Successes Due to Previous Mitigation

Puerto Rico has been impacted by many hurricanes over the decades, including Hurricanes Hugo in September 1989, Marilyn in September 1995 and Georges in September 1998. Several mitigation projects after past disasters have improved disaster resistance of residential construction in Puerto Rico.

3.5.1 Successes Related to Hurricanes Hugo and Marilyn Programs

June 1998, FEMA designated Culebra as the first Project Impact community in Puerto Rico. FEMA first introduced Project Impact in 1997 as a national initiative to help build disaster-resistant communities by forming public-private partnerships, assessing risks and developing action plans for implementing mitigation measures. In 1998, shortly before Hurricane Georges, 124 homes received wind retrofits from trained volunteers (FEMA 1998a). In August 2000, FEMA prepared a Project Impact Culebra multi-hazard risk assessment and vulnerability study (FEMA 2000). The study included risk assessments, vulnerability analyses, hazard maps, and recommendations to address flood, landslide, hurricane wind, and earthquake hazards. The recommendation that was given the highest priority by the study was implementing wind hazard retrofit measures for single-family homes in Culebra, but the MAT could not find any records that any retrofits were carried out by Project Impact. The MAT visited Culebra following Hurricane Maria and observed residential buildings that were retrofitted for wind (Figure 3-70). The Hurricane Georges BPAT (FEMA 1999) observed some older residences on Culebra that had been retrofitted for wind, with roof-to-wall metal framing connectors, but the retrofit measures were found to have not been completed within the few buildings observed.

Figure 3-70: A homeowner in Culebra attempted to increase the resistance of the roof to wind uplift forces by means of a steel cable (red arrow) wrapped over roof members and anchored to a column. Such an addition should consider the design loads.

The MAT also observed several houses (Figure 3-71) that appeared to be constructed according to guidelines developed for a program in the U.S. Virgin Islands (USVI), the Home Protection Roofing Program (HPRP). The HPRP was an HMGP-funded program following Hurricane Marilyn in 1995 to develop wind-hazard-resistant prescriptive residential roof designs. Two HPRP solutions were developed, one to improve the attachment of corrugated metal roofs, the other to build roofs by applying a liquid-applied membrane over plywood. Both options included design solutions for improving the wind resistance of the joists or beams. The MAT was not able to verify that the observed homes in PR were constructed in accordance with HPRP guidelines, but homes that appeared to make use of the membrane-over-plywood construction were observed to perform well.

Figure 3-71: This home on Culebra had a plywood roof with a liquid-applied membrane consistent with the Home Protection Roofing Program in the USVI. The roof performed well.

3.5.2 Floodplain Acquisitions in Villa Monseratte

In 1996, after Hurricane Hortense, an HMGP-funded acquisition and relocation grant purchased vulnerable floodplain structures in Villa Monseratte in Arenas, Toa Baja. In Hurricane Maria, buildings in Villa Monseratte were flooded as high as 10 feet (3 meters), with significant wind damage to elevated wood-framed buildings and wood-framed upper levels of concrete buildings (Figure 3-72). The MAT was unable to determine if specific buildings flooded in Hurricane Maria were included in previous HMGP projects.

Figure 3-72: Elevated concrete house in Monseratte, Toa Baja subjected to flooding and high winds.

3.5.3 Successes Related to Hurricane Georges MAT Recommendations

After Hurricane Georges struck Puerto Rico in September of 1998, FEMA deployed a BPAT to the Commonwealth to assess the storm's impact. The Hurricane Georges BPAT Report included several important recommendations to reduce future building damage to residential and low-rise buildings in Puerto Rico. The most important of these recommendations was for "final adoption" and "aggressive enforcement" of a building code for the Commonwealth pertaining to residential construction (FEMA 1999). In 2011, Puerto Rico succeeded in adopting the 2011 Puerto Rico Building Code (PRBC), which references the 2009 I-Codes, including the 2009 IRC© and the 2009 IBC©, with no weakening amendments. Unfortunately, this code adoption success has been limited by inadequate code enforcement, especially for residential and low-rise construction. Previous post-storm observations by MATs throughout all parts of the U.S. have consistently demonstrated that buildings constructed in accordance with the I-Codes and inspected for compliance perform better than buildings that are not code-compliant. However, the large amount of informal construction observed by the MAT in Puerto Rico indicates that many residential and low-rise buildings are not code-compliant due to a lack of professional design input and construction inspections to verify compliance. The Commonwealth of Puerto Rico understands the importance of this issue, as evidenced by the recent passage of the Permitting Reform Act (Law 19-2017) in April 2017, which created the Unified Information System to streamline the permit application process.

In addition to code adoption and enforcement, the Georges MAT also recommended education and outreach to homeowners on the risks of building in flood-prone areas. Although the FEMA Region II Coastal Outreach Advisory Team provided some floodplain education in Puerto Rico in 2013, the success appears to have been limited in communicating the risk to residents. This is shown by the large amount of residential and low-rise commercial development observed by the MAT in coastal and riverine floodplains throughout the Commonwealth. Additionally, recent studies have shown that despite the widespread availability of flood insurance in Puerto Rico, mostly from private insurers, fewer than 4 percent of households in Puerto Rico have flood insurance (Kousky and Lingle 2018). By contrast, the percentage of U.S. homeowners overall having flood insurance is approximately three times greater (Insurance Information Institute 2016).

The New Secure Housing Program (NSHP), established in 1998, replaced vulnerable buildings in 15 municipalities with concrete houses, ultimately building 1,647 housing units. The MAT and Pre-MAT visited several of the NSHP communities, including Campanilla (Figure 3-73) and Brisas De Campanero in Toa Baja, Riberas Del Bucana in Ponce, Villa Alegria in Vega Alta, and Santo Domingo y Pellejas in Morovis. The NSHP housing units at these locations were typically one- and two-story reinforced concrete residential houses with concrete roofs, such as the house in Campanilla shown in Figure 3-74 and Figure 3-75. The NSHP buildings observed by the MAT performed well and resisted flood and wind damage from Hurricanes Irma and Maria better than most of the residential and low-rise buildings surrounding them. However, some of the Campanilla buildings experienced flooding depths of 1-3 feet (0.3-0.9 meters) above grade during Hurricane Maria (Figure 3-73). The community was elevated on fill to the BFE but experienced flood levels exceeding the 500-year flood (Figure 3-76). The community was isolated after roads flooded. Additional freeboard could have mitigated damage to these buildings. A minimum of one foot (0.3 meters) of freeboard is required for residential buildings in the SFHA by Planning Regulation 13.

Some NSHP houses in Campanilla suffered damage to aesthetic components including clay tile roof coverings blown off by wind (Figure 3-74). One NSHP house had an informally constructed addition that lost its roof covering (Figure 3-75) due to wind. Some NSHP houses in Santo Domingo y Pellejas suffered minor roof leaks due to heavy rainfall and improperly maintained rooftop drains.

Figure 3-73: Aerial image of Campanilla NSHP community, Toa Baja. The community was elevated on fill, resulting in isolation of properties during Hurricane Maria due to flooding of surrounding areas. Homes on the southern portion of the community experienced shallow flooding. Zone AE. Inset, NSHP home in Campanilla showing approximate inundation depth (yellow line).

Local officials in Toa Baja told the MAT that some buildings acquired in previous Hazard Mitigation Assistance (HMA) acquisitions had later been reinhabited. While the MAT was unable to confirm this statement, it is possible that some homes were not razed or properties not deed-restricted per grant requirements. A 2015 audit report by the Department of Homeland Security Office of the Inspector General found that the PRDOH “did not complete the demolition and/or deed restriction requirements for 309 of the 1,364 [NSHP] off-site program participants who received replacement housing under the award” (Department of Homeland Security Office of Inspector General 2015). It is not known whether the problems identified in the 2015 report were successfully addressed. Reoccupation of acquired homes exposes the occupants to continued flood risk.

Figure 3-74: This NSHP house in Campanilla Toa Baja suffered damage to aesthetic components including clay tile roof coverings and decorative eaves blown off by wind.

Figure 3-75: NSHP house in Campanilla has an informally constructed addition which lost its entire roof covering.

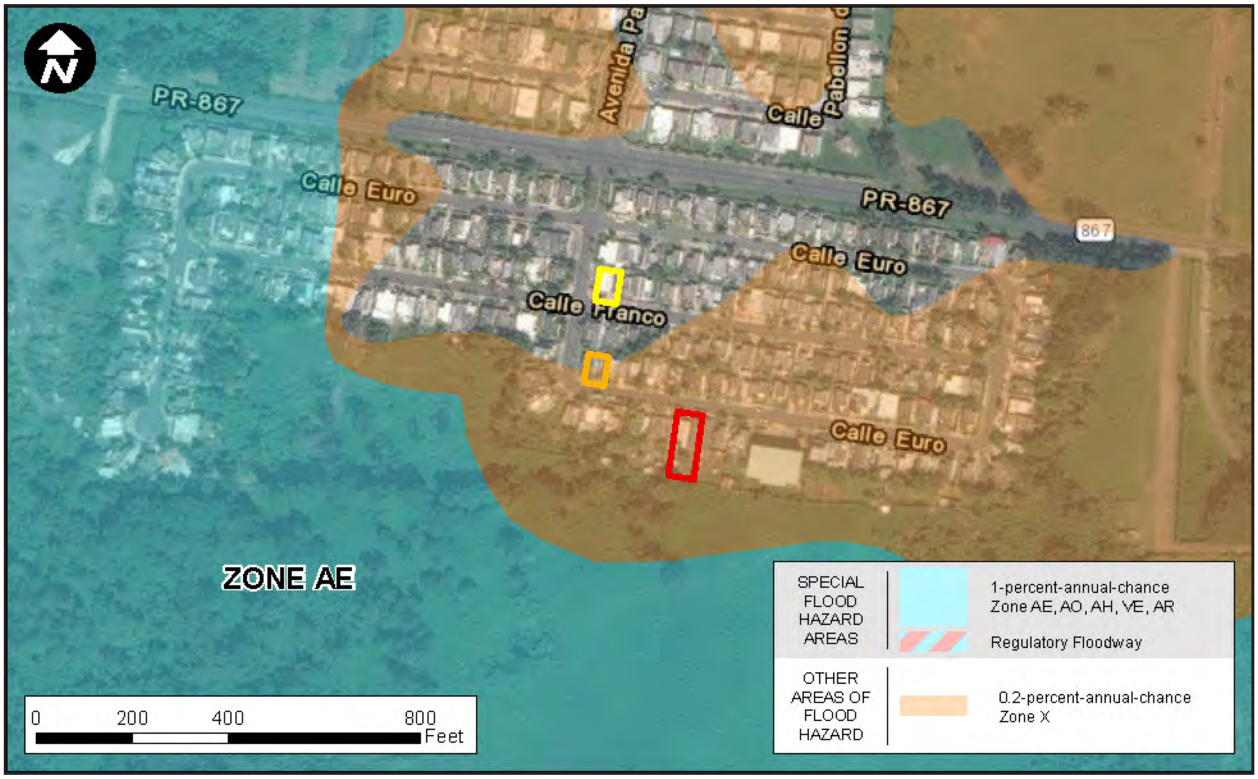
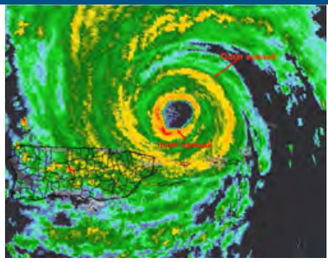
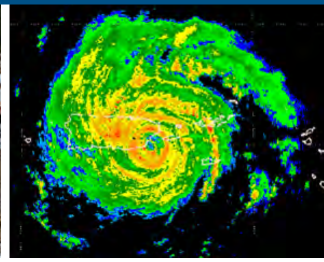


Figure 3-76: A Portion of the 2009 effective FIRM for Campanilla, Toa Baja, with locations of NSHP homes shown in Figure 3-73 (orange box), Figure 3-74 (red box), and Figure 3-75 (yellow box).




4 Performance of Schools and Shelters

School facilities were heavily impacted and damaged by Hurricanes Irma and Maria.

Damage to public schools was reported to be as high as $8.4 billion across Puerto Rico (Brown 2018). Prior to the landfall of Hurricanes Irma and Maria, the Puerto Rico Department of Education (PRDE; Departamento de Educación) was responsible for the management of almost 1,200 schools, supporting approximately 350,000 students, across 78 municipalities. Public schools are under the jurisdiction of PRDE, but the public schools are maintained by a combined effort from PRDE, the Puerto Rico Public Buildings Authority (Autoridad de Edificios Públicos de Puerto Rico) and the local municipalities.

4.1 Summary of School and Shelter Performance

On September 21, the day after Hurricane Maria made landfall, all school buildings were closed except those being used as shelters, and impacts to school facilities were widespread. While this was not unexpected based on the magnitude and intensity of the hurricane, the ability of schools to reopen after the storm was more difficult than many had anticipated. By mid-October, 98 schools had reopened, or roughly 9 percent (Alvarez 2017), but it was not until early December that 1,075, or more than 90 percent, of the schools reopened. During that time, many schools opened with water and basic school services, but a number of buildings were reopened without power, or without full power, limiting some of the activities at the schools. PRDE reported that 38 schools have been identified as unable to be reopened due to building damage that they would not repair.

The MAT visited several schools across the Commonwealth (Figure 4-1). Most of the schools visited had a core (primary) building that was constructed of multi-story reinforced concrete-framed or CMU walls with reinforced concrete roof decks. Additional buildings for supplemental classrooms or administrative office functions were of multiple construction types, including concrete or masonry buildings with steel-framed roof systems, metal building systems (MBSs), and other light-framed construction.

Figure 4-1: Schools visited by the MAT and discussed in this report. Schools with an asterisk were designated for use as shelters.

The most commonly observed impacts to schools, including those used as shelters, were the following:

- Water intrusion through the roof and windows (openings)
- Loss of power and communications, with the resulting loss of HVAC systems support, due to
    - Loss of grid power
    - Lack of backup/emergency generator power on-site
    - Damage to the backup/emergency generator on-site

The additional impacts below were observed at a number of school buildings but were not as common as those notes above:

- Significant damage to building envelope (roof, wall, and window systems and assemblies)
- Site and facility flooding
- Significant structural damage to facilities (due to flood and wind impacts)
- Facility access problems

The following sections present MAT observations related to flood and wind impacts to school facilities. The last section of the chapter presents information on the Puerto Rico Department of Housing (PRDOH; Departamento de Vivienda) program to manage shelters before, during, and after a hurricane makes landfall.

4.2 Effect of Siting on the Performance of School Buildings

While the majority of damage to school facilities was caused by wind and wind-borne debris, some schools were damaged by floodwaters from storm surge, localized flooding from rainfall in low-lying areas, and riverine flooding in mountain areas.

In support of the MAT, FEMA was provided information on damage to a number of school and municipal buildings. Based on the damage reported to FEMA and the reported information on flooding and damage, the MAT visited a number of schools in support of this assessment. The MAT did not visit all damaged schools, however. The damage and observations for the schools presented in this section, and throughout this chapter, are presented to provide an understanding of typical impacts to school buildings and to highlight successes and failures of building performance.

REOPENING OF PUERTO RICO SCHOOLS POST-MARIA

After Hurricanes Irma and Maria, the U.S. Army Corps of Engineers (USACE) performed assessments of the more-than-1,100 schools across Puerto Rico in support of the Government of Puerto Rico and PRDE. Public schools were not allowed to reopen unless they were assessed and given approval to reopen by PRDE. These assessments were performed independently of FEMA's MAT efforts. This section focuses on MAT observations of building performance and impacts to school buildings from the flood and wind events.

The MAT did not observe siting problems related to landslide or slope stability hazards for schools. These buildings are typically located on larger parcels and as a result are not located on hillsides or escarpments[1]. The MAT also did not observe any schools in coastal flood zones.

A program administered by PRDOH evaluates buildings, including schools, for use as shelters/refuge areas pre-event, during the event, and

[1] Although the structures were not impacted by landslide, Escuela Juan D. Stubbe school in Cidra did lose part of its perimeter fence and part of a running track to landslide.

post-event. PRDOH informed the MAT that no public schools used as shelters were in a mapped Special Flood Hazard Area (SFHA).

Prior to the 2017 hurricanes, due to efforts by PRDE and PRDOH, the number of schools in SFHAs was reduced, but some schools are still located in flood-prone areas. The MAT visited the Luis M. Santiago School in Toa Baja, a combined elementary, junior high, and special education school shown in Figure 4-2. Prior to Hurricanes Irma and Maria, this was one of three schools in Toa Baja Pueblo (Old City/Downtown) that were chosen as the sites for school consolidation. The three schools chosen to remain open were Jose Robles Otero Elementary School, the Luis M. Santiago School, and Adolfina Irizarry de Puig School, the latter two of which are located in the mapped AE Zone on the portion of the FIRM shown in Figure 4-3.

Figure 4-2: Mud remains in a classroom that was flooded (yellow line) at the Luis M. Santiago School, located in Zone AE.

Schools in other locations throughout Toa Baja closed, and many of their students were consolidated to schools in Toa Baja Pueblo. However, the MAT could not determine if the flood, wind, or seismic vulnerabilities of the schools were criteria in this consolidation effort. This contrasts with the municipality's approach to the repetitive flood issue at the old Toa Baja Municipal Building (Figure 4-3). In 1995, when a new building was needed, the municipality moved operations to a new building in a location that was believed to be less vulnerable to flooding. Although it is partially in the SFHA on the effective FIRM (Figure 4-4), the building is elevated on fill.

Schools located toward the central portion of the island of Puerto Rico were protected from storm surge but not from flooding related to site drainage or rising waters along tributaries. At the Eduardo Garcia Carrillo High School in Canóvanas (Figure 4-5), the river in the forefront of the photo overflowed its banks and flooded the roadway in front of the school and its parking lot. Fortunately, floodwaters did not enter the school itself, as it is constructed atop a small rise on the site. The extent of the flooding (the edge of the parking school lot) is at the AE Zone boundary. Thus, the flood was exactly the base flood in this location, and a small increase would have flooded the school.

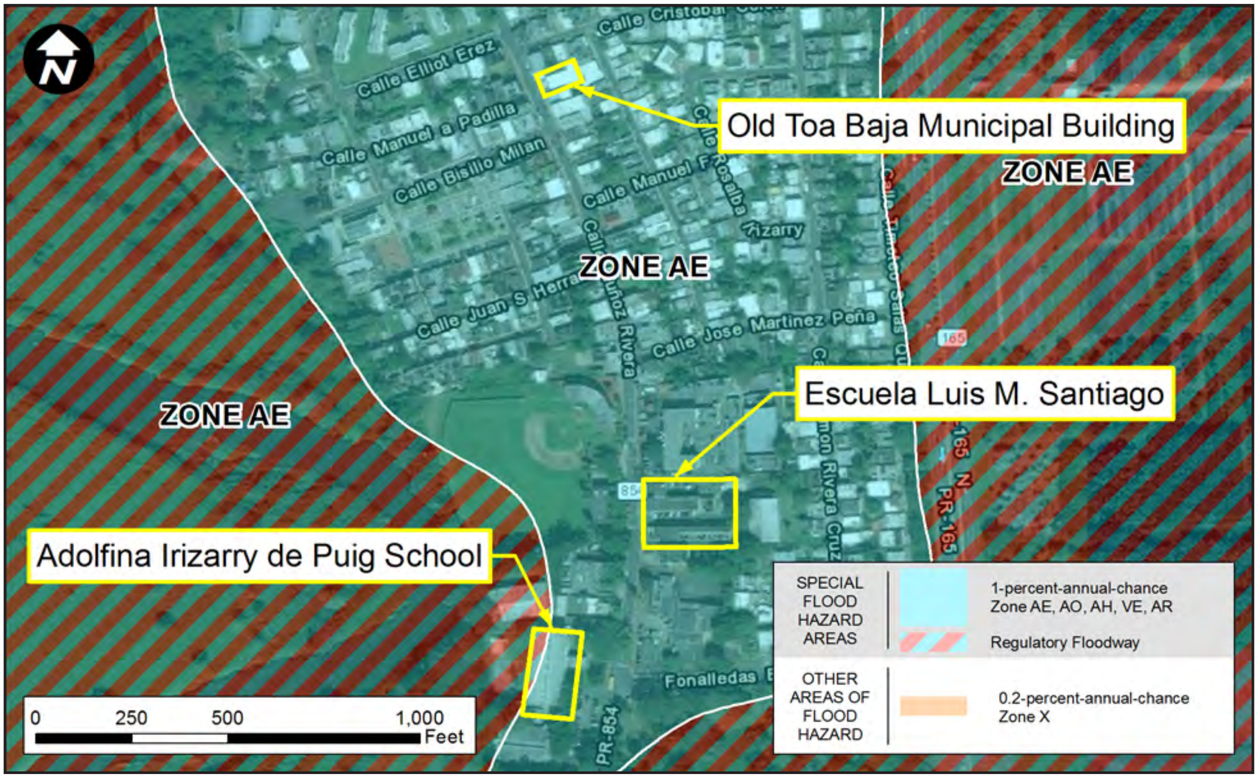


Figure 4-3: A portion of the effective 2009 FIRM showing the old Toa Baja Municipal Building (upper yellow box) and Luis M. Santiago School (lower yellow box).

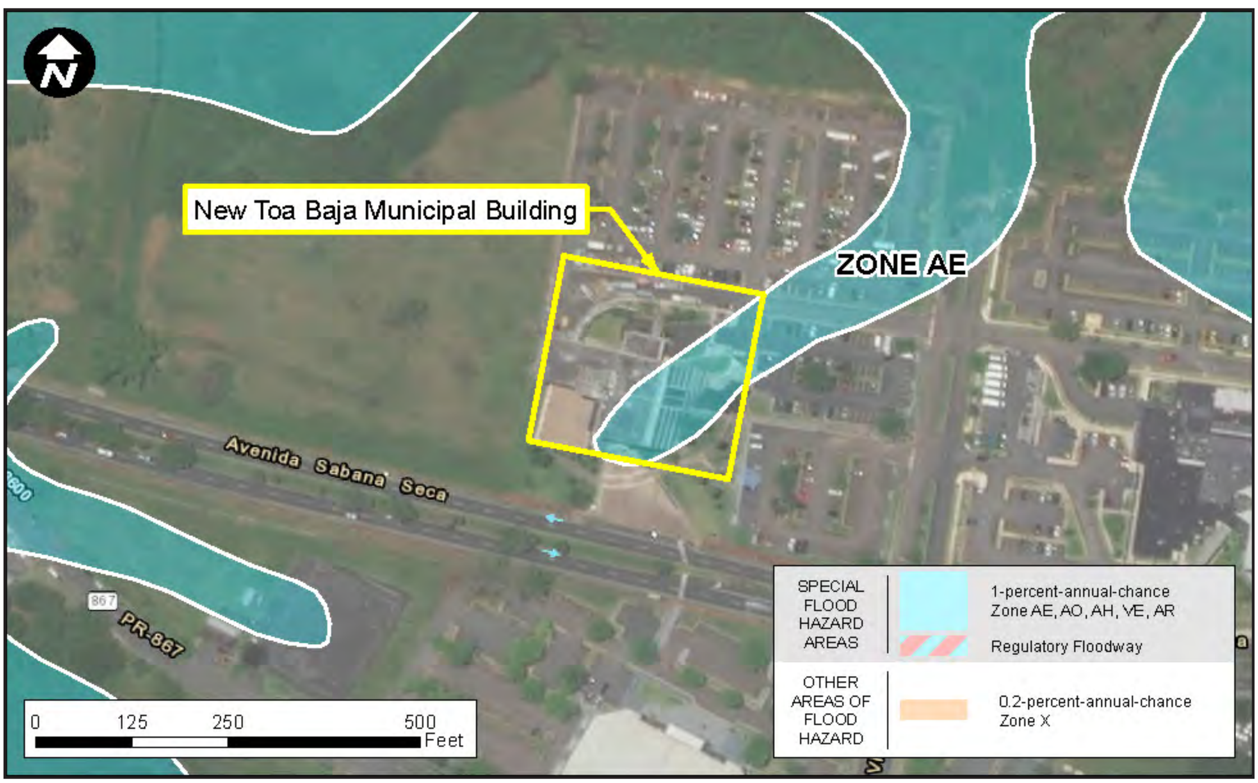


Figure 4-4: A portion of the effective 2009 FIRM showing the new Toa Baja Municipal Building. The facility was relocated in 1995 to reduce flood risk; however, it is partly located inside the SFHA.

Figure 4-5: Floodwaters from the stream under this bridge rose to the edge of the mapped Zone AE (yellow line) in the parking lot immediately adjacent to the school. The floodwaters did not enter the school.

4.3 Performance Relative to Flood

The majority of damage at schools observed by the MAT was wind-related damage. However, some schools are still located within SFHAs and are vulnerable to flooding during hurricanes and other severe rain events. The majority of the schools visited by the MAT were located outside of the SFHA and did not experience flooding or flood damage within the school buildings. However, a few schools were in areas with poor site drainage or were within the SFHA itself. Most of the schools that were in the SFHA experienced some level of flood inundation during Hurricanes Irma and Maria.

4.3.1 Elevation and Freeboard

Two of the schools visited by the MAT were located within the SFHA and were flooded during Hurricane Maria. Luis M. Santiago School in Toa Baja includes one- and two-story slab-on-grade concrete buildings built in 1950 and has a student population of approximately 350. During Maria, the school buildings were flooded inside to a depth of approximately 4–5 feet (1.2–1.5 meters) above grade, judging from high-water marks (Figure 4-6 and Figure 4-7). Flood damage was widespread across all classrooms on the ground level.

This school was constructed long before the development of the FIRMs. The hazard information available at that time, perhaps limited to some information on historical storms, probably explains why the buildings were not elevated to provide some level of protection against expected floods. There was no significant elevation of the buildings above the adjacent grade.

Figure 4-6: Luis M. Santiago School with location of high water mark (yellow line) from Maria.

Figure 4-7: Classroom at Luis M. Santiago School with high-water line indicated (yellow line).

Adolfina Irizarry de Puig School in Toa Baja also experienced flooding. The school accommodates approximately 600 students and is located adjacent to the La Plata River. The main building, built in 1978, is the three-story concrete building shown in Figure 4-8. The building is elevated and appears to have been retrofitted for earthquakes; however, there was one set of rooms below the elevated main floor.

During Maria, the river overflowed its banks and the areas beneath the elevated school experienced 2.5–3 feet (0.8–0.9 meters) of flooding. The flooding resulted in several feet of water, mud, and sediment being deposited into the non-elevated student center (Figure 4-9) underneath the elevated building. At the time of the MAT visit, the facility was not able to reopen due to flood damage, lack of power, and lack of fresh water at the site. In addition to flood damage at the site, wind and wind-driven rain damage included HVAC equipment damage and water damage (infiltration) on the third floor from roof leakage. The water intrusion problem occurred when water trapped on the roof (ponding) leaked into upper floor classrooms, damaging accounting and computer equipment.

Figure 4-8: Adolfina Irizarry de Puig School building partially elevated with bracing added as seismic retrofitting. Wind damaged these HVAC units. The school received 2.5 - 3 feet of flooding (yellow line).

Figure 4-9: Toa Baja High School building student center area underneath the elevated building that flooded during Maria. The school received 2.5- 3 feet of flooding (yellow line).

4.3.2 Mechanical, Electrical, and Plumbing Systems Performance

The flood damage at the Luis M. Santiago School also included flooding of electrical equipment at the school (Figure 4-10). Because the flooding in the buildings was over 4 feet (1.2 meters) in depth, the flooding impacted the electrical system across the first floor.

Figure 4-10: High water mark on wall (red arrow) and electrical panel at the Luis M. Santiago School. Flooding of the electrical panel impacted the electrical system across the first floor.

4.4 Performance Relative to Wind

The MAT visited over a dozen schools in the mountains, the coastal areas, and foothills to observe their performance during the hurricanes. At the sites visited by the MAT, no school building was observed to have experienced complete structural failures, with one notable exception: There were several partial to complete collapses of MBSs used as covered basketball courts and athletic areas. Most of the schools visited were constructed from reinforced concrete or reinforced CMU, with concrete roof decks. Some schools had concrete or CMU walls with metal roof decks, and some were steel-framed. Some schools employed MBSs as additional buildings on school campuses.

The good structural performance of these buildings contrasted in some cases with the poor performance of lighter structural components or building envelopes due to wind pressures or wind-borne debris from Hurricanes Irma and Maria. The poor performance or failures of components and cladding led to widespread water intrusion at school facilities. Water intrusion usually began at roof coverings which appeared to be older and past their design life or at window assemblies that were not designed or rated to resist wind-driven rain or wind-borne-debris impacts.

Windows at school buildings varied in type, glazing, and debris impact resistance. The most common window systems were metal panel jalousie windows which had not been tested for debris impact resistance and are not rated for resistance to water intrusion. Where glazed windows systems were used, it did not appear the windows were rated to resist wind pressures associated with the design wind speed or for water intrusion resistance. Additionally, most of the glazed window systems were not observed to use impact-resistant glazing and were not protected with an impact-resistant shutter system.

Significant water intrusion from the window and roof covering failures, combined with the lack of grid power or backup/emergency power at the facilities, was the primary reason most schools took weeks or months to reopen after the storms. The ability to keep water out of the buildings and the power on are vital for rapid recovery.

4.4.1 Main Wind Force Resisting System

Newer schools constructed of reinforced concrete performed well with only minor water intrusion through windows. However, some newer facilities experienced more significant water intrusion when roof coverings or roof-mounted equipment (including exterior mounted ductwork) did not perform as designed. These buildings were observed to be load-bearing or shear wall construction or multi-story framed construction. The buildings were likely all professionally designed and engineered, and those constructed within the last 20 years appeared to have been designed with consideration of gravity loads as well as wind, flood, and seismic loads. The MAT observed that these buildings did not experience structural failures within the MWFRS due to wind forces alone. In general, these larger buildings had a continuous load path that resisted wind loads without failure, as was the case at Loíza Vocational High School (Figure 4-11). Exceptions to this good performance were observed in MBS buildings used for athletic facilities.

Figure 4-11: Loíza Vocational High School was constructed in 2010 and did not experience structural damage to the MWFRS from Hurricanes Irma and Maria.

The MAT also visited roughly a dozen older school buildings constructed from the 1950s to the 1990s. Eduardo Garcia Carrillo High School, constructed in 1988 in the lower elevations of Canóvanas, a mountainous region, performed well with no damage to the reinforced concrete buildings at the site (Figure 4-12). Storm impacts to these buildings comprised water intrusion through jalousie window assemblies and water intrusion from clogged drainage elements of the roof. Large roof drainage troughs around the perimeter of the school backed up and filled with water when drains were clogged by wind-borne debris. This school also had two metal buildings used for vocational classrooms. The MWFRS performed well without damage, however, both buildings experienced ridge cap loss and wind-borne-debris impacts leading to significant water intrusion in these building areas.

Figure 4-12: Eduardo Garcia Carrillo High School, left, did not experience structural failures to reinforced concrete classroom buildings. Damage at these buildings was due to water intrusion from the roof, right, and through windows.

BACKUP AND EMERGENCY POWER AT SCHOOL BUILDINGS

Most of the schools visited by the MAT had no generator for emergency power or backup power. This included some school buildings that were identified by PRDV for use as shelters.

The lack of backup and emergency power impacted the ability of the municipalities and PRDE to reopen schools after Irma and Maria; especially when the school buildings were unable to receive primary power from the grid. With no ability to provide power for lighting, water and sewer services, and air conditioning (where present), school reopenings were delayed.

The most notable failure of the MWFRS observed at school buildings were at one- and two-story buildings that had roof systems constructed of materials other than reinforced concrete. Several examples of partial roof failures in steel-framed roof systems with metal roof decks were observed. While the rest of the MWFRS performed well, some of these lighter roof decks experienced uplift failures (at corner and edge zones where wind loads are highest).

Figure 4-13 shows the interior and exterior of the Gutierrez Elementary School in Canóvanas. The school buildings were single-story reinforced concrete buildings constructed in the 1950s. In the 1970s, several of the buildings received second-floor additions. The MWFRS of the first- and second-floor walls and roofs performed well structurally, with no observed damage to reinforced concrete classroom sections, although water intrusion from wind-driven rain through jalousie window assemblies was observed.

However, some roof deck damage was observed to one portion of the second-story classrooms (Figure 4-13, right). Some metal purlins were damaged and displaced, and the metal roof deck failed from wind uplift.

Figure 4-13: Gutierrez Elementary School experienced loss of metal roof deck panels and some purlins from wind uplift.

The MAT observed that many MBS buildings performed well, with no structural damage to the MWFRS and little or no damage to the metal panel upper wall and roof covering systems. At a vocational school in Loíza, two of these MBS facilities were located next to each other and performed well with no observed damage from the hurricanes (Figure 4-14). However, others failed due to wind pressures. These include the Felix Pedraza Athletic Complex in Ceiba (Figure 4-15). Parts of the MWFRS of this MBS were damaged as a result of high winds, as steel girders exhibited deformation of the flanges, a column was twisted, and the CMU infill wall partially collapsed. The building also lost much of its wall cladding and metal roof paneling.

Figure 4-14: Two MBSs used as athletic facilities at Loíza Vocational High School that performed well and were not observed to have wind damage from Hurricane Maria.

Figure 4-15: The Felix Pedraza Athletic Complex in Ceiba experienced cladding failures and partial failure of its MWFRS.

By contrast, several MBS athletic buildings were observed to have failed due to section loss from corrosion near the base plates of the framed buildings. (Figure 3-58, Figure 4-16). The MBS athletic facility shown in Figure 4-16, located at the high school in Ceiba, experienced a failure of part of the MWFRS at the end bay of the building. The base of the end column experienced significant section loss and failed as result. The section failed at the bolted connection, but the section also had completely lost additional web material that was observed as a hole in the web of the steel section (red arrow).

Figure 4-16: Left, the end bay of this MBS athletic facility failed when it could not resist wind pressures during Hurricane Maria. Corroded structural members, right, likely contributed to the failure. In this column, a hole had formed in the web (red arrow).

When the bases of framed buildings are not properly designed and constructed, materials can be exposed to standing water and other environmental conditions that result in degradation of structural properties. When structural members corrode or are compromised by other types of damage, they lose their ability to perform as designed and may fail.

4.4.2 Building Envelope Damage to Windows and Openings

The building envelope consists of the non-structural (components and cladding) elements of a building, including infill walls; wall cladding; roof coverings; windows; doors; and small structures attached to the building, such as penthouses and awnings. This section presents MAT observations on the performance of windows, window assemblies, and openings in school facilities.

In all schools observed by the MAT, some or all openings were designed to be less than fully enclosed, meaning they were not air- or watertight. Sealed window assemblies tested and rated to resist wind pressure and water intrusion were observed only in some portions of school buildings or not at all. The most commonly observed window systems were metal panel jalousies (Figure 4-17). The MAT observed that, in the classrooms and large open spaces of the schools, the metal panel jalousies typically had screens behind the louvers. However, in administrative offices, libraries, computer rooms, and other areas requiring air conditioning, plexiglass or plastic panels were installed on the inside of the jalousie assemblies for better control of moisture and temperature in the air-conditioned spaces. The windows along the first floor of the school shown in Figure 4-18 were backed with plexiglass panels for benefit of the laboratory classrooms. This school was used as a shelter during both Irma and Maria despite not being equipped with backup power. The school lost power during Irma and was still without power when the MAT visited in October 2017.

Figure 4-17: Metal panel jalousies at this school were backed with screens across the second-floor classrooms and with plexiglass panels on the first-floor laboratory areas.

At the schools visited by the MAT, none of the jalousie assembles had been blown out of their anchorages in the walls, although some glazed windows experienced that failure mode in both residential buildings and critical facilities. Some of the jalousies had damage from wind-borne debris impacts, but no complete failures of the jalousie assemblies were observed; this was observed even though none of the metal panel jalousies appeared to be rated for debris impact resistance (there was no testing or approval label on the assemblies). Rather, damage was primarily due to water intrusion through the jalousie panels and into the classroom, office, library, or laboratory spaces. Secondary damage was observed to the jalousies themselves; many were inoperable due to being bent or damaged from wind pressures or wind-borne debris impacts during the hurricanes.

Figure 4-18: Metal panel jalousie windows at Georgina Baquero High School, constructed in 1989. These windows are used across the entire exterior for classrooms and offices. This wing of the school was used as a shelter during Hurricanes Irma and Maria.

Rooftop skylights were observed by the MAT at several schools. Failures observed were both from wind pressures removing the windows from the roof as well as glazing breakage from wind-borne debris (Figure 4-19).

Figure 4-19: Broken skylight glazing at a high school in Canóvanas.

4.4.3 Roof Coverings

A variety of roof coverings were observed at the schools visited by the MAT, including metal panels, liquid-applied membrane over concrete roof deck, and single-ply and modified bituminous membranes. Metal panels included exposed fastener systems (corrugated metal panels and R-panels). The most common observed roof covering was modified bitumen.

Performance of the roof coverings was generally poor. While widespread delamination or blow-off was not observed, many of the roof coverings were old and at or past their design life. Old roof coverings had shrunk and separated from the roof deck and other roof materials, peeling up in multiple small areas, and had punctures from wind-borne debris. Figure 4-20 shows two views of the roof covering at the Georgina Baquero High School. This roof had a modified bitumen covering that was only two years old, according to school staff. The roof covering performed well and was reported to have no water intrusion. This was the only roof that the MAT observed that was less than 8 years old. The hot-applied flashing (Figure 4-20, right) extended from the roof surface up and over the parapet. Note the water tanks (Figure 4-20, left, red circle); wind forces broke these tanks free, and they were no longer secured to the roof structure or the piping systems of the building.

Figure 4-20: Modified bitumen roof covering at a school in Canóvanas. Left, water tanks (red circle) broke free of their attachments. Right, the roof covering is terminated and flashed on the backside of the parapet. This roof was approximately 2 years old and performed well during both Irma and Maria.

Figure 4-21 shows the roof covering at Loíza Vocational High School. This covering was eight years old and had experienced performance problems during the storm. The roof covering was punctured and had areas of separation at joints, resulting in some water intrusion through the covering. Note in Figure 4-21 (right) that the roof flashing is on the back of the parapet versus over the top of the parapet in Figure 4-20. The flashing in Figure 4-20 and Figure 4-21 remained in place during the hurricanes.

Figure 4-21: Modified bitumen roof covering at a high school in Loíza.

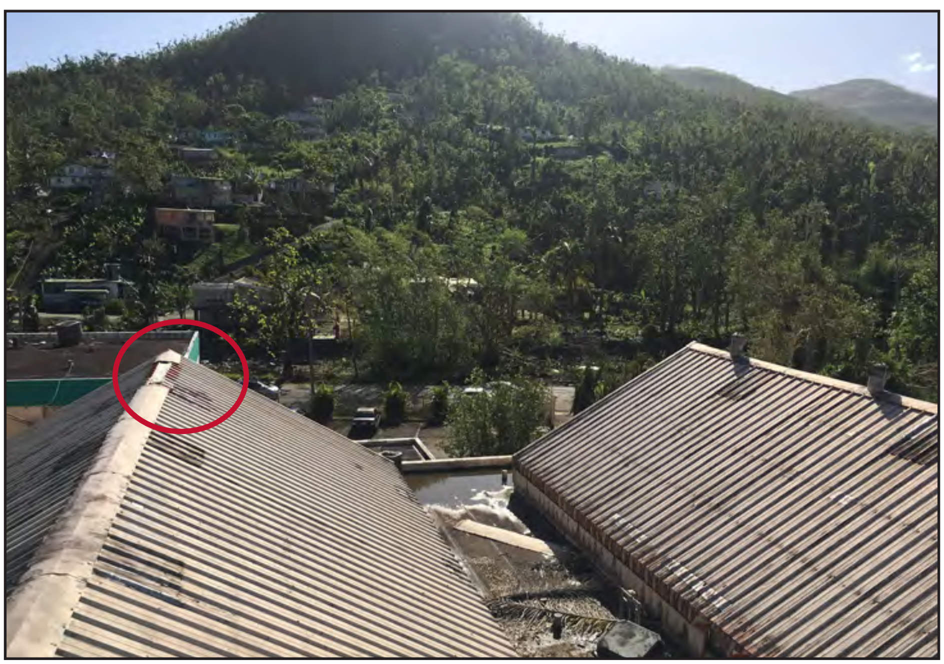
Figure 4-22 shows Jose Robles Otero Elementary School in Toa Baja. Roof damage at this school was primarily due to the loss of roof flashing (red circle). Water damage was observed related to roof flashing loss. The roof flashing was mechanically secured at the top edge of the roof and appeared to lack adequate fasteners to resist wind uplift. School staff indicated there was no flood damage to the school during Irma nor Maria, but the facility did lose power. Additional roof damage at the school included the failure of a metal awning (Figure 4-23).

Figure 4-22: Jose Robles Otero Elementary School. Left, façade; right, roof with lost flashing (red circle).

Figure 4-23: Collapsed awning from wind uplift at Jose Robles Otero Elementary School

Several campuses visited by the MAT had buildings with metal panel roof coverings. These coverings were observed to be part of MBS used at the sites. These panel roof systems performed reasonably well when properly secured to the roof purlins or roof decking. Figure 4-24 shows MBS buildings used for classrooms at Eduardo Garcia Carrillo High School in Canóvanas. The panels at this school were well secured; however, trim and ridge caps were not (red circle). In several locations these ridge caps blew off, leading to significant water intrusion into the classrooms below.

Figure 4-24: Older MBS at Eduardo Garcia Carrillo High School in Canóvanas. These roofs performed well except for ridge cap loss and damage from falling trees.



Culebra Ecological School also used a metal panel roof system (Figure 4-25). While most of the roof was not damaged, several areas did experience damage. This school, constructed after Hurricane Georges on Culebra, is located within 1,500 feet (460 meters) of the coast and exhibited notable corrosion that affected roof performance. In addition to the weakening of roof elements due to corrosion, the metal panel roof covering experienced damage at some locations along the edge zones of the roof. This roof damage appeared to be because of inadequate fasteners on the roof. Figure 4-25 (left) shows where the roof performed well and where the edges of the roof panels were secured by two rows of fasteners (blue arrows). In contrast, Figure 4-25 (right) shows where the roof panels failed, resulting in water intrusion and damage to the adjacent photovoltaic (PV) panels. The roof panels in this location had only one row of fasteners along the roof edge (red arrow). This school also functioned as the main shelter in Culebra and was used during both Irma and Maria.

Figure 4-25: Roof covering with two rows of connections near edge of roof covering, left, performed better than roof covering with only one row of connections near edge, right.

The Palmas Academy in Palmas del Mar (Figure 4-26) was the only school the MAT observed with a tile roof covering. This school had a combination of tile roof coverings and modified bitumen on the flat roof sections. The tile roof covering did not perform well, and in many locations the tile covering was lost; however, the MAT could not determine if the tile failed from wind pressures or wind-borne debris impact.

Figure 4-26: Tile roof failure at The Palmas Academy in Palmas del Mar.

4.4.4 Rooftop Equipment

The MAT observed that rooftop equipment had variable performance. While some systems were anchored and remained in place during the hurricanes, many equipment pieces did not. Failures of three types were observed: failure of the equipment itself, failure of support stands or curbs, and failure of guy wires. Failure of the equipment itself caused not only loss of the mechanical units but water intrusion into the building from the failed equipment. This type of failure was observed at The Palmas Academy (Figure 4 27, left) and Loíza Vocational High School (Figure 4-27, right).

Figure 4-27: Two examples of rooftop equipment failure that allowed water to enter the building. Left, wind removed an HVAC unit access panel at The Palmas Academy. Right, a toppled vent stack (yellow arrow) allowed water intrusion into the building (red arrow) at Loíza Vocational High School.

Many rooftop equipment units were observed to have blown off their curbs or stands on the roof. Figure 4-28 (left) shows parapet walls at Jose Robles Otero Elementary School that were meant to block the wind and help protect this rooftop unit; however, most units at this school did not have parapet walls and were simply blown off curbs and stands to which they had been inadequately secured.

Figure 4-28: Left, Jose Robles Otero Elementary School had concrete walls that may have shielded rooftop equipment from wind. Right, small rooftop equipment at Eduardo Garcia Carrillo High School in Canóvanas was not properly secured and was displaced by wind forces from Maria.

Some schools provided additional tie-downs for rooftop equipment with guy wires (Figure 4-29). The failed connectors can be seen at the bottom left of the photo. The fasteners used on the guy wires were not stainless-steel connectors. While these connectors were less than 10 years old, they failed due to corrosion. Building materials, especially connectors, are vulnerable to corrosion and premature failure when used near the coast. This school is located less than one mile (1.6 kilometers) from the ocean.

Figure 4-29: Vent stacks secured with guy wires at Loíza Vocational High School were toppled by high winds when the threaded adjustment connectors failed due to corrosion, leading to water intrusion in the building.

4.5 School Facilities Used as Event-Specific and Post-Event Shelters

The PRDOH manages and maintains the primary program for identifying and managing hurricane evacuation shelters across the Commonwealth. The program evaluates and tracks buildings and facilities to be used as "event-specific" shelters and post-event shelters. Assessments are conducted on a yearly basis by representatives from PRDOH, PRDE, and the Puerto Rico State Agency for Emergency and Disaster Management (Agencia Estatal para el Manejo de Emergencias y Administración de Desastres, informally the Puerto Rico Emergency Management Agency [PREMA]). Prior to Hurricanes Irma and Maria, PRDOH evaluated 499 buildings and facilities for use as event-specific and post-event shelters. From this group of identified buildings, 383 school buildings had been evaluated and identified for use as event-specific shelters. These event-specific shelters or hurricane evacuation shelters are buildings, or portions thereof, to be used during a storm to provide refuge for the residents of a municipality during a hurricane or major storm event.

However, of all the buildings in the PRDOH shelter inventory, none of the shelter facilities (or portions of facilities) were purpose-built safe rooms or storm shelters defined by the FEMA P-361 criteria or the ICC 500© standard, respectively.

4.5.1 School Shelter Performance

The MAT visited three schools that were used as shelters or were on a primary or secondary shelter list maintained by PRDOH:

1) Georgina Baquero High School, Canóvanas (constructed in 1989)
2) Culebra Ecological School, Culebra (constructed in the early 2000s after Hurricane Georges)
3) Vocational High School, Loíza (constructed in 2010)

SHELTERS AND AREAS OF REFUGE

Chapter 2 presented the terms Safe Rooms and Storm Shelters to refer to purpose-built buildings (or portions thereof) designed to provide life-safety protection during hurricanes. However, there are different uses of the word "shelter" in emergency preparedness and emergency response. In Puerto Rico, PRDOH works with PRDE and the municipalities to identify school buildings to be used by residents who do not want to stay in their homes during a storm event and to come to after a storm event if their homes have been damaged.

While these buildings provide an organized location to take refuge from the storm with some emergency services such as food, water, and cots to sleep on, it should be noted that the buildings identified as shelters were not designed or constructed to provide life-safety protection from flood or wind events. Further, these facilities are assessed for the ability to support the operations, the facilities in the DOH shelter program are only evaluated with a minimal assessment, and in most cases, the structural systems and the building envelope systems have not been evaluated for their vulnerability or susceptibility to damage from flood waters, extreme winds, or wind-borne debris. The presumption that these larger buildings, or public buildings, will perform better during hurricanes and tropical storms may be incorrect for several reasons. If the building has not been evaluated for its ability to resist flood and wind loads without damage or collapse, the ability of the shelter to provide a safe area of refuge cannot be defined or confirmed prior to a storm event.

These emergency shelters, recovery shelters, and post-event shelters are simply a place of refuge and should not be considered to be able to provide the same level of protection as a FEMA 361 Safe Room or an ICC 500 ©compliant storm shelter. Guidance from FEMA can be applied to evaluate buildings proposed for use as shelters or at least to provide a best available refuge area when a storm approaches.

4.5.1.1 Georgina Baquero High School, Canóvanas

Numerous classrooms at this high school in Canóvanas were designated for shelter use by PRDOH and used during both Hurricanes Irma and Maria (Figure 4-30). While the concrete walls and roof of this building provided some level of protection for the occupants, the facility was not designed for life-safety protection and was not supported by a backup or emergency generator. No generator was present on-site, and there is no pre-wired connection panel to connect to a temporary backup generator. Power was lost during Hurricane Irma, and despite this, the school was operated as a shelter during both events. The metal panel jalousies on all exterior windows were not designed or rated to provide debris impact protection and were also the failure points for the building envelope that allowed water intrusion into the shelter spaces.

Figure 4-30: Exterior view of classrooms used for shelters at the high school in Canóvanas.

4.5.1.2 Culebra Ecological School, Culebra

This school (Figure 4-31) was constructed after Hurricane Georges and was designated for use as a shelter by PRDOH. Its identified shelter space was used during both Irma and Maria. This facility was also used as a medical shelter, although critical and pregnant patients were evacuated to the island of Puerto Rico prior to the hurricanes. Several classrooms were used as shelter areas, but the large gymnasium was not.

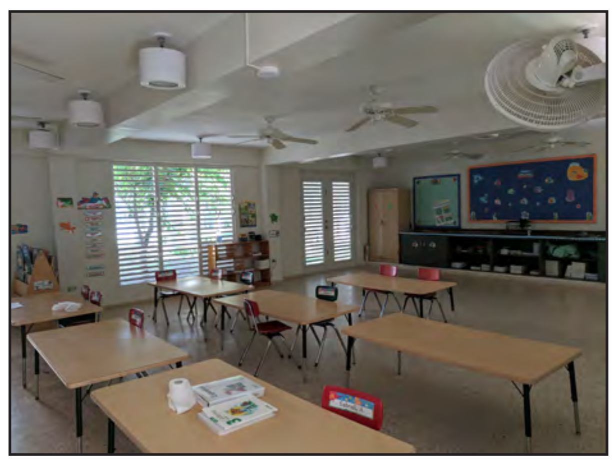


Figure 4-31: Left, multiple rooms within the gym building was used for sheltering during both Hurricane Irma and Maria.

On September 5, before Irma's landfall, PRDOH representatives surveyed the school and designated five classrooms and one room in the gym building for shelter use. One classroom was utilized for hospital patient sheltering. The shelter received an additional backup generator from the U.S. Army Corps of Engineers (USACE), as it was known to be the only community shelter on Culebra. A portable generator from Culebra Community Health Center was brought to the school to provide power for medical equipment. The original generator installed during construction for water and waste water was not operational during the hurricanes, although it was operational during the October MAT site visit.

While the school was able to reopen two days after Hurricane Irma, it had not yet reopened after Hurricane Maria when the MAT visited in October. Water intrusion through jalousie windows were observed in designated shelter areas.

4.5.1.3 Loíza Vocational High School, Loíza

This school (Figure 4-11), constructed in 2010, was designated a second-tier shelter and was not utilized during Irma or Maria. The school consists of two-story reinforced concrete-framed buildings, and the classrooms have been identified by PRDOH for shelter use should the school be activated for such purposes. During the site visits, the MAT was informed that the school has a generator but that it is managed by the municipality and it was not used since Maria made landfall. At the time of the site visit in October, the generator was not working. It had been turned on to provide power to the school so that the school could reopen for class but failed the first day it was operating. It is unclear why the generator was not used prior to that point so the facility could have been used as a shelter during the hurricanes.

4.5.2 Department of Housing Shelter Program

When a storm threatens, PRDOH, PRDE, and PREMA work together to confirm the designations of event-specific shelters and post-event facilities; municipalities then open and operate the facilities. After Hurricane Maria made landfall, 257 event-specific shelters were open and in operation across all 78 municipalities.

While none of these facilities were designed to meet the FEMA P-361 criteria or ICC 500 standard for life-safety protection, residents who chose to evacuate their homes took refuge in these facilities during the storm. While the best solution is to direct residents seeking shelter during storms to safe rooms and storm shelters specifically designed and hardened to provide life-safety protection from wind, wind-borne debris, flooding, and other hazards, the current program identifies available public buildings for use as refuge areas.

4.5.3 Considering Sheltering During School Consolidation

The Government of Puerto Rico, PRDOH, and PRDE are evaluating a number of facility programs after the 2017 hurricane season. One of these programs is related to the inventory of school buildings across Puerto Rico. The government has stated that it is considering a consolidation (PRDE 2018a) that would reduce the number of schools from its current total of approximately 1,100 to 855 to address population changes and financial challenges (PRDE 2017, PRDE 2018b). This presents an opportunity to consider flood, wind, and seismic vulnerabilities when choosing schools to close.

Understanding the effects that floods, hurricanes, and earthquakes can have on public school facilities can also help guide other decisions related to future building use. School districts can use these assessments to close highly vulnerable schools through consolidation, then determine what grant programs may be available for mitigation projects on remaining schools to reduce the impacts from natural hazards and allow schools to reopen sooner after major events.

THE BEST AVAILABLE REFUGE AREA CONCEPT

The term "best available refuge area" (BARA) refers to an area in an existing building that has been deemed by a registered design professional to be likely to protect building occupants during an extreme-wind event better than other areas in the building when a safe room is not available. The BARA should be regarded as an interim measure to be used until a FEMA-compliant safe room or ICC-500 compliant storm shelter can be made available.

FEMA developed the Best Available Refuge Area (BARA) concept and checklist for the first edition of FEMA P-361 to use in assessing a building's susceptibility to damage from extreme-wind events such as tornadoes and hurricanes. The checklist evaluation process guides registered design professionals (architects and engineers) in identifying potential refuge areas at a site with one or more buildings.

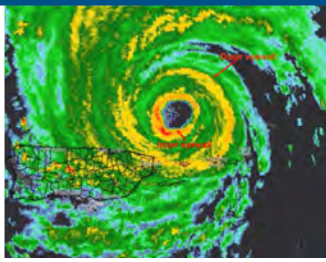
In addition, some school facilities could be identified as BARAs or retrofitted to meet the requirements of ICC 500© for a storm shelter providing life-safety protection for residents during storms. If a school building can be retrofitted to meet ICC 500© storm shelter requirements, or an addition or new building can be constructed on an existing campus, it will provide a great service to the municipality. The municipality, PRDOH, and PRDE could work together to best judge the needs and resources of specific municipalities and whether a building is best suited as a dual-use school and shelter or if it could be used as a multi-use public building and shelter.

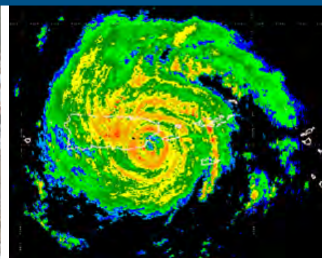
4.6 Residential Safe Rooms and Storm Shelters

The only residential (in-home) safe rooms observed by the MAT in Puerto Rico were identified on the island of Culebra; no other residential safe rooms meeting FEMA P-361 criteria were made known to the MAT. FEMA records indicate that five detached, residential safe rooms were constructed in 2004. These safe rooms were designed and constructed using funding from the FEMA Hazard Mitigation Grant Program (HMGP) after Hurricane Georges.

The MAT observed no damage to any of the residential safe rooms on Culebra following Hurricanes Irma and Maria. However, some had been extensively modified to allow for air ventilation for sleeping and cooking, modifications which increased the vulnerabilities of the buildings. Although no damage was observed, these buildings no longer comply with FEMA P-361 and cannot perform the intended purpose of near-absolute life-safety protection of its occupants. Some safe rooms were in locations with heavy vegetation and appeared poorly maintained. In Figure 4-32, the home around the safe room was damaged.

Figure 4-32: This detached residential safe room funded through HMGP in Culebra was modified into a studio/efficiency apartment and no longer complies with FEMA P-361 criteria. Modifications included additional openings which reduced the level of protection provided by the building.




HURRICANES
IRMA AND MARIA
IN PUERTO RICO

5 Performance of Hospitals, Public Buildings, and Mid-Rise Buildings

This chapter provides the MAT's observations on a variety of low- and mid-rise public buildings. Buildings in this chapter, including police stations, fire stations, other government buildings, and hospitals, are often of vital importance to communities affected by a disaster.

The facilities discussed in this chapter are shown in Figure 5-1. The figure includes four fire stations, three police stations, six public facilities, and five hospitals.

Figure 5-1: Fire stations, police stations, other public buildings, and hospitals visited by the MAT and discussed in this report.

5.1 Hospitals

Hospitals played a critical role while facing major challenges in response to Hurricane Maria. Even as businesses and other public facilities closed ahead of the storm, demand for healthcare services continued. Because Hurricane Maria affected nearly all of Puerto Rico, individual hospitals did not have the option to relocate their patients to other facilities until the storm passed. Yet, hospitals often suffered the same types of damage that affected other buildings. High-speed winds and wind-driven rain damaged hospital facilities, while prolonged power outages impeded services and threatened stores of medicines. Many hospitals suffered extensive physical damage that resulted in complete loss of function. Others worked to continue life-saving care in the face of frequent power outages, limited supplies, and limited usable space. The MAT visited several hospitals and healthcare facilities shortly after the storm to observe facility performance and assess lessons learned for future mitigation.

In October and December 2017, the MAT visited five hospitals in Puerto Rico to evaluate damage and gather information, three on the north side of the island of Puerto Rico, one on the island of Vieques, and one on the island of Culebra:

- Pavia Arecibo Hospital, Arecibo
- Dr. Ramon Ruiz Arnau University Hospital, Bayamón (University Hospital)

- San Juan University Pediatric Hospital, San Juan
- Susana Centeno Family Health Center, Vieques
- Culebra Community Health Center, Culebra

Hospitals are unique critical facilities that generally require some level of continuous operation. During storms, the buildings function not only to allow treatment of patients but to protect valuable equipment, supplies, and medicines needed during recovery. Some facilities can scale down operations ahead of time by cancelling elective procedures, limiting non-emergency cases, and sheltering patients and equipment in place. These strategies only apply to specific levels of service, however. Other functions, such as critical patient care, continuous treatment, and preservation of temperature-dependent medicines, cannot be stopped entirely without severe consequences. The MAT recognizes these inherent complexities and strives to best evaluate building performance, vulnerabilities, and damage along with related infrastructure challenges that can prevent a hospital from completing its mission. The MAT's goal is to provide information on building limitations and vulnerabilities to hospital operators, administrators, and medical staff so that they understand how their operations may be impacted and can plan and execute accordingly.

5.1.1 Summary of Building Performance

Overall, the hospitals in Puerto Rico experienced high levels of roof membrane failures, building envelope failures, wind-driven water intrusion, rooftop equipment damage, and wind-borne debris failure. Much of this affected the usage of space and systems, prompting temporary closures and operational workarounds. Access to stable electrical power became a major challenge for most facilities. Infrastructure damage was widespread, and its lasting impacts became apparent in the weeks and months following the storm. Most hospital facilities were not outfitted with emergency and backup generators designed to provide power for full facility operation for extended periods in the order of months. As time progressed, hospitals lost main, standby, and backup power as equipment became stressed beyond its duty cycle. Fuel demand also became a limiting factor, with full demand consumption rates requiring fuel deliveries as often as every four days. Without power, many critical functions of the hospitals were only intermittently available. Physical damage and the lack of electricity also limited the use of elevators, which are essential for treatment and evacuation of patients who cannot walk. Such limits to mobility further hindered the efforts of hospital staff who may already have been limited to using some portion of a facility.

While damage was often severe, the MAT also observed successful practices that mitigated impacts and assisted in recovery. The following section highlights instances when preparatory steps, operational planning, siting, design, and due diligence in construction helped facilities continue their care. The comparison of these relatively successful and unsuccessful practices can inform ongoing rebuilding efforts and long-term investment strategies.

The most common impacts to hospitals were as follows:

- Water intrusion through the roof, windows and rooftop equipment
- Damage to rooftop equipment

- Loss of power with loss of supported equipment due to
  - Loss of grid power
  - Failure of the hospital's backup and emergency generators
  - Failure of externally supplied emergency generators
- Loss of vertical transportation due to
  - Water intrusion into the mechanical penthouses and controls
  - Water intrusion into the elevator cab and the cab controls
  - Damage to elevator motors and controls from power surges

5.1.2 Performance Relative to Flood

Most of the observed damage to hospitals was from wind and wind-driven rain. The hospitals were typically well sited outside of floodways and SFHAs shown on FIRMs. Of the four hospitals assessed by the MAT, none are in an SFHA according to the effective FIRM nor the Advisory Data, and none were impacted by coastal flooding during Irma or Maria. There were instances of poor site drainage at hospitals that lead to local flooding of areas of their campus, such as at Dr. Ramon Ruiz Arnau University Hospital, where the loading dock was inundated to a depth of 4 feet when area drains were overwhelmed.

5.1.2.1 Coastal Flood Impacts

None of the hospitals visited by the MAT were impacted by coastal flooding during Hurricanes Irma and Maria. The closest hospital to the coast, Pavia Arecibo Hospital (Figure 5-2), is 0.4 miles (0.8 kilometers) south of the north shore of the island of Puerto Rico and 0.25 miles (0.4 kilometers) west of an advisory floodplain drainage basin for a portion of the Arecibo River, as noted on the effective FIRM (Figure 5-3). This places the hospital outside the effective and advisory flood zones and away from storm surge effects while giving access from major roads to the south and west. The hospital did not receive coastal or stream flooding from Irma or Maria.

Figure 5-2: Pavia Arecibo Hospital.

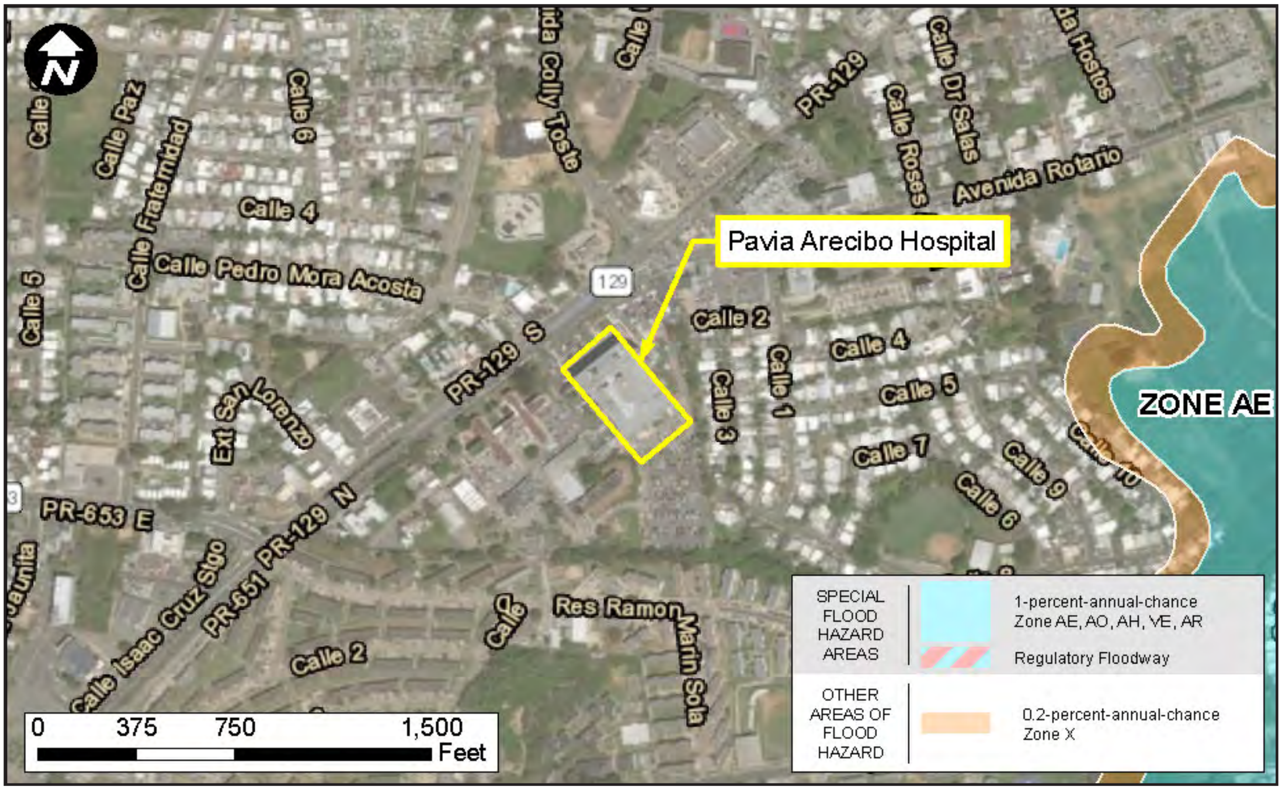


Figure 5-3: A portion of the effective 2009 FIRM showing Pavia Arecibo Hospital in Zone X, an area of minimal flood hazard.

5.1.2.2 Inland Flood Impacts

Dr. Ramon Ruiz Arnau University Hospital is located 6 miles (10 kilometers) south of San Juan Bay and is well inland (Figure 5-4). The hospital is located approximately 120 feet (37 meters) above sea level and is outside the effective and advisory flood zones. It did not receive coastal or stream flooding from Irma or Maria.

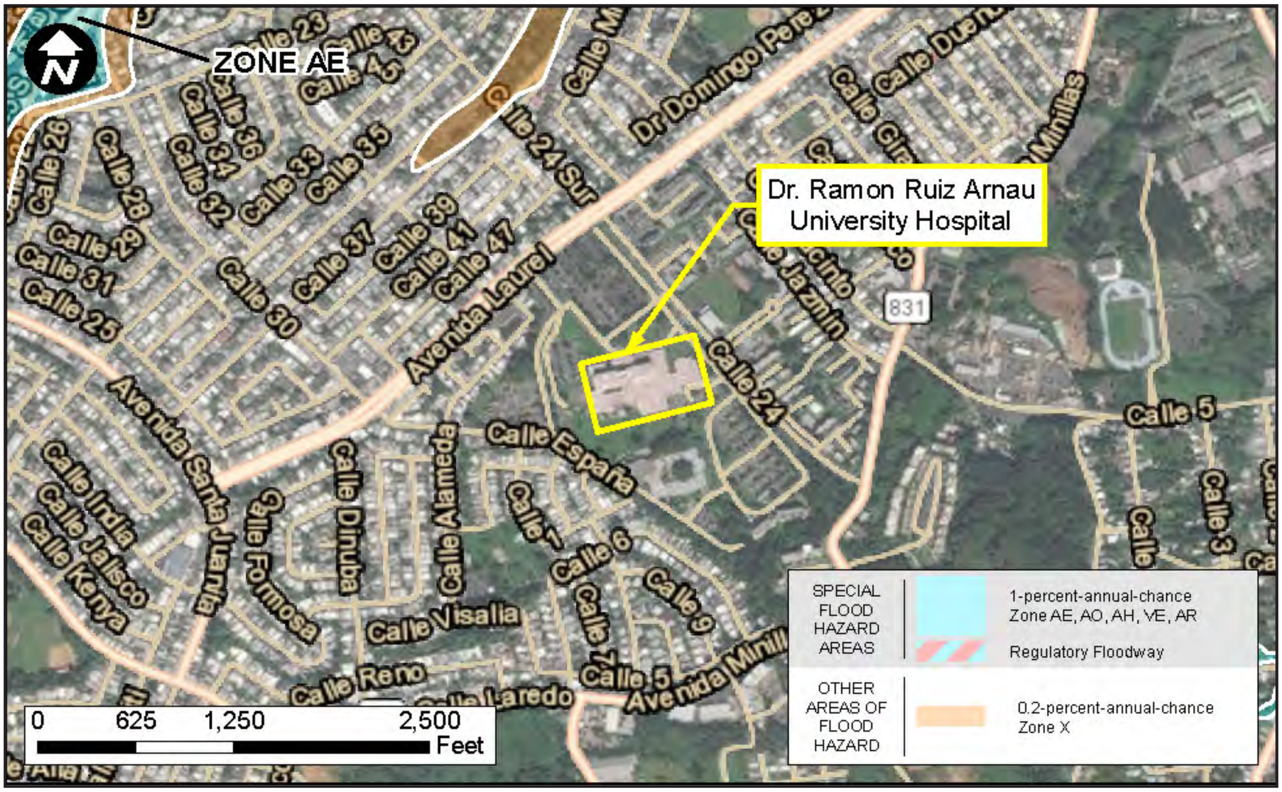


Figure 5-4: A portion of the effective 2009 FIRM showing Dr. Ramon Ruiz Arnau University Hospital, Bayamón, in Zone X.

The generator and fuel tanks for Dr. Ramon Ruiz Arnau University Hospital are behind the building (Figure 5-5). This area is in a depression below the surrounding grade, and storm water must be collected by drains and moved through storm sewer pipes to be removed from the dock area. During the hurricane, surface runoff overwhelmed the area's drains (Figure 5-6) and piping capacity. Water flooded the loading dock to a depth of 4-5 feet (1.2-1.5 meters), reaching the bottom of the generator frame and fuel storage tank.

Figure 5-5: Dr. Ramon Ruiz Arnau University Hospital lower loading dock, which flooded from surface runoff, showing approximate high water level (red line), backup generator (red arrow), fuel tank (blue arrow), trailer mounted generator (yellow arrow), and propane tank (green arrow).

Figure 5-6: The loading dock area at Dr. Ramon Ruiz Arnau University Hospital flooded when the area drains (red arrow) were overwhelmed by surface runoff.

San Juan University Pediatric Hospital (Figure 5-7 and Figure 5-8) is located well inland, 3 miles (4.8 kilometers) southeast of San Juan Bay and 4 miles (6.4 kilometers) south of the island's north shore. This places the hospital outside the effective and advisory flood zones, and it did not receive coastal or stream flooding from Irma or Maria. The hospital is approximately 80 feet (24 meters) above sea level.

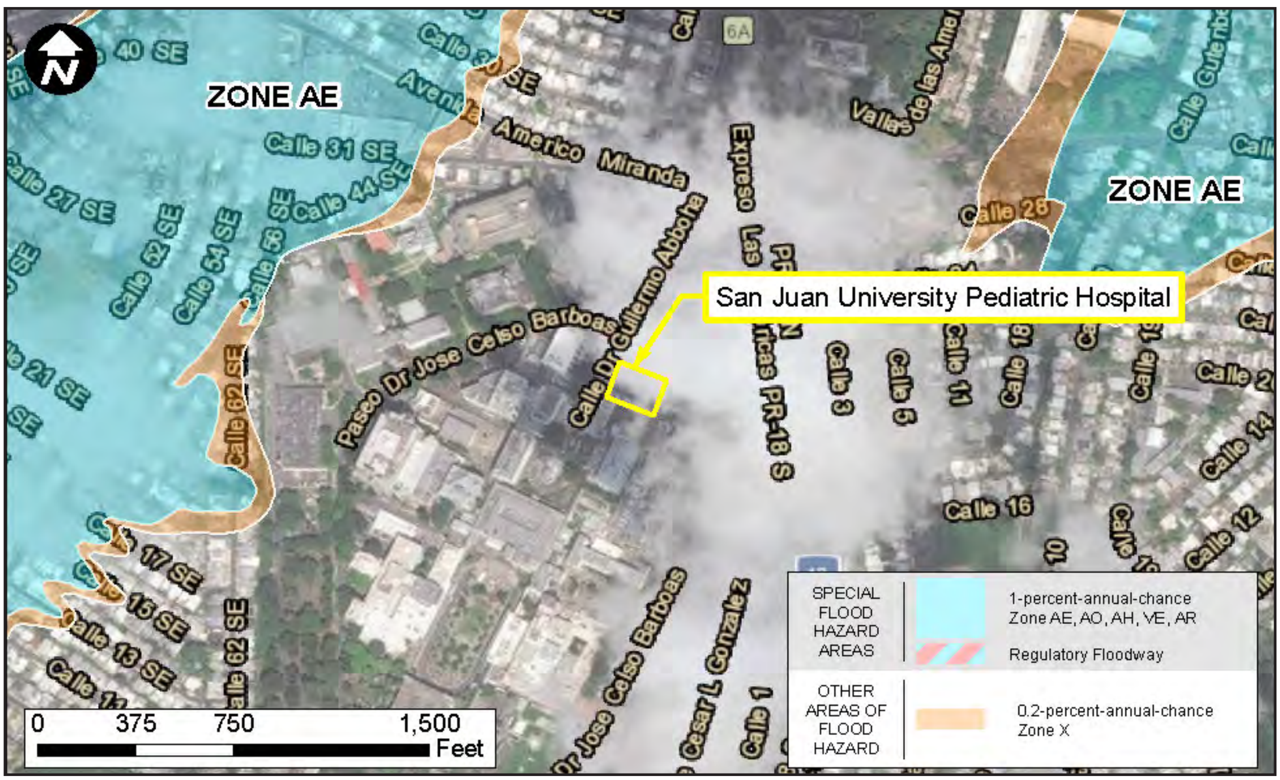


Figure 5-7: Location of San Juan University Pediatric Hospital in Zone X, an area of minimal flood hazard, on the effective FIRM.

Figure 5-8: View of the front entrance of the San Juan University Pediatric Hospital.

Susana Centeno Family Health Center is roughly in the center of the island of Vieques, in an X Zone (Figure 5-9). This places the hospital outside the effective and advisory flood zones, and it did not receive coastal or stream flooding from Irma or Maria.

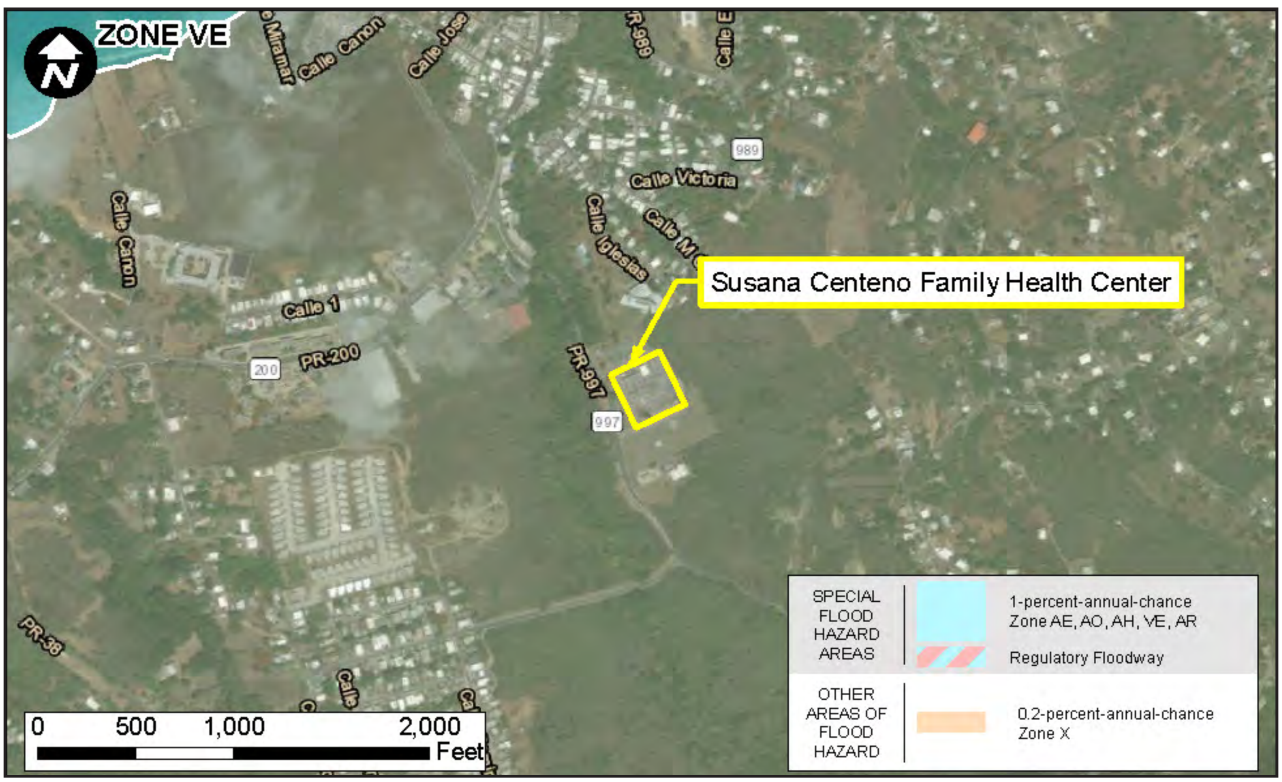


Figure 5-9: A portion of the effective 2009 FIRM showing Susana Centeno Family Health Center in an X Zone.

5.1.3 Performance Relative to Wind

Building performance in high winds depends on the performance of the MWFRS and the building envelope, the latter including openings and the roof covering.

5.1.3.1 Main Wind Force Resisting System

The main structural systems of hospitals performed well during the hurricanes with no observed damage or failures of elements of the MWFRS. Based on the visual assessments conducted by the MAT in October and December 2017, there was no structural damage to the roof decks or any structural elements from the wind events.

5.1.3.2 Openings

Building openings suffered in varying degrees from modest to severe damage. Nearly all the hospitals had some window damage, with San Juan University Pediatric Hospital and Culebra Municipal Health Center having the least. Pavia Arecibo Hospital had several windows breached and blown in, Dr. Ramon Ruiz Arnau University Hospital had an entire row of windows pulled out of the building, and the Susana Centeno Family Health Center had substantial water enter through windows and roof leaks (Figure 5-10).

Figure 5-10: Susana Centeno Family Health Centers in Vieques.

Pavia Arecibo Hospital has a tower section to the north and a low-rise section to the south. The tower section saw window damage from pressure on the sixth floor. Combined with roof covering damage, this led to water intrusion that damaged sections of the drop ceilings on the fourth and sixth floors. In the fourth-floor intensive care unit, a portion of the drop ceiling collapsed, a window was breached, and glass doors that served the helipad were blown out. Some of the first-floor windows and shutters were damaged. Some windows had no glazing protection (Figure 5-11). The first-floor medical records department lost entire windows when wind pressure forced glazing out of window frames and the window frames out of their rough openings in the wall (Figure 5-12). Wind-driven rain entered the mechanical penthouse through ventilation louvers; this water intrusion caused the elevators to fail.

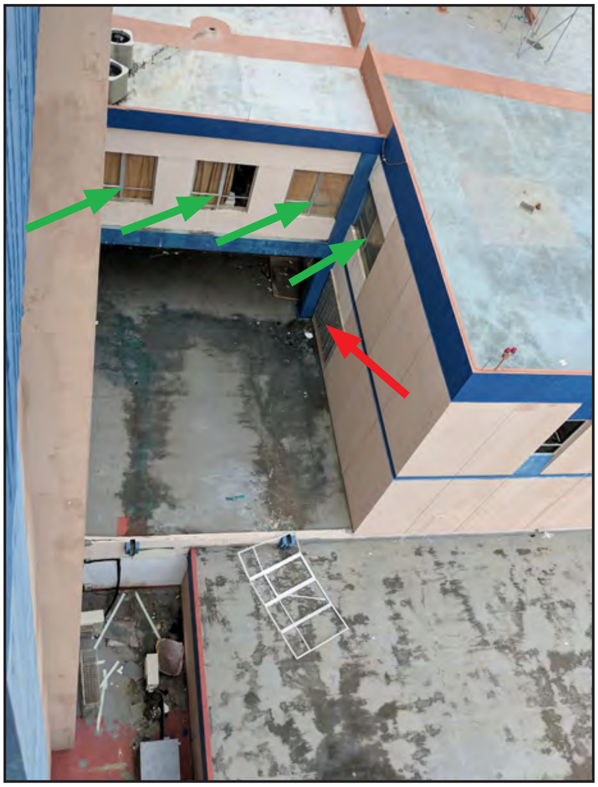


Figure 5-11: This view of Pavia Arecibo Hospital shows that some windows had glazing protection (red arrow) while others did not (green arrows).

Figure 5-12: At Pavia Arecibo Hospital, a window frame was pulled out of the building (green circle). The frame was inadequately anchored to the wall opening.

Figure 5-13: Rain water from the fourth floor of Dr. Ramon Ruiz Arnau University Hospital, Bayamón, migrated to the lower floor through floor penetrations and inundated numerous systems including electrical conduits and communications boxes (green arrow).

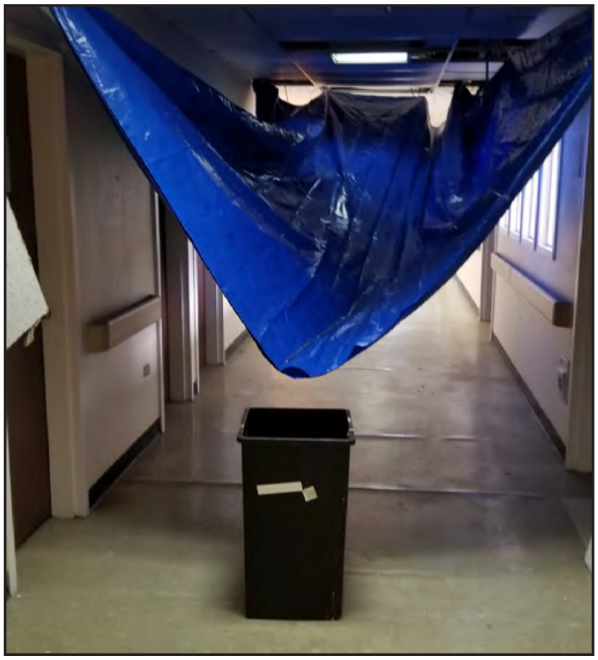


Figure 5-14: Water infiltrated the floors below and was captured to minimize further damage at Dr. Ramon Ruiz Arnau University Hospital.

Dr. Ramon Ruiz Arnau University Hospital had numerous wind failures during the storm, introducing wind and wind-driven rain into the building. While the fourth floor was out of service at the time of the storm, water that reached the fourth floor was able to leak into the operational third floor through floor penetrations (Figure 5-13 and Figure 5-14). Rainwater entered the hospital through gaps around the window frames and through poor window-to-frame connections which led to entire window frames being pulled out of the wall (Figure 5-15 and Figure 5-16). Only two fasteners could be seen restraining the missing 25-foot (7.6-meter) section of a lower window frame (Figure 5-17).

Figure 5-15: View of central section of Dr. Ramon Ruiz Arnau University Hospital showing broken windows as well as entire window and frame missing from wall (red circle).

Figure 5-16: A 25-foot (7.6-meter) section of window and frame are missing from the fourth-floor wall of Dr. Ramon Ruiz Arnau University Hospital (red arrow).

Figure 5-17: Only two fasteners were observable restraining the lower section of the missing 25-foot (7.6-meter) section of window system at Dr. Ramon Ruiz Arnau University Hospital (red arrows).

At San Juan University Pediatric Hospital, debris impacts broke several windows, and several others leaked. None of the windows have storm shutters. It is not known if the windows are impact-rated. The windows flexed and moved, breaking the seals with the frames and walls and allowing wind-driven rain to enter the building. The building's stucco coat was also compromised, allowing water to enter the envelope through cracks and spalls. Broken stucco also became debris for lower floors.

The Susana Centeno Family Health Center did not appear to experience structural failures in the walls or roof deck. However, there was significant water intrusion through windows and through the roof deck after the built-up roof covering was damaged and punctured by wind-borne debris. While all glazed windows and doors had window shutters installed, several windows and doors were damaged or broken because of improper deployment of the shutter systems.

The exterior walls of the Susana Centeno Family Health Center appeared to weather the storms with minimal damage from wind pressure and debris impact. The windows and doors of the facility had variable performance: Most were not broken or damaged, as all glazed windows and most glazed doors were protected by accordion shutter systems. However, there were problems with the installation and maintenance of the shutter systems. Figure 5-18 illustrates several problems related to the deployment and maintenance of storm shutter systems. Note also the metal panel jalousie window in the center of the wall that is not protected against water intrusion or debris impact. Proper maintenance and operations procedures, including periodic shutter deployment exercises, could have proactively identified these problems that prevented full deployment of the building's shutters.

Figure 5-18: Successes and problems related to installation of shutter systems over glazed doors and windows, including a shutter system properly installed (green arrow), a shutter system with a track missing at a glazed door (red arrow), a window air conditioning unit preventing a shutter being deployed (orange arrow), and a pair of glazed doors without glazing protection (yellow arrow).

The windows and doors around the facility allowed entry of wind-driven rain, which wetted the interior of the building. This wetting combined with a loss of power after the hurricanes resulted in mold and poor air quality throughout the facility.

5.1.3.3 Roof Coverings

Failures of roof coverings and resulting water intrusion were primary causes of severe damage and loss from the hurricanes. The MAT encountered membrane roof systems as well as single-ply and modified bitumen roof membranes. Performance of the roof coverings was typically poor, with some hospitals experiencing near complete blow-off, while other experienced multiple punctures.

DESIGNING SAFER HOSPITALS

FEMA 577 *Design Guide for Improving Hospital Safety in Earthquakes, Floods, and High Winds: Providing Protection to People and Buildings* (FEMA 2007) has information on the variety of vulnerabilities faced by hospitals exposed to earthquakes, flooding, and high-winds risks, as well as the best ways to mitigate the risk of damage and disruption of hospital operations caused by these events. Although not a comprehensive mitigation design manual, it introduces the fundamental principles of natural hazard risk reduction, with an emphasis on mitigation planning and the design of hospital buildings. The guide is available at https://www.fema.gov/media-library/assets/documents/10672

The roof covering at San Juan Pediatric Hospital had minor damage and was essentially intact but developed leaks during the extended period of heavy rainfall and high winds.

Pavia Arecibo Hospital suffered roof damage that caused interior ceilings to collapse. Damage included lost roof sealant/membranes, roof and window damage on the sixth floor, and damage to sections of drop ceilings on the fourth and sixth floors. In the fourth-floor intensive care unit, a portion of the drop ceiling collapsed, and a window was breached from wind pressure. Also, one HVAC unit was displaced by the high winds partially as a result of salt spray and corrosion damage.

Dr. Ramon Ruiz Arnau University Hospital performed well structurally, but the building envelope suffered substantial breaches, including roof breaches. The membrane covering the central section peeled off, exposing most of the cap sheet and allowing water to infiltrate the floors below (Figure 5-19). The single-ply membrane tore free from its mechanical fasteners (Figure 5-20). At the time of the MAT visit in October, the hospital was waiting for emergency roof coverings to be deployed.

Figure 5-19: The roof membrane over the central section of Dr. Ramon Ruiz Arnau University Hospital peeled off over most of the roof, allowing water intrusion into the floors below.

Figure 5-20: The roof membrane at Dr. Ramon Ruiz Arnau University Hospital tore free from its mechanical fasteners.

The Susana Centeno Family Health Center's roof covering appeared to be the original roof coverings installed during construction. The roof covering stayed in place but developed leaks from a number of punctures across the roof likely caused by debris. Some of the debris may have come from failure of a solar array on the east corner of the roof (section 6.2.3.1). However, much of the debris was likely generated from homes on the hillside above the facility that were damaged during the storm. While the roof covering did not peel away, it was punctured and damaged. The built-up roof materials had large impact holes through the roof cover and the supporting insulation. This resulted in the insulation becoming exposed and saturated by the rain from the event. Figure 5-21 shows one of the larger holes in the roof covering caused by wind-borne debris. The hospital staff stated there were multiple roof leaks (with additional water infiltration through the windows and doors), but no tarps or patches were observed covering the holes in the roof during the December site visit (Figure 5-22). Rapidly repairing this type of damage is vital for disaster recovery and preventing further damage.

Figure 5-21: Roof covering puncture at Susana Centeno Family Health Center.

Figure 5-22: View across the roof of Susana Centeno Family Health Center, looking south.

Culebra Community Health Center had two wings, each with a metal gable roof. The roof of the surgery wing experienced some water intrusion (Figure 5-23).

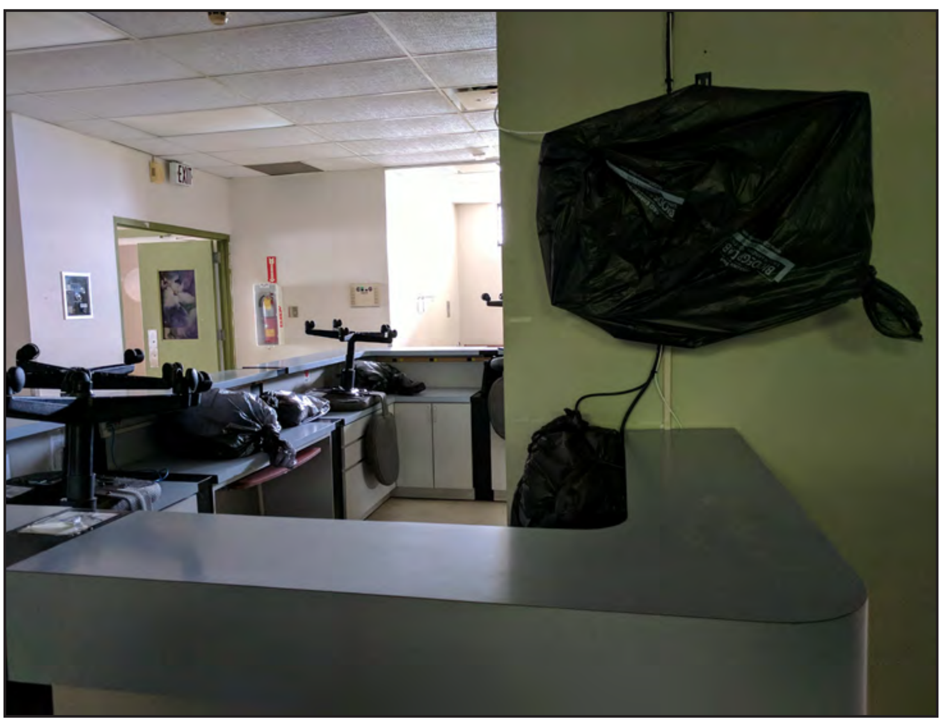


Figure 5-23: Interior of the Culebra Community Health Center, which experienced water intrusion through the roof.

5.1.3.4 Rooftop Equipment

Rooftop equipment was commonly damaged by the high winds, frequently when it was tipped over or otherwise displaced. Connectors that secured equipment were often broken. Some connectors had been weakened by corrosion. Using more and larger fasteners and connectors, and using fasteners and connectors made from corrosion-resistant materials, can reduce this kind of damage. Greater numbers of fasteners will assure redundancy, while larger fasteners will provide more sacrificial material as the elements are consumed by the environment. Using corrosion-resistant materials such as stainless steel, brass, or silicon bronze will slow the rate of corrosion, though they will not stop it.

Pavia Arecibo Hospital is relatively close to the coast (0.4 miles [0.6 kilometers]) and had considerable corrosion of rooftop equipment and connectors. Proximity to the coast exposes the hospital to salt spray. The aggressive environmental effects had pronounced impacts on rooftop structures including vents, frames, and rooftop mounted air conditioning units (Figure 5-25). Several pieces of rooftop mechanical vents and equipment were blown off their mountings during the storm (Figure 5-24 and Figure 5-25), including two 7.5-ton-capacity vents and one 5-ton-capacity HVAC unit with two complete condensers. The connections to their mounts were inadequate and weakened by corrosion. These fasteners and connections failed after being overstressed. The rooftop HVAC serving the lower section was also damaged, as were rooftop vents. Lightning protection systems and antennas found on the roof appeared to be undamaged from the winds.

Figure 5-24: Damage to rooftop HVAC equipment at Pavia Hospital Arecibo.

Figure 5-25: Damaged rooftop HVAC unit at Pavia Arecibo Hospital showing extensive corrosion. The unit is upside down and is missing side panels. The anchorage points on the bottom (now facing up) are rusted through and torn out.

The Pavia Arecibo Hospital signage was also blown off (Figure 5-26). The sign backing and armature were not able to withstand the forces generated by the high winds. Roof vent coverings were damaged or lost, and the roof covering was damaged. All building components must be designed for the forces presented by high winds, including appurtenances and signs.

Figure 5-26: Loss of signage at Pavia Hospital Arecibo. The sign frame or armature was inadequately attached to the parapet, and the fasteners failed.

Dr. Ramon Ruiz Arnau University Hospital had damage to rooftop equipment as well as roof coverings. Exhaust fans on the central tower section of the hospital were moved off their mounting pads and frames under the hurricane-force winds (Figure 5-27). The damage rendered them inoperable and exposed the floors below to rainwater. These fans did not have sufficient connectors to hold them in place. Design of these connectors requires special attention, because the fans must be placed on vibration isolation mountings. The connectors must be flexible and must provide adequate strength in compression and in uplift. Additional straps or cables could be used to account for the vibration isolation mounts.

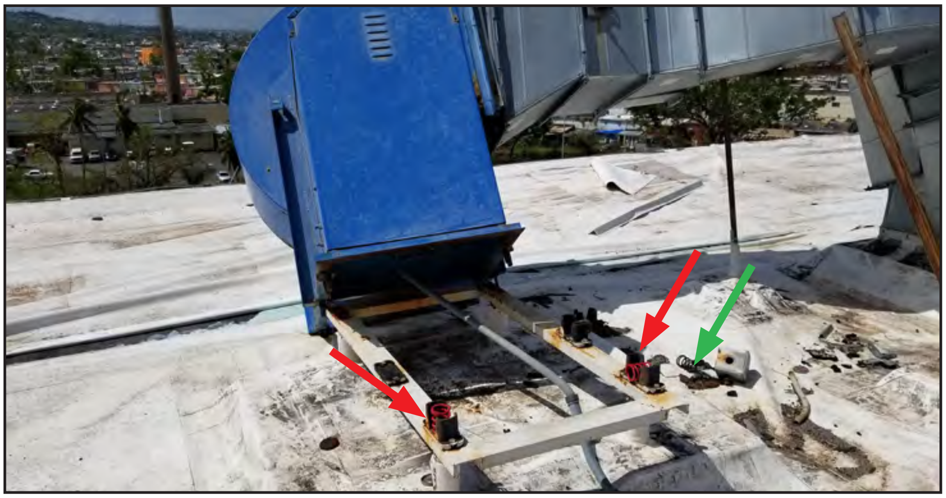


Figure 5-27: Rooftop fan at Dr. Ramon Ruiz Arnau University Hospital displaced from support frame by hurricane winds. Vibration isolation mounts can be seen in the corners (red arrows) and part of another next to the frame (green arrow).

Much of the rooftop equipment at San Juan University Pediatric Hospital was protected behind parapets on lower levels, but some rooftop equipment was blown over. Figure 5-28 shows a fan that was turned over at the top of one of the towers, while Figure 5-29 shows a rooftop fan cowling blown off, exposing the floors below to water infiltration from rainfall. The screws that attached the upper cowling pulled through the sheet-metal. Additional screws could have been used to provide more resistance to the wind loads and stainless-steel cables could have been added as is a common practice in high wind areas. Both of these fans lacked secondary straps to secure them in their original positions. There were cases where the ductwork insulation was blown off, allowing water to enter the ductwork and flow into the building.

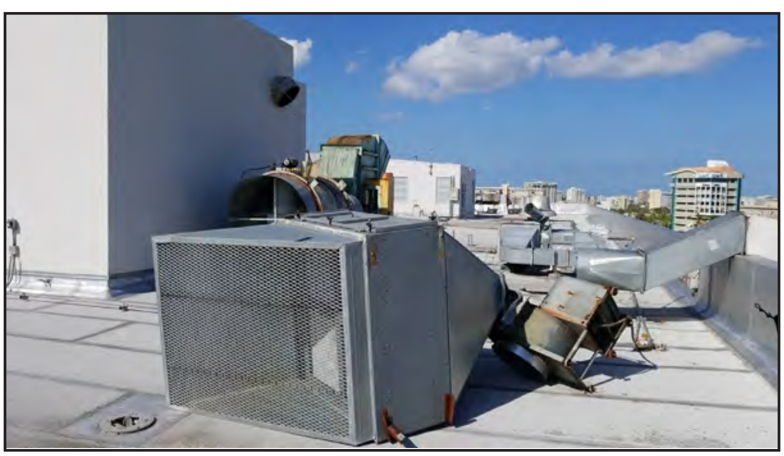


Figure 5-28: Rooftop equipment located on top of one of University Hospital towers that was blown over.

Figure 5-29: A rooftop fan damaged by winds at Dr. Ramon Ruiz Arnau University Hospital.

There was not a large amount of rooftop equipment at the Susana Centeno Family Health Center. Some small air-handling units and vent hoods were damaged and displaced (Figure 5-30), although most vent hoods remained in place without damage. The largest equipment feature on the roof was the solar array on the east side of the roof (Figure 5-31). A number of panels were missing from this array, particularly from the two rows nearest the edge of the roof, apparently having been removed by wind forces. Several of the remaining panels had been damaged by wind-borne debris impacts (Figure 5-32).

Figure 5-30: Small air handling units displaced and off their stands on top of the roof. Note displaced electrical conduit in background of photo (red arrow).

Figure 5-31: Rooftop solar array at east corner of hospital roof. The blue arrow indicates the direction of the strongest winds based on debris fields observed around the hospital.

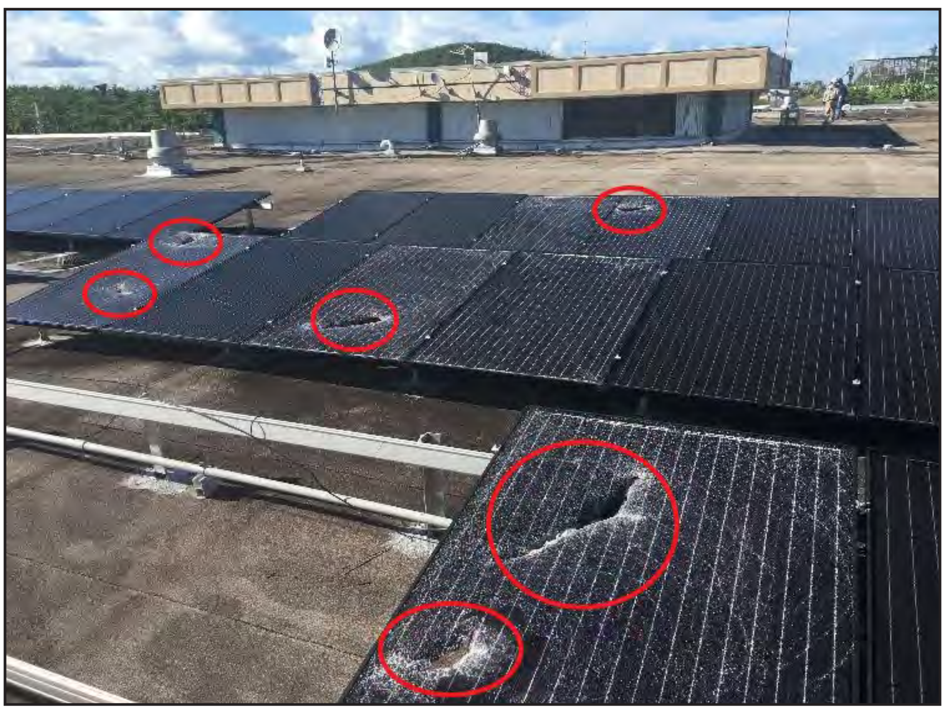


Figure 5-32: Rooftop solar array at east corner of hospital roof showing damage from wind-borne debris impacts (red circles).

5.1.4 Impacts to Operations

The most important operational challenges to hospitals from Hurricanes Irma and Maria were related to the loss of emergency and backup power and the loss of conveyances.

5.1.4.1 Emergency Power and Backup Power

Hospitals use electrical power for many vital functions: maintaining indoor air quality and temperatures, powering medical equipment, cooling medicines and supplies, preparing and storing food, providing lighting and communications, running cleaning and sanitation equipment, and providing mobility and vertical transportation. Loss of power in a hospital renders it out of service and requires patients to be moved to other locations.

Pavia Arecibo Hospital lost grid power and was reliant on backup and emergency power generation. The hospital's own emergency generators also failed, and additional generators were supplied by FEMA. The hospital has two FEMA-supported generators in addition to the existing emergency generator for emergency circuits and lights (Figure 5-33). The hospital has two substations that provide 2.5 megawatts (MW) and 1 MW, respectively, and a single 1 MW generator. At the time of the site visit in October 2017, only one of the two FEMA generators was working.

Figure 5-33: Hospital Generator (blue arrow) and two FEMA-Supplied Generators (yellow arrows) at Pavia Hospital Arecibo.

The loss of power created cascading losses of function. The hospital towers are dependent on vertical transportation to provide access and move patients and supplies. The loss of power also left HVAC inoperable, allowing air temperatures to rise and rendering some spaces unusable.

Dr. Ramon Ruiz Arnau University Hospital lost grid power during the hurricane and ran on their own backup generator. This generator failed after 13 hours, possibly due to water intrusion into the wiring. Small portable generators were used to provide some lighting and critical services for the emergency room. Power from the city was restored after 11/2 weeks; however, it remained unreliable and intermittent. Five days later, the generator was brought back into service, and a trailer-mounted emergency generator was delivered but not connected. With the hospital running on generator-supplied power, only 30 percent of hospital functions were supported, including the emergency department, intensive care unit, and parts of other departments. The hospital does not have a full-building uninterruptible power supply, and when power from the city is disrupted, there is a 10-to-15-second period during which all systems go offline before the backup generator restores power.

The hospital's generator and fuel tanks are at the back of the building (Figure 5-5). After surface runoff overwhelmed the area's drains and piping capacity, water flooded the loading dock to a depth of 4-5 feet (1.2-1.5 meters), reaching the bottom of the generator frame and fuel storage tank in the loading dock area. This location places the generator and fuel tank in a location that cannot be served in flood events. Should the area drains fail completely, access could be lost for weeks. These mission-critical elements should be relocated to high ground not subject to flooding and with access in severe conditions. Prolonged loss of backup systems will further reduce the hospital's ability to function. The new location for the relocated gear does not necessarily need to be adjacent to the building and can be located several hundred feet away, also reducing emissions and noise in the hospital. Standardized emergency connections should also be considered so that trailer mounted generators can be quickly put into service when necessary.

Figure 5-34: View of one of the standby generators (red arrow), two of the backup generators (green arrows), and a fuel tank (blue arrow) at San Juan University Pediatric Hospital.

San Juan University Pediatric Hospital has four generators that can provide 100 percent of the hospital's power requirements (Figure 5-34). Tower One has a 1,700 kilowatt (kW) standby generator, and Tower Two has a 1,250 kW standby generator. There are two 750 kW backup generators for the towers as well (Figure 5-35).

The backup generators were not working at the time of the MAT visit; however, this was not directly due to hurricane damage but to protection systems and warning lights that required maintenance and repairs.

The hospital had been functioning on generator power for weeks at the time of the visit, and fuel demand was a concern. Tower One's generator can run for five days on a full tank, while Tower Two's can run for seven days. This means that a fuel delivery (Figure 5-35) is required twice a week. FEMA was instrumental in coordinating fuel deliveries to keep the hospital functioning. The frequent deliveries required access to a fuel delivery point co-located with a main entrance. The fuel truck is on the sidewalk under the porte-cochere within inches of the roof. The delivery location lacked spill controls, fire controls, traffic controls, separation from pedestrian traffic, exhaust and fume management, and storm water management measures. Facilities that rely on fuel deliveries to maintain operations, especially as a regular occurrence, should have well designed access and delivery points that provide for safe and efficient use.

Power to Vieques and the Susana Centeno Family Health Center was provided by an underwater cable from the main island prior to Hurricanes Irma and Maria. Hospital staff attempted to provide emergency services during the hurricanes. After the cable was damaged during Hurricane Irma, the hospital was able to operate on generator power for two weeks. Shortly after external power was restored, Hurricane Maria damaged the underwater cable again, forcing the hospital to return to generator power. After two weeks, the generator failed, and the facility was without power.

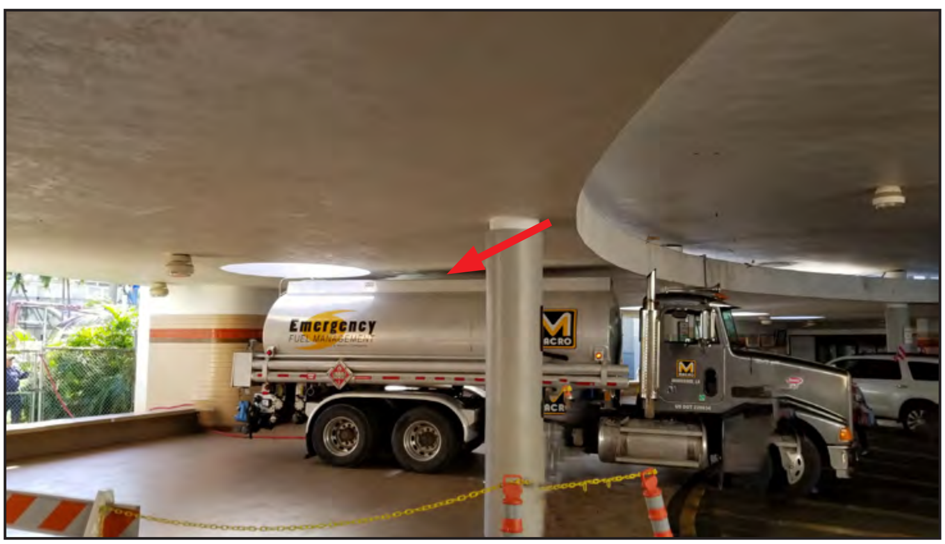


Figure 5-35: View of fuel truck refilling the fuel tank for University Hospital Tower One. Note the tight clearance between the porte-cochere ceiling and the top of the tanker truck (red arrow.)

By the time of the December 2017 MAT observations, the facility was able to partially operate on a 250 kilovolt-ampere Tesla solar and battery power system operating in the parking lot of the hospital. Power was available to provide lighting and some air handling to the approximately six medical tents at the site and some of the hospital building. However, the building was not fully functional on the limited power supplied by the solar power system. While there were secondary emergency generators on site, they did not function. (The MAT was unable to determine the backup power generator size or fuel tank capacity.) Although the hospital stores water on site in a 50,000-gallon (189,000-liter) cistern, the water could not be used because of insufficient power for the water pumps. Due to the lack of available water, the poor air quality, and the possible presence of mold, the Government of Puerto Rico has determined it must close.

At Culebra Community Health Center (Figure 5-36), patients able to evacuate were moved to the island of Puerto Rico prior to the hurricanes. Those unable to evacuate were brought to a school designated for use as a shelter, as discussed in chapter 4. One of the hospital's two wings was functional at the time of the MAT visit, but the other, the surgery wing, was not functional due to water intrusion through the roof that had resulted in hazardous conditions. A securely strapped HVAC unit (Figure 5-37) is an example of successful mitigation that helped the facility continue in partial operation after the hurricanes.

Figure 5-36: Culebra Community Health Center functioned on generator power after Hurricanes Irma and Maria. Source: Hector Huyke Villeneuve / FEMA, December 9, 2017 https://www.fema.gov/media-library/assets/images/154945

Figure 5-37: This HVAC unit at the Culebra Community Health Center is strapped to a concrete platform; however, it rests on plastic supports that are not mechanically anchored.

5.1.4.2 Conveyances

Vertical transportation is a critical element to a hospital's function as staff, patients, supplies, and equipment are constantly moving within the facilities. One hospital noted that loss of their elevators was the single biggest problem they faced after Hurricanes Irma and Maria.

The elevators at Pavia Arecibo Hospital were rendered inoperable for days after the storms due to water infiltration through the roof and mechanical penthouse. This water then entered the elevator shafts, eliminating most of the vertical transportation. While the main logic controls were not damaged, the water damaged the elevator cab controls in the service elevator and 2 personnel elevators. The elevators were repaired after five days, but the absence of vertical transportation meant that extraordinary efforts were required to maintain functioning of the hospital for the following week. Three times a day, a human chain was used to move food, supplies, fresh linens, and other materials up into the upper floors and also to move waste and soiled linens down and out of the tower.

The vertical conveyance system at Dr. Ramon Ruiz Arnau University Hospital suffered significant damage and loss of function from the hurricanes. Only two of the five elevators remained in service during and after the hurricanes. The mechanical penthouse that protected the motors and controls was inundated by wind-driven rain (Figure 5-38), which entered through ventilation louvers required to provide air movement and maintain acceptable operating temperatures during normal conditions. These ventilation openings allowed water to spray the gear and controls during the hurricane (Figure 5-39). The motors and gear are robust and were minimally affected, but the control cabinets and controls were damaged, and the elevators served by these damaged controls went out of service (Figure 5-40). No injuries were reported as a direct result of the elevator failures.

Figure 5-38: Elevator mechanical penthouse enclosing the elevator gear at Dr. Ramon Ruiz Arnau University Hospital. Note ventilation louvers on the sides where rain entered.

Figure 5-39: Elevator controls that were inundated with wind-driven rain and failed during the hurricane at Dr. Ramon Ruiz Arnau University Hospital.

Figure 5-40: Elevator gear and controls located in the elevator penthouse at Dr. Ramon Ruiz Arnau University Hospital.

Hurricanes Irma and Maria left eight of the twelve elevators at San Juan University Pediatric Hospital's two towers out of service, nearly eliminating hospital function and greatly affecting mobility. Hospital staff stated that lack of vertical conveyance was the most difficult issue to manage. Two elevator machine rooms and four elevators were damaged by power surges, which also started fires at the controls. Smoke from these fires escaped back into the building and temporarily caused poor air quality.

5.2 Police and Fire Stations

The MAT assessed several fire and police stations. The facilities observed were built with reinforced concrete and did not suffer any structural damage. The Toa Baja Fire Station could be considered a structural success, because it suffered only minor damage due to its elevated floor and metal shutters; however, not all facilities performed as well. The Corozal Police Station was inundated by more than six feet (1.8 meters) of water, damaging the generator and other building contents. The Palmas del Mar Fire Station suffered wind damage to several windows, mostly from wind-borne debris.

5.2.1 Performance Relative to Flood

This section summarizes the performance of police and fire stations exposed to coastal and inland (riverine) flooding. Most of these facilities observed by the MAT were not in SFHAs and did not flood. However, some riverine flooding was observed.

5.2.1.1 Coastal Flood Impacts

The Culebra Police Station and the Luquillo Fire Station are located along the coast of Puerto Rico and are outside of the Advisory SFHA (Figure 5-41 and Figure 5-42). The MAT assessment did not identify any signs of coastal inundation. However, the proximity to the coastline provides little cover and leaves the facilities exposed to unobstructed high winds.

5.2.1.2 Inland Flood and Rainfall Impacts

The Corozal Police Station, in the central-eastern region of Puerto Rico, was inundated with more than 6 feet (1.8 meters) of water. The effective FIRM showed the facility to be just outside the SFHA (Figure 5-43, top); however, the Advisory Data shows the facility inside the SFHA (Figure 5-43, bottom).

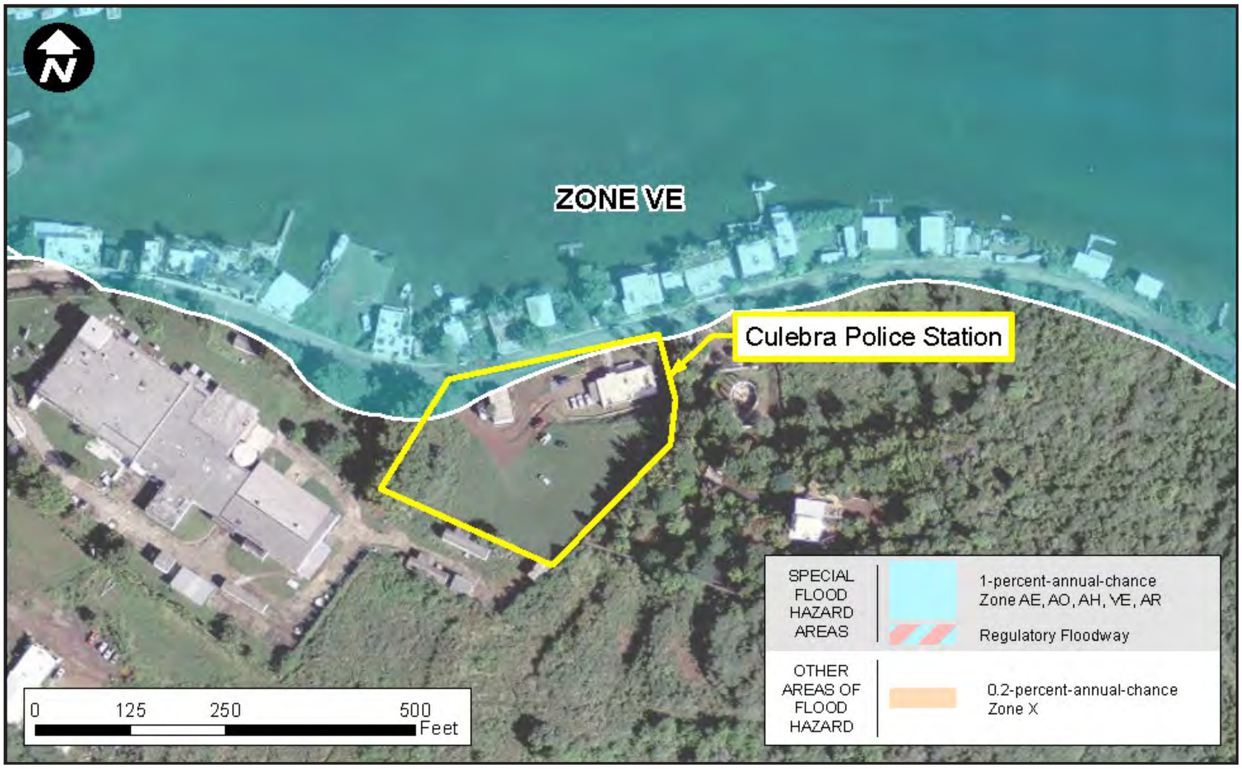


Figure 5-41: Location of the Culebra Police Station on the effective 2009 FIRM. The facility was not damaged by coastal inundation.

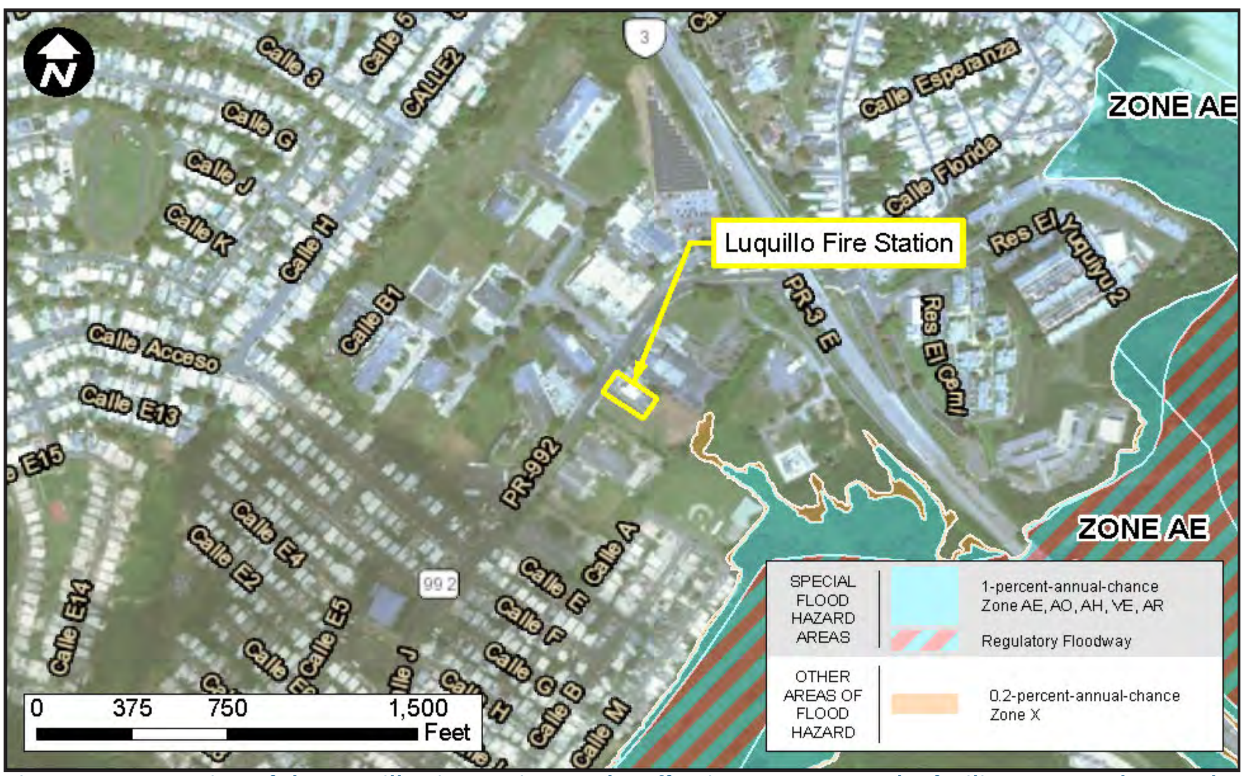


Figure 5-42: Location of the Luquillo Fire Station on the effective 2009 FIRM. The facility was not damaged by coastal inundation.

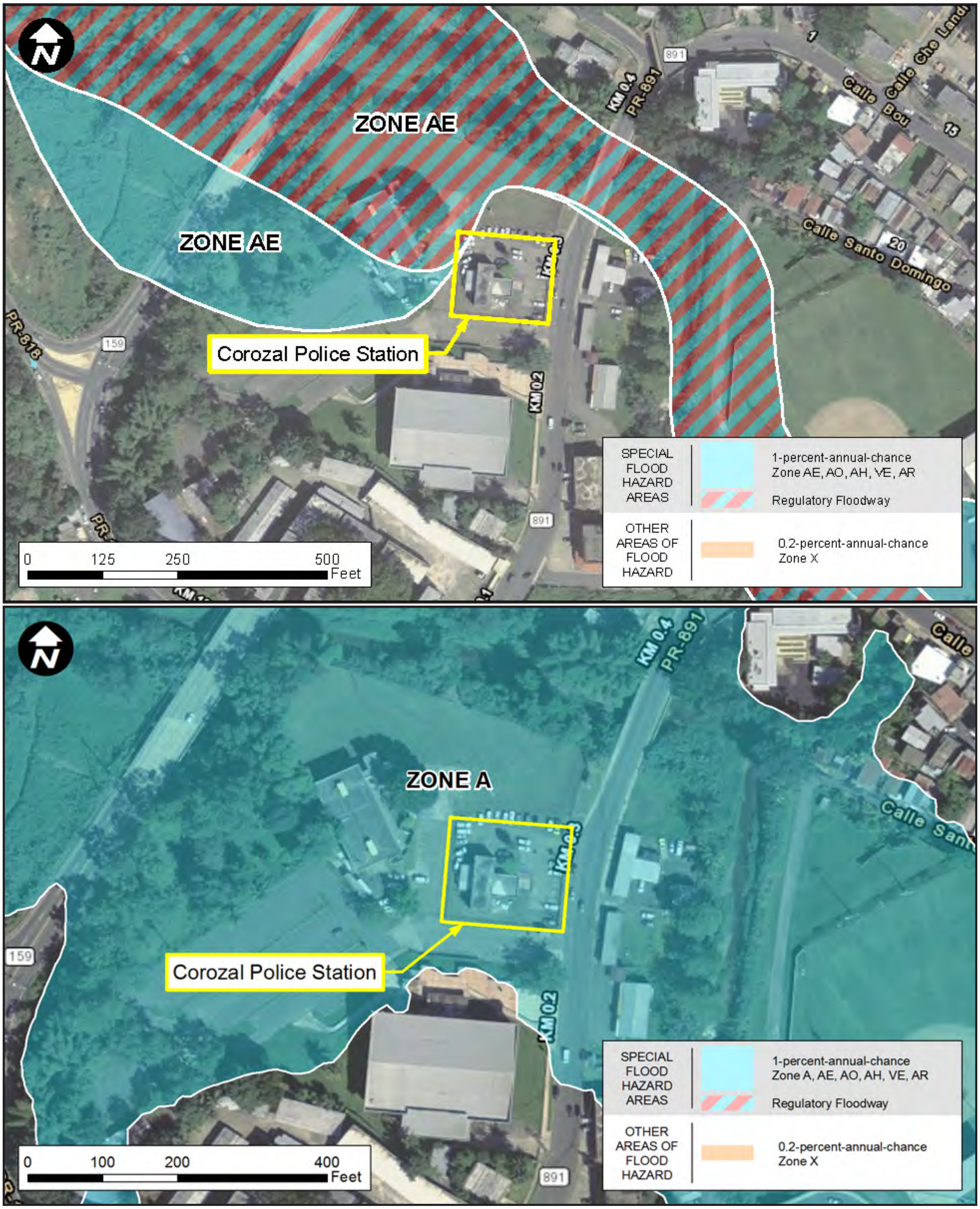


Figure 5-43: Corozal Police Station, top, shown on the effective 2009 FIRM; bottom, shown on the Advisory Data.

Floodwaters from the adjacent Rio Corozal inundated the ground floor of the Corozal Police Station (Figure 5-44, left), inundating the power generator (Figure 5-44, center) and damaging other building contents. The MAT was unable to determine the first-floor elevation of the facility[1]. However, the second story did not suffer any visible flood damage and was operated by a portable generator (Figure 5-44, right) during the MAT assessment. Placing the generator on the second floor would have avoided inundation of the generator and reduced the facility's operational downtime.

Figure 5-44: Corozal Police Station, left, overview; center, damaged backup generator; right, portable generator used after Hurricane Maria. Yellow line indicates high water mark.

The municipality of Toa Baja, located on the north coast of the island, was one of the areas most impacted by riverine flooding. The Toa Baja Police Station is located inside the 100-year floodplain (Figure 5-45) and was inundated with 4-5 feet (1.2-1.5 meters) of water. The facility's staff moved most of the computer systems and files to the second floor; however, some operational aspects were compromised due to the first-floor flooding. Tile and concrete walls helped reduce damage; however, electrical (Figure 5-46) and plumbing damage was observed. The Municipality is considering relocating the facility to a location outside of the SFHA.

The Toa Baja Fire Station sits across the street from the Toa Baja Police Station (Figure 5-46). The facility is located inside the 100-year floodplain, less than 300 feet (91 meters) from the floodway of the Rio La Plata; however, it suffered little or no structural damage from flooding. To protect against flooding, essential components of the facility including communications, firefighting equipment, and the generator are elevated above the design flood elevation (Figure 5-47). In the case of a flood event, the fire trucks are relocated to a higher elevation to avoid any inundation damage. Metal shutters protected the facility's doors and windows from wind-borne debris.

[1] The 500-year-flood elevation given on the effective FIRM is 258.5 feet (78.5 meters) above mean sea level.

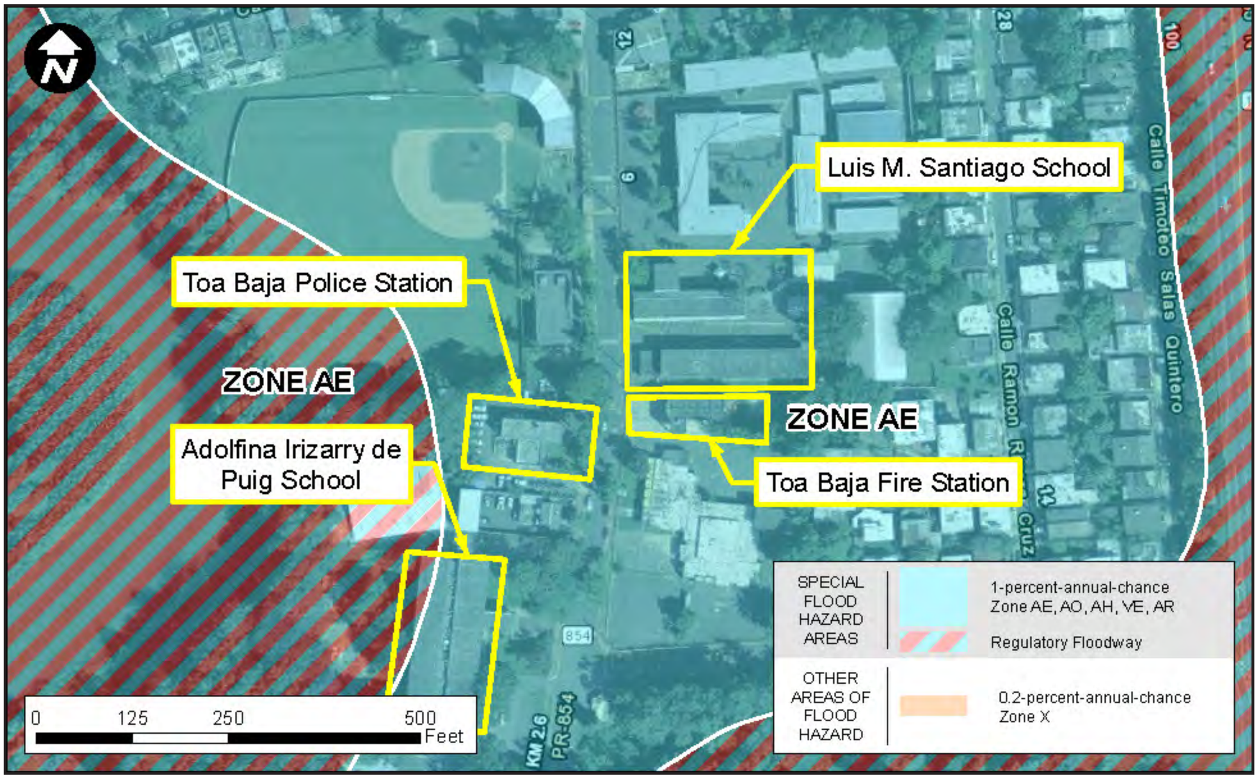


Figure 5-45: A portion of the effective 2009 FIRM showing the Toa Baja Police Station.

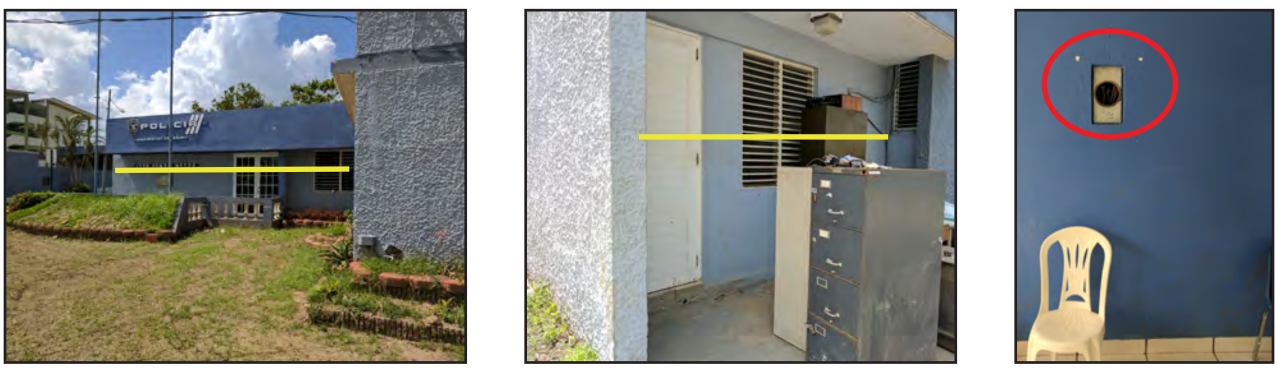


Figure 5-46: Toa Baja Police Station (left), damaged files and office equipment (center), electrical damage (red circle-right). Yellow line indicates high water mark.

Figure 5-47: Left, approximate flood elevation and power generator (red circle) in the background; right, steps to the first floor (right) of the Toa Baja Fire Station.

5.2.2 Performance Relative to Wind

All the police and fire stations observed by the MAT were built with reinforced concrete. All performed well in the hurricanes' high winds, with none showing signs of structural damage.

5.2.2.1 Openings

At the Culebra Police Station, jalousie windows allowed water intrusion caused by wind-driven rain. However, the MAT observed several cases in which properly installed shutters provided sufficient protection to openings on fire and police stations. The Toa Baja Fire Station had security grilles in the truck bays (Figure 5-48, left) and metal window shutters (Figures 5-48, right) that successfully protected the facility from wind debris impacts.

Figure 5-48: Toa Baja Fire Station. Left, security grills (red arrows) protected equipment from wind-borne debris. Right, metal shutters (blue arrows) protected the building from wind-borne debris.

Florida Fire Station and Luquillo Fire Station had storm shutters that successfully protected their windows from impact, though the MAT observed wind-borne debris nearby, (Figure 5-49). However, Luquillo Fire Station suffered minor damage from water intrusion through its jalousie windows.

Figure 5-49: Metal shutters installed at the Luquillo Fire Station successfully protected the facility's openings.

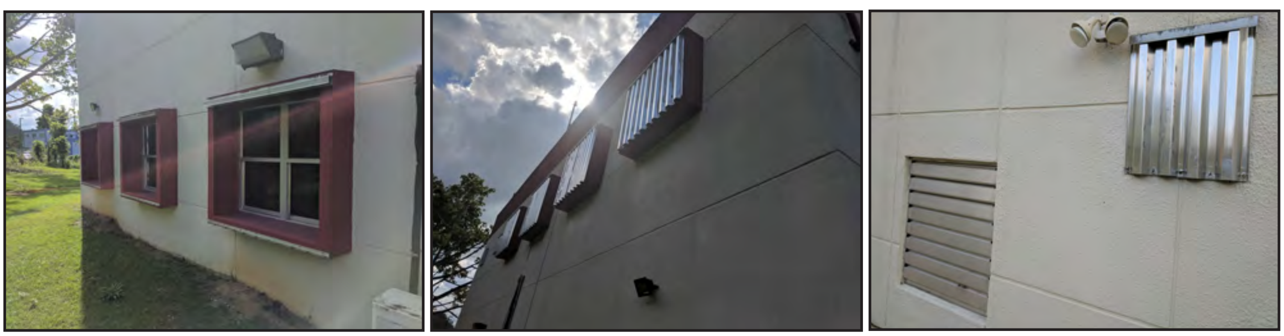


Figure 5-50: Metal shutters installed at the Florida Fire Station successfully protected the facility's openings.

The shutter systems installed on the Palmas del Mar Fire Station performed well when properly deployed. However, some shutters were not in place at the time of the event, resulting in window damage caused by wind-borne debris (Figure 5-51). The damage may be attributed to storage issues and lack of a maintenance and installation plan. The metal shutters deployed on this facility are commonly used in the region due to their moderate cost and easy installation. However, they must be installed and taken down for every event. This creates a need for storage space and requires additional planning by the facility manager.

Figure 5-51: The Palmas del Mar community requires decorative tile roofs. The Palmas del Mar Fire Station included decorative tile roof coverings over portion of the building (red circles). The tiles were not mechanically attached, and some failed, contributing to wind-borne debris.

Figure 5-52 illustrates tiles lost from the facility's roof covering, which contributed to wind-borne debris.

Figure 5-52: Damage to tile roof (red oval) covering at the Palmas del Mar Fire Station. Red arrows indicate broken tiles.

5.2.2.2 Roof System

The Culebra Police Station suffered water damage from water intrusion through the roof and windows. There were visible ponding and signs of poor maintenance on the roof at the time of assessment (Figure 5-53).

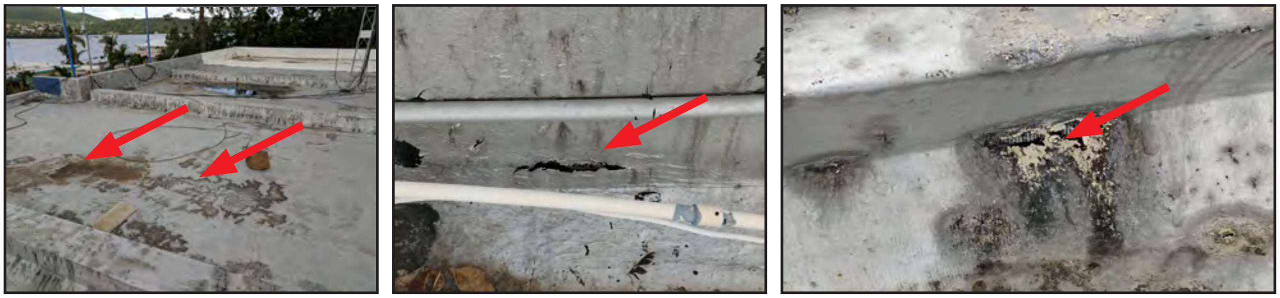


Figure 5-53: Ponding and roof damage (red arrows) at the Culebra Police Station.

The air conditioning unit (Figure 5-54, left) of the Luquillo Fire Station was successfully strapped in place. However, the practices recommended in Puerto Rico Recovery Advisory 1, *Rooftop Equipment Maintenance and Attachment in High-Wind Regions* (FEMA PR-RA1, Appendix D) would require one additional mechanical attachment. The cooling fan (Figure 5-54, center) came loose due to the strong winds. The facility suffered minor damage from water intrusion through the roof and windows. There were visible signs of poor maintenance on the roof at the time of assessment (Figure 5-54, right).

Figure 5-54: Rooftop equipment at the Luquillo Fire Station, including, left, air conditioning unit; center, cooling fan; right, rooftop damage.

The Florida Fire Station suffered minor roof damage due to ponding and maintenance issues (Figure 5-55, left). The facility's grade-mounted AC condensers were successfully strapped and did not tip over (Figure 5-55, right).

Figure 5-55: Florida Fire Station, with, left, minor roof damage, right, strapped AC condensers.

SAN JUAN EMERGENCY OPERATIONS CENTER

The San Juan Emergency Operations Center (EOC) (Figure 5 56) is an underground facility originally built in the 1970s and renovated in the early 2000s after the attacks of September 11, 2001. The facility was operational during Hurricanes Irma and Maria and was running with backup power at the time of the MAT visit. Backup power consisted of twin diesel generators operated alternately so that one provided power while the other was maintained. The EOC operated on backup power for several months until grid power was restored. The San Juan EOC complex hosts a 911 emergency call center, which also remained operational during both hurricanes. The complex did not show signs of flood or wind damage.

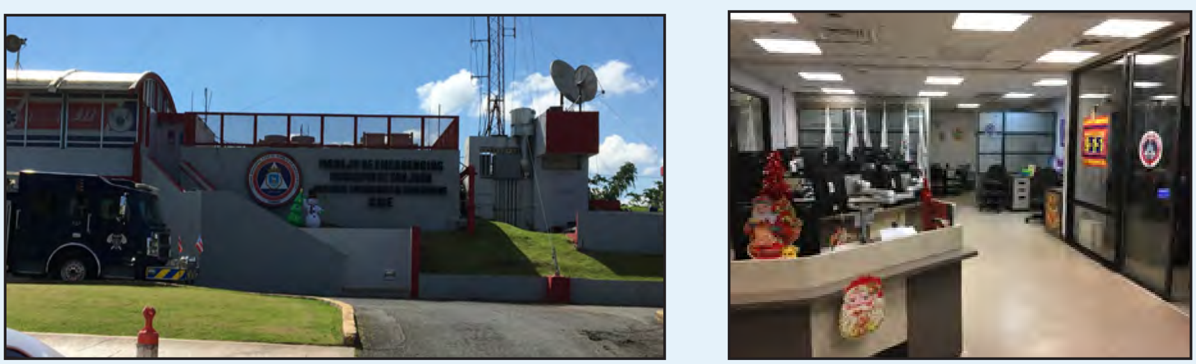


Figure 5-56: San Juan EOC, left, exterior, right, interior.

5.2.3 Impacts to Operations

Hardening the Toa Baja Fire Station with metal shutters and elevating or relocating the essential components successfully protected the building and its components. However, the facility was not operational for more than a month after the event due to generator failure. The facility's generator was elevated (Figure 5-57, left) but was not operational at the time of the MAT visit due to a mechanical problem; however, when it was in use, its location allowed fumes to enter the sleeping quarters. To address this problem, a temporary piping system had been installed to convey smoke away from the building. This solution could reduce the efficiency of the generator. A second generator had been provided (Figure 5-57, right) but had no fuel at the time of the MAT visit. At Luquillo Fire Station, the emergency generator was not functioning at the time of the MAT assessment. At both fire stations, the lack of a proper operations and maintenance plan prevented the facility from being a complete success story.

Figure 5-57: Toa Baja Fire Station. Left, generator (red circle) with temporary piping system (red arrow) installed to convey generator smoke away from the building. Right, portable generator supplied after Hurricane Maria.

5.3 Mid-Rise Buildings

Mid-rise buildings are buildings having from five to approximately 10 floors. Due to their height, they require the use of elevators. The MAT assessed several mid-rise buildings, all of which had governmental functions. Typical uses of mid-rise buildings in Puerto Rico are apartments, hotels, condominiums, health care and office buildings.

5.3.1 Summary of Building Performance

Mid-rise buildings require professional design due to their complexity and technical challenges. Mid-rise buildings typically had reinforced concrete cores and did not suffer structural damage from wind. The facilities were all sited well and remained above or outside areas of flooding. However, the MAT observed considerable damage to and loss from these buildings due to breaches and failures that admitted wind and wind-driven rain.

5.3.2 Performance Relative to Flood

No mid-rise facilities investigated by the MAT were inundated by coastal or riverine flooding from Irma or Maria, although some are located in the SFHA and are vulnerable to future flooding. Some of these successes are the result of buildings having been relocated to areas of lower flood risk after previous disasters.

5.3.2.1 Coastal Flood Impacts

The Department of Justice of Puerto Rico (PRDOJ; Departamento de Justicia de Puerto Rico) occupies a building in San Juan 0.5 miles (0.8 kilometers) south of the north shore and less than 0.25 miles (0.4 kilometers) from San Juan Bay (Figure 5-58). The PRDOJ building is approximately 20 feet (6.1 meters) above sea level and is outside the effective and advisory flood zones (Figure 5-59); it did not receive coastal or riverine flooding from Irma or Maria.

Figure 5-58: View of the northeast corner of the PRDOJ building in San Juan after hurricane Maria.

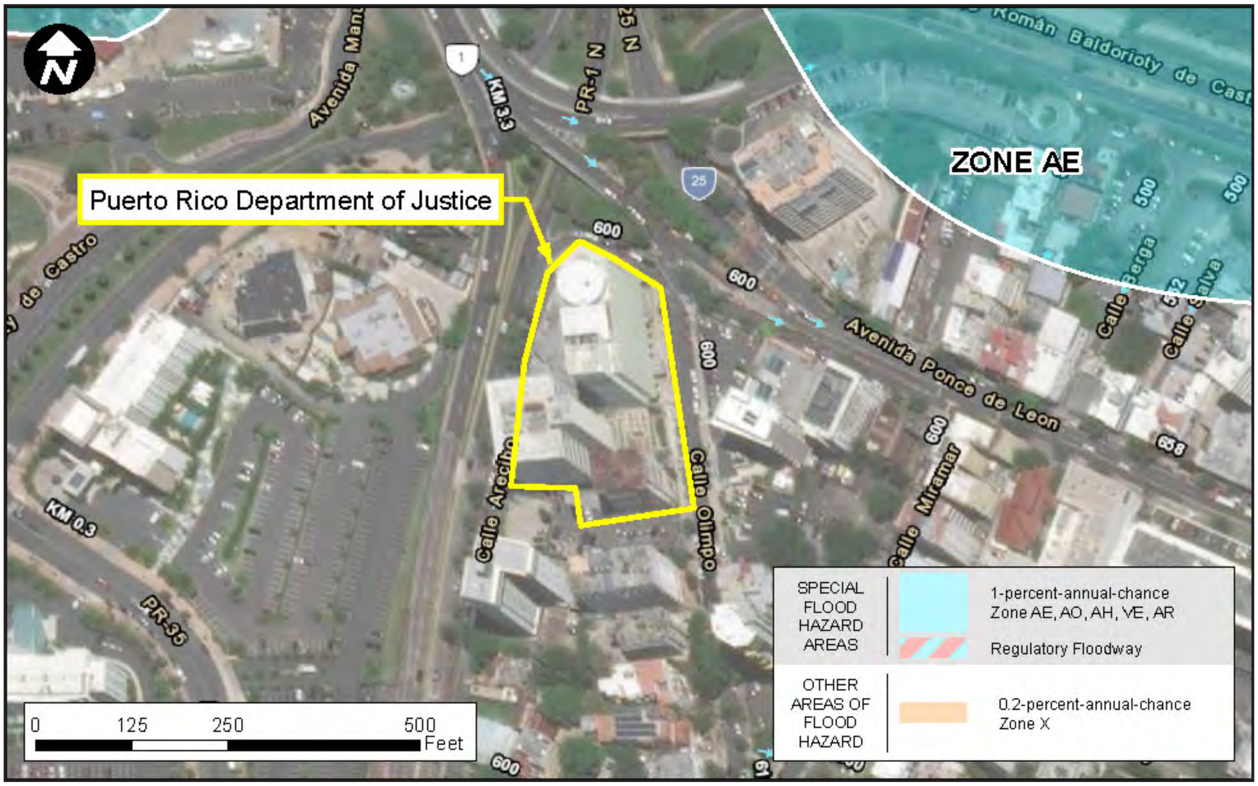


Figure 5-59: A portion of the effective 2009 FIRM showing the PRDOJ building in the X Zone.

Toa Baja is a low-lying community near the north shore of Puerto Rico 8 miles west of San Juan. The Toa Baja Municipal Building was previously located in an area prone to flooding from Rio de la Plata, the longest river in Puerto Rico, and was approximately 2 miles (3 kilometers) south of the north shore. When a larger building was needed, a new one was built 2 miles away, approximately 2.5 miles (4 kilometers) from the ocean and 2 miles (3 kilometers) from the Rio de la Plata, elevated on fill. The new building was inaugurated in 1996. With this choice of location (Figure 5-60) and building elevation, the building did not flood during the hurricanes. However, the building is still partially in the SFHA, and an underground parking structure (Figure 5-61), due to its low elevation, is at risk of inundation during flood events less severe than the base flood.

Culebra City Hall is located in the Culebra Municipal Building. The building is within 100 feet (30 meters) of the shore but was located well and did not experience coastal flooding. However, the failure of a sump pump allowed surface water to flood a portion of the building. The building is located at the boundary of the SFHA on the FIRM (Figure 5-62).

Figure 5-60: Toa Baja Municipal Building showing relief from surrounding terrain by use of elevation on fill. Stairs lead to the building's elevated pad (red arrow).

Figure 5-61: Toa Baja Municipal Building showing relief from surrounding terrain and entrance to underground parking (red arrow).

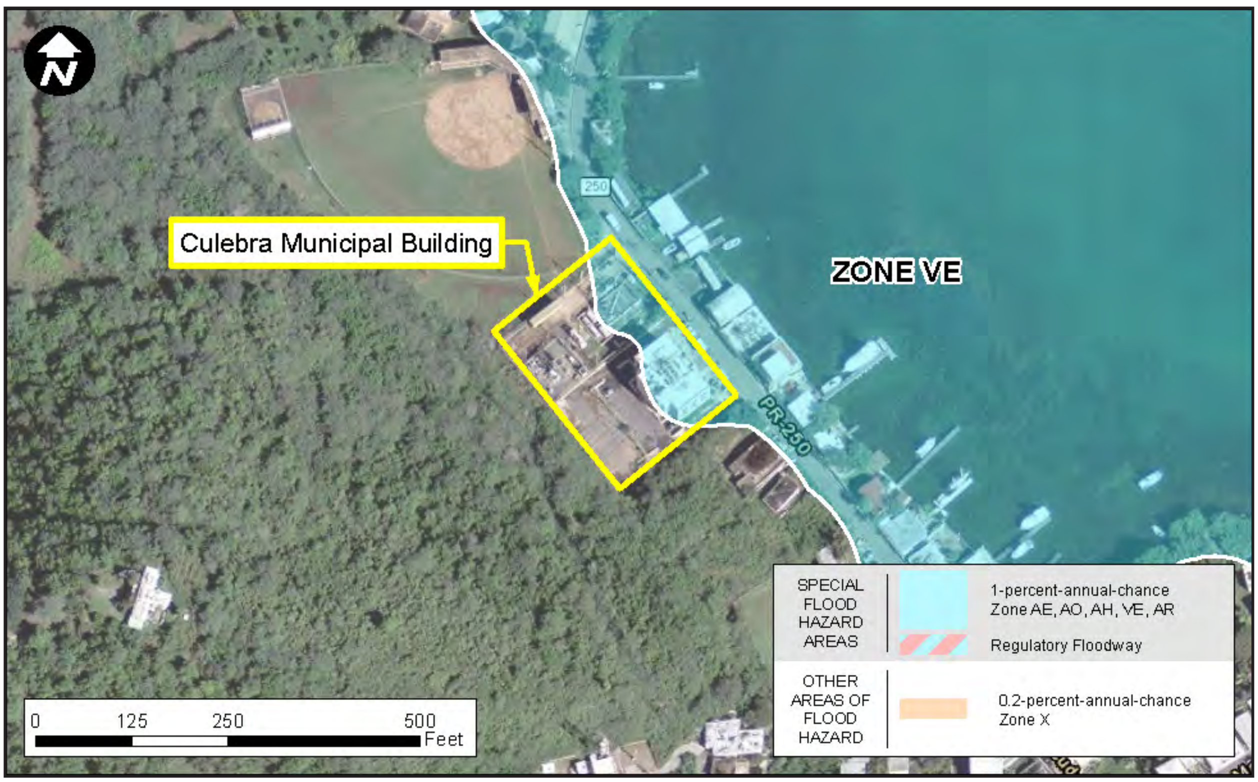


Figure 5-62: A portion of the effective 2009 FIRM showing the Culebra Municipal Building. The facility is partially in the SFHA but was not damaged by coastal inundation.

5.3.2.2 Inland Flood Impacts

The Vega Alta Municipal Building (Figure 5-63) is located 15 miles west of San Juan and well over 4 miles (7 kilometers) inland of the north shore. It did not flood. The building is located outside the SFHA on the FIRM (Figure 5-64).

Figure 5-63: Northwest view of Vega Alta Municipal Building. The building is located outside the SFHA and did not flood.

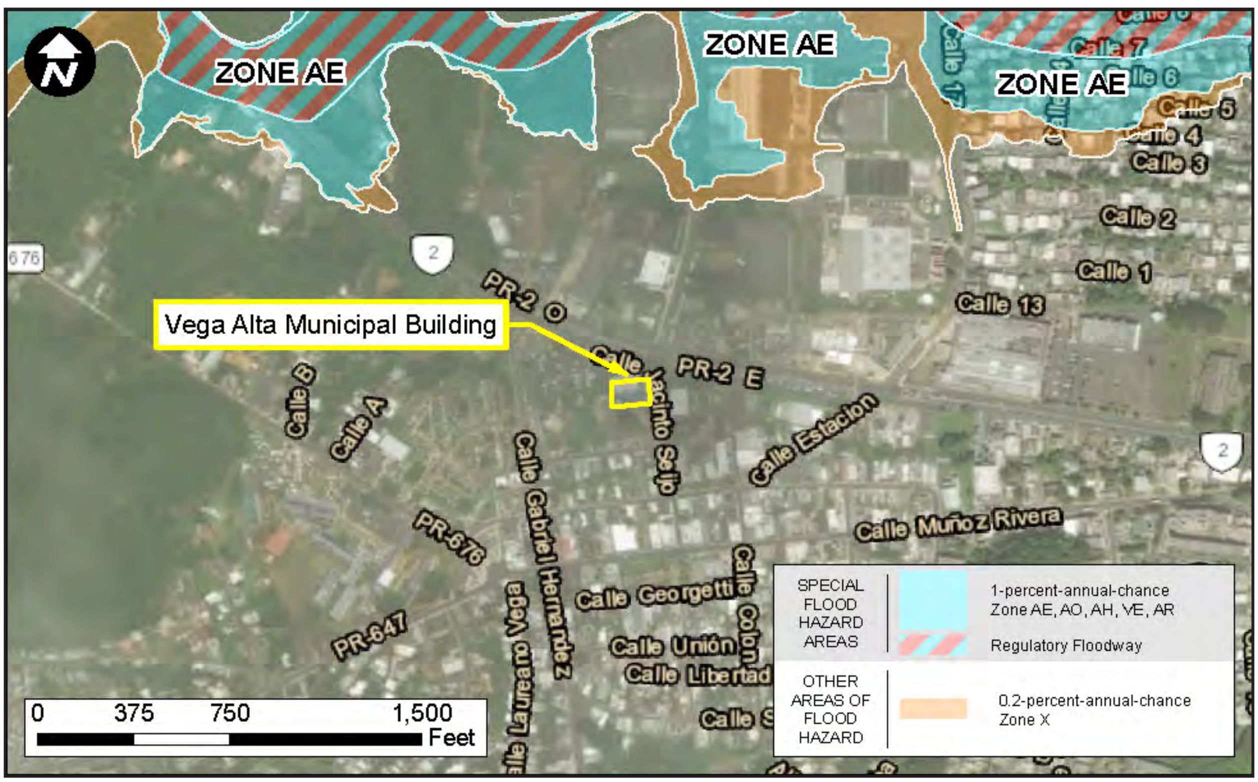


Figure 5-64: A portion of the effective 2009 FIRM showing the Vega Alta Municipal Building in Zone X. The facility was not damaged by flooding.

5.3.3 Performance Relative to Wind

The midrise municipal buildings investigated showed no evidence of failure of their main structural elements or the MWFRS. The performance of the openings, windows, and roofs varied considerably with some experiencing significant damage and others slight damage.

The PRDOJ Building experienced no structural failures in the walls, roof, or foundations. However, water entered the building through broken windows and displaced rooftop equipment. While the lower level windows had shutters installed, many of the shutters failed, resulting in windows damage and breakage. Water was still entering the building at the time of the MAT visit, wetting the floors and causing air quality problems and loss of contents.

Culebra Municipal Building showed very good wind performance with little to no rooftop equipment damage, no damage to the metal roof portion of the building and some minor leakage from a cut in the membrane roof covering from debris.

5.3.3.1 Main Wind Force Resisting System

The Main Wind Force Resisting System (MWFRS) of the midrise building performed well during the storms of 2017. During the MAT investigations in October and December 2017, no structural failures were noted of the structural core or main elements of the buildings. The mid-rise frames tended to be reinforced concrete frames with concrete columns, beams and slabs.

5.3.3.2 Openings

The PRDOJ building had numerous window breakages from debris impact during Hurricanes Irma and Maria (Figure 5-65 through 5-70). Windows failed at all levels from the top to the base of the building. The upper floor window systems failed when their frames were pushed into the building after screws joining the frame and the framed opening broke (Figure 5-66 through 5-68). Metal panel shutters installed in tracks protected lower-level windows. These failed when the shutters and tracks were pulled free from their locations due to undersized anchors (Figure 5-70).

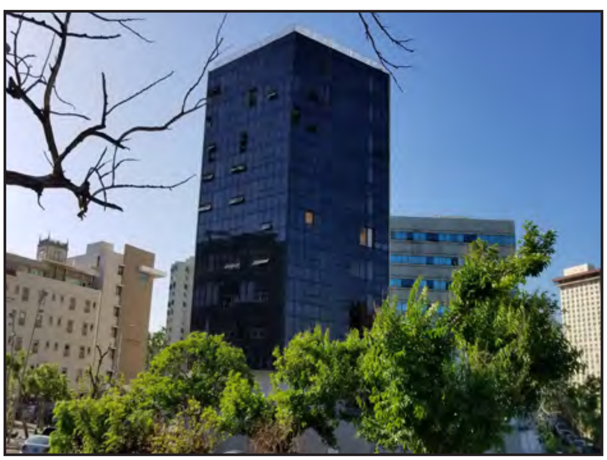


Figure 5-65: View of the northwest side of the PRDOJ building with numerous windows broken.

Figure 5-66: Window frames pushed into the PRDOJ building at the top floor due to the failure of frame-to-structure anchors, (red arrows).

Figure 5-67: View of the undersized anchorage location, (red arrows) in the window frame at the PRDOJ building.

Figure 5-68: The screws that held the window frame in place bent and pulled through the window frame at the PRDOJ building. The anchors (red circles), were too small and too few in number.

Figure 5-69: A shattered window (red arrow) allowed water and wind into the PRDOJ building at this location, inundating the documents on the adjacent shelf.

Figure 5-70: Left, shutters protecting lower floor windows pulled off the PRDOJ building, exposing the glass behind; right, the anchors were undersized, of the wrong type, and too few in number.

The Vega Alta Municipal Building had storm shutters only on windows that faced east (Figure 5-71). The windows that face north, south and west sides of the building had no glazing protection and, some glazing failures and damage were observed on these sides. This damage in combination with rooftop equipment failures resulted in unusable floors.

Figure 5-71: Vega Alta Municipal Building had shutters on only the east side windows (red arrows). No shutters or opening protection is present on windows on this side of the building.

The Toa Baja Municipal Building had no flooding, but roof damage and glazing damage (Figure 5-72) allowed water intrusion that required the building to be closed. Mold grew in the building due to moisture. The building used materials that are more typical of construction practices elsewhere in the US than of Puerto Rico, such as drywall and acoustical ceilings. These materials are more vulnerable to mold if building envelope breaches and loss of power for air handling occur. The building had no natural ventilation, further contributing to mold growth.

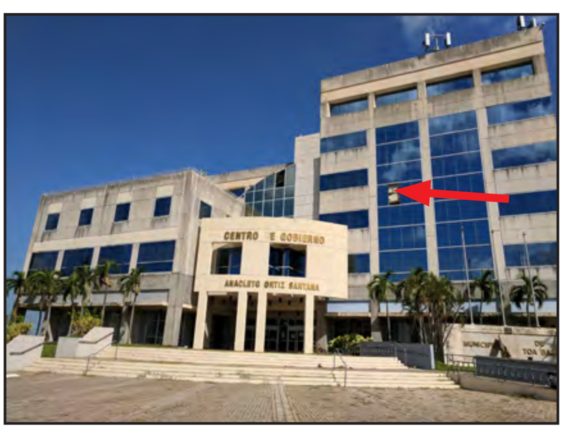


Figure 5-72: Glazing damage (red arrow) at Toa Baja Municipal Building.

Bayamón Municipal Building deployed metal shutters on some first-floor and larger upper-story windows (Figure 5-73). However, some unprotected window glazing was broken by high winds and/or wind-borne debris impacts, leading to water intrusion (Figure 5-74).

Figure 5-73: Metal shutters protected some upper-story glazed windows at Bayamón Municipal Building.

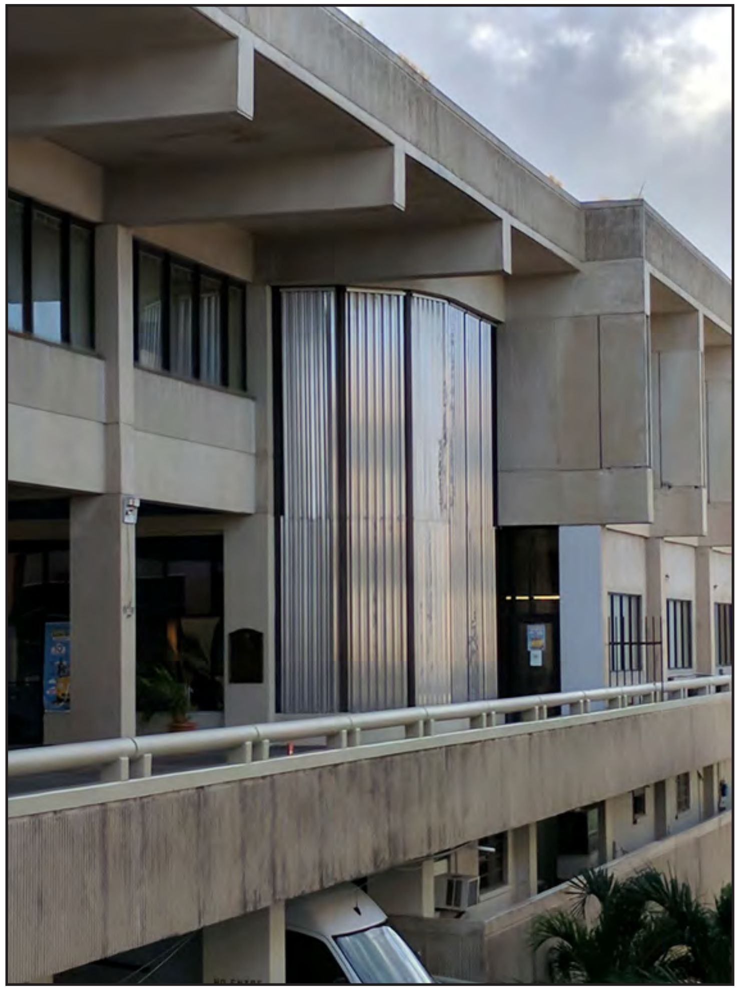


Figure 5-74: Broken window glazing (red arrows) at Bayamón Municipal Building.

5.3.3.3 Roof System

Although the roof covering at the PRDOJ had a few minor leaks, the roof remained essentially intact. No major roofing failures were noted during the MAT site visits. The top roof height of the PRDOJ is higher than the surrounding buildings. Due to the height of the building relative to its neighbors, the building likely did not experience much wind-borne debris from off-site impacting the roof during the hurricane.

The Vega Alta Municipal Building saw roof leaks from various sources such as membrane damage (Figure 5-75) and flashing pull-back.

Figure 5-75: Vega Alta Municipal Building had roof leaks. Flashing can be seen displaced at the mechanical area of the roof. Water entered this location as well as others.

The Toa Baja Municipal Building had no flooding, but roof damage and glazing damage led to water intrusion that necessitated closing the building due to concerns about mold.

At the Culebra Municipal Building, the roof membrane was punctured (Figure 5-76), likely from wind-borne debris, and caused water intrusion into the building. The building had drop ceilings and dry wall that were wet and developed mold (Figure 5-84). However, the metal portions of the roof fared very well (Figure 5-77).

Figure 5-76: Membrane roof covering at Culebra City Hall punctured (red arrow) during hurricane winds led to water intrusion in building that damaged acoustical ceilings (yellow arrow) and drywall.

Figure 5-77: Metal roof covering at Culebra Municipal Building performed well. There is no evidence of corrosion from this view.

At Bayamón Municipal Building, the MAT was told that water intrusion through the roof had occurred, although visible evidence of roof damage (e.g., roof membrane punctures) was not observed.

5.3.3.4 Rooftop Equipment

The PRDOJ rooftop equipment suffered considerable damage. Lightning protection systems, rooftop HVAC units, and rooftop cooling towers were damaged by winds and debris in the hurricanes (Figure 5-78). Rooftop HVAC units mounted on pads were dislodged (Figure 5-79) and blown across the roof, while a rooftop fan was lost entirely (Figure 5-80). A door in a rooftop cooling tower collapsed into the tower due to debris impact (Figure 5-81). Given the elevation of the cooling towers and a degree of protection from the walls, the impact damage was surprising and revealed unexpected vulnerabilities.

Figure 5-78: The lighting protection air terminals (green arrow) tore free from their anchorages (red arrow) atop the PRDOJ building. Rooftop AC units were also displaced (blue arrow).

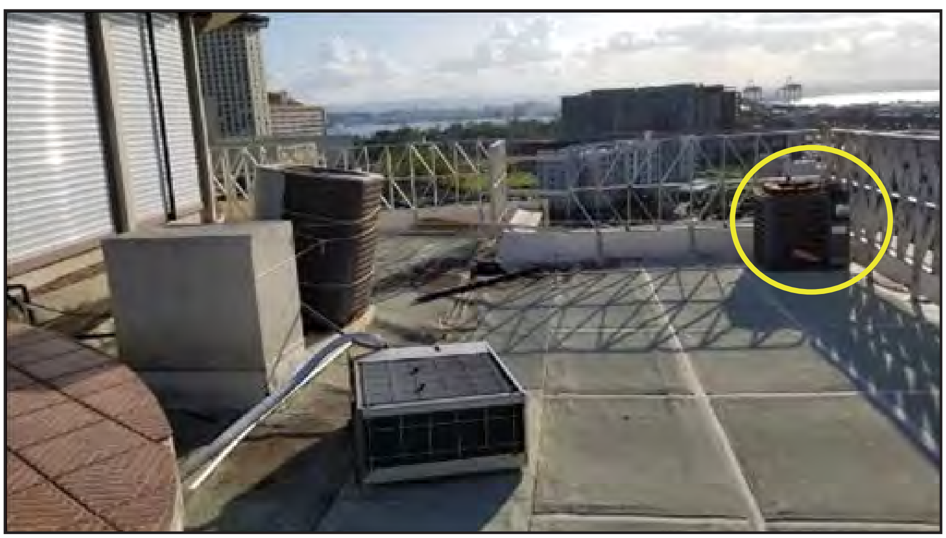


Figure 5-79: HVAC equipment was blown off equipment pads at the roof level of the PRDOJ building. One HVAC condenser has been blown to the edge of the building (yellow circle).

Figure 5-80: A rooftop fan unit is missing from this location atop the PRDOJ building (yellow circle).

Figure 5-81: View of a service access door to the rooftop cooling towers atop the PRDOJ building. The door was driven into the cooling tower by debris impact (red arrow).

While Vega Alta Municipal Building is located somewhat inland and the mechanical equipment was located in a recessed part of the roof, it still suffered considerable damage (Figure 5-82). The HVAC condenser units had been moved off their pedestals and had toppled over in some cases (Figure 5-83). The access panels were blown off as well on several units. Conduit that provided connections for control wires and for power were broken in places. These breaches in conjunction with glazing damage lead to leaks that rendered rooms unusable at the facility.

Figure 5-82: View of rooftop mechanical equipment displaced and damaged by the hurricane winds. Left, the access panels were blown off (yellow circle). Right, the units were moved off their mounting pedestals (red arrow).

Figure 5-83: View of rooftop mechanical equipment displaced (yellow circle) and damaged by the hurricane winds.

At Culebra Municipal Building, most rooftop equipment was mechanically anchored and fared well. The equipment was partly protected by a parapet wall and sat in a mechanical well between several higher roofs. Some fasteners were beginning to corrode, but they were intact (Figure 5-84).

Bayamón Municipal Building was observed to have some equipment screwed to curbs (Figure 5-85, left), while other equipment was inadequately secured. In Figure 5-85 (right), an AC condenser rests unsecured on plastic supports. However, significantly displaced equipment was not observed.

5.3.4 Impacts to Operations

Impacts to operations for these facilities may be classified as being primarily caused by water intrusion or loss of power. Loss of power exacerbated damage due to water intrusion by preventing clean-up and mitigation using equipment including air conditioners, fans, and dehumidifiers.

Figure 5-84: Mechanically attached rooftop equipment performed well at Culebra Municipal Building. Some fasteners were corroded (red arrow) but did not fail.

5.3.4.1 Impacts from Water Intrusion

The PRDOJ building was unable to be occupied for months due to water inundation. As of July 2018, the building is still unoccupied, and the staff work from various locations in San Juan. Many PRDOJ files exist only in hardcopy and were damaged by water. While these files undergo restoration by document preservation experts, PRDOJ is impaired in addressing its workload.

Water still enters the building and floors are wetted by rains. Prolonged wet conditions have created air quality hazards. Addressing these problems has also exposed legacy environmental hazards such as the presence of lead and asbestos, delaying recovery.

The Toa Baja Municipal Building was uninhabitable at the time of the MAT visit due to glazing damage, roof damage, and lack of power. The building envelope damage allowed water to continue to enter the building.

Figure 5-85: Rooftop equipment at Bayamón Municipal Building including, left, HVAC unit attached with screws to a curb; right, an AC condenser resting on plastic supports without anchoring. Rooftop equipment was not significantly displaced during Hurricanes Irma and Maria.

The Culebra Municipal Building was largely unaffected, having only minor flooding of a utility room when a sump pump failed. The building was essentially unaffected, as this small mechanical utility room could still be used.

A main wing of the Bayamón Municipal Building was operational at the time of the MAT visit. This wing was observed to have openings and rooftop equipment failures; however, an HVAC system, powered by a generator, provided ventilation. A separate wing that experienced rooftop and openings damage was not operational at the time of the MAT visit. This wing did not have backup power or proper ventilation and hazardous conditions prevented reoccupation.

5.3.4.2 Impacts from Loss of Power

Lack of power has slowed the recovery and reoccupation of the PRDOJ Building, as there was no practical means to run HVAC equipment, fans, or dehumidification gear. Power was restored to some floors after several months along with some elevator service. However, the HVAC system is non-functional, and the building envelope is still breached. The lack of air movement, lack of moisture and humidity control, and growth of mold and mildew have delayed recovery.

Toa Baja Municipal Building was closed and unusable due in large part to the lack of power. While the building had no flood damage, water from the roof and some broken windows infiltrated the building. Air handling equipment could not be run, and there is no natural ventilation. As a result, indoor air quality deteriorated, and officials cited mold growth. The building also used some finish materials, such as drywall gypsum interior walls and fixed windows, typical of finishes used elsewhere in the U.S., that are less tolerant of humidity and moisture than those commonly used in Puerto Rico.

Impacts to the Bayamón Municipal Building differed between the two wings, which were designed differently: One wing was able to be used because it had natural ventilation, while a large portion of the building was unusable due to lack of power to run air-handling equipment. The loss of air handling resulted in extensive air quality problems and mold growth.

5.4 Successes Since Previous Disasters

All four fire stations discussed in this MAT report had been equipped with hazard-resistant shutters with HMA funding in 2001 under the program discussed in 1.3.3 Other FEMA Hazard Mitigation. Additionally, a number of public buildings received wind retrofits including shutters following Hurricane Irene in 2011. Shutter performance was successful in every case the MAT observed when shutters were fully deployed. In one case, that of the Palmas del Mar Fire Station, some shutters were not in place at the time of the event, allowing windows to be damaged by wind-borne debris. This damage illustrates the need for an adequate operations and maintenance plan and execution of the plan. Additionally, impact-resistant shutters cannot prevent water intrusion through jalousie windows, which are inherently unable to prevent water from seeping between their louvers.

The Culebra Community Health Center and Municipal Building had been equipped with hurricane shutters and/or hurricane-resistant windows by the HMGP-funded Project Impact Culebra in 1999. The MAT was not able to determine whether these original features were still present; however, opening performance at both facilities was good, with glazing undamaged at the Municipal Building and limited water intrusion through openings at both facilities.

HURRICANES
IRMA AND MARIA
IN PUERTO RICO

6 Solar Installations

The MAT observed multiple types of solar installations in Puerto Rico. The solar installations observed were either photovoltaic (PV) power systems or solar water heaters.

PV systems were observed on residential and non-residential buildings, while solar water heaters were only observed on residential buildings. Structurally, solar installations can be ground- or roof-mounted. The observed ground-mounted systems were typically large power-generating facilities (solar farms). Performance within and among these categories varied widely, as discussed below.

6.1 Ground-Mounted Solar Arrays

The MAT observed large ground-mounted solar photovoltaic (PV) arrays in Humacao, Isabela, and San Juan (Figure 6-1). Observations are focused on the ground-mount structures and panel performance. Because of the differences in wind speeds and local terrain features, few direct comparisons of performance can be made among the three sites.

DESIGN GUIDANCE FOR GROUND-MOUNTED PV ARRAYS

ASCE 7-16 does not provide criteria for determining wind loads on ground-mounted PV systems. However, some guidance is provided in SEAOC PV2-17.

FM Global Loss Prevention Data Sheet 7-106 provides guidelines and recommendations for the design, installation, and maintenance of ground-mounted PV systems.

Figure 6-1: Location map showing ground-mounted PV facilities visited by the MAT.

6.1.1 Reden Solar Array, Humacao

In Humacao, a large ground-mounted PV system belonging to Reden Solar (formerly Fonroche) experienced major damage from high winds. Located approximately 2.5 miles (4 kilometers) from the eastern coast of Puerto Rico, Humacao experienced severe wind speeds estimated at 140 mph (225 kph) at 33 feet (10 meters) above ground over flat open terrain (Figure 1-2 and Figure 1-7). Two phases of the facility experienced significantly different effects from the hurricane winds. The first 20-megawatt (MW) phase was constructed in 2016, followed by the second 20 MW phase, which was completed in 2017. The Phase 2 area of the facility was severely impacted by hurricane wind forces and wind-borne debris, while Phase 1 performed relatively well (Figure 6-2, left). Based upon aerial imagery, it is estimated that 75 percent of the solar panels in Phase 2 were damaged or removed from the ground-mount structure, compared to about 25 percent for Phase 1.

Several differences were identified between the Phase 1 and Phase 2 PV arrays (Figure 6-2) during the MAT assessment:

- **Location:** The overview (Figure 6-2, middle) illustrates how the system is positioned. Phase 1 is mostly located on the left side in the photograph, while Phase 2 is to the right. It is possible that the two phases were impacted differently due to the topographic effects created by the surroundings.

- **Elevation above grade:** The PV panels located on Phase 1 (Figure 6-2, left) were installed closer to the ground (low end 26 inches [66 centimeters] above grade, high end 58 inches [147 centimeters]). The panels located on Phase 2 (Figure 6-2, right) were installed at a higher elevation (42-72 inches [108-183 centimeters]) above grade.

- **Installation:** The cantilevered length of the top panel differed between the two phases. On Phase 1, the upper panel was cantilevered 18 inches (46 centimeters). On Phase 2, the upper panel was cantilevered 24 inches (61 centimeters). Because the upper end of the array was likely exposed to more wind pressure, the extra six inches of overhang may have played a role in the failure.

Figure 6-2: High wind damage to ground-mounted photovoltaic (PV) systems in the Reden Solar Array, Humacao, showing panels in Phase 1, left; hill separating the two phases, center; and Phase 2, right.

The Reden solar array in Humacao consists of 1 x 2 meter (39 x 78 inch) panels installed on fixed tilt systems. Each frame has two rows of panels and is angled for solar exposure from south (low) to north (high). The structural members of the ground-mounted system are composed of open-channel (C-shaped) cold-formed metal framing sections. Each pair of posts supports a sloped beam. Two to four lateral rails run perpendicular to the sloped beams (Figure 6-3) and carry the solar panels.

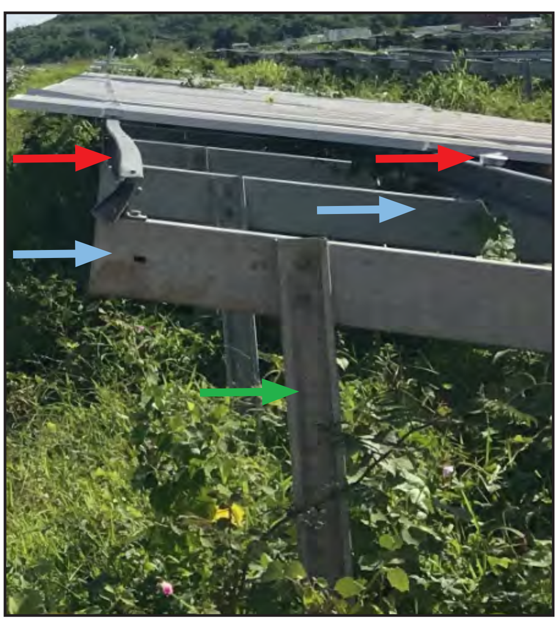


Figure 6-3: Reden solar array in Humacao, with ground-mounted posts (green arrow), sloped beams (blue arrows), and lateral rails (red arrow), that directly support the PV panels. In this image some of the panels have been lifted off the ground-mount structure, with the failure occurring at the panel clips.

The panels are attached to the lateral rails through hat-shaped bolted clips. Two images of the hat-shaped clips (Figure 6-4) display the side and overhead views of the PV attachment to the ground-mount structure. Each clip has only one bolt, and four clips secure a single PV panel. The lack of redundancy in this system means that if one clip or bolt fails, an entire panel will likely be lifted off the ground-mount structure. With a single nut, the bolted connection is also susceptible to loosening as winds cause the panels to vibrate. During numerous wind cycles, as can occur in a hurricane, the panel clips may eventually become loose enough to allow wind pressure to lift panels off the ground-mount structure (Figure 6-5).

Figure 6-4: Reden solar array in Humacao: Left, side view of a hat-shaped clip showing its bolted connection to the lateral rail member underneath. Right, top view showing that a single bolt secures it to the rail.

Figure 6-5: Reden solar array in Humacao: A deformed hat-shaped clip still bolted to its supporting lateral rail. The PV panel to the left was lifted out of position when the hat-shaped clip could not resist the wind uplift pressures and was bent upward.

In addition to clip failure, the lateral rails and lateral rail angle connections exhibited deformation due to debris impacts or wind pressures, which lifted panels out of position, leaving the panels still connected to the rails (Figure 6-6 and Figure 6-7).

Figure 6-6: Reden solar array in Humacao: In this image, only the bent angle (red circle), remains after the steel lateral rail and bolted attachment were pried away in the hurricane.

Figure 6-7: Reden solar array in Humacao: Three deformed steel lateral rails (red arrows). In a number of cases the C-shaped lateral rail connections were unable to maintain connection to the steel beams in the high winds.

As the PV arrays and ground-mount structure were lifted and pried off their supports, these objects became wind-borne debris that impacted other ground-mounted arrays. The successive failure of many of the PV rows in Phase 2 demonstrates the devastating effects of components that begin to fail and add wind-borne debris impacts to systems already pushed to the limit of failure from wind pressures. As a result, some areas of Phase 2 contained only a small number of panels in their original positions (Figure 6-8).

Figure 6-8: Reden solar array in Humacao: Aerial view of the Phase 2 Array with most PV panels removed from their ground-mount supports and many structural members damaged.

6.1.2 Oriana Solar Array 1

Oriana Solar Array 1 is in northwestern Puerto Rico near Isabela, approximately 3 miles (5 kilometers) from the coast and was constructed in 2016[1]. The PV panels at Oriana Solar Array 1 experienced lower wind speeds of approximately 90 mph (145 kph) at 33 feet (10 meters) above ground over flat open terrain (Figure 1-2 and Figure 1-7) and appeared to have a more robust structural support system than the Reden array in Humacao. Overall, this array demonstrated far less damage than the Reden site (Figure 6-9). For a typical ground-mount structure, approximately 10 percent of the solar panels were damaged or removed.

[1] Oriana Solar Array 2 is located approximately 1.4 miles (2 kilometers) north of Oriana Solar Array 1, but the MAT did not visit this site. Post-Maria NOAA imagery suggests Array 2 was considerably less damaged than Array 1.

Figure 6-9: Oriana Solar Array 1: Aerial view of one of the more damaged areas within the Oriana Solar Array.

The arrays have two rows of panels and are angled for solar exposure from south (low side) to north (high side). Each array is supported by cold-formed metal framing using open-channel (C-shaped) sections (Figure 6-10). Each pair of posts supports a beam member, which in turn carries the lateral rails running perpendicular to the beams. A set of two lateral rails bears a row of PV panels.

The Oriana Solar Array included additional structural bracing such as bracing between posts both perpendicular and, in some cases, parallel to the lateral rails (Figure 6-10 and Figure 6-11). Some of the PV arrays also utilized horizontal bracing (Figure 6-11). This structural member helps the PV array resist wind loads on the ground-mount system and assists the PV panels in bracing the lateral rails.

Figure 6-10: Oriana Solar Array 1, showing ground-mounted posts (green arrows), sloped beams (blue arrows), and lateral rails (red arrows), directly supporting the PV panels. This array also has a brace connecting each row of posts (pink arrows).

Figure 6-11: Oriana Solar Array 1: The brace connecting each row of posts (pink arrows) provides additional strength to the posts and helps limit the overall sway or movement of the PV array perpendicular to the lateral rails (red arrow). The yellow arrow in the image points to a brace which connects posts parallel to the lateral rails. This brace will assist the system in a similar manner in the opposite direction.

Figure 6-12: Oriana Solar Array 1: The horizontal brace (blue arrow) connecting rows of lateral rails (red arrow) helps distribute wind loads through the structural system and utilize less dependence upon the PV panels to brace the structural system. The horizontal brace also helps resist torsional or twisting action on the ground-mount system.

Although fewer solar panels were lifted off the ground-mount structure, most failures seemed to be generated at the hat-clip connection between the PV panel and the steel lateral rails. Figure 6-13 shows a common example of a missing hat clip where an adjacent PV panel was removed from the PV array. Typically, hat clips were secured to the lateral rails with a single steel nut (Figure 6-14). The winds created by hurricanes can induce fluttering of structural components, and single steel nuts are susceptible to loosening through vibration. Once loose, the PV panels may begin to twist and impose unexpected loading conditions, leading to the panel being blown off the ground-mount supports.

Figure 6-13: Oriana Solar Array 1: Steel lateral rail missing bolt and Hat-clip which held the adjacent PV panel.

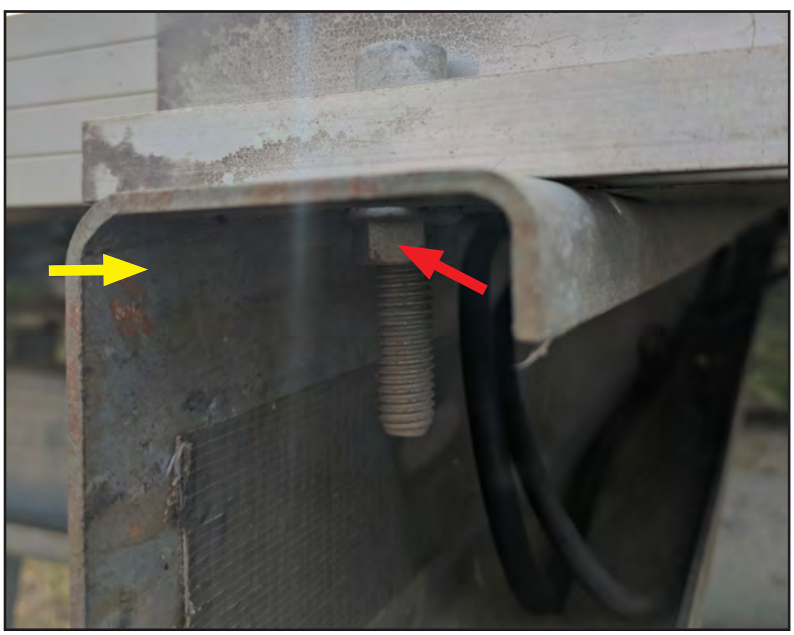


Figure 6-14: Oriana Solar Array 1: Steel lateral rail (yellow arrow) still bolted to the clip which secures the PV panel to the ground-mount system. Notice the single steel nut (red arrow) which could back off the bolt.

6.1.3 Puerto Rico Convention Center Solar Array

The Puerto Rico Convention Center in San Juan has approximately 17,000 solar panels located over parking spaces which offer shade and energy production. The system produces around 8,000 MWh of electricity annually (Trina Solar 2018) and was constructed in 2014. Each array is approximately 330 feet (100 meters) long by 45 feet (14 meters) wide. The steel ground-mount structure and solar panels exhibited good performance and resilience during Hurricane Maria. Although wind speeds were estimated at 140 mph (225 kph) at 33 feet (10 meters) above ground over flat open terrain (Figure 1-2 and Figure 1-7), the system appeared to have lost fewer than 5 percent of the PV panels to debris impact and wind uplift (Figure 6-15).

Figure 6-15: Puerto Rico Convention Center Solar Array: Some PV panels were lost (red circles) from these carports. Based upon aerial imagery, it is estimated that fewer than 5 percent of the panels at this site were damaged or removed (Civil Air Patrol 2017).

The ground-mount structures at the site are predominantly composed of a single steel column supporting a steel girder with a tapered cross-section. The girder cantilevers beyond the column in each direction with assistance from steel kickers. Each girder then carries four steel beams, which hold steel lateral rails that directly support the PV panels (Figure 6-16). The PV panels were connected to the steel rails at four locations using a steel bolt, a washer, and a nut. As mentioned in previous sections, the use of only a single nut raises concerns that the nut could loosen in high winds, allowing the panels to flutter. No damage was observed to the structure.

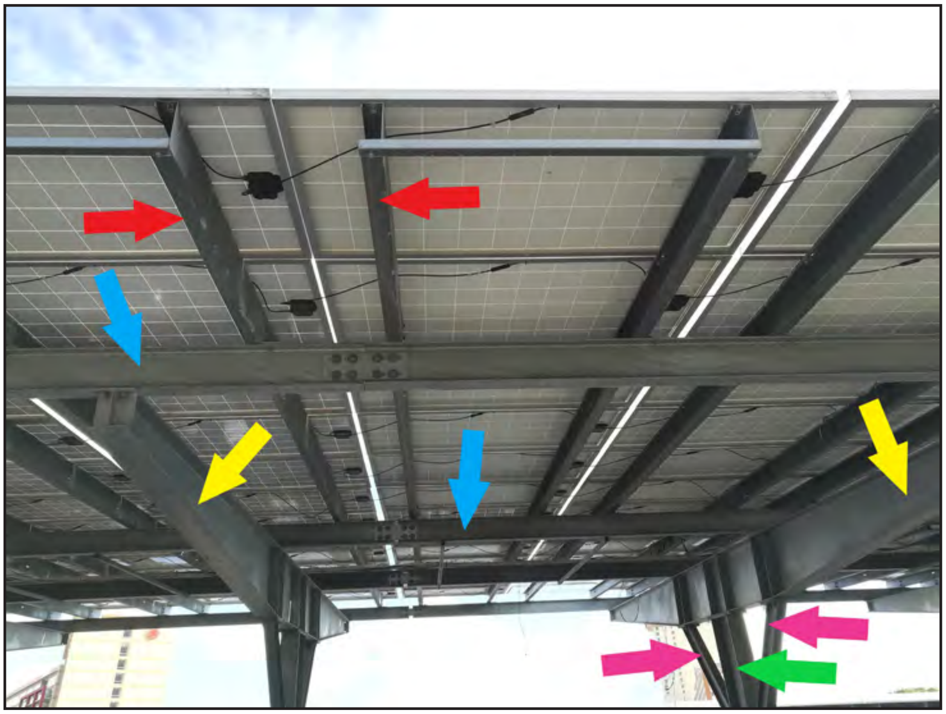


Figure 6-16: Puerto Rico Convention Center Solar Array, showing structural members supporting the solar array looking from the underside of the canopy. The arrows designate the following structural members: steel column (green arrow), tapered steel girder (yellow arrows), steel kickers (pink arrows) supporting girder, steel beams (blue arrows) running perpendicular to the girder, steel lateral rails (red arrows) directly supporting the PV panels.

6.2 Rooftop Solar Equipment

The MAT observed rooftop solar equipment including solar water heaters and PV power systems. The solar water heater industry in Puerto Rico dates to the 1960s, and today, both technologies are viable ways for building owners in Puerto Rico to reduce energy costs.

The solar water heater industry in Puerto Rico benefited from Puerto Rico's inclusion in the U.S. Department of Energy Weatherization Assistance Program (WAP) funded by the American Recovery and Reinvestment Act (ARRA) of 2009. Puerto Rico received $65 million in WAP funding, weatherizing over 15,000 housing units between 2010 and 2011, nearly all single-family homes. Seventy-three percent of these (about 11,173 units) received a solar water heater of either the flat plate collector or evacuated tube type. Solar water heaters were only installed on homes with concrete roofs (Tonn and Rose 2015).

The 2011 Puerto Rico Building Code drove solar water heater adoption by requiring that only solar water heaters be used for new one- and two-family homes and townhouses, with no exemptions

(Energy.gov 2018a). Similarly, the implementation of PV power systems in residential and commercial applications has become feasible since the Government of Puerto Rico enacted net-metering legislation in August 2007 (Energy.gov 2018b).

PREPA, with the Puerto Rico Infrastructure Financing Authority (PRIFA; Autoridad para el Financiamiento de la Infraestructura de Puerto Rico), has developed several solar rebate programs including the Solar Water Heater Rebate Program (OpenEI.org 2018) and the Sun Energy Rebate Program (OpenEI.org 2018).

Wind forces on PV panels are not specifically addressed in the 2011 PRBC, which references the 2009 IBC© and ASCE 7-05 wind load provisions. With the adoption of the 2018 I-Codes, which reference ASCE 7-16, engineers will have guidelines to estimate wind loads on rooftop PV power systems.

6.2.1 Residential Solar Water Heaters

Overall, the observed performance of solar water heaters was excellent. This may be partly due to the fact that panels on many water heater systems are attached to a more robust frame that also supports the heavy water tank. The weight of the collector is also likely greater that of a PV array of similar area, increasing resistance to wind forces. Also, the majority of these systems are installed in concrete homes. Typical anchoring systems used in concrete slab roof systems in Puerto Rico are shown in Figure 6-17.

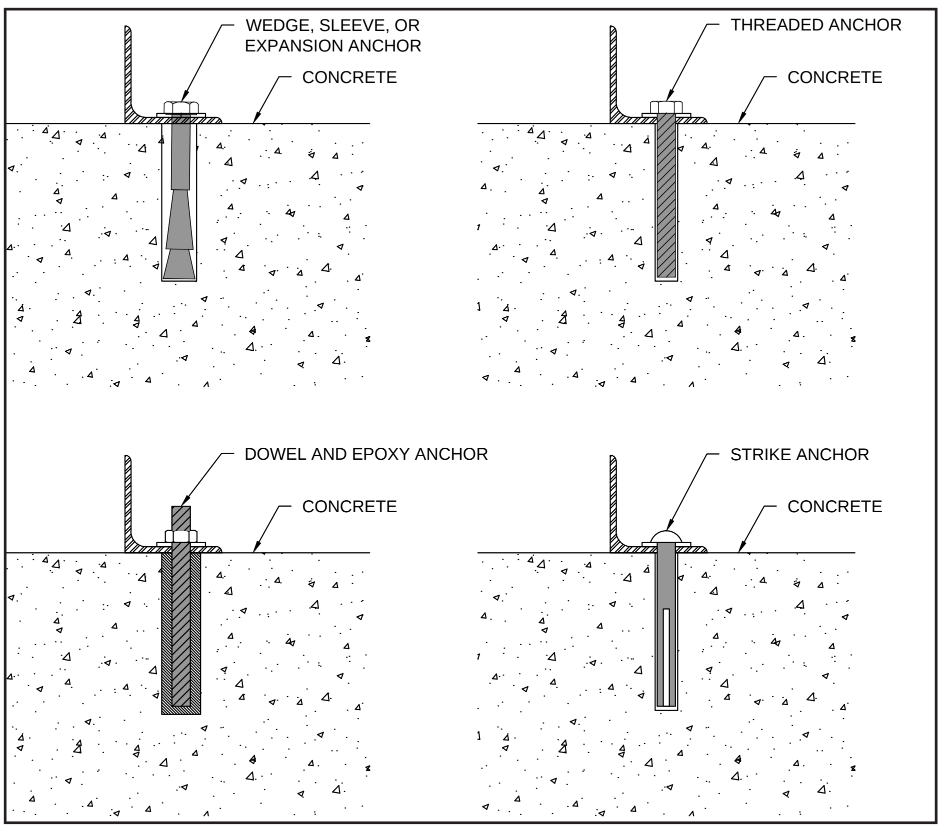


Figure 6-17: Typical anchoring system used for rooftop equipment in concrete slab roof, with, top, concrete anchoring system using an expansion plug placed in the roof slab after drilling a hole, bottom, a concrete expansion anchorage bolt.

MAT field observations revealed that the vast majority of the assessed solar water heaters installed on concrete roofs performed well, with minimal damage associated with wind forces. Figure 6-18 shows a system installed on a NSHP home in Canóvanas; the water heater was not damaged. Figure 6-19 shows a damaged solar water heater installed on a two-story house in the community of El Negro in Yabucoa; in this case, the solar collector panel of the heating system is missing.

Figure 6-18: Solar water heater unit with flat solar collector panel in Canóvanas.

Figure 6-19: Solar water heater system missing solar collector panel on the flat slab concrete roof of a two-story concrete house in El Negro, Yabucoa.

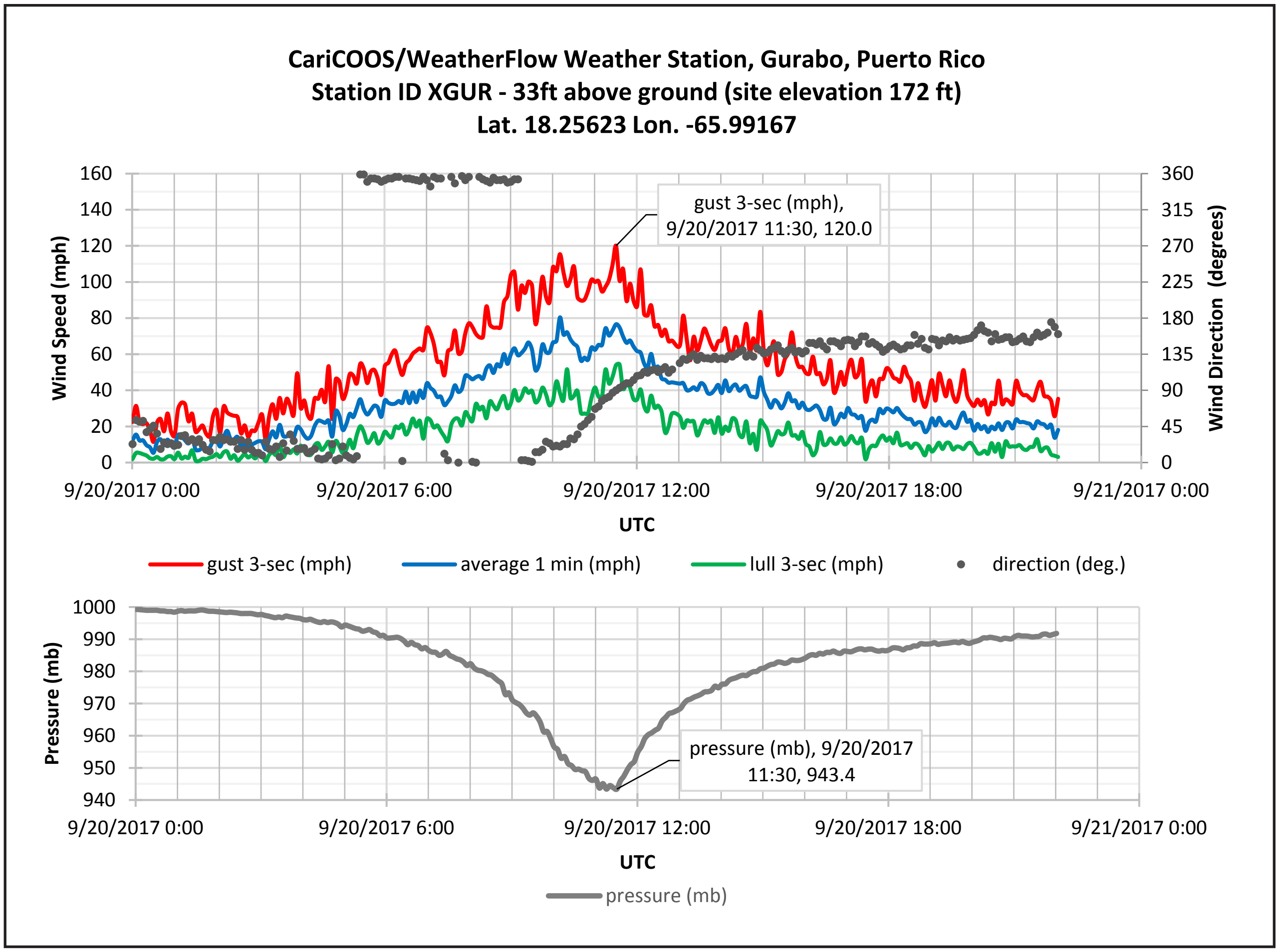


Figure 6-20: Reference wind speed near Caguas at CariCOOS/Weather Flow meteorological station, Gurabo.

Figure 6-21 shows a solar water heater installed on a one-story house in Caguas; in this case, the system shows no signs of wind damage. A nearby CariCOOS/WeatherFlow weather station at the Agricultural Experimental Station of the UPRM approximately 5 miles (8 kilometers) northeast from the house reported a maximum wind gust of 120 mph (193 kph) on September 20, 2017, at 7:30 AM AST (Figure 6-20).

Figure 6-21: Solar water heater system with no evident wind damage on a concrete slab roof of a one-story concrete house in Caguas.

6.2.2 Residential Photovoltaic Systems

In contrast to the consistently good performance of solar water heaters, the performance of PV power systems varied depending on the type of anchoring system and the type of clamping system connecting the PV panels to the aluminum frame. In a typical configuration, PV panels are attached to an aluminum frame system and are typically connected to the framing system at the corners (four points) using a clamp. The MAT observed PV panels that had failed due to wind loads, wind-borne-debris impact, and clamping mechanism failure.

Figure 6-22: PV power system installed on a flat concrete slab roof in Naguabo with no visible damage.

Most of the wind failures and damage associated with PV systems were associated with the failure of the PV panel, failure of the panel connections to the framing system (typical clamp connector mechanism), and, in some cases, lack of proper anchoring to the roof.

Figure 6-23 shows a PV system installed on the roof of a one-story concrete house located in Naguabo with no evident wind damage.

Figure 6-23: PV power system installed on a flat concrete slab roof in Caguas with no visible damage.

In Caguas, the MAT observed a one-story concrete house with a PV system installed on the roof (Figure 6-24). In this case, there was no wind damage to the PV panels, although there was wind damage to the clay roof. Figure 6-25 is a close-up view of the clamp joining the PV panel to the aluminum framing. Figure 6-26 shows the anchoring system of the aluminum framing to the concrete roof. The front portion of the house has an inclined roof with aesthetic ceramic roof tiles; some of the tiles were damaged by high winds, but ceramic tile debris did not damage the PV panels. The homeowner told MAT members that the system had no battery bank and that the house, therefore, had no electrical power at the time of assessment. The homeowner relied on portable gas power generators.

Figure 6-24: Clamp on a PV power system installed on a flat concrete slab roof in Caguas.

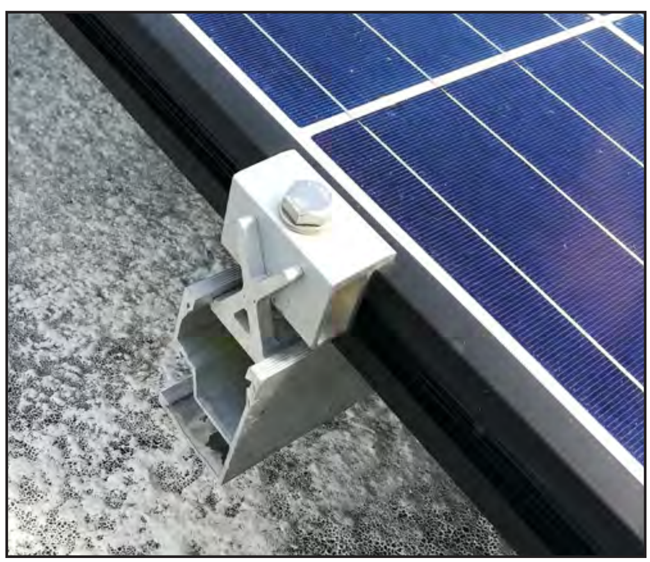


Figure 6-25: Left, PV power system anchored to a flat concrete roof slab in Caguas; right, closeup of bolted connection.

6.2.3 Non-Residential Photovoltaic Systems

This section represents a summary of MAT observations of non-residential rooftop PV systems. The MAT did not encounter solar water heaters in use on non-residential buildings.

6.2.3.1 Susana Centeno Family Health Center, Vieques

The Susana Centeno Family Health Center is a general acute care hospital. Its primary function is to provide inpatient diagnostic and therapeutic services for a variety of medical conditions, both surgical and non-surgical, to the community. The facilities were built in 1996, and the Vieques Rural Outpatient Clinic of the Veterans Affairs Caribbean Healthcare System, which is a Satellite of the San Juan Veterans Affairs Medical Center, was established on January 29, 2011, to improve access to Primary Care services for veterans in Vieques.

It is estimated that wind speeds in Vieques were near the design wind speed per ASCE 7-05, which is 145 mph (233 kph). A nearby weather station located 18 miles (29 kilometers) northeast of Vieques at the Culebrita Lighthouse reported a peak three-second wind gust of 138 mph (222 kph), and it is estimated that the maximum wind speeds were from the southeast (Figure 6-36).

The MAT assessed the PV power system installed on the roof of the acute general hospital Susana Centeno Family Health Center in Vieques. The PV system was installed in 2016 with a capacity of 30 KW with a cost investment of $126,000[2] (State Office of Public Energy Policy 2016). The PV panels shown in Figure 6-26 are on the south portion of the roof edge. For Hurricane Maria, this was the windward edge of the roof building that received the strongest winds. For this facility, the performance of the PV panels with respect to wind loads was poor. Panels were observed to have failed due to wind-borne debris impact (Figure 6-27) and failure of the panels' clamp connection (Figure 6-30). Figures 6-28 through 6-33 show close-up views of the clamping mechanism used to attach the PV panels to the aluminum frame system; the clamp connection consisted of stainless-steel

[2] This is approximately $155,000 in inflation-adjusted September 2017 dollars.

custom bolts that slid through an aluminum slotted section, tightened using regular stainless-steel nuts with a custom clamping mechanism. In addition, the anchoring of the conduit system to the roof was insufficient to withstand the high winds and performed poorly (Figure 6-34).

Figure 6-26: PV power system installed at Susana Centeno Family Health Center in Vieques. The system had significant wind damage due to wind-borne debris impact and clamp failures.

Figure 6-27: PV power system installed at Susana Centeno Family Health Center in Vieques. Close-up view showing PV panels damaged by impact debris.

Figure 6-28: Clamps used at Susana Centeno Family Health Center.

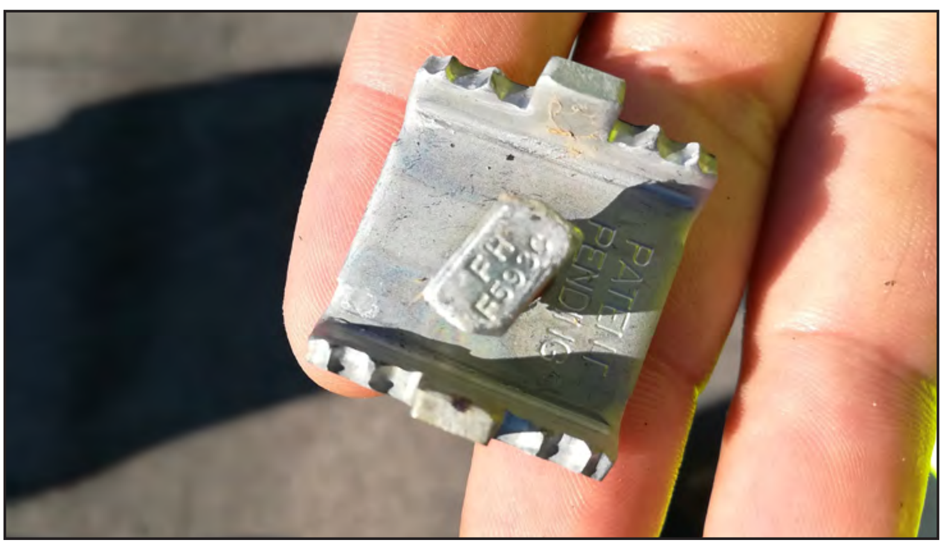


Figure 6-29: Clamp used to hold adjacent PV panels to frame.

Figure 6-30: Clamp used to attach adjacent PV panels to frame.

Figure 6-31: Side view of clamp used to attach adjacent PV panels to frame.

Figure 6-32: Close-up view of the anchoring connection to the roof concrete slab.

Figure 6-33: Close-up view of the clamping mechanizing connection used to hold PV panels at the edges.

Figure 6-34: Failure of conduit connected to the roof used for the PV power system.

The PV power system was significantly damaged by the strong wind of Hurricane Maria. At the time of the MAT observations, the system was not operational. The system was installed close to the roof edge. The aerial shown in Figure 6-35, taken days after Maria, shows that almost the entire first two rows of PV panels close to the edge (orange rectangle) of the roof were blown off the railing system. The MAT observed that fluttering and vibration of the panels due to wind uplift exerted cyclical loading on the clips and frames, contributing to the failure of these components. Wind-borne debris impacts also affected the PV system.

Figure 6-35: PV power system installed on the roof of Susana Centeno Family Health Center, Vieques (Source: aerial image taken September 24, 2017 [NOAA 2017]).

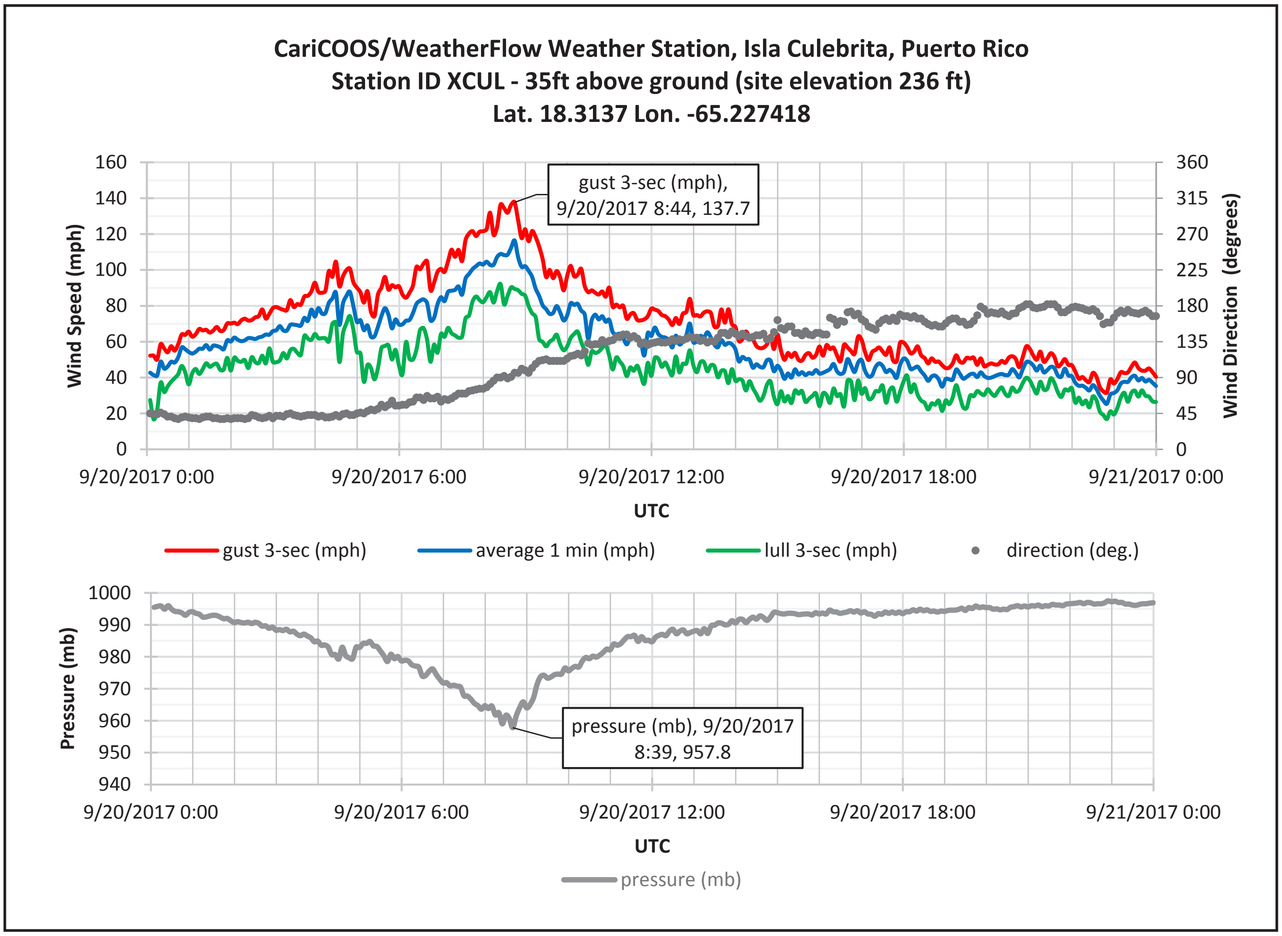


Figure 6-36: Reference wind speed at CariCOOS/WeatherFlow meteorological station, Culebrita.

6.2.3.2 Culebra Ecological School, Culebra

Culebra Ecological School was built after hurricane Georges (1998) to be used as the principal shelter facility for the island of Culebra. During the MAT assessment, the PV power system was not operating due to lack of maintenance of the battery bank.

It is estimated that wind speeds in Culebra were near the design wind speed per ASCE 7-05, which is 145 mph (233 kph). A nearby weather station located 5 miles (8 kilometers) east of Vieques at the Culebrita Lighthouse reported a peak three-second wind gust of 138 mph (222 kph) (Figure 6-36).

The MAT assessed the PV power system installed on the roof of Culebra Ecological School (Figure 6-37). The PV panels are installed on a mono-slope concrete roof with a metal roof covering. The panels appeared to be properly anchored to the concrete roof using structural aluminum angles; however, the metal roof covering failed on part of the roof due to the high winds. The PV panels were located on the windward side of the roof during Hurricane Maria, exposing them to intense winds from open water. The metal roof covering was installed on top of rigid insulation foam installed between the metal covering and the concrete. The roof had severely corroded along the failure zone. It was evident that this corrosion had reduced the structural integrity of the connection of the metal roof covering to the concrete slab.

Figure 6-37: Views of the rooftop PV array at Culebra Ecological School, clockwise from top left: undamaged portion of the roof, roof covering failure, close-up of structural aluminum angle anchoring system attaching the PV panels to the concrete roof, open water exposure for the upwind fetch of the intense winds, close-up of failed roof covering section showing exposed rigid insulation foam, view of corrosion on metal roof edge flashing on portion of roof with roof covering failure.

6.2.3.3 Zimmer Biomet Facility

Zimmer Biomet is a medical device manufacturer in the Mercedita region of Ponce. After Hurricanes Irma and Maria, the company announced that the facility had sustained relatively minor damage from the storms (Zimmer Biomet 2017). The company's manufacturing operations were partially restored and were expected to gradually ramp up as central power was brought back online in the following months. The facility includes a roof-mounted PV array.

Winds speed near Mercedita may have been below the design wind speed per ASCE 7-05. As indicated on ARA wind speed maps (Figure 1-2 and Figure 1-7), estimated wind speed (modeled for comparison to ASCE 7 design wind speeds) was in the range of 90–100 mph (145–161 kph). Although no nearby ground-truthed wind data is available due to instrument and telecommunications failures, a nearby meteorological buoy, located about 12 miles (20 kilometers) south of Mercedita and operated by CariCOOS, reported maximum sustained wind of 58 mph (93 kph) with a maximum gust of 78 mph (125 kph) at 12:00 PM on September 20, 2017 (Figure 6-38).

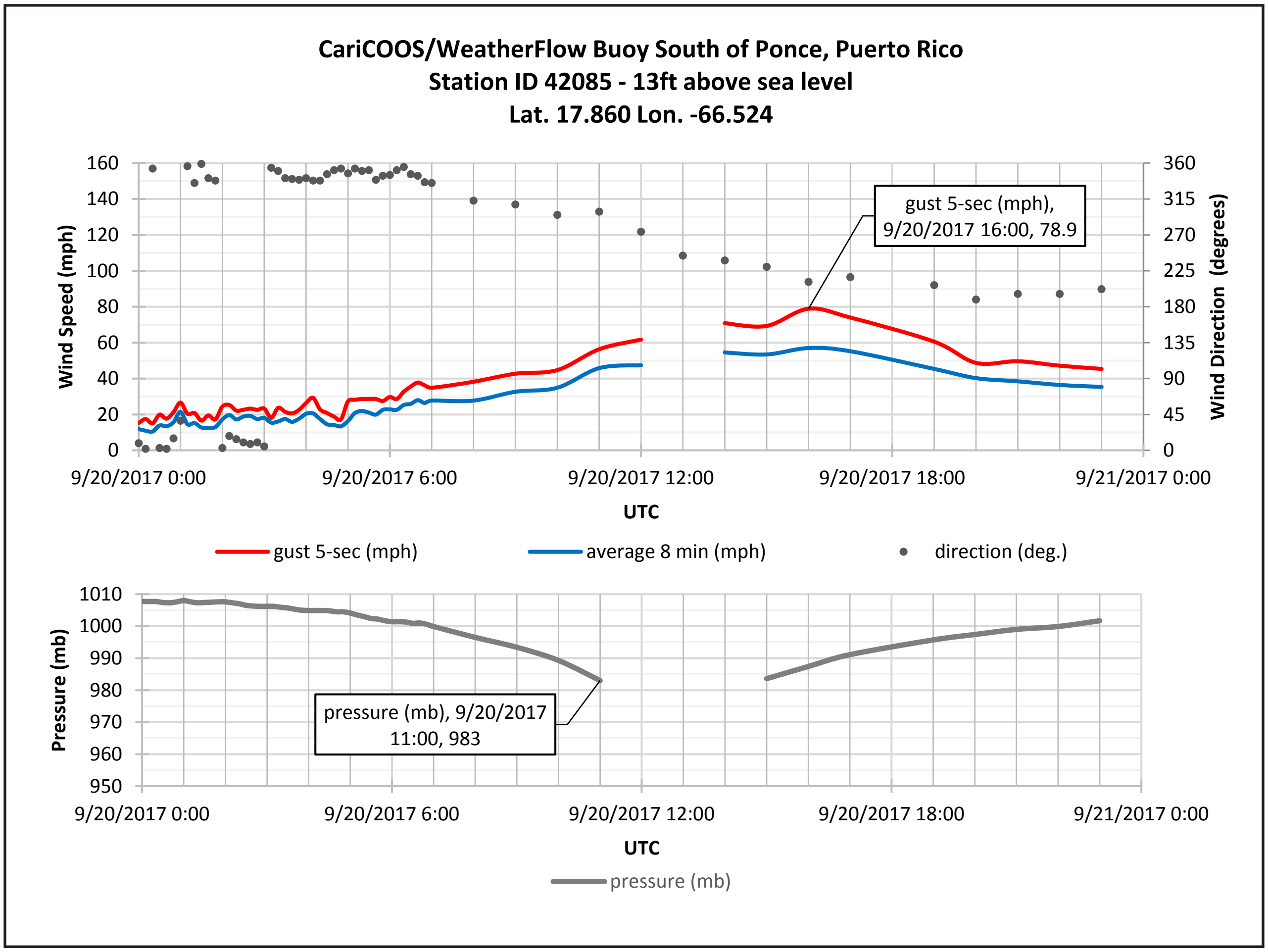


Figure 6-38: Reference wind speed at CariCOOS/WeatherFlow meteorological station buoy south of Ponce. The station failed to record some values during Hurricane Maria; therefore, actual wind speeds and pressures at this station may be more extreme than those discussed.

The PV power system (Figure 6-39) consisted of eight PV panels installed on an aluminum frame system attached to the roof of a concrete structure. After Irma and Maria, only four panels remained in place.

Figure 6-39: PV power system at Zimmer Biomet in Mercedita, Ponce, which lost four of its eight panels.

The PV array was most likely damaged due to insufficient anchorage of the PV panels to the aluminum framing (Figure 6-40). Although the estimated wind speed was below the design wind speed at this location, wind uplift forces and fluttering effects appear to have caused a partial failure.

Figure 6-40: Close-up views of the aluminum framing system of the PV power system at Zimmer Biomet facility in Mercedita, Ponce.

COMMUNICATION TOWERS AND WIND TURBINES

The MAT observed multiple failures of communication towers and wind turbines. The failure of these structures limited coordination efforts and reduced electrical power generation following the hurricanes. These failures create wind-borne debris, which can threaten lives and harm surrounding structures and property.

Adjacent to a community basketball court in Cayey, a three-legged lattice communication tower failed. The communication tower had a triangular steel cross section and failed at the lower third. Figure 6-41 displays steel angles which snapped in the hurricanes. The MAT could not definitively establish the cause of failure, but wind-borne debris, high winds, or a combination thereof are likely candidates.

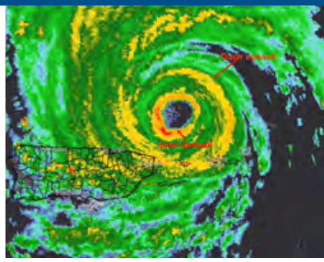
Approximately 7 miles (11 kilometers) east of the failed communication tower in Cayey, another tower supporting a doppler radar enclosure (the radome or bubble) was ripped apart by Hurricane Maria (Figure 6-43). Located on the peak of a mountain at approximately 2,700 feet (823 meters), the radar bubble could not withstand the estimated 125 mph (201 kph) wind speeds. However, the steel tower structure demonstrated good performance and appeared to suffer no significant damage.

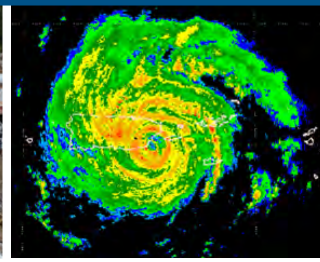
The Punta de Lima Wind Farm is composed of 13 three-bladed turbines. Located in Naguabo, it began operation in 2013. Wind speeds of approximately 130 mph (209 kph) caused severe damage to the turbine blades (Figure 6-42). Some of the blades were broken off their supports, while other blades appeared shredded by the wind. In some cases, all three blades and the top portion of the tower were severed from the tower support.

Figure 6-41: Failure of steel communication tower in Cayey.

Figure 6-42: Wind turbines damaged by the hurricanes in Naguabo, along the northeastern coastline of Puerto Rico.

Figure 6-43: Failure of radar bubble on communication tower in Cayey. The tower itself appeared undamaged.




7 Conclusions and Recommendations

The conclusions and recommendations presented in this report are based on the MAT's observations in the areas studied; evaluations of relevant codes, standards, and regulations; and meetings with Commonwealth and local officials and other interested parties.

The conclusions and recommendations are intended not only to assist Puerto Rico communities, businesses, and individuals in their recovery, but to help improve the resilience of communities and buildings impacted by flood and design-level wind events like Hurricanes Irma and Maria. The authors of the MAT Report also wish to acknowledge the actions Puerto Rico has already taken, or is taking, to improve resilience consistent with the recommendations found in the report.

7.1 Summary of Conclusions and Recommendations

The 2017 hurricane season was devastating for the residents of Puerto Rico. Hurricane Maria made landfall in Puerto Rico as a category 4 hurricane and destroyed or severely damaged much of the Commonwealth's infrastructure. The 3.3 million residents were left without power for months, and 95 percent of cellular sites were out of service, leading to a complicated and delayed recovery.

The impact of the hurricanes was felt not only in the power and telecommunication sectors, but also by individual homeowners. Many of the residences in Puerto Rico are of informal construction, not built to a building code or standard. In addition, the advanced age of residential building stock and the limited adoption of flood insurance in the Commonwealth have impacted many residents. Irma and Maria destroyed thousands of homes and, without proper insurance to assist reconstruction, these homeowners' ability to rebuild is uncertain.

This report provides several recommendations to assist in rebuilding a resilient Puerto Rico. The recommendations are presented as guidance for a variety of stakeholders from the public, private and non-profit sectors. The following are three especially important recommendations in order of urgency, from one requiring immediate action to one which may take longer to implement.

Recommendation PR-3a. OGPe should finalize the adoption of the latest hazard-resistant building codes and standards. To enable new buildings and those that have been substantially damaged or will be substantially improved to better resist disasters, the latest editions of the building code and reference standards should be considered for adoption. OGPe should review the I-Codes and determine the most relevant to adopt for the Commonwealth. In addition, Puerto Rico should consider local amendments to ensure that the hazard-resistant provisions are not weakened and that local conditions are accounted for.

Recommendation PR-9a. FEMA should consider working with the Insurance Institute for Business & Home Safety (IBHS) to conduct a review of private flood insurance policies for equivalency and effectiveness. Private flood insurance can offer different protections than NFIP policies. Because Puerto Rico's reliance on private insurance is unique in the U.S., a study is warranted after this event to assess the efficacy of private insurance on homeowners' ability to rebuild more quickly while reducing the burden on U.S. taxpayers.

Recommendation PR-35a. Require specific educational and first responder facilities to provide a storm shelter. Safe rooms and storm shelters provide buildings or portions of buildings that have been designed and constructed to provide life-safety protection from high wind events such as hurricanes. Puerto Rico should create a local amendment to the PRBC to require that any new facilities constructed for Educational Group E Occupancies with an aggregate occupant load of 50 or more (including public and private schools, but excluding Group E day-care facilities or Group E occupancies accessory to places of religious worship), 911 call stations, emergency operations centers and fire, rescue, ambulance and police stations comply with IBC© table 1604.5 as a Risk Category IV structure and be provided with a storm shelter constructed in accordance with ICC 500©. In addition, OGPe and PRDOH should keep a record of all ICC-compliant community shelters in the Commonwealth.

7.2 General Conclusions

Conclusion PR-1

Many of the damaged buildings observed lacked a continuous load path: Most of the buildings observed by the MAT that experienced partial or total failure of their structural systems lacked a continuous load path. While some buildings experienced failures when individual structural members failed, this was not common. The most common type of failure occurred when a connection between two structural members failed. When continuous load paths were provided, and designs corresponded with what is in the newer codes, the MAT observed no structural failures.

> **Recommendation PR-1a. OGPe should develop and publish prescriptive design guidance and load path details for designers and contractors.** Prescriptive load path details and connections suitable for Puerto Rico should be compiled and published for use by designers, building officials, and contractors. Although building codes require a load path, they do not prescriptively address the connections. Load path details specifically addressing framing or MWFRS connections from the roof to the foundation should be developed by OGPe to help guide design and construction activities. These details will help provide a guide for design professionals to follow and supports a consistent set of potential solutions for contractors to select from and implement.

> **Recommendation PR-1b. OGPe should require construction documents to list critical design parameters and show load path connections.** OGPe should require that critical design parameters for flood, wind, and seismic design, as well as load path connections, be clearly listed and shown on building construction documents. A design professional should evaluate the number, size, corrosion protection, and type of load path connectors necessary to resist the applicable building loads. Construction documents should describe and identify load path connections for new construction and construction that is being repaired or renovated.

Conclusion PR-2

Many building owners had limited awareness of hurricane hazard risks and vulnerabilities: Many building owners and occupants had limited or differing awareness or understanding of the impending risk of the hurricanes. The vulnerability of their building to flood, wind, and other hazards was unknown and many assumed that a specific building type or location ensured their personal safety. The understanding of vulnerability may have been due to the information sources used to identify the risks, as well as local government recommendations about whether to close the facilities during the event. Many building managers and owners may not have been aware of the higher risks from such severe hurricane events.

> **Recommendation PR-2. Facility and building owners should consider performing vulnerability assessments for all relevant hazards prior to a natural hazard event.** Facility and building owners should consider having vulnerability assessments performed by a team of knowledgeable professionals to help determine options available to mitigate hazards and risks for buildings, including critical facilities, key assets, and other structures that may be heavily impacted by a hazardous event. Owners should

identify vulnerabilities and include mitigation measures in short- and long-term facility maintenance and capital improvement programs to realistically address the vulnerabilities over time, where possible. Facility owners and operators should work with key internal staff and design professionals to analyze their facilities, key systems and components, operational assumptions, and operation plans to determine a path forward for developing project priorities and funding capital improvements that maximize facility and operational resiliency. FEMA P-424 Design Guide for Improving School Safety in Earthquakes, Floods, and High Winds (FEMA 2010a), FEMA P-543 Design Guide for Improving Critical Facility Safety from Flooding and High Winds (FEMA 2007a) and FEMA P-577 Design Guide for Improving Hospital Safety in Earthquakes, Floods, and High Winds: Providing Protection to People and Buildings (FEMA 2007b) are building-use-specific guidance documents that include multi-hazard vulnerability assessment checklists for schools, critical facilities, and hospitals, respectively.

7.3 Building Codes, Standards, and Regulations

This section addresses conclusions and recommendations broadly related to codes and policy, including those pertaining to the PRBC, permitting and enforcement entities, the I-Codes, NFIP and outreach and process stakeholders.

ADOPTION OF THE 2018 I-CODES

OGPe 2017-10 orders the establishment of a committee to revise and adopt the PRBC based on the 2018 I-Codes. The proposed codes for adoption include the 2018 Editions of the following:

- International Building Code
- International Energy Conservation Code
- International Existing Building Code
- International Fire Code
- International Fuel and Gas Code
- International Mechanical Code
- International Plumbing Code
- International Private Sewage Disposal Code
- International Residential Code
- International Swimming Pool and Spa Code

FEMA supports OGPe's decision to update the 2011 PRBC. The 2018 I-Codes include the most recent hazard-resistant provisions and criteria for wind, flood, and seismic hazards. A full discussion of OGPe 2017-10 is provided in chapter 2.

7.3.1 PRBC

Conclusion PR-3

The PRBC can be updated to higher standards: The MAT reviewed the current codes adopted in Puerto Rico. The existing PRBC is based on the 2009 I-Codes. Since the adoption of the 2011 PRBC the 2012, 2015 and 2018 I-Codes have been published.

> **Recommendation PR-3a. OGPe should finalize adoption of the latest hazard-resistant building codes and standards.** To enable new buildings and those that have been substantially damaged or will be substantially improved to better resist the impacts of hurricanes, floods, and seismic events, the latest edition of the building code and reference standards should be considered for adoption. OGPe should review the I-Codes and determine the most relevant to adopt for the Commonwealth. In addition, Puerto Rico should consider local amendments to ensure that the hazard-resistant provisions are not weakened and that local conditions are accounted for.

> **Recommendation PR-3b. OGPe should review and update the PRBCs hazard-resistant building codes and standards according to a recurring code update cycle.** Puerto Rico should consider a regular adoption cycle of the building code and update any necessary inclusions of the local amendments.

Conclusion PR-4

Corrosion of fasteners and connectors contributed to building failures throughout Puerto Rico. The MAT observed corrosion of fasteners and connectors on many buildings throughout the Commonwealth. Building damage due to corrosion notably included roof damage from blown-off rooftop equipment secured with fasteners that had corroded, and failures at column base plates for Engineered Metal Buildings Systems.

> **Recommendation PR-4. OGPe should develop a local amendment to the PRBC requiring corrosion-resistant materials.** OGPe should develop, adopt, implement, and enforce requirements for the use of corrosion-resistant materials for exposed structural members, connections, fasteners, metal straps, and anchoring mechanisms throughout Puerto Rico. Structures should comply with the Corrosive Environments criteria in ASCE 24, Section 5.2.2. OGPe should consider reviewing the following documents for additional connector information:
>
> 1) Technical Bulletin 8: *Corrosion Protection for Metal Connectors in Coastal Areas* (1996)
> 2) FEMA P-55, *Coastal Construction Manual* (2011)
> 3) FEMA P-499 *Homebuilders Guide to Coastal Construction* (2010)

Conclusion PR-5

Staged Construction remains unnecessarily exposed to the elements, degrading exposed structural elements over time: The MAT observed staged construction throughout the Commonwealth. Much of the staged construction appeared to have structural elements that were left exposed to the elements for extended periods of time leading to possible corrosion and weakening of the structural components.

> **Recommendation PR-5a. Protect material during staged construction.** Where extended open permit periods exist for staged construction, OGPe should provide requirements for ensuring that the materials used in construction maintain their original strength (i.e., capping exposed rebar).
>
> **Recommendation PR-5b. Limit extended open permit periods for staged or phased construction.** Staged and phased construction is not addressed with specific time durations within the IRC©. OGPe should consider providing guidance on permits and construction that is left incomplete (i.e., extended rebar through roof sections for future second stories, partially completed additions, etc.) and providing specific timeframes after which a new permit would be needed. OGPe should consider adding inspection requirements for any permit renewal for staged or phased construction.

7.3.2 Planning Board, OGPe, and Autonomous Municipalities

Conclusion PR-6

OGPe lacks adequate staffing, which has affected hazard-resistant design compliance and impacted its ability to enforce the latest building codes and standards: Staffing constraints at the Commonwealth and municipal levels have resulted in a minimal approach that often places responsibility for the review of hazard-resistant design on the certifying engineer or architect. The requirements of the latest building codes make it essential that knowledgeable, trained staff be available to review and issue permits, evaluate design and construction packages and inspect and enforce the building code. The building code requires new construction (including residential construction) and repairs past an identified threshold to have approved permits accompanied with design and construction documents that are signed and sealed by a registered design professional. The current staffing within OGPe limits the resources available to perform the compliance and enforcement activities set forth by the PRBC.

> **Recommendation PR-6a. OGPe should consider hiring additional code enforcement staff.** Working collectively with the Commonwealth and municipalities, OGPe should consider hiring, training and supporting additional staff for permit, inspection, and code enforcement efforts during post Hurricanes Irma and Maria reconstruction activities. After providing the initial surge of support, OGPe can determine the number of staff to be retained for long-term support of the building code.
>
> **Recommendation PR-6b. The PRPB, OGPe, and autonomous municipalities should consider evaluating plan review staffing and guidance.** Staffing constraints at the Commonwealth and municipal level have resulted in a streamlined approach that focuses on only certain structures for inspections. Proper staffing and guidance

including checklists could enable a more comprehensive approach to inspections and more detailed review of plans for hazard-resistant design compliance.

Recommendation PR-6c. Municipalities should consider participating in the Insurance Service Office's (ISO) Building Codes Effectiveness Grading Schedule (BCEGS). Participation in BCEGS would give officials standardized evaluations of a municipality's ability to effectively conduct permit activities and better enforce building codes.

PUERTO RICO HAZARD MITIGATION GRANT PROGRAM (HMPG) FUNDS FOR CODE ADOPTION AND ENFORCEMENT

Puerto Rico was awarded an HMGP grant to expedite code adoption in the Commonwealth as it updates its building code by adopting the 2018 I-Codes. The grant will fund the formal review of the new codes; the purchase of new code materials for training and use by permit issuers, code enforcement officials, and others as needed (including municipal and legislative officials); public education and outreach related to the new codes; elected official meetings; public meetings; and other related activities necessary for the formal adoption of the updated codes. Performing these activities will allow for expedited adoption of the new codes to ensure they are in place during the design phase of disaster recovery activities related to Hurricane Maria.

Puerto Rico was also awarded a second HMGP grant to support post-disaster code enforcement. The grant will fund increased staff support for PRPB and OGPe; investment in technological solutions to support operations; establishment of a robust, recurring training curriculum and outreach program; increased data collection and sharing between state agencies; and an increased pool of trained experts to maintain and enhance resiliency and compliance in the future. Staff to be hired under this program include 25 Compliance Inspectors (PRPB), 145 Project Inspectors (OGPe), 5 Supervisor Inspectors (PRPB), 50 Specialized Inspectors (Licenses and Certifications) (OGPe), 21 Technicians (Licenses and Certifications) (OGPe), 12 Buildability Technicians (OGPe); 12 Uses Technicians (OGPe), and 4 Environmental Compliance Technicians (OGPe). The project also has the goal of increasing the number of CFMs in Puerto Rico to 50. Increased revenue from permit fees and fines collected during the grant are expected to make these improvements self-sufficient for the long term so that informal construction practices may be reduced and eventually eliminated.

Conclusion PR-7

Training was insufficient for code enforcement staff and in-house technical experts: Building codes cannot be fully implemented and enforced without adequately trained staff. Discussions with OGPe, municipal officials and local experts all echoed the need for additional training of code enforcement staff.

Recommendation PR-7. OGPe should train building code enforcement staff on Puerto Rico building code and local amendments. OGPe should provide training on the latest codes being adopted. This will help code enforcement staff be better prepared for implementing the new code. OGPe will have the opportunity to review policies, answer questions, address gaps in guidance or local amendments or issues of concern before implementation occurs, making for a smoother transition. Training should include an emphasis on hazard-resistant construction and consider ICC© certifications.

Conclusion PR-8

Professional licensure and training positively affected quality: Hazard-resistant, code-compliant construction requires design and construction professionals to have extensive, up-to-date professional training. Without a regulatory regime that confirms and enforces professional licensure where appropriate, there can be no assurance that those performing these duties are qualified.

Recommendation PR-8a. Establish a licensure program for contractors in Puerto Rico. OGPe should establish a licensure program for contractors and require contractors to be licensed. OGPe should consider developing requirements for contractors which may include continuing education units (CEU's) covering design, engineering, codes and construction.

Recommendation PR-8b. Train design professionals and contractors on the latest hazard-resistant design and construction techniques and best practices. OGPe should provide training on the 2018 I-Codes and local amendments to the adopted model code. Training should include an emphasis on hazard-resistant design and construction and best practices provided in FEMA guidance. This training may include load path design, and coastal, flood and wind/seismic design and construction details.

Recommendation PR-8c. Establish public database of actively licensed and registered design professionals and contractors. OGPe should work with Professional College of Engineers, Puerto Rico College of Architects & Landscape Architects (CAAPPR), and Land Surveyors (Colegio de Ingenieros y Agrimensores de Puerto Rico [CIAPR]) to establish a public database of licensed and registered design professionals and contractors.

PUERTO RICO LAW 19-2017

Law 19-2017 was enacted to unify and consolidate permitting. The law created the Unified Information System to integrate Commonwealth and municipal permits and licenses in a consistent manner online. The uniform approach to building permits for the Commonwealth and municipalities provides a standardized approach to permitting in Puerto Rico and allows design professionals and contractors to follow a single consistent procedure. Under a standardized system, implementation and guidance on complying with hazard-resistant provisions in the permitting process can be leveraged throughout the Commonwealth. Law 19-2017 includes a Joint Regulation instructing all autonomous municipalities with permitting offices to follow one set of zoning and construction rules regardless of the project's location.

Conclusion PR-9

Few homeowners have flood insurance and of those that do, the majority have private flood insurance: Although flood insurance is available in Puerto Rico through the NFIP and private insurers, adoption rates are very low. The MAT literature review found that there may be as many as 40,000 private residential flood policies in Puerto Rico at the time of the hurricane compared to only 4,200 NFIP policies. Private flood insurance policies make up 90 percent of the flood policies in Puerto Rico versus only two percent nationwide. The MAT did not undertake a full assessment of insurance in Puerto Rico, but it is believed that the unique construction of the island and the prevalence of concrete homes allow for reduced private insurance premiums compared to NFIP rates. However, quality and comparison of benefits has not been studied.

Recommendation PR-9a. FEMA should consider working with the Insurance Institute for Business & Home Safety (IBHS) to conduct a review of private flood insurance policies for equivalency and effectiveness. Private flood insurance can offer different protections than NFIP policies. Because Puerto Rico's reliance on private insurance is unique in the U.S., a study is warranted after this event to assess the efficacy of private insurance on homeowners' ability to rebuild more quickly while reducing the burden on U.S. taxpayers.

Recommendation PR-9b. FEMA in conjunction with IBHS should consider developing materials, outreach, and partnerships to educate homeowners on flood insurance (both private and NFIP) options and importance. Flood insurance reimburses for covered building and contents coverage up to certain limits and helps the insured recover from flood events. Materials should include simplified handouts that outline minimum requirements of a recommended flood insurance policy.

Conclusion PR-10

Administrative Order 2017-07 (OGPe 2017) exempted certain recovery efforts and essential activities from ordinary construction permits: Rebuilding and repair of certain infrastructure was exempt from construction permitting for a period of 120 days. Construction during this time required construction plans certified by a licensed engineer or architect.

Recommendation PR-10a. Develop a process for documentation of short-term, post-disaster repairs. OGPe should develop a process for documentation of short-term, post-disaster repairs. Rebuilding and repairing during the 120-day exemption period required a construction plan certified by a licensed engineer or architect. Documenting rebuilding and repairs enables retroactive review to confirm compliance with applicable building codes and policies. This process could be leveraged for emergency repairs, so that if a presidential disaster declaration is made, a database and process would be in place to document short-term post-disaster repairs.

Recommendation PR-10b. Develop process for retroactive permit review of rebuilding and repairs. OGPe should develop a process to retroactively review construction plans and other relevant documents for rebuilding and repairs conducted during any permit exemption period.

7.3.3 Planning Regulation 13

Conclusion PR-11

Puerto Rico's Floodplain Management Ordinance has not been coordinated with the 2018 I-Codes: The current Puerto Rico floodplain management ordinance and the 2009 I-Codes are reasonably closely-linked for floodplain management purposes. However, the current floodplain management ordinance no longer properly coordinates with the many changes that have been made over the past eight years to the 2018 I-Codes. This will result in confusion in implementing the Floodplain Management Ordinance and could lead to development that is not compliant with the current building code.

> **Recommendation PR-11. Integrate the update to the Puerto Rico Floodplain Management Ordinance with the proposed updates to the PRBC.** The Puerto Rico Floodplain Management Ordinance should be updated and integrated with the flood-resistant provisions currently included in the 2018 I-Codes proposed for adoption into the PBRC. This document needs to be properly integrated with IBC© Section 1612, IBC Appendix G, and IRC© Sections R301, R322, and R401 (and other sections), enabling effective compliance for all development with the flood-resistant provisions of the I-Codes and the NFIP. The flood-resistant provisions of the IBC© and IRC© and their reference standards, primarily ASCE 24, provide improved criteria for flood-resistant construction. The PRPB should utilize FEMA's model floodplain ordinance to help them develop and adopt its own that seamlessly integrates with the I-Codes.

7.3.4 NFIP

Conclusion PR-12

Not every community has a Certified Floodplain Manager (CFM): Puerto Rico has five NFIP communities that collectively include all seventy-four municipalities. Additionally, eighteen of the seventy-four municipalities have autonomous capabilities, including many that issue construction permits. The Association of State Floodplain Managers lists only six CFM certifications in Puerto Rico.

> **Recommendation PR-12. All NFIP communities and autonomous municipalities that actively issue construction permits should have a Certified Floodplain Manager or equivalent on staff.** All NFIP communities and autonomous municipalities that issue construction permits should have at least one staff member that is a Certified Floodplain Manager or that holds an equivalent certification.

Conclusion PR-13

Only a single community, Ponce, participates in the Community Rating System (CRS): The CRS is an incentive program that encourages communities to develop more hazard-resistant building practices and provides insurance discounts in communities that do. The MAT observed interest from municipal officials to lower the cost of flood insurance and provide additional outreach on flood to residents.

Recommendation PR-13a. FEMA Region II should consider providing outreach to Puerto Rico on the benefits of participating in the CRS. Participation in the CRS benefits everyone and can provide deep discounts on FEMA NFIP flood insurance. FEMA Region II should consider providing outreach to the communities on the benefits and assist in achieving this goal.

Recommendation PR-13b. The PRPB should encourage participation in the CRS for communities that would benefit. The PRPB should encourage participation in the CRS for the communities that would most benefit, which can provide additional outreach on flood insurance and lower the cost of flood insurance premiums. The CRS recognizes community efforts beyond the NFIP minimum standards by reducing flood insurance premiums for policies in the community. The CRS is similar to, but separate from, programs from the private insurance industry that grade communities on the effectiveness of their fire suppression and building code enforcement. CRS discounts on NFIP flood insurance premiums range from 5 percent up to 45 percent, which may incentivize building owners to purchase flood insurance.

Conclusion PR-14

FIRMs for Puerto Rico do not delineate Coastal A Zones (CAZs): Puerto Rico's current effective FIRM, dated 2009, was prepared prior to the current mapping standard. New coastal studies identify areas where breaking wave conditions in AE Zones are similar to but less severe than those in VE Zones. Laboratory tests and post-disaster investigations have shown that moderate breaking waves as small as 1.5 feet can cause significant structural damage if buildings are not designed to withstand these forces. For new coastal studies, the inland limit of these moderate wave areas, where breaking waves between 1.5 and 3 feet (0.5 and 0.9 meters) are expected during base flood conditions, is identified on the FIRM by the Limit of Moderate Wave Action (LiMWA). The CAZ is the area between the LiMWA and VE Zone boundary and includes requirements in the I-Codes that are similar to VE Zone requirements.

Recommendation PR-14. Ensure new ABFE maps and FIRMs depict LiMWA on all appropriate map products. The LiMWA delimits the CAZ, which includes VE Zone design and construction requirements in the most recent I-Codes. In a CAZ, the 2018 I-Codes require buildings to be designed according to the VE Zone requirements (with exceptions for backfilled stem wall foundations, which may be allowed, depending on site soil conditions) unless otherwise noted by the local floodplain ordinance.

7.3.5 FEMA Technical Publications and Guidance

Conclusion PR-15

Selected FEMA Building Science technical guidance publications should be updated to incorporate lessons learned from the MAT: The Building Science Branch at FEMA HQ develops and maintains over 200 publications and resources that provide technical guidance on how to assess risk; identify vulnerabilities; better understand the NFIP and the regulatory environment with respect to building codes and standards; and provide best practices and mitigation measures that can be taken to reduce vulnerabilities to flood, wind, and seismic hazards. The 2017 hurricane season brought landfalling hurricanes to the island territories and the continental United States. There are many valuable and important damage observations and lessons learned from this and other events, and the observed damage might have been avoided if the guidance from these documents had been incorporated at different building locations. However, while the approaches and theory in these publications are still accurate, many of the building codes have been updated and may impact the current approach outlined in these documents.

Recommendation PR-15a. FEMA should consider translating select publications to Spanish. Most FEMA publications are provided only in English. To aid in the recovery of Puerto Rico, FEMA should consider translating key recovery documents to Spanish.

Recommendation PR-15b. FEMA should complete Guidelines for Wind Vulnerability Assessments for Critical Facilities. FEMA's Building Science Branch has been developing guidance to assess wind vulnerabilities of critical facilities. FEMA should include lessons learned from the 2017 hurricane season in finishing this publication, which would greatly benefit many stakeholders in the U.S.

Recommendation PR-15c. Update select FEMA Building Science Publications impacting coastal construction. FEMA's Building Science Branch, in the Risk Management Directorate, should consider updating its key hurricane technical guidance publications to include lessons learned from the 2017 hurricane season and update to current building codes. These publications might include but not necessarily be limited to the following:

- FEMA P-55 C*oastal Construction Manual* (FEMA 2011b)
- FEMA P-499 *Home Builder's Guide to Coastal Construction* (FEMA 2010b)
- FEMA P-762 *Local Officials Guide for Coastal Construction* (FEMA 2009)
- FEMA P-804 *Wind Retrofit Guide for Residential Buildings* (FEMA 2010c)

Recommendation PR-15d. Update the FEMA Risk Management Series guidance publications for natural hazards. FEMA's Building Science Branch, working with other FEMA and DHS entities, should consider updating select technical documents from the FEMA Natural Hazard Risk Management Series to include lessons learned from the 2017 hurricane season and update to current building codes. These publications might include but not be limited to the following:

- FEMA P-424 *Design Guide for Improving School Safety in Earthquakes, Floods, and High Winds* (FEMA 2010)
- FEMA P-543 *Design Guide for Improving Critical Facility Safety from Flooding and High Winds* (FEMA 2007a)
- FEMA P-577 *Design Guide for Improving Hospital Safety in Earthquakes, Floods, and High Winds: Providing Protection to People and Buildings* (FEMA 2007b)

- FEMA P-1019 *Emergency Power Systems for Critical Facilities: A Best Practices* (FEMA 2014a)

7.4 Planning and Programmatic Mitigation

Conclusion PR-16

Schools have been consolidated into facilities that remain vulnerable to flood hazards: The MAT observed that the consolidation of schools in areas susceptible to flooding still left some schools in use within the SFHA. One of these consolidated school facilities was in the municipality of Toa Baja, which has a high flood risk.

> **Recommendation PR-16. The Puerto Rico Department of Education should consider performing a vulnerability assessment of existing buildings in planning consolidation of schools.** Officials evaluating schools for consolidation should consider the vulnerability of available facilities. A program of the Puerto Rico Department of Housing currently exists to evaluate the vulnerability of potential shelters. In addition to that program, the PRDE officials should consider using the following FEMA publications to help perform the vulnerability assessments: Safe Rooms and Storm Shelters for Life-Safety Protection from Hurricanes (FEMA PR-RA3, Appendix D); Design Guide for Improving School Safety in Earthquakes, Floods, and High Winds (FEMA 2010); and Emergency Power Systems for Critical Facilities: A Best Practices Approach to Improving Reliability (FEMA 2014).

Conclusion PR-17

Many non-compliant homes exist throughout Puerto Rico: Many buildings were constructed informally or without permits throughout Puerto Rico. Stakeholders have an interest in working with homeowners to bring existing, informally constructed homes into compliance with the building code.

> **Recommendation PR-17. Develop processes for bringing noncompliant buildings into compliance.** OGPe should consider developing processes for retrofitting existing informal construction. The goal when retrofitting existing buildings should be to meet the hazard-resistant provisions of the most current building code and floodplain management ordinance requirements.

7.5 General Building Considerations

Conclusion PR-18

Windows (glazed openings) on existing buildings are vulnerable to damage and failure from wind pressures and wind-borne debris: Existing buildings of all types that have unprotected windows (glazing) on exterior walls are vulnerable to failure from wind pressures and wind-borne debris. When these glazed openings fail, the buildings are exposed to additional internal wind pressures and the building interior also becomes exposed to the wind and rain associated with the events. Failures were observed in all building types visited by the MAT including homes, businesses, schools, and critical facilities. In some cases, failures of opening protection systems occurred due to building alterations that made it difficult or impossible to deploy the systems or due to lack of maintenance.

Recommendation PR-18a. **Existing homeowners should consider protecting their windows.** Existing homeowners should consider protecting their windows and glass doors with rated opening protection systems (i.e., storm shutters) or retrofit the home with impact-resistant glazing. Puerto Rico Recovery Advisory 5, Protecting Windows and Openings in Buildings (FEMA PR-RA5, Appendix D) provides guidance on the installation and protection of windows and doors. When those options are cost prohibitive, consider constructing and maintaining plywood panels that are cut and sized to cover each window or glass door at the home (per the wood panel design criteria for opening protection set forth in the 2018 IRC©).

Recommendation PR-18b. Existing non-residential building owners should consider protecting their windows. Existing non-residential building owners should consider protecting their windows and glass doors with rated opening protection systems (i.e., storm shutters) or retrofit the buildings with impact-resistant glazing. FEMA PR-RA5 and U.S. Virgin Islands (USVI) Recovery Advisory 4, Design, Installation, and Retrofit of Doors, Windows, and Shutters (FEMA 2018d) provide guidance on the installation and protection of windows and doors.

Recommendation PR-18c. Existing critical facility owners and operators should protect their windows. Existing critical facility owners and operators should protect their windows and glass doors with rated opening protection systems (i.e., storm shutters) or retrofit the buildings with impact-resistant glazing. Perform a vulnerability assessment as described in the general recommendations section. FEMA PR-RA5 and FEMA USVI-RA4 provide guidance on the installation and protection of windows and doors.

Recommendation PR-18d. Building owners should consider developing a life-cycle management program for roof coverings, rooftop equipment restraints, and opening protection systems. The life-cycle management program should include periodic maintenance and should test deployment of opening protection systems as well as assessments of rooftop coverings and rooftop equipment attachments.

Conclusion PR-19

Water intrusion was prevalent through existing windows (glazed openings) and metal panel jalousie systems: Water infiltration into buildings at glazed openings, and specifically through metal panel jalousie systems, was observed throughout Puerto Rico. Metal panel jalousies were the least effective in keeping wind-driven rain and water out of buildings. This issue was observed in most building types visited by the MAT, including homes, businesses, schools and critical facilities.

Recommendation PR-19. Improve performance of windows and openings to resist water intrusion and windborne debris through glazed openings. When using jalousie window systems, consider the use of flood/water resistant materials within the occupied space where these jalousie windows are used. Where conditioned space exists behind the window system, consider use of impact-resistant glazing or glazed openings that are protected with impact-resistant (opening protection) systems such as shutters. Note, opening protection systems are not rated to reduce water intrusion for the windows and openings they protect.

Conclusion PR-20

Water intrusion was prevalent through existing doors: The MAT observed extensive water intrusion through existing doors. Existing doors did not prevent wind-driven rain intrusion and weather-stripping was often not present.

Recommendation PR-20. Limit water intrusion through doors by design and mitigation. For new construction, building owners should consider constructing a vestibule using flood/water resistant materials. For existing construction, building owners should consider retrofitting the building with weather-stripping to reduce water intrusion. Puerto Rico Recovery Advisory 5, Protecting Windows and Openings in Buildings (Appendix D) and USVI Recovery Advisory 4, Design, Installation, and Retrofit of Doors, Windows, and Shutters (FEMA 2018d) provide guidance on the installation and protection of windows and doors.

Conclusion PR-21

OGPe does not provide a list of specific design criteria for design professionals to include on construction drawings: The IBC© and IRC© provide some guidance for minimal information that should be included on construction documents to clarify and verify design information and criteria. However, the minimum guidance provide in the code is much less than requirements set forth in other areas prone to hurricanes, for example, by many county building departments in South Florida.

Recommendation PR-21. OGPe should consider requiring specific notes and design criteria for hazard-resistant design of a structure, including seismic design loads, and require load path connections to be shown. To implement and enforce the new codes, OGPe staff charged with permitting, plan review and inspections should require a complete list of the flood, wind, and seismic design criteria used for the home or building. The design professional responsible for the design and construction of new residential buildings (as well as repairs to existing buildings) should be made aware of the high seismic design criteria for Puerto Rico. In the permitting process, OGPe should ensure the design professional checks wind loads against seismic loads; these are dependent upon the site condition, the geometry of the house and foundation, and the weight of materials used for construction. In addition, the notes and design criteria should include testing information related to debris impact protection systems for glazing, water intrusion, flood-resistant materials, corrosion-resistant materials, and other performance-based building components.

Conclusion PR-22

Tile roofs resulted in poor performance: The MAT observed poor performance of tile roofs throughout Puerto Rico. Roof tiles often became windborne debris and resulted in damage to nearby buildings due to poor attachments and connections.

> **Recommendation PR-22. Existing tile roofs should be evaluated for proper anchorage and connectors.** Tile roofs, when improperly attached, are often a source of windborne debris. Existing tile roofs should be evaluated against ASCE 7-16 standards to ensure compliance with the updated components and cladding wind pressures[1].

Conclusion PR-23

Building Utilities are at risk of flood damage: The MAT observed many building utilities below the BFE or at ground level where they are susceptible to flood damage. When building utilities were elevated, they were elevated to various heights, sometimes not high enough. Locating utility connections and meters above flood levels limited flood damage.

> **Recommendation PR-23. Building owners should elevate critical systems whenever possible.** Building owners should follow P-348, Protecting Building Utility Systems from Flood Damage. This approach could limit damage and enable quicker reoccupation. Additional resources include Hurricane Isaac Recovery Advisory 2, Minimizing Flood Damage to Electrical Service Components (FEMA 2012).

7.6 Residential and Low-Rise Buildings

Conclusion PR-24

Lack of roof deck (sheathing) under roof panel coverings resulted in increased damage: The MAT observed homes with metal panel roof coverings that performed poorly and resulted in the loss of roof panels during the storms. In most cases, these homes did not have a wood deck beneath the metal panels. The absence of a wood deck resulted in a lack of adequate anchorage for the panels, reduced stability in the roof structure, and full exposure of the building interior when the metal panels were lost.

> **Recommendation PR-24. Require the use of wood deck on wood-framed roofs below any roof covering.** For new and existing homes, if calculations are not submitted to show the open wood frame does not require wood decking to provide lateral support, OGPe should consider requiring the use of wood structural panels or board to provide stability, load path, and a solid roof deck beneath the roof covering to comply with design requirements. See Puerto Rico Recovery Advisory 6, Repair and Replacement of Wood Residential Roof Covering Systems (FEMA PR-RA6, Appendix D) for guidance on how

[1]The FEMA Mitigation Assessment Team Report: Hurricane Charley in Florida (FEMA 2005) provides information on tile roof installation methods.

to create a structural system beneath the roof covering and to establish a load path from metal covering all the way down to foundation.

Conclusion PR-25

Even homes that were undamaged during the hurricanes may be susceptible to future wind and seismic events: The MAT observed many homes that experienced little to no structural damage but remain vulnerable to the effects of high winds. In most cases, the connections between the structural members and a lack of protection for glazed openings are the weakest links in the load path and are vulnerable to failure.

Recommendation PR-25. Homeowners should consider evaluating and retrofitting existing homes for wind and seismic vulnerabilities. Homeowners should consider hiring design professionals to evaluate the existing roof structure to determine if can carry at least 75 percent of the design load. If it cannot, they should consider performing wind retrofits with continuous load path systems in accordance with Repair and Replacement of Wood Residential Roof Covering Systems (FEMA PR-RA6, Appendix D) and Wind Retrofit Guide for Residential Buildings (FEMA 2010). Homeowners can also consider wind retrofit techniques set forth for the different protection levels of FEMA P-804 to holistically improve the hazard resistance of homes.

Conclusion PR-26

Roof Penetrations often caused water intrusion: Where roof penetrations existed, such as at utility service masts, localized roof failure and water intrusion often occurred.

Recommendation PR-26. Avoid rooftop penetrations whenever possible. Do not penetrate the roof whenever possible whenever attaching rooftop equipment. Consider use of design guidance found in Rooftop Equipment Maintenance and Attachment in High-Wind Regions (FEMA PR-RA1, Appendix D) when attaching rooftop equipment or service utility masts.

Conclusion PR-27

It is common practice to use prescriptive home designs in residential construction and permitted by the building code: The MAT obtained prescriptive design plans developed by the Commonwealth of Puerto Rico by PRDOH and from municipalities around the island. The designs included many hazard-resistant design approaches developed in response to Hurricane Georges in 1998 and provided details to allow a homeowner or contractor to successfully construct a home compliant with the 1997 UBC, which had been adopted after Hurricane Georges.

However, availability and access to the plans may have been limited, and no formal program was identified that supported the distribution and use of these designs. Where residential construction appeared to perform well, the homes had many of the features observed in the prescriptive designs, but the homes could not be verified as having been constructed to the prescriptive plans.

Recommendation PR-27. OGPe, with support from stakeholders, should develop prescriptive design plans and make them available to support affordable, code-compliant construction of homes and residential buildings. Providing prescriptive home designs based upon the new 2018 I-Codes through a government program would provide an opportunity to address the informal construction issue in Puerto Rico. Currently, FEMA is supporting OGPe with the development of a select number of prescriptive designs for single-family homes. OGPe should consider developing a program using the design plans under development to address roofing, structural, and building envelope issues in a holistic approach to wind- and multi-hazard mitigation of new homes and existing homes.

7.7 Schools, Hospitals, Public Buildings, and Other Mid-Rise Buildings

Conclusion PR-28

Many buildings flooded because their main floor levels are too low on the site: Several schools, fire stations, and other critical facilities were damaged as localized flooding occurred at the building site (this occurred even at sites where the mapped flood hazard area was identified as Zone X). Although individual site conditions led to the localized flooding, in many cases, had the elevation of the main or first floor of these buildings been constructed several inches higher than the adjacent grade, the flood damage to the facilities would have been mitigated.

Recommendation PR-28. Elevate main (primary) floors of buildings above adjacent grade. Designers and contractors should provide a differential of at least 8 inches between the top of the finished floor elevation of the main (primary) floor and the surrounding grade. As a best practice, buildings should be built with the finished floor elevated above surrounding grade. A common practice is to make the grade difference one stair height or 8 inches above grade at its lowest point. Local practice may call for this elevation to be higher or lower. This allows easy accommodation for access and egress by use of a single stair, ramp, or pad.

Conclusion PR-29

Internal pressures were not adequately addressed through open/louvered window assemblies: Many multi-use and athletic (gymnasium) facilities with long-span roofs were damaged during the hurricanes. While the larger, structural members of the MWFRS did not fail, intermediate structural members (purlins), roof decking, roof coverings, and exterior wall systems were all observed to have failed, apparently from pressurization of the building.

Recommendation PR-29a. Designers must consider and adequately address internal wind pressures. For new construction, and for repairs to existing buildings, use of louvered openings that allow free passage of air into facilities, especially in long-span buildings, must properly account for and address internal wind pressures and the effects they have on building components.

Recommendation PR-29b. Consider retrofitting glazed openings, windows, and doors of existing buildings for current wind design pressures and wind-borne debris protection. Owners of existing buildings should consider retrofitting glazed openings, windows, and doors to comply with wind pressure, wind-driven rain, and debris-impact protection requirements of ASCE 7-16. This will help ensure the building maintains a secure envelope, reducing wind pressures on the building. It will also tend to reduce damage from water intrusion and wind-driven rain.

Conclusion PR-30

Insufficient maintenance of roof coverings resulted in increased damage: Many of the schools and public buildings observed by the MAT had roof coverings and roof systems that were not maintained or were past their useful life. When impacted by the storms, these roof systems failed even though the roof decks supporting them did not, resulting in significant damage or loss of function for the facilities. Further, when roof coverings did remain in place, roofs at hospitals, public buildings, and schools were often punctured by wind-borne debris.

Recommendation PR-30a. Regularly assess, adequately maintain, and repair or replace roofs when needed. Building owners and operators (both public and private) should develop maintenance programs for their building exteriors, specifically for roof coverings and roof systems. Much of the damage and loss of function for schools and critical facilities, including hospitals, could have been limited or avoided if roof coverings were properly installed, maintained, and replaced when worn out. The maintenance programs should include a section to address punctures of the roof coverings (membranes, systems, etc.) for when roof coverings remain in place but are damaged.

Recommendation PR-30b. Avoid the use of single-ply roof membranes. Avoid the use of single-ply roof membranes for critical facilities; these systems are vulnerable to puncture, tearing, and blow-off.

Conclusion PR-31

Debris that damaged roof coverings were often from the building itself: The MAT observed at several locations that the debris that punctured roof coverings at both hospitals, several schools, and some public buildings was likely generated from the building itself. This led to water intrusion even when the roof covering remained in place.

Recommendation PR-31. Adequately anchor HVAC and other equipment to roofs. Design professionals and building managers should adequately anchor HVAC systems to resist high wind loads; this applies to both new and existing buildings and equipment. Puerto Rico Recovery Advisory 2, Rooftop Equipment Maintenance and Attachment in High-Wind Regions (FEMA PR-RA2, Appendix D) provides guidance for anchoring HVAC and other equipment to the roof, roof structure, or parapets. FEMA P-543 and FEMA 577 provide guidance for equipment attachment in high winds at critical facilities and hospitals, respectively. If the equipment cannot be adequately mounted on the roof, then consideration should be given to moving the equipment elsewhere on-site.

Conclusion PR-32

Building systems, including backup power generators, switches, and equipment, should be protected against wind, wind-borne debris and flood: Where building systems were properly protected from wind forces and wind-borne debris, these systems were able to maintain backup and emergency power during the events. However, this was not the case at all critical facilities. In many critical facilities, generator failures were observed due to failures from wind-borne debris penetration or damaged equipment due to wind.

> **Recommendation PR-32. Protect building systems to requirements of ASCE 7 and ASCE 24.** Once vulnerabilities have been identified, design building systems in accordance with ASCE 7-16 and ASCE 24-14. Refer to FEMA P-1019 and Puerto Rico Recovery Advisory 1, Rooftop Equipment Attachment and Maintenance in High-Wind Regions (FEMA PR-RA1, Appendix D) for guidance.

Conclusion PR-33

Failure of equipment penthouses and elevator equipment vents on roofs caused loss of operations: The MAT observed the failure of rooftop equipment, penthouses and vent structures that resulted in impacts to mechanical systems that caused building loss of important operational functions.

> **Recommendation PR-33a. Design mechanical penthouses and equipment housing to resist high winds.** In new construction and critical facilities, mechanical penthouses and equipment houses should be designed to withstand loss of operation due to high winds. These features should be designed per ASCE 7-16 to resist high wind loads.

> **Recommendation PR-33b. Retrofit mechanical penthouses and equipment housing in existing buildings.** Building owners and operators should perform vulnerability assessments of their facilities to identify vulnerabilities to wind hazards. FEMA P-424 (schools), FEMA P-543 (critical facilities), and FEMA 577 (hospitals) provide use-specific guidance for performing vulnerability assessments for flood, wind, and seismic hazards. Once vulnerabilities have been identified, mitigation to secure rooftop equipment should be designed per ASCE 7-16 wind load requirements.

7.8 Shelters

Conclusion PR-34

The PRDOH shelter program is helpful but has shortcomings. The PRDOH manages and maintains a robust system to evaluate facilities to be used as “event-specific” shelters and post-event shelters. However, the MAT observed that the designated structures do not meet FEMA P-361 standards for life-safety protection. During severe weather, building occupants should utilize the location in the building that is least susceptible to collapse or failure. Buildings used as “shelters” before, during, and after the hurricanes were not evaluated by design professionals using a consistent methodology or program to identify vulnerabilities from damage or failure from flood, wind or seismic forces.

Recommendation PR-34a. PRDOH should consider updating the shelter program in accordance with FEMA guidance. This program should be based on the FEMA guidance for safe rooms (P-361), P-424, P-431, and Safe Rooms and Storm Shelters for Life-Safety Protection from Hurricanes (FEMA PR-RA3, Appendix D).

Recommendation PR-34b. FEMA should work with PRDOH to improve the evaluation form for the PRDOH shelter program. The PRDOH form used to identify and evaluate potential shelters records operational information that is useful for PRDOH, PRDE, and PREMA; however, additional information should be collected. All of the 383 currently-identified event-specific shelters are constructed of reinforced concrete and located outside of special flood hazard areas (mapped flood zones), but these two important criteria do not yet appear on the evaluation form. Also, more information related to backup power systems and structural and envelope hardening and protection should be collected.

Conclusion PR-35

The MAT observed no shelters designed in accordance with FEMA P-361 or ICC 500© for protection for residents during hurricanes: Due to its island geography, Puerto Rico has limited ability to evacuate residents from the path of hurricanes and tropical storms, especially those that rapidly intensify or change direction. Safe rooms and storm shelters designed to the criteria of FEMA P-361 or the ICC 500© are needed to provide purpose-built structures to protect residents when these storms impact the islands. Storm shelters and their associated design criteria are identified and defined in the IBC©; however, they are not currently required to be constructed in Puerto Rico. There are no public safe rooms or storm shelters in Puerto Rico that have been constructed to the criteria of FEMA P-361 or the ICC 500©.

Recommendation PR-35a. Require specific educational and first responder facilities to provide a storm shelter. Safe rooms and storm shelters provide buildings or portions of buildings that have been designed and constructed to provide life-safety protection from high wind events such as hurricanes. Puerto Rico should create a local amendment to the PRBC to require that any new facilities constructed for Educational Group E Occupancies with an aggregate occupant load of 50 or more (including public and private schools, but excluding Group E day-care facilities or Group E occupancies accessory to places of religious worship), 911 call stations, emergency operations centers and fire, rescue, ambulance and police stations comply with IBC table 1604.5 as a Risk Category IV structure and be provided with a storm shelter constructed in accordance with ICC 500©. In addition, OGPe and PRDOH should keep a record of all ICC-compliant community shelters in the Commonwealth.

Recommendation PR-35b. Federally funded grantors for safe rooms, such as HUD, should consider requiring that FEMA 361 criteria be met. Where storm shelters are being constructed with federal funding, the flood-resistant construction criteria and safe room operational guidance provided in FEMA P-361 should be considered and implemented in addition to the requirements of the ICC 500©.

Recommendation PR-35c. Encourage residents to build in-residence storm shelters. The IBC© and IRC© also provide the design criteria for in-residence storm shelters by referencing the ICC 500©. Encourage residents who want to construct a place in their homes to shelter in place during a hurricane to request a permit and construct in-residence storm shelters. FEMA has developed prescriptive design and construction plans (in FEMA P-320 Taking Shelter from the Storm [FEMA 2014c]) to construct a safe room in or near a home or small business that comply with the design criteria of ICC 500©.

Recommendation PR-35d. Encourage municipalities and residents to create a system for identifying and tracking residential safe room and storm shelter locations. After a high wind event, trees or debris may fall on shelters, trapping people inside. In addition, communication may be limited. Registering shelters and safe rooms, allows the emergency responders to check the status of residents and rescue survivors as needed. Ensure that OGPe and the local municipalities keep a record of all residential safe rooms and storm shelters in the Commonwealth.

7.9 Siting

Conclusion PR-36

Topography increased wind speeds throughout mountainous areas of Puerto Rico. The MAT observed the effects of topography on the wind speeds across the islands. Many locations were observed to have experienced higher wind speeds due to channeling of the wind through the mountains. Designing for these effects involves using a prescriptive method for estimating wind speed-up in ASCE 7 (incorporated by referenced into the IBC©). To improve performance of buildings in the portions of the island where wind speed-up occurs, better design guidance and outreach are needed. Most locations impacted by wind speed-up did not appear to have hardened buildings to resist the higher wind speeds.

Recommendation PR-36. Develop new design guidance for wind speed-up in Puerto Rico. Puerto Rico should develop and include guidance on topographic effects in the PRBC. The ongoing study to produce special wind hazard maps would provide a simplified approach for designers to address wind speed-up appropriately in building design. When this guidance is complete, it should be adopted into the PRBC and proposed for incorporation into the next edition of ASCE 7.

Conclusion PR-37

Many buildings were observed in highly vulnerable locations: Homes were observed in locations including steep slopes and sited directly over streams. These homes are at very high risk of damage or destruction from natural hazards. These buildings were extremely vulnerable to landslide and other slope stability hazards.

Recommendation PR-37a. Puerto Rico and local municipalities should consider acquisition of highly vulnerable buildings. Acquisition of buildings in highly vulnerable locations including floodways, unstable slopes, and eroding coastlines should be prioritized.

Recommendation PR-37b. FEMA and the USGS should consider development of enhanced guidance for addressing slope stability and erosion vulnerabilities for new and existing construction. Enhance guidance could include maps, fact sheets and flowcharts to address vulnerabilities.

Recommendation PR-37c. OGPe should require documentation of geotechnical review for areas with slope stability concerns. Include documentation of geotechnical review in areas with slope stability concerns.

Recommendation PR-37d. OGPe should require erosion vulnerability assessment for new construction in known erosion hazard areas. Include documentation of erosion vulnerability assessment for permits in areas with known erosion impacts.

7.10 Solar Heating and PV Systems

Conclusion PR-38

Ground-mounted PV systems heavily damaged by the storm hindered the full return of electrical utility service: In specific cases, catastrophic failure of ground-mounted, grid-connected PV solar facilities impacted the restoration of power to residents. Some of the systems provided a substantial proportion of the energy portfolio on their respective islands, and damage limited overall island production. This forced a greater reliance on fuel imports and daily fuel shipments observed following the storms. For homeowners reliant on the utility grid, the damage to PV facilities may have affected the restoration time and/or price of their power supply.

Recommendation PR-38. Incorporate mitigation and preparedness aspects into PV system repairs. Incorporate mitigation and preparedness best practices into ground-mounted PV solar facilities connected to the utility grid.

Conclusion PR-39

Structural performance may have been impacted by incorrect sizing: Damage ranging from significant to catastrophic failure were observed at ground-mounted PV solar arrays due to potential incorrect sizing. The degree and type of failures typically were caused by load path discontinuity and indicated that structural support systems, clips, and other connections were inadequately designed for the magnitude and cyclical loading anticipated of the high wind events.

Recommendation PR-39. Improve the sizing of structural systems for ground-mounted PV solar arrays. When designing ground-mounted PV solar arrays, engineers should consider the design wind speeds that inform other building types on the islands and size members and connections appropriately to withstand the proper magnitudes and cyclical loading regimes. Generally, stronger structural systems were needed at numerous facilities, and can be achieved in a variety of ways through a comprehensive design process with reference to appropriate related standards.

Conclusion PR-40

Open cross-section framing members do not have the same performance as closed cross-section members due to differences in member strength and torsional rigidity: In a comparison between multiple ground-mounted PV solar arrays on the islands, structural systems that featured similarly-sized framing members performed significantly better when they utilized closed sections instead of open sections in their designs. Members such as C-section beams did not provide adequate torsional strength when exposed to high wind events and the cyclical loading and flutter associated with them. Sections that had closed ovular or rectangular shapes provided more robust resistance and allowed for a consistent transfer of loads throughout the rest of the system.

> **Recommendation PR-40. Use closed shape cross-sections for the design of structural framing members.** Designs for ground-mounted PV solar arrays should consider the use of closed ovular or rectangular section framing members instead of open section members to provide the necessary torsional resistance required to withstand the unique wind loads exerted by high speed wind events.

Conclusion PR-41

Installation of arrays does not allow for bolt checks: The current installation procedures for ground-mounted PV solar arrays do not include specifications for the torque levels of bolted connections. An observed array that included this procedure experienced only minor damage to and loosening of bolt connections, which bolstered the continuity of the load path. Similarly, annual torque checks and checks following high wind events are not provided for after construction. These checks ensure that bolts remain at the proper necessary torque levels despite the inevitable loosening of connections from dynamic loading over time.

> **Recommendation PR-41. Ground-mounted PV solar installation and O&M procedures should account for proper bolt torque specifications and checks.** Upon installation, all bolted connections should be tightened and checked for the appropriate level of torque as specified by the design requirements for high speed wind events. These torque levels should be, at minimum, checked annually and following high wind events. Any loose connections should be tightened accordingly to ensure adequate design performance.

Conclusion PR-42

Vibrations from dynamic, cyclical loading caused failure of bolted connections of ground-mounted PV solar arrays: The high wind loads experienced by the framing systems for ground-mounted PV solar arrays caused nuts to back out of their bolt connections. This resulted in the failure of the connection and a discontinuity in the system's load path. Without connections in place, framing members and attached PV panels are easily lifted from their bases by high speed winds and further damaged. One observed array performed notably well except where bolts backed out and caused such weakness. This system did not have any type of locking mechanism to prevent back-cycling of the connector.

> **Recommendation PR-42. Designers should consider utilizing a stainless-steel locking nut with a nylon insert for all bolted structural connections of ground-mounted PV solar arrays.** Any bolted connections that support the wind loads of the framing system

should include a stainless-steel locking nut with a nylon insert to prevent back-cycling. These nuts provide resistance to the vibrations caused by dynamic wind loading and will not significantly loosen during a high wind event.

Conclusion PR-43

Current design standards for ground-mount PV solar arrays do not provide for dynamic testing: Design standards specified by entities such as UL and FM Global do not include dynamic wind load testing in their standards development. Much of the damage observed in Puerto Rico to ground-mounted PV solar arrays resulted in part from the cyclical loading of dynamic wind loads. Without further research into the necessary design criteria for such impacts, engineers and owners will lack the detailed performance-based standards necessary to ensure the adequacy of their systems to real-world events.

> **Recommendation PR-43. Consider research into dynamic testing of ground-mount PV solar arrays.** Standards developers, system manufacturers, and university- and government-based researchers should consider further research into the effects of dynamic testing on structural performance. Wind-tunnel-based research will allow investigation into how connections are loosened over time and structural members fail under conditions more correlated to actual storm events.

Conclusion PR-44

Current design standards do not provide recommended design loads specific to ground-mount PV solar arrays: ASCE 7-16 and the Structural Engineers Association of California Wind Design for Solar Arrays (SEAOC PV2 2017) specify design wind loads and procedures for rooftop PV solar arrays but do not provide similar guidance for ground-mount PV solar arrays. The overall lack of design criteria available for ground-mount PV solar arrays furthered the variable performance of systems in Puerto Rico and brings up questions over the ability of new systems to withstand high wind events. Following Hurricanes Irma and Maria, the lack of guidance for designers became evident through the multiple means of failure observed across the islands. This indicated that incomplete design standards were not limited to a single area of focus.

> **Recommendation PR-44. ASCE should consider adding specific design criteria for ground-mount PV solar arrays to ASCE 7-22.** New and appropriate design standards for ground-mount PV solar arrays in ASCE 7-22 could be referenced by SEAOC PV2, the I-Codes, and the Puerto Rico Building Code to provide for more consistent performance of such systems in high wind events. Any new standards would require the focused coordination of researchers, industry professionals, and code officials to ensure that such criteria are adequate without being overly prescriptive.

Conclusion PR-45

Current design standards do not clearly provide recommended design loads specific to solar water heaters: ASCE 7-16 and the Structural Engineers Association of California Wind Design for Solar Arrays (SEAOC PV2 2017) specify design wind loads and procedures for rooftop PV solar arrays but do not provide clear guidance for rooftop solar water heaters.

Recommendation PR-45. ASCE should consider adding specific design criteria for solar water heaters to ASCE 7-22. At a minimum, ASCE should provide guidance in the ASCE 7 Commentary (e.g., C29.4.3) on applying solar panel criteria to solar water heaters. Appropriate design standards for solar water heaters in ASCE 7-22 could be referenced by SEAOC PV2, the I-Codes, and the Puerto Rico Building Code to provide for more consistent performance of such systems in high wind events. Any new standards would require the focused coordination of researchers, industry professionals, and code officials to ensure that such criteria are adequate without being overly prescriptive.

7.11 Flood-Damage-Resistant Materials

Conclusion PR-46

The use of flood-damage-resistant materials minimized damage due to water intrusion and flooding and facilitated quicker recovery: The MAT observed reoccupation of concrete and CMU buildings that were subjected to flood depths exceeding 2 feet (0.6 meters) or that experienced water intrusion through openings including jalousie windows.

Recommendation PR-46. Building owners should use flood-damage-resistant materials in existing concrete and CMU buildings. This approach could limit damage and enable quicker recovery. Building owners may refer to Puerto Rico Recovery Advisory 4, Best Practices for Minimizing Flood Damage to Existing Structures (FEMA PR-RA4, Appendix D) and NFIP Technical Bulletin 2, Flood Damage-Resistant Materials Requirements (FEMA 2008a) for guidance.

7.12 Summary of Conclusions and Recommendations

Table 7-1 summarizes the conclusions and recommendations presented in chapter 7 and categorizes them according to their Recovery Support Function under the National Disaster Recovery Framework[2]. Categories include Community Planning and Capacity Building (CPCB), Economic, Health and Social Services (HSS), Housing, Infrastructure Systems, and Natural and Cultural Resources. Additionally, FEMA has launched a sector-based approach to recovery in Puerto Rico to prioritize critical issues and allow for targeted planning[3]. The table categorizes conclusions and recommendations with respect to these sectors, which include Housing, Energy, Water, Transportation, HSS, Public Buildings, Communications, Economic, Capacity Building, and Natural and Cultural Resources.

[2] For more information on the Recovery Support Functions, see https://www.fema.gov/recovery-support-functions

[3] For more information on the sector-based approach, see https://www.fema.gov/news-release/2018/03/16/six-months-after-maria-progress-made-work-continues

Table 7-1: Table of Conclusions and Recommendations

Supporting Observations	Conclusions	Recommendations	NDRF Recovery Support Function	Sector-Based Approach for Puerto Rico
Sections 3.4.1, 3.4.4, 4.4.1 and 4.4.3	PR-1 – Many of the damaged buildings observed lacked a continuous load path.	PR-1a. OGPe should review and publish prescriptive design guidance and load path details for designers and contractors. PR-1b. OGPe should require construction documents to list critical design parameters and show load path connections.	CPCB, Housing	Capacity Building, Housing
Sections 6.6	PR-2–Many building owners had limited awareness of hurricane hazard risks and vulnerabilities.	PR-2. Facility and building owners should consider performing vulnerability assessments for all relevant hazards prior to the natural hazard event.	CPCB, Housing, HSS	Capacity Building, Housing, HSS
Sections 2.1 and 2.2	PR-3–The PRBC can be updated to higher standards.	PR-3a. OGPe should finalize the adoption of the latest hazard-resistant building codes and standards. PR-3b. OGPe should review and update the PRBCs hazard-resistant building codes and standards according to a recurring code update cycle.	CPCB	Capacity Building
Sections 3.4.3, 3.4.4, 4.4.1. 4.4.3, 4.4.4, 5.1.2 and 7.2.2	PR-4–Corrosion of fasteners and connectors contributed to building failures throughout Puerto Rico.	PR-4. OGPe should develop a local amendment to the PRBC requiring corrosion-resistant materials.	CPCB	Capacity Building
Section 3.3.1	PR-5–Staged construction remains unnecessarily exposed to the elements, degrading exposed structural elements over time.	PR-5a. Protect material during staged construction. PR-5b. Limit extended open permit periods for staged or phased construction.	Housing CPCB	Housing Capacity Building

Supporting Observations	Conclusions	Recommendations	NDRF Recovery Support Function	Sector-Based Approach for Puerto Rico
Sections 2.3.2, and 2.3.3	PR-6–OGPe lacks adequate staffing, which has affected hazard-resistant design and impacted its ability to enforce the latest building codes and standards.	PR-6a. OGPe should consider hiring additional code enforcement staff.	CPCB	Capacity Building
		PR-6b. The PRPB, OGPe, and autonomous municipalities should consider evaluating plan review staffing and guidance.	CPCB	Capacity Building, Municipalities
		PR-6c. Municipalities should consider participating in the Insurance Service Office's (ISO) Building Codes Effectiveness Grading Schedule (BCEGS).	CPCB	Capacity Building, Municipalities
Sections 2.3.2 and 2.3.3	PR-7–Training was insufficient for code enforcement staff and in-house technical experts.	PR-7. OGPe should train building code enforcement staff on Puerto Rico building code and local amendments.	CPCB	Capacity Building
Sections 2.3.3 and 2.3.4	PR-8–Professional licensure and training positively affected quality.	PR-8a. Establish a licensure program for contractors in Puerto Rico.	CPCB	Capacity Building
		PR-8b. Train design professionals and contractors on the latest hazard-resistant design and construction techniques and best practices.	CPCB, Housing	Capacity Building, Housing
		PR-8c. Establish public database of actively licensed and registered design professionals and contractors.	CPCB, Housing	Capacity Building, Housing
Section 2.4	PR-9–Few homeowners have flood insurance and of those that do, the majority have private flood insurance.	PR-9a. FEMA should consider working with the Insurance Institute for Business & Home Safety to conduct a review of private flood insurance policies for equivalency and effectiveness.	CPCB, Housing	Capacity Building, Housing
		PR-9b. FEMA in conjunction with IBHS should consider developing materials, outreach, and partnerships to educate homeowners on flood insurance (both private and NFIP) options and importance.		

Supporting Observations	Conclusions	Recommendations	NDRF Recovery Support Function	Sector-Based Approach for Puerto Rico
Section 2.3.4	PR-10–Administrative Order 2017-07 (OGPe 2017-07) exempted certain recovery efforts and essential activities from ordinary construction permits.	PR-10a. Develop process for documentation of short-term, post-disaster repairs. PR-10b. Develop process for retroactive permit review of rebuilding and repairs.	CPCB	Capacity Building
Section 2.2 and 3.2.1	PR-11–Puerto Rico's Floodplain Management Ordinance has not been coordinated with the 2018 I-Codes.	PR-11. Integrate the update to the Puerto Rico Floodplain Management Ordinance with the proposed updates to the PBRC.	CPCB	Capacity Building
Section 2.3.3	PR-12–Not every community has a Certified Floodplain Manager.	All NFIP communities and autonomous municipalities that actively issues construction permits should have a Certified Floodplain Manager or equivalent on staff.	CPCB	Capacity Building
Section 2.4	PR-13–Only a single community, Ponce, participates in the Community Rating System (CRS).	PR-13a. FEMA Region II should consider providing outreach to Puerto Rico on the benefits of participating in CRS. PR-13b. The PRPB should encourage participation in the CRS for communities that would benefit.	CPCB	Capacity Building, Municipalities
Sections 2.3 and 3.2.1	PR-14–FIRMs for Puerto Rico do not delineate Coastal A Zones. PR-15–Selected FEMA Building Science technical guidance publications should be updated to incorporate lessons learned from the MAT.	PR-14. Ensure new ABFE maps and FIRMs depict LiMWA on all map products. PR-15a. FEMA should consider translating select publications to Spanish. PR-15b. FEMA should complete Guidelines for Wind Vulnerability Assessments for Critical Facilities. PR-15c. Update select FEMA Building Science Publications impacting coastal construction. PR-15d. Update the FEMA Risk Management Series guidance publications for natural hazards	CPCB Housing, HSS Housing, HSS Housing, HSS Housing, HSS	Capacity Building Housing, HSS Housing, HSS Housing, HSS Housing, HSS

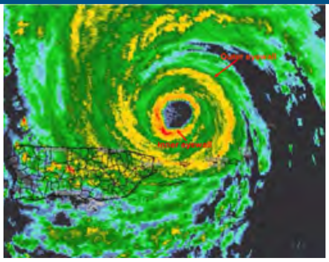
Supporting Observations	Conclusions	Recommendations	NDRF Recovery Support Function	Sector-Based Approach for Puerto Rico
Section 4.2.1	PR-16–Schools have been consolidated into facilities that remain vulnerable to flood risks/ hazards.	PR-16. The Department of Education should consider performing a vulnerability assessment of existing buildings in planning consolidation of schools.	HSS	Education, HSS
Sections 2.3.4 and 3.5	PR-17–Many non-compliant homes are present throughout Puerto Rico	PR-17. Develop process for bringing non-compliant buildings into compliance.	CPCB, Housing	Capacity Building, Housing
Sections 3.4.3 and 4.4.2	PR-18–Windows (glazed openings) on existing buildings are vulnerable to damage and failure from wind pressures and wind-borne debris.	PR-18a. Existing homeowners should consider protecting their windows.	Housing	Capacity Building, Housing
		PR-18b. Existing non-residential building owners should consider protecting their windows.	HSS	Capacity Building, HSS
		PR-18c. Existing critical facilities owners and operators should consider protecting windows.	HSS	Capacity Building, HSS
Sections 3.4.3, 4.4.2, 5.1.2, 5.2.2, 5.3.2 and 5.5.2	PR-19–Water intrusion was prevalent through existing windows (glazed openings) and metal panel jalousie systems.	PR-19. Improve performance of windows and openings to resist water intrusion and windborne debris through glazed openings.	Housing, HSS	Housing, HSS, Public Buildings
Sections 3.4.3 and 5.4.2	PR-20–Water intrusion was prevalent through existing doors.	PR-20. Limit water intrusion through doors by design and mitigation.	Housing, HSS	Housing, HSS, Public Buildings
Section 2.3.4	PR-21-OGPe does not provide a list of design criteria for design professionals to include on construction drawings.	PR-21. OGPe should consider requiring specific notes and design criteria in hazard-resistant design of a structure, including seismic design loads, and to show load path connections.	CPCB	Capacity Building
Sections 3.4.4, 3.5.3, 4.4.3 and 7.1.1	PR-22–Tile roofs resulted in poor performance.	PR-22. Existing tile roofs should be evaluated for proper anchorage and connectors.	Housing, HSS	Housing, HSS
Sections 3.3.3 and 4.3.2	PR-23–Building utilities are at risk of flood damage.	PR-23. Building owners should elevate critical systems whenever possible.	Housing, HSS	Housing, HSS, Public Buildings
	PR-24–Lack of roof deck (sheathing) under roof panel coverings resulted in increased damage.	PR-24. Require the use of wood deck on wood-framed roofs below any roof covering.	Housing	Housing

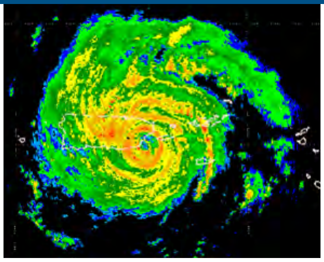
Supporting Observations	Conclusions	Recommendations	NDRF Recovery Support Function	Sector-Based Approach for Puerto Rico
Section 3.4.1	PR-25–Even homes that were undamaged during the hurricanes may be susceptible to future wind and seismic events.	PR-25. Homeowners should consider evaluating and retrofitting existing homes for wind and seismic vulnerabilities.	Housing	Housing
Section 5.4.2	PR-26–Roof penetrations often caused water intrusion.	PR-26. Avoid rooftop penetrations whenever possible.	HSS	HSS
Section 1.3.2	PR-27–It is common practice to use prescriptive home designs in residential construction and permitted by the building code.	PR-27. OGPe, with the support from stakeholders, should develop prescriptive design plans and make them available to support affordable, code-compliant construction of homes and residential buildings.	Housing, HSS, Infrastructure	Capacity Building, Housing
Section 4.3.1	PR-28–Buildings flood because their main floor levels are too low on the site.	PR-28. Elevate main (primary) floors of buildings above adjacent grade.	HSS	HSS
Section 3.4.3 and 4.4.2	PR-29–Internal pressures were not adequately addressed through open/louvered window assemblies.	PR-29a. Designers must consider and adequately address internal wind pressures. PR-29b. Consider retrofitting glazed openings, windows, and doors of existing buildings for current wind design pressures and windborne debris protection.	Housing, HSS	HSS
Sections 3.4.4, 4.4.1, 4.4.3, 4.4.4, 5.1.2 and 5.2.2	PR-30–Insufficient maintenance of roof coverings resulted in increased damage.	PR-30a. Regularly assess, adequately maintain, and repair or replace roofs when needed. PR-30b. Avoid the use of single-ply roof membranes.	Housing, HSS	Housing, HSS
Section 4.4.4	PR-31–Debris that damaged roof coverings were often from the building itself.	PR-31. Adequately anchor HVAC and other equipment to roofs.	HSS	HSS
Sections 4.3.2, 5.1.3, 5.2.5 and 5.3.5	PR-32–Backup power generators, switches, and equipment should be protected against wind, wind-borne debris, and flood.	PR-32. Protect backup and emergency generator systems and equipment to requirements of ASCE 7.	HSS	HSS, Public Buildings

Supporting Observations	Conclusions	Recommendations	NDRF Recovery Support Function	Sector-Based Approach for Puerto Rico
Section 5.2.4	PR-33–Failure of equipment penthouses and elevator equipment vents on roofs caused loss of operations.	PR-33a. Design mechanical penthouses and equipment housing to resist high winds. PR-33b. Retrofit mechanical penthouses and equipment housing in existing buildings.	HSS	HSS
Sections 4.5.1 and 4.5.2	PR-34–PRDV shelter program helpful but has shortcomings.	PR-34a. PRDV should consider an update of the shelter program in accordance with FEMA guidance. PR-34b. FEMA should work with PRDV to improve the evaluation form for PRDV shelter program.	CPCB, HSS	Capacity Building, Education, HSS, Public Buildings
Sections 4.5.1, 4.5.2 and 4.6	PR-35–There are no safe rooms designed in accordance with FEMA P-361 or storm shelters designed in accordance with ICC 500 for protection for residents during hurricanes.	PR-35a. Require specific educational and first responder facilities to provide a storm shelter. PR-35b. Federally funded grantors for safe rooms, such as HUD, should consider requiring that FEMA 361 criteria be met. PR-35c. Encourage residents to build in-residence storm shelters. PR-35d. Encourage municipalities and residents to create a system for identifying and tracking residential safe room and storm shelter locations.	HSS HSS Housing Housing	Education, HSS, Public Buildings Education, HSS, Public Buildings Education, HSS, Public Buildings Education, Housing, Public Buildings
Chapter 4	PR-36 – Topography increased wind speeds throughout mountainous areas of Puerto Rico.	PR-36– Develop new design guidance for wind speed-up in Puerto Rico.	CPCB	Capacity Building

Supporting Observations	Conclusions	Recommendations	NDRF Recovery Support Function	Sector-Based Approach for Puerto Rico
Section 3.2.1 and 3.2.2	PR-37–Many buildings were observed in highly vulnerable locations.	PR-37a. Puerto Rico and local municipalities should consider acquisition of highly vulnerable buildings.	Housing	Housing
		PR-37b. FEMA and the USGS should consider development of enhanced guidance for addressing slope stability and erosion vulnerabilities for new and existing construction.	Housing	Housing
		PR-37c. Require documentation of geotechnical review for areas with slope stability concerns.	CPCB	Capacity Building
		PR-37d. Require erosion vulnerability assessment for new construction in known erosion areas.	CPCB	Capacity Building
Section 6.5	PR-38–Ground-mounted PV systems heavily damaged by the storm hindered the full return of electrical utility service.	PR-38. Incorporate mitigation and preparedness aspects into PV system repairs	Infrastructure	Energy
Section 6.5.1	PR-39–Structural performance may have been impacted by incorrect sizing.	PR-39. Improve the sizing of structural systems for ground-mounted PV solar arrays.	Infrastructure	Energy
Section 6.1.1	PR-40–Open cross-section framing members do not have the same performance as closed cross-section members due to differences in member strength and torsional rigidity.	PR-40. Use closed shape cross-sections for the design of structural framing members.	Infrastructure	Energy
	PR-41–Installation of arrays does not allow for bolt checks.	PR-41. Ground-mounted PV solar installation and O&M procedures should account for proper bolt torque specifications and checks.	Infrastructure	Energy
Sections 6.5.1 and 6.5.2	PR-42–Vibrations from dynamic, cyclical loading caused failure of bolted connections of ground-mounted PV solar arrays.	PR-42. Designers should consider utilizing a stainless-steel locking nut with a nylon insert for all bolted structural connections of ground-mounted PV solar arrays.	Infrastructure	Energy

Supporting Observations	Conclusions	Recommendations	NDRF Recovery Support Function	Sector-Based Approach for Puerto Rico
Section 2.5	PR-43–Current design standards for ground-mounted PV solar arrays do not provide for dynamic testing.	PR-43. Consider research into dynamic testing of ground-mount PV solar arrays.	Infrastructure	Capacity Building, Energy
Section 2.5	PR-44–Current design standards do not provide recommended design loads specific to ground-mounted PV solar arrays.	PR-44. ASCE should consider adding specific design criteria for ground-mount PV solar arrays to ASCE 7-22.	Infrastructure	Capacity Building, Energy
Section 3.3.1	PR-45–Current design standards do not clearly provide recommended design loads specific to solar water heaters.	PR-45. ASCE should consider adding specific design criteria for solar water heaters to ASCE 7-22.	Housing	Housing
Section 3.3.1	PR-46-The use of flood-damage-resistant materials minimized damage due to water intrusion and flooding and facilitated quicker recovery.	PR-46. Building owners should use flood-damage-resistant materials in existing concrete and CMU buildings.	Housing	Housing

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Acknowledgments

The Federal Emergency Management Agency (FEMA) would like to acknowledge the contributions of the following persons to the Mitigation Assessment Team study of the areas affected by Hurricanes Irma and Maria in Puerto Rico:

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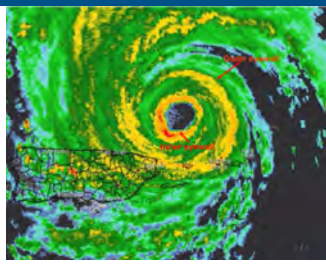

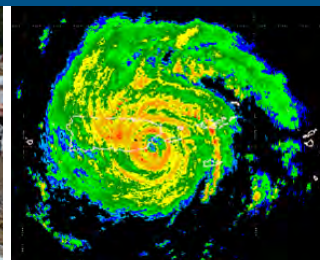


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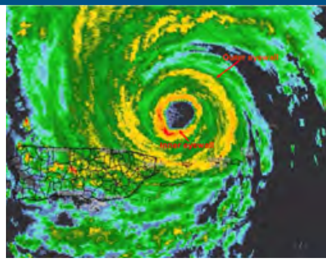

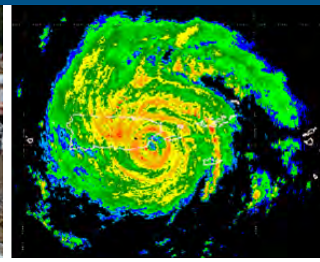


HURRICANES

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C Acronyms

ABFE	Advisory Base Flood Elevation
AC	Air conditioning
ARA	Applied Research Associates, Inc.
ARPE	Administración de Reglamentos y Permisos (Regulations and Permits Administration)
ARRA	American Recovery and Reinvestment Act
ASCE	American Society of Civil Engineers
AST	Atlantic Standard Time
ASTM	American Section of the International Association for Testing Materials, now ASTM International
BARA	Best available refuge area
BCEGS	Building Code Effectiveness Grading Schedule
BFE	Base Flood Elevation
BPAT	Building Performance Assessment Team
CAZ	Coastal A Zone
CIAPR	Colegio de Ingenieros y Agrimensores de Puerto Rico (Professional College of Engineers and Land Surveyors of Puerto Rico)
CMU	Concrete masonry unit

CPCB	Community Planning and Capacity Building
CRS	Community Rating System
DFE	Design flood elevation
DHSOIG	Department of Homeland Security Office of the Inspector General
EOC	Emergency Operations Center
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Map
HMA	Hazard Mitigation Assistance
HMGP	Hazard Mitigation Grant Program
HSS	Housing and Social Services
HPRP	Home Protection Roofing Program
HUD	Housing and Urban Development
HVAC	Heating, ventilation, and air conditioning
I-Codes	International Code series
IBC	International Building Code
IBHS	Insurance Institute for Business and Home Safety
ICBO	International Conference of Building Officials
ICC	International Code Council
IEBC	International Existing Building Code
IRC	International Residential Code
JFO	Joint Field Office
kph	kilometers per hour
MAT	Mitigation Assessment Team
MBS	Metal Building System
MEP	Mechanical, electrical, and plumbing
MHHW	Mean high high water
mph	miles per hour
MW	Megawatts
MWFRS	Main wind-force resisting system
MWh	megawatt hours
NFIP	National Flood Insurance Program

NIST	National Institute of Standards and Technology
NOAA	National Oceanographic and Atmospheric Administration
NSHP	New Secure Housing Program
NSSA	National Storm Shelter Association
OGPe	Oficina de Gerencia de Permisos (Permits Management Office)
ORNL	Oak Ridge National Laboratory
PRBC	Puerto Rico Building Code
PRDE	Puerto Rico Department of Education (Departamento de Educación)
PRDOH	Puerto Rico Department of Housing (Departamento de Vivienda)
PRDJ	Puerto Rico Department of Justice (Departamento de Justicia de Puerto Rico)
PREMA	Puerto Rico Emergency Management Agency, formally the Puerto Rico State Agency for Emergency and Disaster Management (Agencia Estatal para el Manejo de Emergencias y Administración de Desastres)
PREPA	Puerto Rico Electric Power Authority (Autoridad de Energía Eléctrica)
PRIFA	Puerto Rican Infrastructure Financing Authority (Autoridad para el financiamiento de la Infraestructura)
PRPB	Puerto Rico Planning Board (Junta de Planificación de Puerto Rico)
PV	Photovoltaic
SEAOC	Structural Engineers Association of California
SST	Sea surface temperature
UBC	Uniform Building Code
UL	UL LLC, formerly Underwriters Laboratories
UPR	University of Puerto Rico
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
USVI	U.S. Virgin Islands
WAP	Weatherization Assistance Program

HURRICANES
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D Recovery Advisories for Hurricanes Irma and Maria in Puerto Rico

FEMA has prepared new Recovery Advisories (RAs) that present guidance to engineers, architects, homeowners, and local officials on mitigation measures that can be taken to minimize building damage in a hurricane event. Five advisories are referenced in this Appendix:

PR - RA 1: Rooftop Equipment Maintenance and Attachment in High-Wind Regions

PR - RA 2: Siting, Design, and Construction in Coastal Flood Zones

PR - RA 3: Safe Rooms and Storm Shelters for Life-Safety Protection from Hurricanes

PR - RA 4: Best Practices for Minimizing Flood Damage to Existing Structures

PR - RA 5: Protecting Windows and Openings in Buildings

PR - RA 6: Repair and Replacement of Wood Residential Roof Covering Systems

These advisories are online at https://www.fema.gov/media-library/assets/documents/158123

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