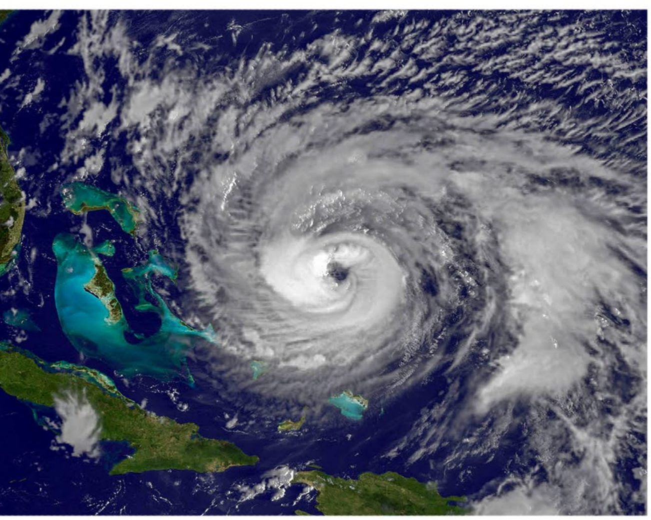

NIST SP 1262

A PROGRESS REPORT

LEARNING from HURRICANE MARIA'S IMPACTS on PUERTO RICO

January 2021

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Learning from Hurricane Maria's Impacts on Puerto Rico: A Progress Report

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Dedication

On September 20, 2017, a powerful Category 4 hurricane struck the Commonwealth of Puerto Rico. The resulting impact from Hurricane Maria on the island, its economy, and its people was catastrophic. In addition to the lives lost and injuries incurred, the storm affected many services provided and relied upon by businesses, schools, health care institutions, individuals, and governments at all levels. Puerto Rico is still experiencing the impacts from that storm, while also dealing with disruptions from a series of seismic events and a major public health emergency.

This study by the National Institute of Standards and Technology (NIST) is examining the characteristics of the hurricane and specific impacts on Puerto Rico, its buildings and infrastructure systems, and selected services. The goal is to improve our understanding of these kinds of events and recommend improvements in building codes, standards, and practices that would make communities in Puerto Rico and across the United States more resilient to hurricanes and
other disasters.

This report is dedicated to those whose lives were lost or disrupted by this hurricane, and to those who will act on the findings and recommendations of future reports in order to improve the safety of people in Puerto Rico and elsewhere.

Abstract

On September 20, 2017, Hurricane Maria had a devastating impact on much of Puerto Rico, damaging buildings that its communities relied upon for medical care, safety, communications, education, business, and more. To better understand how the buildings and infrastructure failed, and how we can prevent such failures in the future, in 2018, the National Institute of Standards and Technology (NIST) launched a multi-year effort to study how critical buildings performed during the storm, as well as how emergency communications systems worked. The NIST Hurricane Maria Program is investigating (1) the wind environment and technical conditions associated with deaths and injuries, (2) the performance of representative critical buildings, and designated safe areas in those buildings, including their dependence on lifelines, and (3) the performance of emergency communications systems and the public's response to such communications. These correspond to the three goals of a technical investigation under the National Construction Safety Team Act (NCST Act). Under the National Windstorm Impact Reduction Program (NWIRP), authorized by the National Windstorm Impact Reduction Act, NIST is also conducting a research study on the impacts to and recovery of (1) businesses and supply chains, (2) education and healthcare services, and (3) infrastructure systems that support the functioning of critical buildings and emergency communications. As complementary components of the NIST Hurricane Maria Program, the NCST technical investigation and the NWIRP research study are closely coordinated. This report explains in detail the rationale for launching this effort, the specific areas selected for investigation and study by an interdisciplinary Team, and the approach that NIST is using, which includes building upon information gathered by others, but also conducting extensive original data collection and analyses. The report also summarizes progress to date.

Keywords: Hurricane Maria; building performance; emergency communications; mortality; injuries; Puerto Rico; infrastructure; businesses; supply chains; hospitals; schools; shelters; recovery.

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Executive Summary

Introduction

On September 20, 2017, Hurricane Maria had a devastating impact on much of Puerto Rico, damaging buildings that its communities relied upon for medical care, safety, communications, education, business, and more. To better understand how the buildings and infrastructure failed, and how we can prevent such failures in the future, in 2018, the National Institute of Standards and Technology (NIST) launched a multi-year effort to study how critical buildings performed during the storm, as well as how emergency communications systems worked. Ultimately, the goal of this effort is to recommend – and encourage the widespread adoption of – improved building codes, standards, and practices that would make communities in Puerto Rico and across the United States more resilient to hurricanes and other hazard events. A non-regulatory science and engineering agency of the U.S. Department of Commerce, NIST has a long history of impartial studies of disasters and failures with the goal of learning from them. NIST disaster and failure studies are focused on fact-finding, not fault-finding, and events are studied separately from decisions by other agencies and organizations about funding of repair, recovery, or other assistance efforts.

This report explains in detail the rationale for launching this effort, the specific regions of focus selected by the interdisciplinary Team, and the approach that NIST is using, which includes building upon information gathered by others, but also conducting extensive original data collection and analyses. The report also summarizes progress to date. To get the most complete and accurate information possible, NIST is coordinating this undertaking with other organizations, including Puerto Rico government agencies, federal agencies, companies and business associations, hospitals, schools, and public utilities. Multiple contractors, including experts based in Puerto Rico, are supporting and adding substantial capacity to the NIST Team of engineers, sociologists, anthropologists, economists, meteorologists, epidemiologists, and other experts. In addition to NIST employees, formal Team members include outside experts from the National Weather Service, the National Center for Disaster Medicine and Public Health, and the University of Puerto Rico at Mayagüez.

NIST Response and Scope of the Hurricane Maria Program

Following Hurricane Maria's landfall in Puerto Rico as a strong Category 4 storm, NIST deployed four staff members to Puerto Rico in December 2017 to conduct preliminary reconnaissance of the hurricane's impacts, including field surveys and interviews. As part of the preliminary reconnaissance, NIST staff also reviewed information provided by other government agencies, academic institutions, and private-sector organizations on the characteristics of the hurricane and its impacts. Observations from the preliminary reconnaissance were evaluated with respect to the criteria set forth by the National Construction Safety Team (NCST) Act for establishment of an investigation Team, with specific consideration of the hazard intensity, exposed population and mortality, physical damage to buildings and infrastructure, evacuation and emergency response challenges, and economic and social impacts. Based on consideration of these factors, it was concluded that an investigation of the building performance during and after the storm, and of the challenges in emergency response and evacuation procedures, is expected to result in novel insights that will lead to important recommendations for codes, standards, and practices. Based on this information and analysis, on February 21, 2018, the NIST Director established a Team under the NCST Act to conduct a technical investigation of the Hurricane Maria event.

The goals of the NCST technical investigation are to characterize (1) the wind environment and technical conditions associated with deaths and injuries, (2) the performance of representative critical buildings and designated safe areas in those buildings, including their dependence on lifelines, and (3) the performance of emergency communications systems and the public's response to such communications. Complementary to the NCST technical investigation, NIST is conducting a research study on the impacts to and recovery of (1) businesses and supply chains, (2) education and healthcare services, and (3) infrastructure systems that support the functioning of critical buildings and emergency communications. This research study is being conducted under the authority of the National Windstorm Impact Reduction Act, which designates NIST as the lead agency of the National Windstorm Impact Reduction Program (NWIRP). As complementary components of the NIST Hurricane Maria Program, the NCST technical investigation and the NWIRP research study are closely coordinated. To provide an appropriate scope for the Hurricane Maria Program, and to facilitate integration of data and analyses across the seven technical projects within the program, four regions of Puerto Rico have been selected for particular focus.

Progress in Carrying out the Hurricane Maria Program

Highlights of progress-to-date in carrying out the Hurricane Maria Program include the following:

- ***Information Requested and Obtained from Other Agencies and Organizations:*** To get the most accurate information possible, and in accordance with the NCST Act's mandate that NIST coordinates its efforts with other organizations, NIST has requested and received relevant information from many other agencies and organizations. Memorandums of Agreement have been established with FEMA, providing NIST with access to important information about damages to schools and healthcare facilities. The Department of Health and Human Services (HHS) Office of the Assistant Secretary for Preparedness and Response (ASPR) has shared information regarding their support of the health and social services recovery, focused on hospitals and schools. Additional information has been provided by Puerto Rico government agencies, including information on the shelter program provided by the PR Department of Housing, information on hospitals provided by the PR Department of Health, information on the transportation system provided by the PR Department of Transportation and Public Works, and information on businesses and supply chains provided by the PR Ports Authority and the PR Department of Labor and Human Resources. The body of the report provides additional examples of information requested and obtained.

- ***Wind-Field Model Development:*** Accurate quantification of wind speeds is critical for evaluating the performance of buildings and infrastructure and to provide context for other aspects of the program. Challenges in characterization of Hurricane Maria's wind field include the limited measurements available, with many weather stations having failed during the event, and the influence of Puerto Rico's mountainous topography, which can cause significant local speed-up of winds, with corresponding increases in the wind loads on structures. To address these challenges, an initial wind-field model has been developed for Hurricane Maria, obtained by fitting a hurricane wind-field model to the available surface-level meteorological observations, including consideration of topographic effects. This model provides estimated time histories of wind speed and direction across the entire commonwealth, with topographic speedup factors as high as 1.8 observed in some regions. In developing the final wind-field model for Hurricane Maria, further improvements will include more refined modeling of topographic effects based on the results of wind tunnel testing, computational modeling, and field measurements described subsequently. The wind-field modeling work is being supported through a contract awarded to Applied Research Associates in February 2019.

- ***Wind Tunnel Testing and Computational Modeling:*** The effects of Puerto Rico's topography on local wind speeds, and on the resulting wind loads experienced by buildings and infrastructure systems, are being investigated using a combination of wind tunnel testing and computational fluid dynamics (CFD) modeling. A first phase of wind tunnel testing, currently underway, involves scale models of topographic features, including models of selected regions in Puerto Rico as well as models of generic ridge and plateau features. Scale models of topographic features have been fabricated, flow characterization measurements have been performed to ensure that the incoming flow matches the target profiles, and measurements have been completed for a subset of the topographic model tests. Measurements from the topographic models will be used for validation of CFD models for evaluation of topographic effects on wind fields in Puerto Rico. A future phase of wind tunnel testing will involve scale models of selected critical buildings, to enable detailed evaluation of the wind loads as influenced by the surrounding topography, buildings, and terrain. Wind tunnel testing is being performed in a large, reconfigurable boundary layer wind tunnel at the University of Florida, through a contract awarded in May 2019.

- ***Deployment of Anemometers at Cell Tower Sites:*** To provide real-world data for evaluation of topographic effects on wind-speed profiles, and for validation of wind tunnel and CFD models, anemometers have been deployed on three cell towers in the Yabucoa region, at sites where the surrounding topography produces significant increases in wind speeds. The Team has started to record wind speed data, including the capture of high wind data from Tropical Storm Isaías in July 2020 and Tropical Storm Laura in August 2020. These field measurements will be compared with wind tunnel measurements of flow profiles at the tower sites using a scale model of the Yabucoa region. Field measurement of winds is being supported through a subcontract awarded to WeatherFlow by the University of Florida. Space on the cell towers is being provided by American Tower, Inc.

- ***Evaluation of Critical Buildings:*** Evaluating the performance of critical buildings requires documentation of the characteristics of the buildings and their initial design requirements, as well as the damages and loss of function that were sustained from the hurricane. Support in collection of such information for selected hospitals, schools, and storm shelters is being provided through a contract with Stantec, Inc., awarded in March 2020. The key personnel on the contract are based in Puerto Rico, providing local knowledge and a critically important local presence to support this effort. Specific facilities have been selected for evaluation, and contacts have been made with managers of these facilities as part of the effort to gather additional information. Collection and review of relevant documentation are currently underway, to be followed by interviews with facility managers. For one of the selected hospital facilities, located at a site with particularly significant topographic speed-up of winds, drone photography of the facility has been performed, and a 3D model of the facility has been created from the drone images, to support the fabrication of a scale model for wind-tunnel testing.

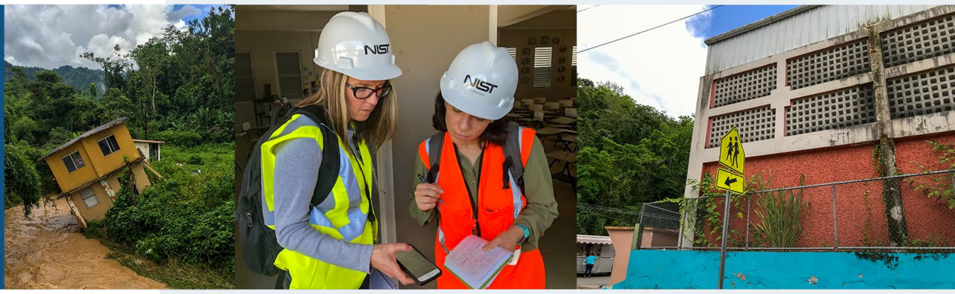
- ***Characterization of Morbidity and Mortality:*** Identifying deaths in Puerto Rico directly and indirectly tied to Hurricane Maria, especially those associated with building failures, requires identifying specific causes of death, including indirect deaths that might have been missed in the past. To support the collection of such information, a contract was awarded in September 2020 to the Milken Institute School of Public Health (SPH) at the George Washington University (GW), with collaborating team members at the University of Puerto Rico-Graduate School of Public Health and the Institute for Health Metrics and Evaluation at the University of Washington. The work plan for this contract has been developed and finalized with NIST input. This effort will focus specifically on identifying deaths attributed to building and/or building system failure(s). It will not produce another death count.

- ***Sample Design for Surveys and Interviews:*** Social science methodologies, including surveying and interviewing, are essential to the technical approaches of four projects within the Hurricane Maria Program, including an NCST project focused on public response to emergency communications and three NWIRP projects focused on recovery of business and supply chains, social functions, and infrastructure systems. These projects will require collection of information from information providers, households, businesses, schools, hospitals, and infrastructure representatives in the power, water, and transportation sectors. Statistically sound sample designs have been developed for the surveys and interviews to be conducted for each of these projects, and necessary administrative reviews for information collection activities are currently being completed to ensure that proper protocols are followed. This work is being supported by a contract awarded in December 2019 to the Horsley Witten Group, Inc., with subcontractors Eastern Research Group, Inc., Issues & Answers, Inc., and Albizu University in Puerto Rico.

- ***Data Collection on Recovery of Business and Supply Chains:*** As an example of the relationships that NIST has established with other organizations, the *Recovery of Business and Supply Chains* project team collaborated with the Puerto Rico Manufacturing Extension, Inc., (PRiMEX) and the NIST Manufacturing Extension Partnership (MEP) in conducting site visits in the summer of 2019 to collect data on the recovery of key businesses within the Food Preparation Manufacturing sector and the Medical Device Manufacturing sector. Data on initial recovery of small- and medium-sized enterprises, collected from field observations and other sources, have been compiled to support future analyses.

In carrying out the Hurricane Maria Program, NIST has made adjustments in plans to account for the impact of events since Hurricane Maria, including the COVID-19 pandemic and a series of earthquakes that began affecting Puerto Rico in late December 2019. Earthquake hazards in Puerto Rico's multi-hazard context have been an important consideration since the inception of the program, and earthquake engineering experts on the Team will ensure that earthquake hazards, in addition to wind hazards, are considered in the development of NIST's recommendations related to Hurricane Maria. To date, most of the earthquake-related damage has been concentrated in an area that is outside of NIST's primary regions of focus, and the Team anticipates that this damage will have a limited impact on the program's efforts, particularly for the projects within the NCST technical investigation. For the three technical projects within the NWIRP research study that are focused on recovery from Hurricane Maria's impacts, NIST researchers are taking special care to design data collection instruments that ensure the ability to account for the compounding effects of the earthquake sequence and the pandemic on the recovery process. In response to the COVID-19 pandemic, projects that rely on social science surveying and interview methodologies (five of the seven technical projects) have altered plans to use phone- and web-based modes of data collection. The NIST Team continues to explore creative ways to achieve the program's goals, while prioritizing safety in this uncertain and complex environment.

Collection of data through document requests, interviews, surveys, site visits, wind tunnel testing, and field measurement of winds is expected to continue through 2021. NIST will continue to provide regular updates of progress through the Hurricane Maria program website and through presentations to the Federal Advisory Committee, chartered with providing feedback on the NCST investigation. After the Team completes its analysis of the data, NIST will prepare findings and recommendations from the NCST investigation for public review and comment. NIST will widely disseminate its draft and final reports. In addition to taking action on any NCST recommendations within NIST's purview for follow-up research or other activities, NIST will reach out to all relevant federal agencies as well as the Puerto Rico government and others in the public and private sectors to encourage leadership in supporting voluntary implementation of the NCST recommendations. Finally, as required by the NCST Act, NIST will track and provide public annual reports on progress that the agency and others are making to implement its NCST recommendations.



LEARNING FROM HURRICANE MARIA'S IMPACTS ON PUERTO RICO
A PROGRESS REPORT

1. Introduction

This report summarizes progress being made in the course of the NIST Hurricane Maria Program from its formal launch in February 2018 through September 2020. The report complements information about the Hurricane Maria Program provided on a dedicated NIST website,[1] which is updated regularly and contains more detailed information.

1.1 NIST's Role in Studying Disasters and Failures

A non-regulatory science and engineering agency of the U.S. Department of Commerce, NIST has a long history of impartial studies of disasters and failures with the goal of learning from them.[2] Over many decades, NIST studies have led to a better understanding of how structures perform and how people respond to a range of hazard events. In turn, recommendations based on these findings have yielded improved standards, codes, and practices. For example, after the World Trade Center (WTC) disaster in 2001, NIST's recommendations have led to changes in consensus standards and codes that govern building construction and emergency response.[3] These consensus standards and codes are widely relied upon and incorporated by states and localities into their own requirements that govern new and renovated buildings and other structures. NIST's recommendations have also led to changes in practices by professionals involved in the design and construction of buildings and in responding to and communicating about disasters. Similarly, NIST studies of tornadoes, hurricanes, fires, earthquakes, and construction collapses have resulted in changes to standards and practices to improve safety.

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[1] www.nist.gov/topics/disaster-failure-studies/hurricane-maria

[2] Further information on NIST's Disaster and Failure Studies Program: www.nist.gov/topics/disaster-failure-studies

[3] Further information on the WTC disaster study recommendations and their implementation status: www.nist.gov/topics/disaster-failure-studies/world-trade-center-disaster-study/recommendations

NIST has statutory authority to study disasters and failures and to make recommendations. Specifically, the National Construction Safety Team (NCST) Act (Public Law 107-231)[4] authorizes the NIST Director to establish investigative Teams "to assess building performance and emergency response and evacuation procedures in the wake of any building failure that has resulted in substantial loss of life or that posed significant potential of substantial loss of life." In addition, the National Windstorm Impact Reduction Act (Public Law 114-52),[5] designates NIST as the lead agency for the National Windstorm Impact Reduction Program (NWIRP) and gives NIST responsibility for "carrying out research and development to improve model building codes, voluntary standards, and best practices for the design, construction, and retrofit of buildings, structures, and lifelines" with the purpose of achieving "measurable reductions in the losses of life and property from windstorms."

While NIST has statutory authority to study disasters and failures, it has no regulatory authority to require its recommendations to be followed. Rather, NIST works cooperatively with government agencies at all levels and with private-sector building codes and standards developing organizations. NIST's role as a neutral party and its participation in the voluntary standards process are especially important factors contributing to its success in implementing the recommendations.

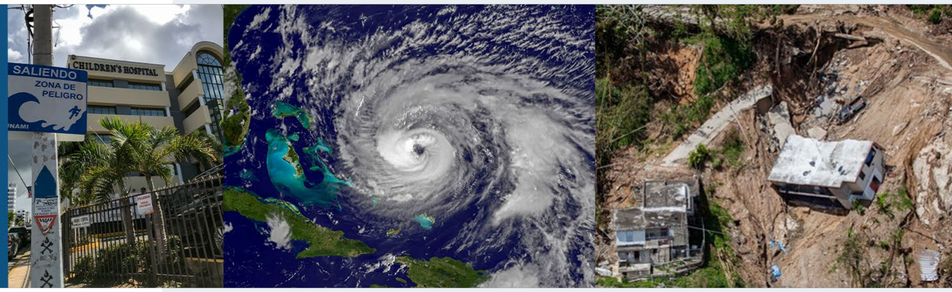
NIST disaster and failure studies are focused on fact-finding, not fault-finding, and events are studied separately from decisions by other agencies and organizations about funding of repair, recovery, or other assistance efforts. NIST broadly disseminates its findings and NCST recommendations and tracks their implementation.

1.2 Scope and Organization of Progress Report

This progress report begins with a review of Hurricane Maria's hazard characteristics and impacts on the U.S. territory of Puerto Rico and the factors considered in the decision to establish a Team to study this disaster. This review, in Section 2, provides a summary of observations from NIST's preliminary reconnaissance on storm hazard characteristics, exposed population and mortality, physical damage to the built environment, challenges with evacuation and emergency response, and social and economic impacts, including information from partnering organizations that was considered in the decision to establish a Team. Section 3 describes the NIST Hurricane Maria Program, including its scope and goals, Team leadership and members, technical plan and projects, and the NCST Advisory Committee[6], along with a discussion of supporting efforts by other organizations and the estimated duration and cost of the program. Section 4 then presents progress-to-date in carrying out the program, including

[4] www.congress.gov/107/plaws/publ231/PLAW-107publ231.pdf
[5] www.congress.gov/114/plaws/publ52/PLAW-114publ52.pdf
[6] www.nist.gov/topics/disaster-failure-studies/national-construction-safety-team-ncst/advisory-committee

the selection of areas of study, liaison status with other agencies, award of supporting contracts, initial data collection and analysis, and advisory committee review. Finally, Section 5 outlines the plan for publication of final reports to document the findings and recommendations at the conclusion of the study, along with subsequent efforts to implement these recommendations, in partnership with other agencies and organizations.



2. Preliminary Reconnaissance and Decision to Establish a Team

Hurricane Maria[7] made landfall in Puerto Rico on September 20, 2017, as a strong Category 4 storm. NIST deployed four staff members to Puerto Rico on December 10-15, 2017, to conduct preliminary reconnaissance of the hurricane's impacts, in coordination with a Mitigation Assessment Team (MAT) deployed by the Federal Emergency Management Agency (FEMA). One of the NIST staff members was also a member of the FEMA MAT and contributed to the MAT Report.[8,9] Figure 1 shows the locations of data collection sites from NIST's preliminary reconnaissance, including field surveys and interviews. As part of the preliminary reconnaissance, NIST staff also reviewed information provided by other government agencies, academic institutions, and private-sector organizations on the characteristics of the hurricane and its impacts. The following subsections summarize key findings of the preliminary reconnaissance and document the factors that were considered in the decision to establish a Team to conduct further investigation. Subsequent progress in data collection and analysis, after the preliminary reconnaissance in 2017, is not incorporated here but is reported in Section 4.

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[7] In 2011, a hurricane also named 'Maria' struck Puerto Rico: www.nhc.noaa.gov/data/tcr/AL142011_Maria.pdf

[8] FEMA P-2020, Hurricanes Irma and Maria in Puerto Rico: Building Performance Observations, Recommendations, and Technical Guidance, (FEMA 2018): www.hsdl.org/?view&did=818977

[9] While Mitigation Assessment Teams and National Construction Safety Teams may both be activated for the same disaster, they have different but complementary purposes. FEMA Mitigation Assessment Teams will typically conclude their evaluations and publish reports within months of the disaster, with the goal of quickly identifying lessons to help inform rebuilding in the disaster-affected community. NIST NCST Investigations are comprehensive technical investigations that typically take three to five years to complete and are targeted to identifying recommended changes to building codes, standards, and practices to mitigate risks of future building failures and loss of life in hazard-prone communities across the United States.

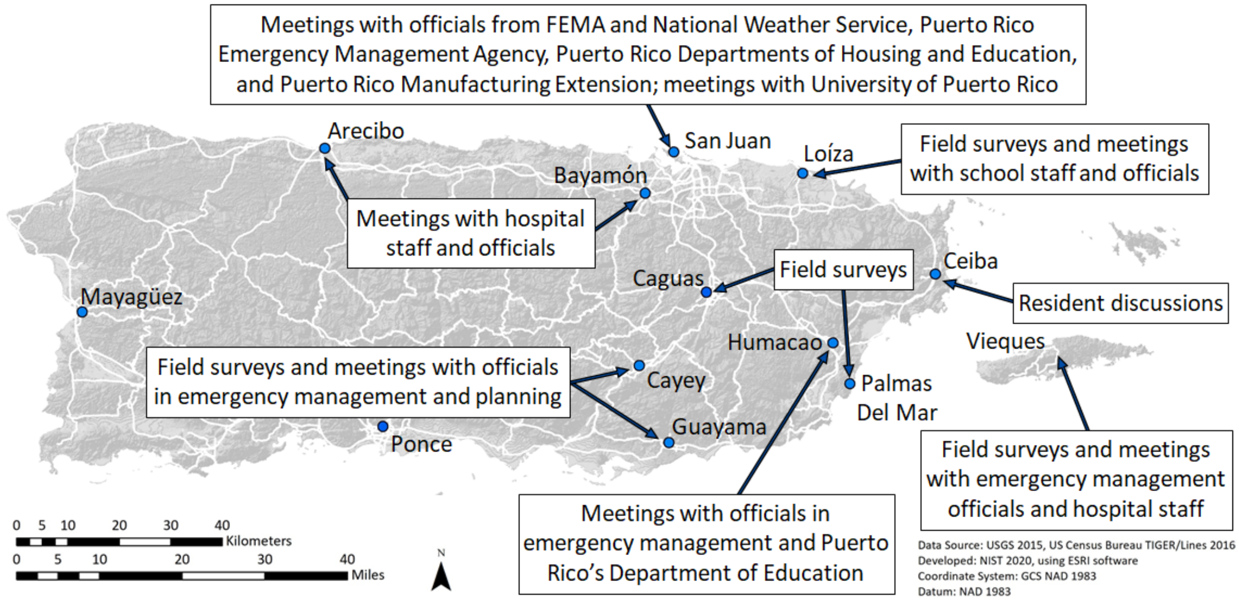

Figure 1. Locations of data collection sites from NIST's preliminary reconnaissance.

2.1 Hazard Intensity

Forming west of the Lesser Antilles as a tropical storm on September 16, 2017, Hurricane Maria intensified in two days to a Saffir-Simpson Category 5 hurricane, with maximum sustained winds of 175 mph. The hurricane made landfall in Puerto Rico on September 20, 2017, as a strong Category 4 storm with sustained winds of 155 mph, the most intense hurricane to strike Puerto Rico since the Category 5 Okeechobee Hurricane of 1928, known locally as San Felipe. Maria impacted Puerto Rico just 13 days after Hurricane Irma, which brought tropical-storm-force winds, along with significant rainfall, to the entire Commonwealth.

The hurricane made landfall near Yabucoa and tracked diagonally across Puerto Rico, with hurricane-force winds extending over the entire Commonwealth. The greatest wind speeds occurred in the eastern third of Puerto Rico and on Vieques, with maximum peak wind gusts over land estimated at approximately 140 mph, as shown in Figure 2(a). The estimated peak gust wind speeds in Figure 2(a) were generated within days after the hurricane made landfall based on surface-level meteorological measurements available at the time, under a mission assignment from FEMA to NIST. Though it was recognized that the mountainous topography of Puerto Rico would have resulted in significantly increased wind speeds in certain regions, topographic speedup effects were not included in these rapid initial wind speed estimates.

Hurricane Maria subjected Puerto Rico to multiple hazards in addition to strong winds, including storm surge, heavy rainfall and flooding, and extensive landslides, as shown in Figure 2. Storm surge occurred around the entire perimeter of Puerto Rico and the smaller Commonwealth islands, with surge elevations in most coastal areas ranging from 2 feet to 6 feet above mean sea level (Figure 2(b)). The resultant storm surge flooding typically did not extend very far inland because of the narrow coastal plains. Heavy rainfall was experienced across Puerto Rico, along with rain-induced flooding over much of the Commonwealth. Total estimated rainfall accumulations for Hurricane Maria ranged between 5 inches and 40 inches across Puerto Rico (Figure 2(c)). However, many rainfall measurement stations were unable to report because of damage sustained from the hurricane, presenting significant challenges for quantifying rainfall from this event. Hurricane Irma also deposited an estimated 5 inches to 15 inches of rain across most of Puerto Rico less than two weeks prior to Hurricane Maria, which left soils still saturated with rainfall when Hurricane Maria made landfall. These pre-saturated soils contributed to an increased risk of flooding, slope instability, and landslides. As shown in Figure 2(d), many hundreds of landslides occurred across Puerto Rico, mostly concentrated within the mountainous central regions. These multiple hazards to life safety introduced challenges in the attribution of deaths and injuries associated with the event, as is further discussed in the following section.

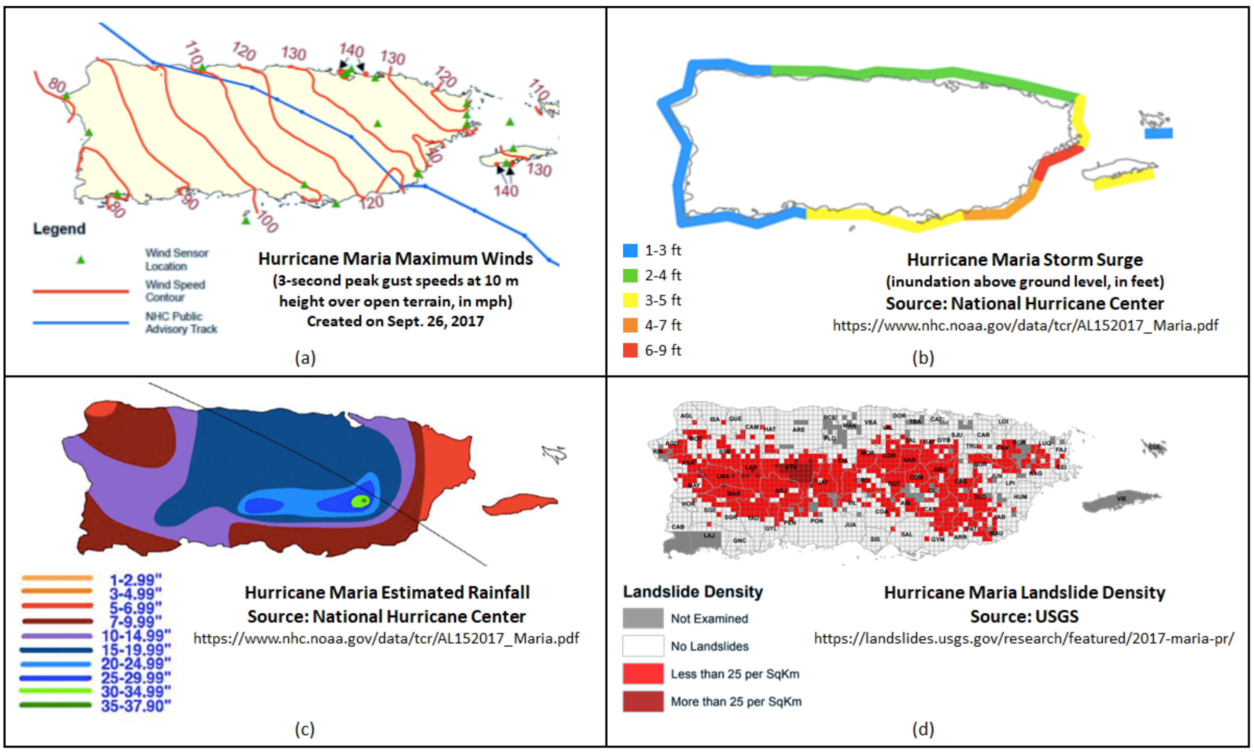

Figure 2: Hurricane Maria storm hazards: (a) wind speeds, (b) storm surge, (c) rainfall, (d) landslides.

2.2 Exposed Population and Mortality

The entire Commonwealth, with its population of 3.4 million people pre-Hurricane Maria, was exposed to impacts of the hurricane. Approximately 250 shelters were opened for the hurricane, and approximately 15% of those shelters were still operating at the time of NIST's preliminary reconnaissance, three months after Hurricane Maria made landfall. At that time, there was no consensus on the number of deaths caused by Hurricane Maria, in part because of ambiguity on the definition of hurricane-related deaths. Because the U.S. lacks a standardized data collection and reporting approach for the attribution of deaths to disaster events,[10] death certificates are used as the means of assessing disaster-related deaths (both direct and indirect). This often results in an underestimation of deaths attributed to disasters. At the time of the preliminary reconnaissance in December 2017, the official death toll by Puerto Rico's Department of Public Safety was 64,[11] although an estimate from the *New York Times* indicated that the actual death toll could be over 1000 based on analyses using data from Puerto Rico's Vital Statistics Records Office.[12]

2.3 Physical Damage to Buildings and Infrastructure

The hurricane subjected buildings and infrastructure (including transportation and utility systems) to extreme wind speeds across a large geographical area. Most of the eastern half of the island experienced estimated peak wind gusts in excess of 120 mph (Figure 2(a)), and the maximum peak wind gusts (approximately 140 mph) approached the level considered in the design of some buildings and other structures.[13] Within the building stock, non-engineered buildings experienced the most severe physical damage and loss of function, with extensive wind damage observed to light-framed wood construction. Non-engineered buildings with concrete masonry walls and wood frame roofs often experienced complete roof loss or extensive roof damage. Unpermitted or "informal" construction performed poorly.

Common engineered building systems in Puerto Rico include reinforced concrete and concrete masonry buildings with concrete roofs, and preliminary observations indicated that these types of buildings generally sustained minimal structural damage in Hurricane Maria. Some roof failures were observed on reinforced concrete and concrete masonry buildings with wood frame or steel frame roof systems, as opposed to concrete roofs. Extensive wind damage to metal building systems was observed, and corrosion was observed to be a contributing factor in some of these wind-induced metal building failures.

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[10] Combs D.L., Quenemoen L.E., Parrish R.G., Davis J.H., 2009. "Assessing disaster-attributed mortality: Development and application of a definition and classification matrix." International Journal of Epidemiology 28(6): pp. 1124–9.

[11] As discussed in Section 3.3.4, the Government of Puerto Rico later updated the official death count to 2975 based on the estimated excess mortality from a study by the George Washington University.

[12] Robles, F., Davis, K., Fink, S, Almukhtar, S., 2017. "Official Toll in Puerto Rico: 64. Actual Deaths May Be 1,052." The New York Times. December 9, 2017.

[13] The FEMA MAT provides a review of design wind speeds for Puerto Rico: www.hsdl.org/?view&did=818977

Although the preliminary reconnaissance team observed better structural performance for engineered buildings, many of these buildings suffered extensive nonstructural damage and loss of function due to rainwater penetration of the building envelope. Observed types of non-structural damage that resulted in rainwater penetration included the following (see Figure 3):

- roof covering and rooftop equipment damage from wind and windborne debris (Figure 3a,b);
- window and door damage caused by wind and windborne debris (Figure 3c);
- rainfall ponding on the roof due to excessive rainfall rates and debris blocking drains;
- wind-driven rain penetration through undamaged cladding, such as windows and doors

Wind-induced failures of rooftop equipment were commonly observed, and corrosion was observed to be a factor in some of these failures.

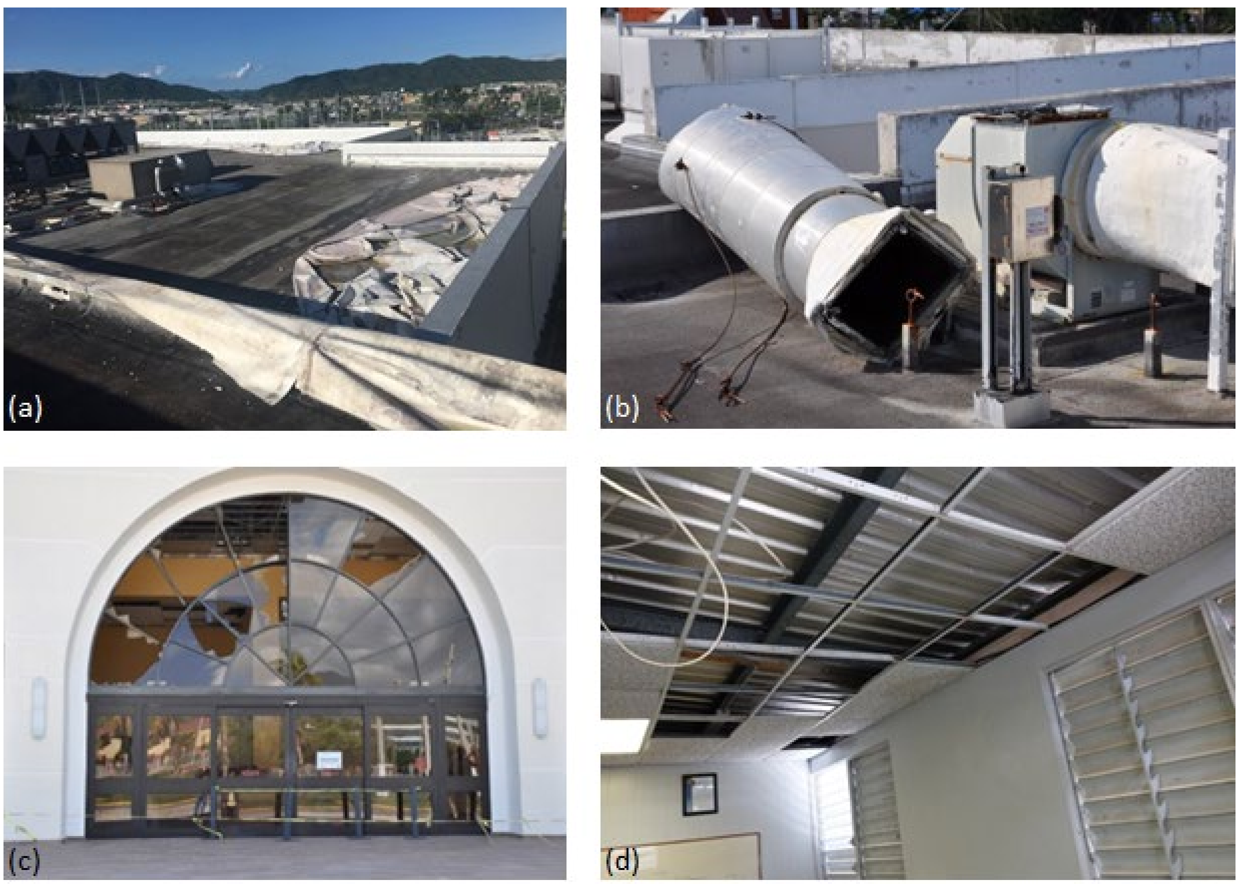

Figure 3: Non-structural damage to engineered buildings: (a) roof covering damage, (b) rooftop equipment damage, (c) window damage, (d) interior damage caused by rainwater penetration.

Further, Hurricane Maria caused severe physical damage and loss of function of infrastructure systems. There was a complete electrical outage across Puerto Rico, with extensive physical damage to electric power transmission and distribution systems. These failures of the electrical infrastructure had cascading effects on other infrastructure systems, including water and wastewater, transportation, and communications. There was near-complete loss of digital communications across Puerto Rico. Factors that contributed to the widespread loss of digital communications, besides the loss of electrical power, included extensive physical damage to tower- and building-mounted cellular communications equipment, extensive damage to fiber-optic cable (which impacted both wireless and wireline communications), and some collapses of cell towers. Infrastructure failures also had cascading impacts on critical buildings, with loss of power and failure of backup generators disrupting the function of some schools and healthcare facilities.

2.4 Evacuation and Emergency Response Challenges

Emergency information for Hurricane Maria was provided via multiple channels and by multiple sources, including the National Weather Service, Commonwealth and local governments, news media, and social media. Prior research has demonstrated that the perceived credibility of the information source and communication channels are key to appropriate and efficient public response to emergency messages. This becomes especially true when there are numerous sources providing potentially different messages. Preliminary observations and discussions identified many challenges to emergency response, evacuation, and other protective actions during and after the hurricane; these challenges were exacerbated by the failure of communications systems across Puerto Rico.

The near-complete failure of communications systems led to a lack of communication among emergency officials, critical facilities, shelters, and with the public for an extended period of time. Officials and residents relied on less efficient communication techniques to deliver and retrieve information. For example, there was widespread use of "runners" to convey information directly to the intended recipients. However, transportation on the island made this task challenging in many instances and resulted in incomplete or delayed transmission of critical information needed for an effective response and recovery. Several AM radio stations were able to continue their operations, which required physical presence but did permit communications with portions of the public over distances. Amateur radio operators enabled some communications to continue during and immediately after the hurricane; however, the island had few such operators in place before the event. In sum, Puerto Rico emergency managers, first responders, other government officials, businesses, and residents were reliant primarily on traditional landline and cellular communications – few of which were available during and for an extended period after the event.

Among the emergency response activities that posed an immediate challenge were the instances of flooding and related rescues that occurred in multiple municipalities across the island. These events raise questions about the types of evacuation warnings received by residents and their response to these warnings. For example, reports indicated that some people felt safer remaining in their homes than going to a shelter. However, given that some areas experienced flooding for the first time, residents may have incorrectly assessed the safety of their homes. The perceptions and concerns of residents regarding evacuation and other protective actions are an important part of understanding their comprehension of risk communication messages and compliance with evacuation instructions. Further analysis of message content, how messages were received, and evacuation decision-making processes is important to determine how the public responded to emergency messages.

2.5 Economic and Social Impacts

Impacts from Hurricane Maria were physical, economic, and social, and all were extensive. Economic losses, including the closures of business establishments, were not fully documented as of December 2017. Businesses, individuals, and the broader economy in Puerto Rico are heavily reliant on a supply chain composed of many small businesses, particularly in the manufacturing and service sectors, with extensive shipping services. Even without precise data, it is evident that the damage they incurred as well as the degree and speed of their recovery are key factors in determining the future health and potential growth of the island's economy into the future.

Among the most severe impacts were those affecting Puerto Rico's social functions. This includes the education sector, with many school buildings suffering structural damage, non-structural damage, or the loss of critical infrastructure services–and in some cases, all three. Moreover, many schools that experienced no damage or less extensive damage, were also designated to serve as emergency shelters for local populations. It was not unusual for those schools to still be serving as shelters, rather than as schools, for months after the hurricane, which directly impacted the education of Puerto Rico's school-age population and subsequently complicated childcare for many families.

Similarly, many of the critical buildings relied upon for delivering healthcare to the population did not suffer severe structural damage, but operations were still affected by the lack of communications capabilities and electrical power. Other buildings experienced non-structural damage such as generator failures. This damage, among other factors, affected the delivery of healthcare services widely in Puerto Rico. Patients in multiple facilities were forced to evacuate, potentially resulting in further degradation of their conditions.

The combination of physical damage and related post-storm crises (e.g., distribution of food, water, and gas) led to uncertainty and stress among the population. Communities across Puerto Rico experienced major social disruptions, in some cases severe enough to jeopardize their future viability. Following the preliminary reconnaissance, the Team noted the significant population loss (outmigration) that occurred across Puerto Rico as a result of Hurricane Maria.[14]

[14] https://www.census.gov/library/stories/2020/08/estimating-puerto-rico-population-after-hurricane-maria.html

2.6 Decision to Establish a Team

The NCST Act and its implementing regulations (15 CFR Part 270.102)[15] set forth the criteria that the NIST Director must use in determining whether to establish and deploy a Team "after an event that caused the failure of a building or buildings that resulted in substantial loss of life or posed significant potential for substantial loss of life." The criteria to be considered and the analysis of the Hurricane Maria event against each criterion are presented below.

Criterion 1: *The event was any of the following:*

- *(i) A major failure of one or more buildings or types of buildings due to an extreme natural event (earthquake, hurricane, tornado, flood, etc.);*
- *(ii) A fire that resulted in a building failure of the building of origin and/or spread beyond the building of origin;*
- *(iii) A major building failure at significantly less than its design basis, during construction, or while in active use; or*
- *(iv) An act of terrorism or other event resulting in a Presidential declaration of disaster and activation of the National Response Plan.*

Analysis: The September 20, 2017 storm event in Puerto Rico falls within category (i). The hurricane resulted in the failures of many buildings, including failures of building envelopes and nonstructural systems that resulted in loss of function for engineered buildings that housed essential services. Of the many deaths attributed to Hurricane Maria, the number of deaths that resulted directly from building failures is not yet known. However, these building failures certainly posed significant potential for substantial loss of life.

Criterion 2: *A fact-finding investigation of the building performance and emergency response and evacuation procedures will likely result in significant and new knowledge or building code revision recommendations needed to reduce or mitigate public risk and economic losses from future building failures.*

Analysis: The hurricane produced rare near-design wind speeds for engineered buildings and other structures across a large geographical area housing a heterogeneous building stock, which provides a unique opportunity to assess the effectiveness of performance objectives set forth by current design standards for critical buildings. This event also provides a unique opportunity to evaluate emergency communications standards and practices in an environment that experienced widespread and long-lasting infrastructure failures. It is therefore expected that an investigation of the building performance during and after the storm, and of the challenges in emergency response and evacuation procedures, will result in novel insights that will lead to important recommendations for codes, standards, and practices.

[15] https://www.ecfr.gov/cgi-bin/text-idx?SID=23c803795bccfbf11fcb929f4ab5692e&mc=true&node=pt15.1.270

In evaluating the criteria set forth above, the NIST Director also considered the five factors listed in 15 CFR 270.102(b) and made the following conclusions with regard to these factors:

1. Sufficient financial and personnel resources are available to conduct an investigation.
2. The investigation of the building failures caused by Hurricane Maria warrants the advanced capabilities and experiences of a National Construction Safety Team.
3. Although some of the technical causes of building failures are readily apparent, the investigation is likely to result in relevant knowledge with potential for new recommendations for changes to codes, standards, and practices.
4. Deployment of a Team will not substantially duplicate local or state resources equal in investigatory and analytical capability and quality to a National Construction Safety Team.
5. Based on the preliminary reconnaissance of the sites of building failures, additional study of the event is recommended.

Based on the information gathered during the preliminary reconnaissance and the analysis of the criteria described above, on February 21, 2018, the NIST Director established a Team under the NCST Act to conduct a technical investigation of the Hurricane Maria event.

3. The NIST Hurricane Maria Program

3.1 Scope and Goals

The NIST Hurricane Maria Program comprises two distinct but complementary studies of Hurricane Maria's impacts on Puerto Rico, which are being conducted under the two authorities described previously in Section 1.1: a technical investigation under the National Construction Safety Team Act and a research study under the National Windstorm Impact Reduction Act.

The goals of the NCST technical investigation are to characterize:

1. the wind environment and technical conditions associated with deaths and injuries;
2. the performance of representative critical buildings, and designated safe areas in those buildings, including their dependence on lifelines; and
3. the performance of emergency communications systems and the public's response to such communications.

The goals of the NWIRP research study are to characterize the impacts to and recovery of:

1. small and medium-sized manufacturers (SMMs), as well as businesses in retail and service industries;
2. education and healthcare services; and
3. infrastructure systems, with a focus on infrastructure that supports the functioning of critical buildings (i.e., hospitals and schools) and emergency communications.

By carrying out these distinct but complementary studies as part of a single coordinated effort, the Hurricane Maria Program will enable a more comprehensive characterization of the hurricane's impacts on Puerto Rico than either study would provide on its own. For example, building failures can be considered in the context of the social services that the buildings provide and the recovery of those services over time, and infrastructure failures can be considered in the context of the critical buildings whose functioning they support. The benefit of this broader context is expected to strengthen the findings and recommendations that will ultimately be developed from the NCST investigation.

3.2 Team Leadership and Members

Contributors to the NIST Hurricane Maria Program[16] represent a variety of technical disciplines, including civil, wind, and structural engineering; sociology; economics; anthropology; operations research; meteorology; and epidemiology. A subset of these contributors, listed below, has been designated by the NIST Director as formal members of the National Construction Safety Team investigating Hurricane Maria's effects on Puerto Rico. In addition to NIST employees, formal NCST members include outside experts from the National Weather Service, the National Center for Disaster Medicine and Public Health, and the University of Puerto Rico at Mayagüez.

3.2.1 Team Leadership

As of February 13, 2020, Dr. Joseph Main has been designated by the NIST Director as the Lead Technical Investigator for the Hurricane Maria NCST investigation, and Dr. Maria Dillard has been designated as the Associate Lead Technical Investigator. Prior to that date, Dr. Erica Kuligowski was the Lead Technical Investigator, having led the NCST investigation since its establishment in February 2018, with Dr. Main previously serving as the Associate Lead Technical Investigator.[17] Dr. Main also serves as Program Manager for the larger Hurricane Maria Program, and Dr. Maria Dillard is the Associate Program Manager.

3.2.2 National Construction Safety Team Members

The following is a listing of the NIST employees who have been designated by the NIST Director as formal members of the Hurricane Maria National Construction Safety Team. All of these NIST employees are affiliated with the Engineering Laboratory (EL) at NIST. Their affiliations within EL and their relevant areas of expertise are listed below.

Dr. Joseph Main, Lead Technical Investigator

Affiliation: Research Structural Engineer, Structures Group

Relevant Areas of Expertise: wind loads on structures and computational assessment of structural performance under extreme loads, including modeling the response of structural systems beyond local failure to global collapse

[16] www.nist.gov/topics/disaster-failure-studies/hurricane-maria/hurricane-maria-team

[17] The Hurricane Maria Program leadership changes came with the departure from NIST of Dr. Erica Kuligowski.

Dr. Maria Dillard, Associate Lead Technical Investigator

Affiliation: Acting Director, Disaster and Failure Studies Program, and Research Social Scientist, Community Resilience Group

Relevant Areas of Expertise: community response to hazards and chronic stressors, methods for measurement and modeling community resilience, sampling and surveying expertise

Dr. Erica Kuligowski, Lead Technical Investigator (February 2018 to February 2020)

Affiliation: Research Social Scientist, Wildland-Urban Interface Fire Group

Relevant Areas of Expertise: human behavior in emergencies, including preparedness, response and recovery behaviors, emergency communications, community resilience, behavioral modeling, and the modeling of social systems

Mr. Benjamin Davis

Affiliation: Management and Program Analyst, Disaster and Failure Studies Program

Relevant Areas of Expertise: project management and contract support

Dr. Jazalyn Dukes

Affiliation: Research Structural Engineer, Earthquake Engineering Group

Relevant Areas of Expertise: earthquake engineering, seismic retrofits of existing buildings and infrastructure, damage assessment and modeling

Dr. Kenneth Harrison

Affiliation: Operations Research Analyst, Community Resilience Group

Relevant Areas of Expertise: decision-making under uncertainty, infrastructure modeling, interdependencies of distributed infrastructure and building functions, systems analysis

Dr. Jennifer Helgeson

Affiliation: Research Economist, Applied Economics Office

Relevant Areas of Expertise: resilience to hazards in the built environment, with consideration for cost-effectiveness of community-scale mitigation and adaptation efforts, sampling and surveying expertise

Dr. Katherine Johnson

Affiliation: Social Scientist, Earthquake Engineering Group

Relevant Areas of Expertise: social science, earthquake risk mitigation policy, risk perception and communications

Dr. Marc Levitan

Affiliation: Research Structural Engineer, Structures Group

Relevant Areas of Expertise: standards for instrumentation and its deployment to measure wind, structural response to severe wind loading, development of wind standards, model codes, and better building practices

Dr. Judith Mitrani-Reiser

Affiliation: Associate Chief, Materials and Structural Systems Division
Relevant Areas of Expertise: performance of critical facilities, structured tool development for field reconnaissance, safety and economic impacts of hazards on the built environment, and interaction of humans with the built environment

Dr. Scott Weaver

Affiliation: Director, National Windstorm Impact Reduction Program
Relevant Areas of Expertise: dynamic and diagnostic analyses of North American hydroclimate variability in observationally constrained and climate model datasets, and characterization of extreme climatic events (i.e., droughts and floods)

Dr. DongHun Yeo

Affiliation: Research Structural Engineer, Structures Group
Relevant Areas of Expertise: extreme wind climatology, atmospheric boundary-layer winds, bluff-body aerodynamics, computational fluid dynamics, wind tunnel testing, advanced analysis of structural performance under wind loads, development of wind load provisions in standards

In addition to these NIST employees, the following outside experts have also been designated by the NIST Director as formal members of the Hurricane Maria National Construction Safety Team.

Dr. Luis D. Aponte-Bermúdez

Affiliation: Federal Contractor, Stantec, Inc., and Professor, Department of Civil Engineering and Surveying, University of Puerto Rico at Mayagüez
Relevant Areas of Expertise: Measurements and modeling of the wind environment in Puerto Rico and assessing post-hurricane building damage

Mr. Joel Cline

Affiliation: Tropical Program Coordinator, National Weather Service (NWS), National Oceanic and Atmospheric Administration (NOAA)
Relevant Areas of Expertise: tropical weather hazards, hurricane winds and coastal inundation, operational hurricane forecasting, risk communication, post-hurricane assessment of communication activities

Dr. Thomas Kirsch

Affiliation: National Center for Disaster Medicine and Public Health (NCDMPH), Uniformed Services University of the Health Sciences (USUHS)
Relevant Areas of Expertise: board-certified emergency physician, disaster management and science, and qualitative and quantitative epidemiologic methods to improve assessment and disaster management

3.3 Technical Plan and Projects

NIST has organized the Hurricane Maria Program into seven technical projects, several of which are interrelated, and one administrative project. The following subsections describe the background, objective, and plan for each of the seven technical projects.

To provide an appropriate scope for the Hurricane Maria Program while retaining the major opportunities for findings and recommendations that will result, the NIST Team has selected four regions of Puerto Rico for particular focus. These regions were selected in light of their geographic and socio-economic diversity, the path of the storm, and the variety of Hurricane Maria's hazards and impacts in these regions (i.e., rainfall and flooding, landslides, wind speeds, and impacts to hospitals and schools). The four selected regions are the San Juan, Caguas, Humacao, and Utuado regions (Figure 4), which comprise 26 municipalities (*municipios*). Some projects will require information gathering and assessment beyond these four regions so as to align with the goals and objectives of the work, and several projects have selected the municipality of Mayagüez as an additional area of study. However, all of the technical projects plan to prioritize data collection and analysis in the four selected regions, and the selection of these regions facilitates coordination across the multiple projects within the Hurricane Maria Program. The initial basis for the selection of these regions was the 2017 map of emergency management zones, which was in effect at the time of Hurricane Maria. Although the emergency management zones have been revised since 2017, the NIST Team is maintaining the selection of these four regions of focus for the Hurricane Maria Program. In August 2018, members of the NIST Team visited selected hospitals, schools, shelters, and communities in each of the four regions to finalize the selection of these regions of common focus.

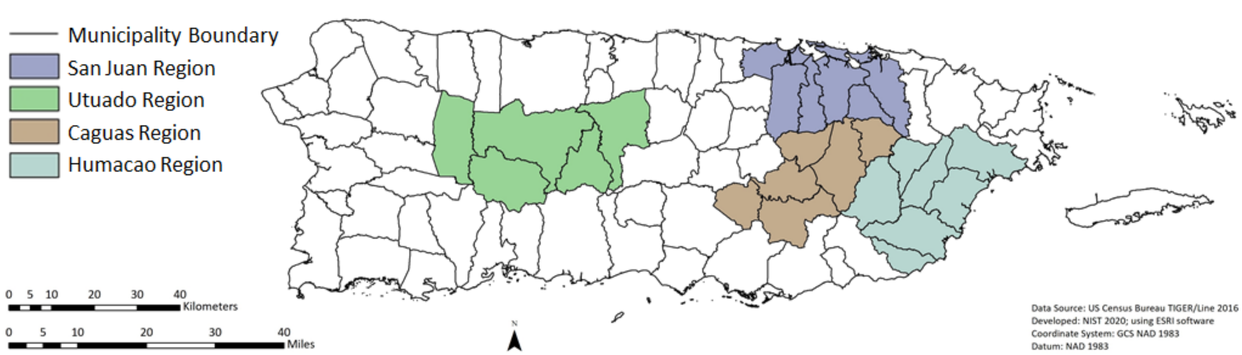

Figure 4: Study regions for the NIST Hurricane Maria Program.

3.3.1 Hazard Characterization

Background: Accurate characterization of the multiple hazards associated with Hurricane Maria is of fundamental importance for multiple projects across the program. Hazard information is a critical input for evaluating the performance of buildings and infrastructure, and it provides important context for evaluation of emergency communications and public response, deaths and injuries, and recovery of businesses and social functions. As discussed in Section 2.1, Hurricane Maria subjected Puerto Rico to multiple hazards, including extreme winds, coastal inundation, and heavy rainfall, which resulted in inland flooding and landslides. The storm caused extensive damage to instrumentation, introducing significant challenges in the quantification of hazards. In some cases, a combination of measurements and modeling will be required to characterize the spatial and temporal variation of the hazards. It is recognized that Puerto Rico's topography (hills and mountains) can dramatically increase wind speeds when compared to the same weather pattern over flat terrain, although this effect was not captured in the initial wind speed estimates for Hurricane Maria (Figure 2(a)). Quantifying this "topographic speedup" is important in order to have an accurate understanding of the wind loads experienced by the structures of interest, especially because critical infrastructure (e.g., cell towers and transmission towers) are often located on ridges and high terrain, as are some buildings.

Objective: To characterize the wind environment associated with Hurricane Maria's impact on Puerto Rico, including topographic effects, and to document other hazards associated with the hurricane, including storm surge, rainfall, flooding, and landslides.

Plan: The wind hazard of Hurricane Maria in Puerto Rico is being comprehensively investigated by four investigative methods consisting of wind field modeling, wind tunnel testing, field measurements, and CFD (Computational Fluid Dynamics) simulations. This investigation focuses on (1) identification of wind speed-up effects based on wind tunnel modeling of Puerto Rico's topography, in conjunction with CFD simulations and field measurements and (2) integration of the results of these topographic studies with a hurricane wind-field model to accurately characterize the wind environment associated with Hurricane Maria's impact on Puerto Rico.

The detailed investigation plan for characterization of the wind hazard is to:

- Develop the initial hurricane wind field model based on existing empirical methods using surface-level observations of wind speed (gust and mean), wind direction, and atmospheric pressure across Puerto Rico acquired from federal, commonwealth, and other meteorological stations and mesonets. The initial model will provide preliminary wind field data for Hurricane Maria to assist in the development of project plans in the early stage of the investigation.

- Perform wind tunnel tests on generic topographic models consisting of two-dimensional ridge and plateau features. The generic topographic tests will provide the datasets for validating the numerical results of CFD models being developed.
- Perform wind tunnel tests on Puerto Rico region models representing Mayagüez and Yabucoa. The Mayagüez model testing data will be used for wind characterization in that region and for approach flow information for building/area model tests in the Performance of Critical Buildings project. The wind field data from the Yabucoa model tests will be compared with the counterparts from field measurements and the CFD simulations.
- Deploy and install anemometers at multiple heights on cell towers in an area of Puerto Rico with significant topographic effects to obtain full-scale wind velocity data. Data will be collected for one year. The field data will be used to evaluate topographic effects on wind speed profiles at full scale and compare with those obtained from wind tunnel tests and CFD models.
- Develop CFD models for topographic simulations, verify CFD simulations, and validate CFD results against wind tunnel and field measurement data. These validated CFD models will then be used to evaluate and characterize topographic speedup effects in Puerto Rico.
- Improve the initial wind field model by optimizing the fit of the hurricane model to the observed asymmetric wind-field data, based on statistical assessment of goodness-of-fit, including quantification of uncertainty, with incorporation of additional wind measurement records that have been identified.
- Finalize the optimally fitted wind field model once the topographic wind speedup data from the wind tunnel experiments, field measurements, and CFD simulations are obtained and analyzed. The final wind field model will generate the time histories of wind speed and direction of Hurricane Maria at gridded locations across Puerto Rico to characterize the wind hazard for other aspects of the investigation.

In addition to characterizing the various wind speed parameters of interest, other hazards that affected Puerto Rico during Hurricane Maria need to be evaluated and documented. To accomplish this, NIST is conducting outreach to other federal earth science agencies and has collected information on landslides, storm surge, rainfall, and flooding from their analyses of Hurricane Maria's hazard impacts on Puerto Rico. Given the striking variability in total rainfall estimates over Puerto Rico for Hurricanes Irma and Maria and the central role of rainfall in causing flooding and landslides, NIST is also conducting a detailed evaluation of the measurement science issues associated with the disparate rainfall observations from different measurement sources. Rainfall measurements play an important role as the primary input into hydrologic models used to predict flooding and landslides and to develop retrospective maps of these hazards in post-windstorm investigations.

The technical plan for other Hurricane Maria hazards is to:

- Continue outreach to other agencies and organizations regarding data sources and modeling capabilities that may be available to better characterize the hazards and their spatial and temporal variation.
- Continue to assess an array of in situ and remotely sensed rainfall observations to better understand measurement platform differences as a function of event severity and or other relevant parameters (e.g., topography).
- Evaluate the sub-daily rainfall evolution as a function of measurement platform and event severity to better understand the evolution of measurement biases and temporal relationships with the primary wind hazard.

3.3.2 Performance of Critical Buildings

Background: Although structural damage to engineered buildings was generally limited, significant damage to building envelopes was sustained, including damage to roof coverings, rooftop equipment, windows, and doors caused by wind and windborne debris. Penetration of rainwater through building envelopes resulted in extensive nonstructural damage and loss of function for many engineered buildings. Loss of power and failure of backup generators also disrupted the function of many buildings, including some critical buildings such as hospitals, schools, and storm shelters. Understanding the performance of hospitals and storm shelters (many of which were schools) is of particular importance, not only because of their critical role in disaster response, but also because these facilities were generally designed to the same building codes and standards used elsewhere in the United States. Lessons learned from the performance of these facilities can therefore inform findings and recommendations for improvements that may be needed to existing building codes and standards.

Objective: To characterize the performance of critical buildings in Hurricane Maria by evaluating damage and loss of function for representative hospitals, schools, and storm shelters with respect to the hazards they experienced and by evaluating the selection criteria and design requirements for storm shelters.

Plan: The initial data collection phase, in coordination with Puerto Rico government agencies, federal partners, and other organizations, seeks to identify and collect relevant existing data on the characteristics and performance of critical buildings in Hurricane Maria. These buildings include hospitals, schools, and storm shelters. Initial data collection will also include information on the shelter program in Puerto Rico, such as the shelter selection criteria and the facilities used during Hurricane Maria. Representative hospitals, schools, and shelters will then be selected for detailed evaluation based on the characteristics of the buildings, the hazard exposure, reported damages, and other factors. Detailed evaluations of the critical facilities will be performed to document the physical characteristics of the buildings prior to Hurricane Maria and the impacts to the buildings that resulted from the hurricane. This includes impacts on life safety and on the function and operation of the facility. For a subset of the selected critical buildings, the effects of surrounding topography, buildings, and terrain on wind loads will be studied using scale models of buildings in the wind tunnel.

The data collected will be used to evaluate the performance of the selected critical buildings, considering the wind loads and other hazards experienced during Hurricane Maria, the impacts of these hazards on building function and life safety of occupants (including operational challenges encountered), and the adequacy of existing codes, standards, and practices. Shelter selection and design criteria and operational guidance will also be evaluated for the larger population of shelters in Puerto Rico. Consideration will be given to the hazard levels encountered at shelter sites, the damage to shelter buildings, the shelter population per site over time, including relocation of occupants, and the adequacy of existing selection and design criteria and shelter operations plans. Finally, recommendations will be made, as appropriate, for specific improvements to building standards, codes, and practices. Recognizing that Puerto Rico is subject to significant seismic and wind hazards, both wind and seismic hazards will be considered in the development of any recommended changes in codes, standards, and practices based on the findings from this study.

3.3.3 Public Response to Emergency Communications

Background: Preliminary reconnaissance data and observations showed challenges in evacuation and emergency communications. The island's heterogeneous terrain posed varied hazard risks (flooding, heavy winds, storm surge, landslides) that required different protective actions. There is a societal preference for sheltering in place, and there was a lack of key communication channels for extended periods of time due to power and communication outages. Many people required emergency rescue, demonstrating a need for improvements to better support pre-event protective-action decision making.

Objective: To investigate the role of emergency communications in public response for those under imminent threat from Hurricane Maria. This project will also examine the use of communications during response and recovery (during and immediately after the hurricane).

Plan: A four-pronged approach has been developed that will meet the two primary goals: (1) characterize the use of emergency communications (technology and information) before, during, and after the hurricane; and (2) identify factors that influenced the public's decision to take protective action by evacuating prior to the hurricane, including understanding the role of emergency communications in that decision.

1. Qualitative content analysis will be conducted on emergency communications and messages to assess their distribution and effectiveness.
2. Semi-structured interviews with expert information providers will help characterize message dissemination, organizational interactions and constraints, and areas to facilitate communication effectiveness. Thirty-five interviews are planned to gather information across a variety of relevant information providers.

3. Data regarding the public's protective action decision-making process will be gathered via structured surveys that will investigate: pre-hurricane activities, experiences, and risk perceptions; knowledge of risk zones (including for flooding and landslides); the types of emergency information received; trustworthiness of information; other environmental/social cues; protective action decisions; information needs during and after the event; and health or medical care needs after the hurricane. In total, 1520 surveys are planned across the four study regions (Figure 4) to provide a representative sample for the population.
4. Interviews with the public will enable more in-depth qualitative inquiry into the factors relevant to evacuation decision-making. At least 100 interviews will be conducted with individuals through the household survey to identify key factors influencing protective action decision-making before and after the storm.

Together, these activities will enable NIST to assess the performance and effectiveness of emergency communications systems and procedures, to evaluate the public's protective action decision-making and response to such communications, and to recommend research or other appropriate actions needed to prevent injuries and lessen loss of life in future events.

3.3.4 Characterization of Morbidity and Mortality

Background: As described in Section 2.2, death certificates generally underestimate deaths caused by disaster events because of a lack of standards and consistent data collection and reporting (i.e., death certificates) for attribution of deaths to disaster events.[18] A standard for disaster-related mortality attribution was proposed in 1999,[19] but was not widely adopted, nor has it been applied to a large natural disaster with a long recovery period.[20] Given these challenges, many studies and investigations by public health scientists and reporters attempted to characterize the extent of mortality in Puerto Rico after Hurricane Maria made landfall using available data and collecting primary data. For example, a study led by Harvard[21] public health scientists found that interruption of medical care was the primary cause of sustained high mortality rates in the months after the hurricane. The George Washington University Milken Institute School of Public Health estimated a total excess mortality post-hurricane to be 2975,[22]

[18] Combs D.L., Quenemoen L.E., Parrish R.G., Davis J.H., 2009. "Assessing disaster-attributed mortality: Development and application of a definition and classification matrix." International Journal of Epidemiology 28(6): pp. 1124–9.
[19] Combs DL, Quenemoen LE, Parrish RG, Davis JH. Assessing disaster-attributed mortality: development and application of a definition and classification matrix. Int J Epidemiol 1999;28:1124–9.
[20] National Center for Health Statistics. A Reference Guide for certification of deaths in the event of a natural, human-induced, or Chemical/Radiological disaster. (Reference guide No. 1). CDC, National Center for Health Statistics 2017. Retrieved from https://www.cdc.gov/nchs/data/nvss/vsrg/vsrg01.pdf
[21] Kishore N, Marques D, et al. *Mortality in Puerto Rico after Hurricane Maria*. NEJM 2018; 379:162-170
[22] George Washington University , in collaboration with the University of Puerto Rico Graduate School of Puerto Rico, 2018. "Ascertainment of the Estimated Excess Mortality from Hurricane Maria in Puerto Rico," a Project Report for the Governor of Puerto Rico, August 28, 2018.

which has been adopted as the official death toll of Hurricane Maria in Puerto Rico. This study concluded that the lack of appropriate death certification practice after the hurricane and the local lack of communication about death certificate reporting prior to the storm limited the count of deaths that were reported as related to Hurricane Maria.

Objective: To complete a quantitative morbidity and mortality assessment of Puerto Rico in order to better understand how damaged buildings and failures in the supporting infrastructure played a role in the injuries and deaths associated with Hurricane Maria. The study results will provide guidance to improve building codes and standards, and to inform future approaches to accurately attribute and predict life loss due to building failure(s) caused by windstorms.

Plan: To date, several studies[23,24,25] have focused on assessing Hurricane Maria's death toll using excess mortality approaches, such as daily and monthly comparisons with previous years. Additionally, a single population-based study[26] characterized the predominant reasons associated with deaths in their sample as attributable to a lack of healthcare access. *The NIST mortality project will not produce another death count; instead, NIST will use rigorous, scientific methods to understand the injury mechanisms of those that perished due to the storm, within the greater context of the hazards and the building and infrastructure system failures experienced by those individuals.*

One key task of this project is the development of an integrated database of deaths in Puerto Rico. The impacts of the storm lingered in Puerto Rico for many months after it made landfall, likely impacting the risk of death. One excess mortality study[27] found that the risk of death was higher and persistent for almost six months after the storm, and especially elevated at the end of February 2018 for populations living in low socioeconomic development municipalities. NIST will collect and merge geocoded data on the deaths occurring in Puerto Rico up to six months after Hurricane Maria made landfall on the island. Possible data sources include the Puerto Rico Vital Registration System with available datasets from the Bureau of Forensic Sciences. Additional data to consider are 911 emergency calls obtained from the Bureau of Police and funeral and burial assistance data from the Federal Emergency Management Agency (FEMA) and the American Red Cross. The goal is to link as many data sources as possible for individual deaths. The integrated database of the deaths that occurred after Hurricane Maria will allow for

[23] Robles, F., Davis, K., Fink, S, Almukhtar, S., 2017. "Official Toll in Puerto Rico: 64. Actual Deaths May Be 1,052." The New York Times. December 9, 2017.
[24] Santos-Lozada AR, Howard JT. Use of Death Counts from Vital Statistics to Calculate Excess Deaths in Puerto Rico Following Hurricane Maria. JAMA; Aug. 2, 2018: doi:10.1001/jama.2018.10929.
[25] George Washington University , in collaboration with the University of Puerto Rico Graduate School of Puerto Rico, 2018. "Ascertainment of the Estimated Excess Mortality from Hurricane Maria in Puerto Rico," a Project Report for the Governor of Puerto Rico, August 28, 2018.
[26] Kishore N, Marques D, et al. Mortality in Puerto Rico after Hurricane Maria. NEJM 2018; 379:162-170.
[27] George Washington University , in collaboration with the University of Puerto Rico Graduate School of Puerto Rico, 2018. "Ascertainment of the Estimated Excess Mortality from Hurricane Maria in Puerto Rico," a Project Report for the Governor of Puerto Rico, August 28, 2018.

analysis of spatial clustering and cause of death at different time periods. The analysis will include the entire island. This task will result in maps that tell the story of mortality on the island due to the storm and will help connect data being collected by other projects, such as the Hazard Characterization Project and the Critical Buildings Project.

To further explore those deaths that were caused by the storm and better understand if building and infrastructure failures were the underlying causes to any of them, NIST will complete *verbal autopsies*[28] with the next of kin of the decedents or *key informants*[29] for the deaths that might have been caused by a building and/or building system failure(s). The sample for the verbal autopsy (VA) deployment will be identified using inclusion (e.g., occurred within 14 days of the storm's landfall) and exclusion criteria (e.g., deaths for whom the information to locate relatives or key informants is not available). NIST will augment the World Health Organization's most recently published verbal autopsy standards of 2016[30] to include any hazard and/or building-specific questions to more completely characterize deaths related to the storm.

3.3.5 Recovery of Business and Supply Chains

Background: Manufacturing and retail business services are an important part of understanding the economic impacts of Hurricane Maria, as well as the long-term recovery of Puerto Rico and its supply chains. Manufacturing activity in the Commonwealth accounts for about 45% of Puerto Rico's Gross Domestic Product (GDP) and over 20% of its employment.[31] According to FEMA, 40% of small businesses never reopen after a disaster, and another 25% that do reopen fail within a year.[32] The effects of Hurricane Maria exacerbated pre-existing financial and business stress in Puerto Rico.[33]

Objective: To characterize the recovery of small- and medium-sized enterprises (SMEs), including manufacturing, retail, and service sectors in Puerto Rico, to provide greater

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[28] Verbal autopsy (VA) is a method of determining individuals' causes of death and cause-specific mortality fractions in populations without a complete vital registration system. Verbal autopsies consist of a trained interviewer using a questionnaire to collect information about the signs, symptoms, and demographic characteristics of a recently deceased person from an individual familiar with the deceased. (Source: www.healthdata.org/verbal-autopsy)

[29] In survey and interview research, *key informant* refers to the person with whom an interview about a particular issue, organization, or problem is conducted. The key informant is a proxy for the individual or group with the desired information (Lavrakas 2008).

[30] World Health Organization. Verbal autopsy standards: the 2016 WHO verbal autopsy instrument. Geneva: World Health Organization, 2016.

[31] Bureau of Labor Statistics (BLS). (2017). https://www.bls.gov/regions/new-york-new-jersey/puerto_rico.htm

[32] Federal Emergency Management Agency (FEMA). (2015). "Make Your Business Resilient." https://www.fema.gov/media-library-data/1441212988001-1aa7fa978c5f999ed088dcaa815cb8cd/3a_BusinessInfographic-1.pdf

[33] Puerto Rico Oversight, Management and Economic Stability Act of 2016: https://oversightboard.pr.gov/documents/

understanding of business continuity resilience planning and supply chain continuity and how these may differ among industries or affected regions.

Plan: A two-pronged approach has been developed that will meet the goals of understanding the recovery of SMEs. First, the study will model the supply chain, leveraging transportation network information for two key Puerto Rico-based industries: food processing and medical device manufacturing. These industries have been selected due to their high market share in the Puerto Rican manufacturing sector. Medical device manufacturing contributes greatly to Puerto Rican exports to the rest of the United States and the world, while food processing[34] is a major sector that affects local supply chains (i.e., much of the finished product stays within Puerto Rico). The data for this modeling effort will largely make use of data provided by Puerto Rico government agencies and data collected through site visits conducted during the summer of 2019, coordinated in conjunction with the NIST Manufacturing Extension Partnership (MEP) and the Puerto Rico Manufacturing Extension, Inc. (PRiMEX). Modeling efforts will be conducted using two methods:

1. Complex Network Theory (CNT): a method to assess the network vulnerability using the transportation networks of Puerto Rico, weighted by business density, population density, and road type
2. Discrete Event Simulation (DES): a simulation process that is used to model event-based systems and explicitly understand how different supply chain components are affected under different conditions

Second, initial findings from the modeling process described above will inform sampling and surveying of SMEs in the manufacturing and service/retail sectors, as well as representatives of shipping and transportation companies. For this project, the research questions are focused on the institutional level of the SME (employs <250 individuals at a given site) and are asked of the SME owner or manager. The research questions include interdependencies of economic and supply chain recovery with physical infrastructure[35], social institutional recovery, and other elements of community resilience. The sample is planned to include 250 small and medium-sized manufacturers (SMMs) and the same number of SMEs in the retail/service sector (e.g., grocery, clothing, and restaurants). Additionally, there will be a sample of 30 representatives of transportation/shipping companies. This project will sample across the four study regions common across most projects (Figure 4), as well as Mayagüez and Ponce. Mayagüez is included in order to capture the SMEs near a critical hospital; Ponce is the second largest seaport in Puerto Rico and home to many SMMs.

[34] Food Processing Sector (NAICS 311) Food processing is part of the manufacturing sector (NAICS 31 - 33). This covers commercial manufacturing that starts with raw animal, vegetable or marine materials and transforms them into food stuffs or edible products such as dairy, meat, vegetable, bakery, grain and cereals.

[35] The major infrastructure considered will be transportation systems through application of the Shipping and Transportation Interview Guide (STIG). Additional services provided by utility infrastructure (i.e., water, electricity, cellular) will be considered as limiting factors to recovery.

Project methods will also include structured surveys of 300 owners/managers of SMEs evenly divided between SMMs and retail/service SMEs. A brief semi-structured section will be asked of a subset of the larger sample. The survey instruments will be aimed at providing the data needed for an empirical model that seeks to explain variation in the dependent variable, recovery status, using a selection of independent variables.[36] These instruments will include questions about pre-existing states, impacts on services and physical damage (e.g., building, contents, machinery, inventory), infrastructure interruptions, nonphysical impacts, financial and other available resources (e.g., recovery assistance), policy impacts, plans in place, decisions, delays, and resilience characteristics. The semi-structured interviews will allow for in-depth questioning on particular topics, such as supply chain robustness and decision-making in response to Hurricane Maria and during the recovery process.

3.3.6 Recovery of Social Functions

Background: Both education and healthcare services are an important part of understanding the impacts of Hurricane Maria, as well as the long-term recovery of Puerto Rico. Approximately one-quarter of the schools have closed in Puerto Rico, disproportionately affecting rural communities where the majority of school closures have taken place.[37]

Objective: To examine the recovery trajectories of sampled schools and hospitals in Puerto Rico to identify the underlying characteristics and conditions associated with recovery of critical social functions from Hurricane Maria.

Plan: For this project, the research questions are focused on the institutional level recovery and the interdependencies of social functions on physical infrastructure, business and economic recovery, as well as other aspects of community recovery. The study plans for data collection from institutions at three points in time, also known as "waves," using a longitudinal design. The design allows the same cases to be observed over time so as to better document the recovery process. The sample (n=410) includes K-12 public and private schools and hospitals within the municipalities comprising the four main NIST study regions (Figure 4) as well as Mayagüez.

Project methods include structured surveys of representatives of hospitals and school institutions at three different time points and semi-structured interviews with a subset of the sample at a single time point. The survey instruments are aimed at providing the data needed for an empirical model that seeks to explain variation in the dependent variable, recovery

[36] The concepts of independent and dependent variables are used in a mathematical sense, meaning that the value of a dependent variable changes in response to that of an independent variable. In research design, independent variables are those that can be manipulated or changed while the dependent variables are the responses to the effects of independent variables. (Source: Salkind, Neil J., Ed. 2010. Encyclopedia of Research Design. Sage Publications. http://methods.sagepub.com/Reference/encyc-of-research-design/n184.xml)

[37] Hinojosa, Meléndez and Severino Pietri, "Population Decline and School Closure in Puerto Rico" https://centropr.hunter.cuny.edu/sites/default/files/PDF_Publications/centro_rb2019-01_cor.pdf.

status, using a selection of independent variables. The survey will include questions about services, physical damage (e.g., building, contents, equipment), infrastructure damage and disruption, nonphysical impacts, financial and other resources, policies, plans in place, decisions, delays, and resilience characteristics. The interviews will allow for in-depth questioning on particular topics, such as decision-making following Hurricane Maria and throughout the recovery process. Further, the interview data will be used to inform remaining time points of survey data collection.

3.3.7 Recovery of Infrastructure Systems

Background: Failures in the power, water, and transportation infrastructure systems presented emergency response and recovery challenges. The island's electrical system experienced extensive damage to transmission and distribution systems, resulting in a complete electrical outage across the island with cascading effects to other lifelines. There was also a near-complete loss of digital communications across Puerto Rico.

Objective: To evaluate the dependencies of building function on infrastructure (power, water, and transportation), including cascading loss of function and sequencing of recovery activities following Hurricane Maria, and to examine the causes of the loss of functionality and extended-duration outage of the wireless communications system.

Plan: The plan consists of two components: The first focuses on the recovery of power, water, and transportation infrastructure system support of critical buildings. The second focuses on the failure modes of the wireless communication system following Hurricane Maria.

The technical plan for the study of power, water, and transportation infrastructure systems that support critical buildings consists of the following steps:

1. Secondary data collection: A wide variety of data sources will be reviewed, including academic, government, and other sources of information. This information feeds into the subsequent steps, informing the primary data collection effort, analysis, and modeling. Data from the relevant agencies within Puerto Rico that plan for and operate the power, water, and transportation infrastructure systems provide a key source of information for this project.
2. Primary data collection: New primary data is collected via structured interviews to gain community-scale data pertaining to the infrastructure system interdependencies and their support of critical buildings. Officials involved in the planning and management of the infrastructure systems, as well as municipal officials, will be interviewed. Information is sought on the infrastructure condition prior to Hurricane Maria, its impacts, and recovery. The goal is to systematically gather information that can inform an understanding of infrastructure systems interdependencies and critical building support.

3. Extend NIST Resilient Communities Model: NIST's Alternatives for Resilient Communities (ARC) model[38] will be extended as necessary based on the results of the secondary and primary data collection efforts. The NIST ARC model aims to capture interdependencies in these infrastructure systems, for which there are few existing tools. The model is being developed within the NIST Community Resilience program, with a beta version released in September 2020.
4. Case study: NIST ARC will then be applied to a community within Puerto Rico to demonstrate the ability to address interdependencies in resilience planning at the community scale.

The study plan for wireless telecommunications consists of the following steps:

1. Collect data on the damage caused by Hurricane Maria to cell towers, equipment, cabling, and related components of wireless communications systems, from regulatory agencies, telecommunications companies, and telecommunications support industries.
2. Collect data on other causes of service outages, including the loss of power and damage to backhaul (i.e., the connection between the cell site and the core network).
3. Collect information on codes, standards, and regulations governing the design and construction of cell towers and wireless communication equipment.
4. Determine the hazard levels experienced at cell site locations using information from the Hazard Characterization Project.
5. Evaluate tower and equipment performance with respect to the hazard levels experienced at each site and code design requirements.

3.4 Advisory Committee

The National Construction Safety Team Advisory Committee[39] is a federally chartered advisory committee that advises NIST on carrying out investigations of building failures conducted under the authorities of the NCST Act. Members are internationally respected experts in a variety of fields, selected based on their technical expertise and experience, established records of distinguished professional service, and their knowledge of issues affecting NIST studies. Since the establishment of the Hurricane Maria National Construction Safety Team in February 2018, the Team has provided multiple public briefings to the Advisory Committee on the plans and progress of the investigation (see Section 4.5).

[38] https://www.nist.gov/programs-projects/development-first-generation-community-resilience-systems-model
[39] https://www.nist.gov/topics/disaster-failure-studies/national-construction-safety-team-ncst/advisory-committee

3.5 Coordination with Other Organizations

To get the most accurate information possible, and in accordance with the NCST Act's mandate that NIST seek out and coordinate its efforts with other organizations (including state, local, and federal organizations as well as the broader community as appropriate), the NIST Team is engaging directly or indirectly with the following:

- municipalities (*municipios*),
- local and regional emergency management officials,
- Commonwealth building departments,
- power, transportation, and water and wastewater public utilities and agencies,
- education and healthcare officials,
- other local, regional, and Commonwealth elected officials and civil servants,
- companies and business establishments,
- business associations, and
- individuals.

NIST is working with and involving other federal agencies in planning and carrying out its Hurricane Maria Program, building on work by others who have gathered information and conducted assessments after the hurricane. This includes receiving information collected by other agencies. Especially noteworthy are the Memorandums of Agreement established by NIST with the Federal Emergency Management Agency (FEMA), providing NIST with access to important information about damages to schools and healthcare facilities, which is being used to advance the Team's work in accordance with carefully developed guidelines to ensure limited and appropriate use of that data. Federal agency involvement also includes the direct participation of experts from NOAA's National Weather Service (NWS) and the Uniformed Services University's National Center for Disaster Medicine and Public Health, who serve as members of the NCST Hurricane Maria Team. Further details about some of these supporting efforts are provided in Section 4.2.

Several teams of contractors, including experts based in Puerto Rico, are supporting NIST engineers, sociologists, anthropologists, economists, meteorologists, epidemiologists, and other researchers who are carrying out the studies. (See section 4.4 for additional details on contractors' assignments.)

3.6 Estimated Duration and Cost

NIST will conduct the Hurricane Maria Program until the stated goals and objectives are achieved. Although there are no direct precedents for the Hurricane Maria Program, previous NCST investigations have taken between three and seven years to produce a final technical report and recommendations. As the first NCST investigation of a hurricane event, the

Hurricane Maria Program is considerably broader in geographic scale and scope than previous NCST investigations. The Hurricane Maria Program will consider multiple hazards that affected multiple buildings across the entire Commonwealth of Puerto Rico, incorporate a more in-depth investigation of deaths and injuries, and include complementary research projects under the NWIRP statutory authority. The establishment of the Hurricane Maria Program was announced in February 2018, and initial projects were announced in May 2018. With key contracts to support data collection awarded in January, March, and July 2020, data collection is expected to continue through fiscal year 2021, and data analysis is expected to continue into fiscal year 2022. Following the completion of data analysis, documentation, and internal review, a draft report will be issued for public comment. After considering all comments received, NIST will issue a final report.

In fiscal year 2018, NIST allocated slightly more than $5 million to start the Hurricane Maria Program. In fiscal years 2019 and 2020, NIST allocated slightly more than $4 million per year to support the program. These funds, along with any additional funding that will be needed, come from the redirection of NIST laboratory allocations.

3.7 Impact of Events in Puerto Rico Following Hurricane Maria

The NIST Hurricane Maria program is a large and complex undertaking because of the geographic scale of the event, the extraordinary level of damage, the protracted recovery time, and the number of different organizations involved in response and recovery efforts. The effort has been further complicated by events since Hurricane Maria. A series of earthquakes began affecting Puerto Rico in late December 2019 and has continued periodically through September 2020. The COVID-19 public health crisis, which resulted in a lockdown in Puerto Rico in March 2020, has also affected Puerto Rico and the activities of the NIST Hurricane Maria Program.

In response to these events, NIST has taken several actions. Since December 2019, NIST has monitored the earthquake sequence, the impacts, and response (via event scoring[40] and participation in interagency coordination calls, including those organized by the National Earthquake Hazard Reduction Program) in order to assess possible effects on the study areas of focus and challenges of these events to the Hurricane Maria projects. Most of the earthquake damage has been concentrated in the southwestern portion of Puerto Rico, which is outside of NIST's primary study regions for the Hurricane Maria work (Figure 4). As of September 2020, the Team anticipates that earthquake-related damage will have a limited impact on the

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[40] The Disaster and Failure Studies Program uses four criteria (loss of life, exposure, hazard intensity, and physical damage) to assess Event Consequence and two criteria (evacuation and emergency response activities) to evaluate Challenges in Evacuation and Response. Together, these scores inform whether a preliminary reconnaissance team should be deployed to a disaster or failure site to conduct a field study. The criteria ratings are based on the best available information at the time the event is being screened. The ratings may be updated as new information becomes available, and the event(s) may be scored multiple times before a decision to deploy a Team is reached.

program's efforts, particularly the technical projects within the NCST technical investigation. For the three technical projects within the NWIRP research study, which are focused on recovery from Hurricane Maria's impacts, NIST researchers are taking special care to design data collection instruments that ensure the ability to account for the compounding effects of the earthquake sequence and the pandemic on the recovery process. Earthquake hazards in Puerto Rico's multi-hazard context have been an important consideration since the inception of the program, and earthquake engineering experts on the Team will ensure that earthquake hazards, in addition to wind hazards, are considered in the development of NIST's recommendations related to Hurricane Maria.

NIST is continuing to evaluate the ramifications of COVID-19 on the Hurricane Maria projects as the pandemic evolves, and the full impact has yet to be determined. Modes of data collection and the timing of various elements of multiple projects are being adjusted in relation to current public health guidance and the institution-level decisions being made by NIST and contractors. For example, in-person data collection efforts may be transitioned into other modes such as telephone, web, and mail. This is particularly true for the projects using social science methods where the sample sizes would require substantial interaction with households, emergency communication information providers, businesses, officials in schools and hospitals, and representatives of power, water, and transportation sectors if the data were to be collected face to face. Safety protocols are being developed and implemented alongside staff training to better operate within the pandemic context. Additionally, efforts to engage key personnel at hospitals and select businesses that are heavily involved in the pandemic response are being planned with great sensitivity to the additional roles and responsibilities of these institutions. The NIST Hurricane Maria Team and its contractors are exploring creative ways to achieve the program's goals in this uncertain environment. The recommendations resulting from the Hurricane Maria Program will be informed by the multi-hazard, multi-event context of Puerto Rico.

4. Progress in Carrying Out the Hurricane Maria Program

The following subsections describe NIST's progress in carrying out the Hurricane Maria Program, which includes outreach to other agencies and organizations (Section 4.1), award of supporting contracts (Section 4.2), and initial data collection and analysis (Section 4.3). As described in Section 4.4, NIST has held multiple public meetings with the NCST Advisory Committee to present plans and progress and receive advice.

4.1 Liaison Status with Other Agencies and Organizations

4.1.1 Puerto Rico Government Agencies

NIST has held multiple meetings in Puerto Rico and Washington, D.C. with senior officials – in nearly all instances the most senior officials – from the following Puerto Rico government departments and agencies, which NIST had sought to contact based on their anticipated information and insights on the hurricane's impact on the island and related recovery efforts:

- Department of Economic Development and Commerce
    - Permit Management Office
    - Puerto Rico Industrial Development Company
- Department of Education
- Department of Health
- Department of Housing
- Department of Public Safety
- Department of Transportation and Public Works
- Federal Affairs Administration
- Planning Board
- Puerto Rico Aqueduct and Sewer Authority

- Puerto Rico Emergency Management Agency
- Puerto Rico Electric Power Authority
- Puerto Rico Ports Authority
- Telecommunications Regulatory Board

NIST also has been in contact with officials at the Central Office for the Recovery, Reconstruction and Resilience of Puerto Rico and the Department of Labor and Human Resources. In addition, NIST has held initial meetings with regional emergency management officials, including the directors of the Emergency Management Zones in operation at the time of Hurricane Maria[41] in Arecibo, Caguas, Humacao, and San Juan.

NIST has requested the cooperation of these departments and agencies and has identified the type of information potentially available from those offices that will assist NIST in gaining access to relevant information. To ensure that the Hurricane Maria projects are as informed and accurate as possible in their work, it is important for NIST to secure access to information that others have already obtained and are able to share. NIST also has made it clear that it aims to avoid placing burdens on these agencies and on others, especially as they seek to recover from the hurricane, earthquakes, and pandemic. Puerto Rico government organizations relevant to the NIST investigation and study have met with NIST multiple times and are sharing the requested information. As needed, NIST is continuing to work with and to seek information from many of the government agencies noted above.

4.1.2 Puerto Rico Private and Public Sector Organizations

NIST also has briefed or consulted with multiple private sector organizations and academic institutions operating and/or based in Puerto Rico. These include:

- University of Puerto Rico Mayagüez
- University of Puerto Rico Río Piedras
- Polytechnic University of Puerto Rico
- American Tower Corporation
- PR Wireless
- Puerto Rico Manufacturing Extension
- Puerto Rico Manufacturers Association

In each of these instances, representatives of these organizations indicated their willingness to cooperate with NIST's efforts and to assist by providing information and perspectives or recommended contacts for additional information. Several have shared data and otherwise assisted the Team.

[41] Since Hurricane Maria in 2017, Puerto Rico has shifted the boundaries and jurisdictions of its Emergency Management Zones.

4.1.3 Federal Government Agencies

NIST also is working with and involving other federal agencies in planning and carrying out its Hurricane Maria efforts. That includes, but is not limited to:

- NOAA's NWS, which has provided an expert in meteorology, who serves as a formal member of the Hurricane Maria Team working on the emergency communications and hazard characterization projects.
- The Uniformed Services University's National Center for Disaster Medicine and Public Health (NCDMPH), which has provided an expert in epidemiology, who serves as a formal member of the Hurricane Maria Team working on the project to better understand how damaged buildings and supporting infrastructure played a role in the injuries and deaths associated with the hurricane.
- The Department of Health and Human Services (HHS) Office of the Assistant Secretary for Preparedness and Response (ASPR), which has shared information regarding their support of the health and social services recovery, focused on hospitals and schools. In addition, the HHS Centers for Disease Control and Prevention (CDC) has provided an expert in epidemiology who serves as a scientific advisor of the Hurricane Maria Team working on the project to better understand whether and how damaged buildings and supporting infrastructure played a role in the injuries and deaths associated with the hurricane.
- FEMA, which is assisting – through formal information-sharing memoranda – with exchanges of data, including information about the storm's impact on critical buildings (hospitals and schools) from the assessments performed under mission assignment by the U.S. Army Corps of Engineers (USACE). NIST joined with FEMA in late 2017 and contributed to that agency's Mitigation Assessment Team and recovery advisories;[42] that preliminary deployment informed NIST's decision to launch its Hurricane Maria Program.
- USACE, which has provided information about the storm's impact on the power system and its recovery.
- U.S. Geological Survey (USGS), which has provided information and insights on landslides associated with Hurricane Maria.

In some cases, formal agreements were required before other agencies could share information and data with NIST. Those agreements were developed and now are in place.

42 www.fema.gov/emergency-managers/risk-management/building-science/mitigation-assessment-team

4.2 Award of Supporting Contracts

NIST is relying on multiple contractors with specialized capabilities, including staff expertise and testing facilities, to support and add substantial capacity to the Hurricane Maria Team. To date, contracts have been awarded for the following types of assistance, and work is underway or has been completed in these areas:

4.2.1 Wind Field Modeling

Accurate quantification of wind speeds is critical for evaluating the performance of buildings and infrastructure and to provide context for other aspects of the program. A contract was awarded on February 8, 2019, to Applied Research Associates, Inc., to support the wind field modeling efforts and develop a time-dependent wind-field model of Hurricane Maria's impact on Puerto Rico that optimally matches available measured data. The preliminary version of the wind field model incorporates a basic estimate of topographic effects. The final version of the wind field model will incorporate additional surface-level meteorological observations, improve characterization of hurricane asymmetry, optimize the model-fitting process, quantify uncertainty in the results, and refine the modeling of topographic effects based on the results of wind tunnel experiments and numerical calculations.

4.2.2 Wind Tunnel Testing and Field Measurement of Winds

The mountainous terrain in Puerto Rico can have a significant effect on local wind speeds and the resulting wind forces experienced by buildings and infrastructure systems. To support detailed investigation of such effects, a contract was awarded to the University of Florida (UF) on May 1, 2019 to conduct wind tunnel testing and field measurements of winds. Experiments are being conducted at the National Science Foundation's UF Natural Hazards Engineering Research Infrastructure Experimental Facility (NHERI EF) in Gainesville, Florida, in a large, reconfigurable boundary layer wind tunnel. The scope of work includes wind tunnel testing of both topographic models and building models. The purpose of the topographic wind tunnel experiments is to obtain flow-field measurements from wind flow over topographic features to provide experimental data with quantified uncertainties for characterization of topographic speedup effects and to validate numerical models. Wind tunnel testing of building models will enable detailed evaluation of the wind loads on buildings as influenced by the surrounding topography, buildings, and terrain. In addition to the wind tunnel measurements, a subcontract to WeatherFlow provides for deployment of anemometers at cell towers in Puerto Rico to obtain field measurements of topographic effects on winds. These real-world data will be used to validate wind tunnel test results and numerical models.

4.2.3 Engineering Evaluation of Critical Buildings

Evaluating the performance of critical buildings requires documentation of the characteristics of the buildings and their initial design requirements, as well as the damages and loss of function that were sustained from the hurricane. Support in evaluating the performance of critical buildings is being provided through a contract awarded to Stantec, Inc., on March 3, 2020. Key personnel on the Stantec team include the Project Manager, Juan C. Virella Crespo, PhD, PE, President of Virella Crespo & Associates, based in Mayagüez, Puerto Rico, and the Field Team Leader, Luis D. Aponte-Bermúdez, PhD, PE, a Professor at the University of Puerto at Mayagüez. The contractor is documenting the performance of selected critical facilities during Hurricane Maria, including hospitals, schools, and storm shelters. Document review and site visits will be complemented by interviews with facility key personnel. Building characteristics being reviewed include facilities' structural and nonstructural components (e.g., type of roof covering, type of structural system, and type of windows, doors, and opening protective systems), age (e.g., date of construction and building code used for design), utility redundancies (e.g., the capacity of any existing backup generators and emergency water supplies), and mitigation efforts before the hurricane's landfall (e.g., sandbagging and anchoring of rooftop equipment). Data on damage (e.g., to the envelope, roofing system, structural system, rooftop equipment, etc.) will help to identify trends in structural performance by occupancy type, construction era, and structural system. Stantec will also collect data on the facilities' functionality immediately following landfall, including relocation of services and/or building occupants, status of availability of lifelines in the following days, and hazardous conditions encountered by building occupants.

4.2.4 Social Science Data Collection and Support

Social science methodologies such as surveying and interviewing are essential to the technical approaches of four of the NIST Hurricane Maria projects where information will be collected from information providers, households, businesses, schools, hospitals, and infrastructure representatives in the power, water, and transportation sectors. These projects are receiving social science data collection support through a contract awarded on December 12, 2019, to Horsley Witten Group, Inc., which will be aided by subcontractors Eastern Research Group, Inc., Issues & Answers, Inc., and Albizu University in Puerto Rico. The contractors will support the Public Response to Emergency Communications project by surveying households in regions at risk of floods and interviewing officials who provided emergency information to the public to better understand factors that influenced households to evacuate (or not evacuate) and the role emergency communications played in those decisions. The contractors will also provide data collection services for three projects relating to recovery after the hurricane. This includes surveys of small- and medium-sized businesses in the manufacturing, retail, and service sectors to improve understanding of business continuity resilience planning. Interviews with representatives knowledgeable of the supply chain will also be conducted for the Recovery of Business and Supply Chains Project. The contractors will also conduct surveys of schools and hospitals to identify the underlying characteristics and conditions associated with recovery of critical social functions for the Recovery of Social Functions Project and structured interviews to examine dependencies of building function on infrastructure (power, water, and transportation), including cascading loss of function and sequencing of recovery activities for the Recovery of Infrastructure Systems Supporting Critical Buildings and Emergency Communications Project.

4.2.5 Morbidity and Mortality

Deaths and injuries in Puerto Rico during and after Hurricane Maria may be attributable to a number of primary causes: direct exposure to wind, storm surge, floodwaters, or landslides; failure of a building; failure of critical infrastructure (e.g., power and water); loss of healthcare supplies (medicine or medical devices) or healthcare services; or other conditions. A contract was awarded to the George Washington University (GW) on July 27, 2020, to identify deaths in Puerto Rico directly and indirectly related to Hurricane Maria and, more specifically, to identify deaths attributed to building and/or building system failure(s).[43] GW will collect and merge data on the deaths that occurred up to six months after Hurricane Maria made landfall in Puerto Rico. They will develop an integrated database from various data sources, which may include the Puerto Rico Vital Registration System, DMORT E-Cases records, pathology registry records, 911 emergency calls obtained from the Bureau of Police, and funeral and burial assistance data from FEMA and the American Red Cross. GW will geocode the deaths and submit a text-searchable database alongside a report documenting the process for merging data sources, as well as the data coverage and quality from each source, highlighting the potential added value of integration of data from specific sources. Subsequently, GW will: analyze the integrated database to calculate cause-specific mortality rates adjusted for age and gender and compare these to the prior years; examine each broad cause of death (i.e., ICD-10 chapters) and specific causes of death typically attributed to hurricanes (e.g., drowning, death from a fallen object) and compare them to previous years; calculate age and gender-adjusted cause-specific mortality rates for other specific causes of death that are identified as being significantly greater following Hurricane Maria (compared to the previous year); identify any significant increases in death rates from particular causes between the period after the storm and years prior and flag all deaths from those causes in the first two weeks after the storm; and identify spatial and temporal clusters of deaths occurring up to six months after the storm in study areas identified by NIST staff.

[43] Under 15 CFR § 270.100, "a building failure may involve one or more of the following: structural system, fire protection (active or passive) system, air-handling system, and building control system. Teams established under the Act and this part will investigate these technical causes of building failures and will also investigate the technical aspects of evacuation and emergency response procedures, including multiple-occupant behavior or evacuation (egress or access) system, emergency response system, and emergency communication system."

Based on the integrated database, the University of Puerto Rico (UPR) School of Public Health, a subcontractor to GW, will identify next-of-kin or other key informants in order to conduct verbal autopsies to determine attribution of deaths that occurred immediately after the storm made landfall. GW will develop a verbal autopsy instrument and script (instructions to the respondent and interviewer) to be used to determine if a death was the direct or indirect result of a building and/or building system failure(s) or the indirect result of the forces of the hurricane, including wind, storm surge, flooding or landslides. If a death was the direct or indirect result of the building and/or building system failure(s), this means that the person died from injury related to the structural failure, damage to the building, or loss of function of building systems.

4.2.6 Communication Support

NIST is committed to clearly communicating the goals, progress, and findings from the Hurricane Maria program, including translation into Spanish in order to most effectively reach key stakeholders in Puerto Rico. Several additional contracts are providing communication support for the Hurricane Maria Program. On April 23, 2019, a contract for translation and interpretation support services was awarded to Lazar Translating Services, Inc. On February 26, 2019, a contract for technical writing support services was awarded to CATMEDIA, Inc. In addition, a contract for the development of a communications strategy and support in implementing stakeholder outreach was awarded on February 12, 2019, to Strativia, LLC.

4.3 Initial Data Collection and Analysis

Beyond developing the initial methodological approaches and identifying information needs and contact points, each of the seven Hurricane Maria technical projects have made progress in refining the methodology, gathering data, and conducting initial analyses. These projects are being integrated to the extent feasible and supportive of the objectives of the NCST investigation and NWIRP study. This integration is exemplified by the focus on common study areas, by the alignment of sampling strategies, and through specific elements of the data collection plan. In addition to planning and coordinating the technical projects to be conducted, the Team has built an extensive information infrastructure to support its data gathering, exchange, and analysis. This includes processes to ensure only appropriate access to and the protection of personally identifiable information and other information consistent with federal government requirements and good practice.

The following are several examples of notable progress in cross-project coordination:

- The NIST Team joined with the National Center for Disaster Medicine and Public Health to hold an open meeting in September 2018 to discuss the state-of-the-practice in postdisaster field data collection methods, including sampling methodologies across multiple disciplines.

- The Team developed an initial sampling strategy for hospitals, schools, and shelters that considers available information on building characteristics, hazard exposure, and damages. The sampling strategy was focused on the Critical Buildings Project, though it informs the Recovery of Social Functions and the Recovery of Infrastructure Projects.
- Data sharing agreements were arranged, and the following types of data were acquired: communications damage and recovery (American Tower Corporation), building damage assessments (FEMA), hospital data (HHS), water infrastructure data (PR Aqueduct and Sewer Authority), transportation infrastructure data (PR Department of Transportation and Public Works), and hospital data (PR Department of Health). These data are beneficial to multiple projects.
- Draft data analysis strategies that define inputs and outputs across projects were developed.
- A geodatabase for spatial data needed to produce base maps for all technical projects has been developed and shared with all projects.

The following subsections present progress in data collection and analysis progress for each of the technical projects.

4.3.1 Hazard Characterization

Wind-Field Modeling

- An initial wind-field model for Hurricane Maria was developed, providing time histories of wind speed and direction across the commonwealth, including consideration of topographic effects on the wind speeds (see *Background* discussion in Section 3.3.1). Estimated peak wind speeds with and without topographic effects are shown in Figure 5. This wind-field model was developed by fitting the model to available surface-level meteorological observations. Figure 6 shows values of the Topographic Speedup Factor (TSF), defined as the ratio of the peak gust wind speeds with and without topographic effects. Significant speedup effects are observed in certain regions, with values of the TSF as high as 1.8.
- Subsequent to the completion of the initial wind-field model, further improvements to the wind-field model have been made using previous hurricane data, including the development of a methodology to optimize how the model fits the observed data, with quantification of uncertainty.

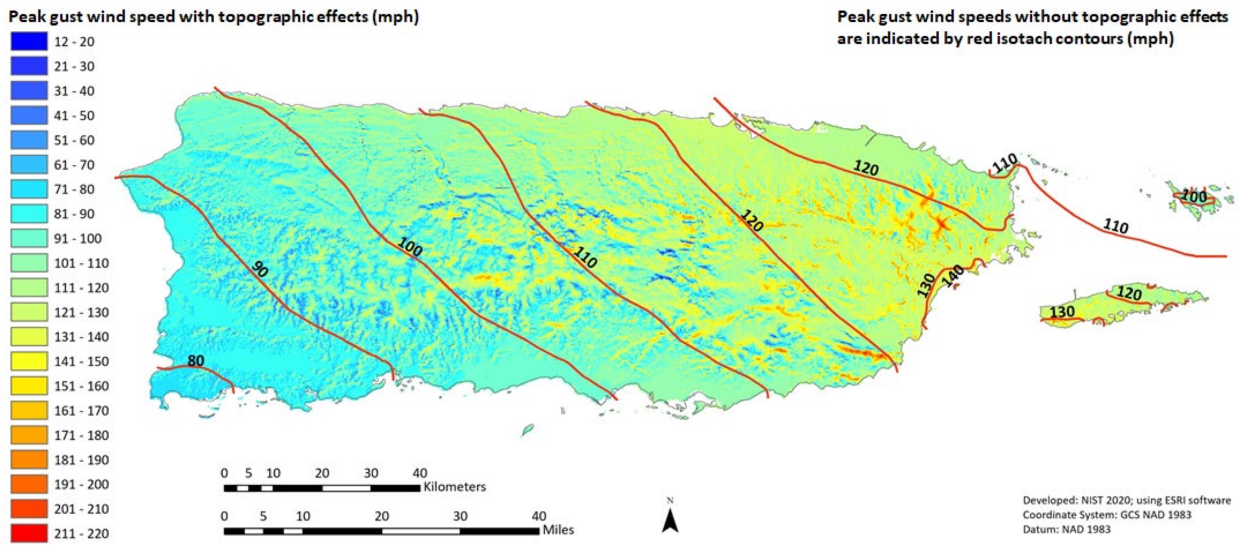


Figure 5. Estimated peak gust wind speeds with and without topographic effects from initial wind field model for Hurricane Maria.

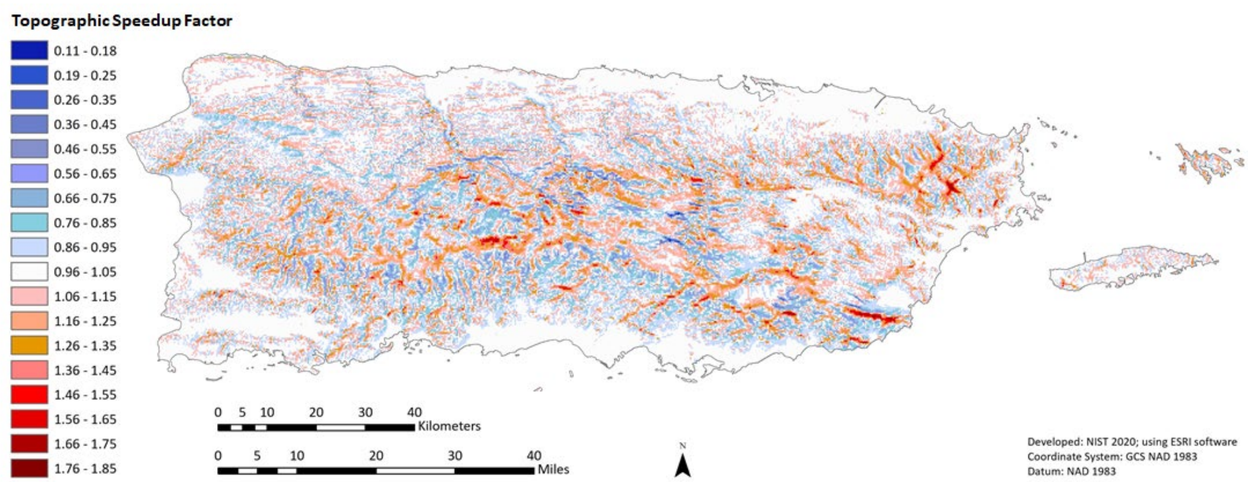
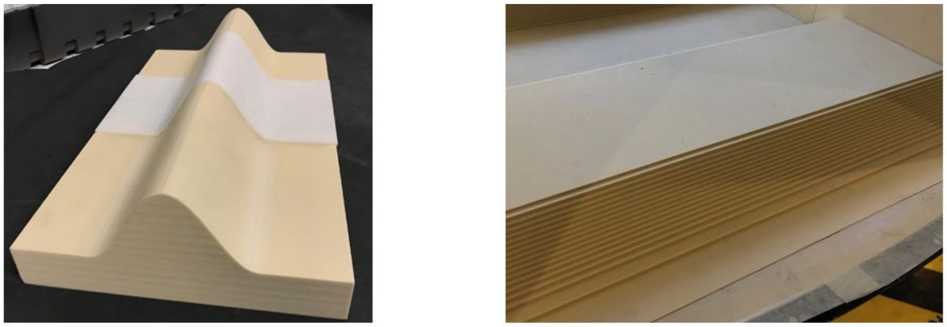


Figure 6. Estimated topographic speedup factors from initial wind field model.

Wind Tunnel Testing

- The testing plan has been completed for wind tunnel testing of generic two-dimensional topographic models, and the generic topographic models have been fabricated (Figure 7). Models with three types of surface roughness will be tested: smooth, rough, and terraced wall. Figure 7 shows examples of a smooth model and a terraced model.
- The testing plan has been completed for wind tunnel testing of scale models of the Mayagüez and Yabucoa regions in Puerto Rico. Figure 8 shows the model of the Yabucoa region in the Boundary Layer Wind Tunnel at the University of Florida. Fabrication of the Mayagüez model is underway.
- Flow measurements in the wind tunnel have been completed, to characterize the incoming flow profile for different terrain categories and to ensure that incoming flow

matches the target profile. Testing of topographic models is currently underway, and measurements have been completed for a subset of the tests.



(a) Ridge model with smooth surface (b) Plateau model with terraced surface

Figure 7. Wind tunnel models of generic two-dimensional topographic features.

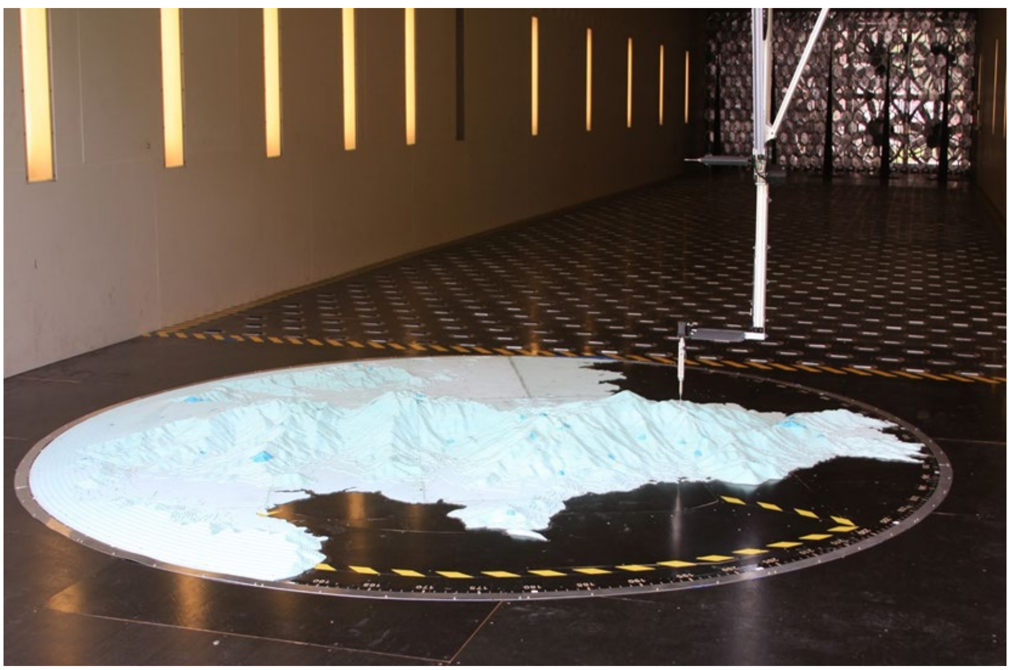


Figure 8. Topographic model of the Yabucoa region.

Computational Fluid Dynamics Simulations

- Computational Fluid Dynamics topographic models for generating approach flow and accounting for terrain surface roughness have been developed, including simulation of flow over roughness blocks in the wind tunnel, as illustrated in Figure 9.
- Simulations of flow over the generic topographic models are being performed (Figure 10).

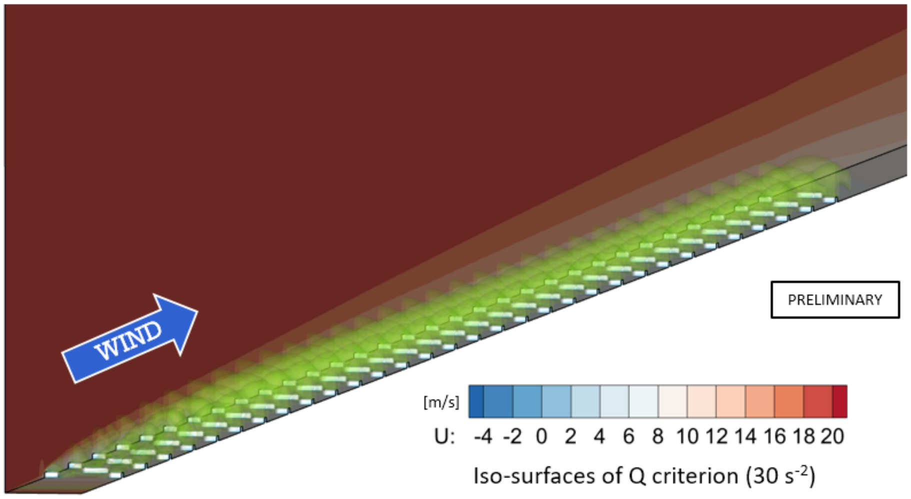


Figure 9. Computational Fluid Dynamics simulation of boundary layer approach flow generated by roughness blocks in the wind tunnel.

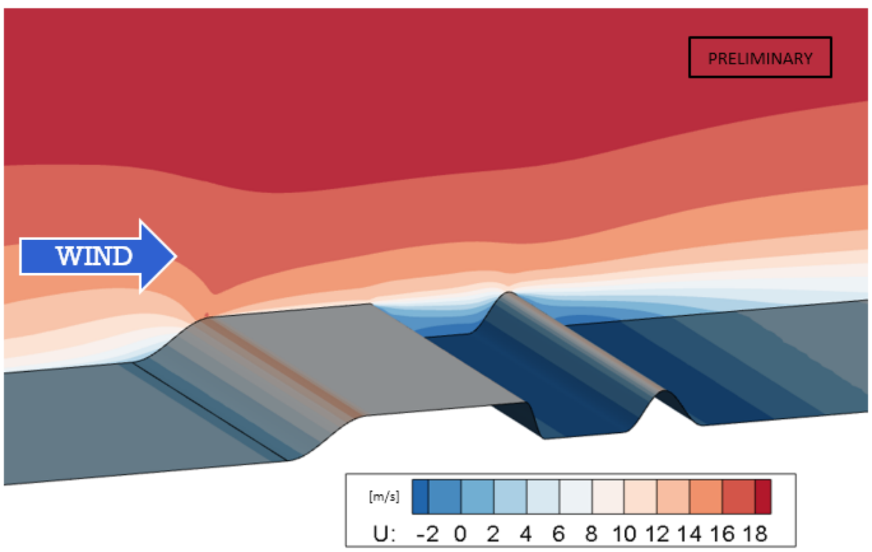


Figure 10. Longitudinal wind velocity field over two-dimensional generic topographic models.

Field Measurement of Winds

- Three cell towers in the Yabucoa region were selected for field measurement of topographic speedup effects, and a deployment plan was developed for installation of anemometers at multiple heights on each tower (Figure 11), with space on the towers provided by American Tower Corp., the owner of the towers.
- Anemometers have been installed at all three of the selected tower sites by WeatherFlow, a NIST subcontractor (see Section 4.3.2), and the Team has started to record wind speed data (Figure 12), including capture of high wind data from Tropical Storm Isaías in July 2020 and Tropical Storm Laura in August 2020.

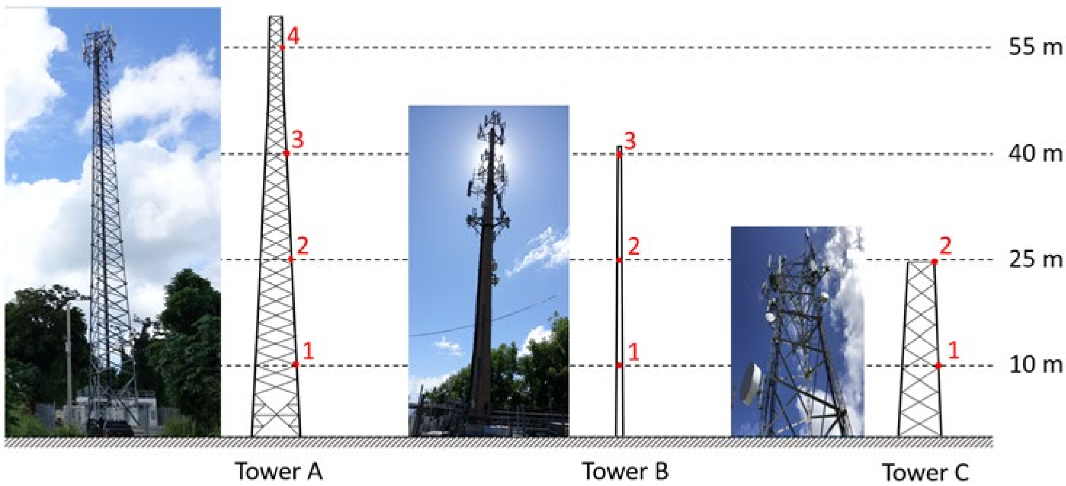


Figure 11. Positions of anemometers installed on cell towers in the Yabucoa region.

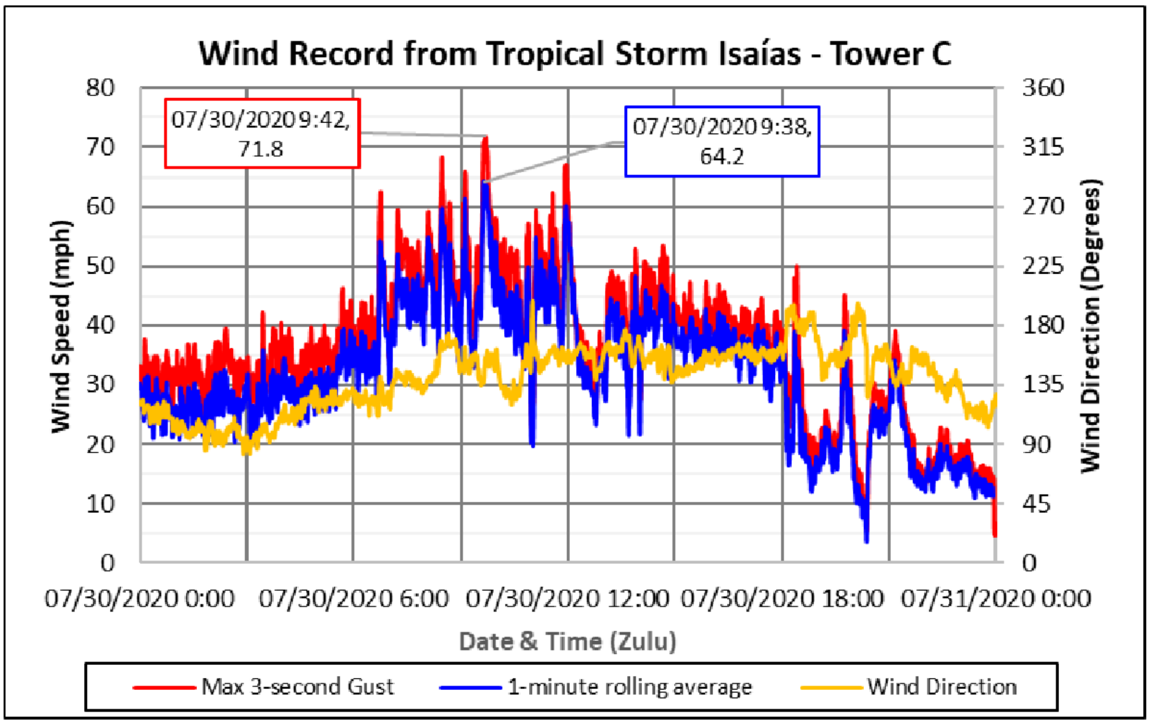


Figure 12. Example of wind speed data recorded from Tower C in Yabucoa.

Characterization of Non-Wind Hazards

- Outreach to other agencies and organizations has been coordinated, and data sets have been collected to provide an island-wide assessment of non-wind hazards, including rainfall, flooding, landslides, and storm surge.
- In situ and satellite-based rainfall and other hydrological data products have been collected from NOAA, NASA, USGS, and the University of California at Santa Barbara.

- Initial analysis of storm total rainfall for Hurricane Maria has been completed (Figure 13).

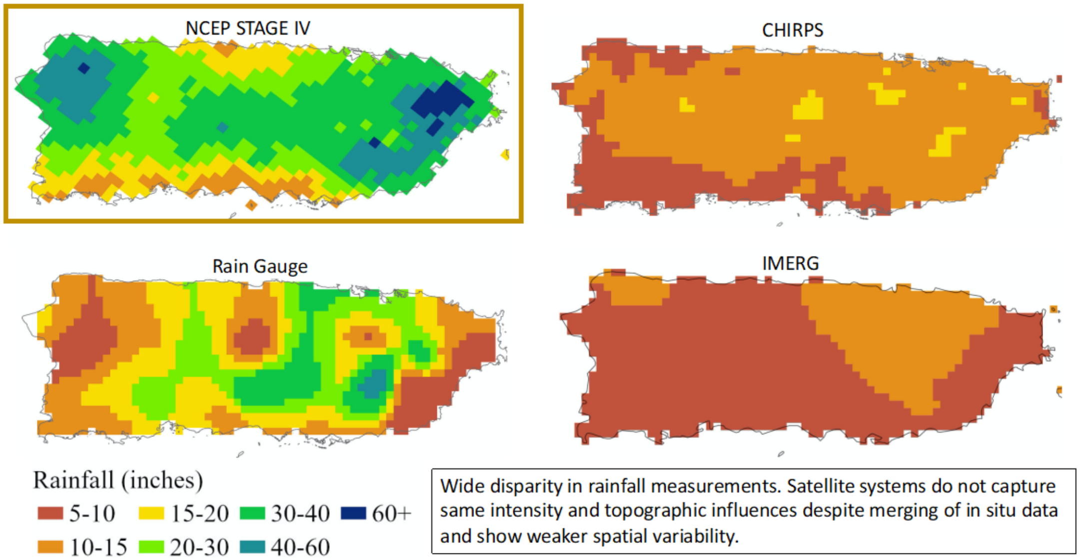


Figure 13. Comparison of land-based (left column) and space-based (right column) storm total precipitation estimates for Hurricane Maria. The NCEP Stage IV data (upper left) is widely viewed as the gold standard for rainfall estimates.

4.3.2 Performance of Critical Buildings

Initial Data Collection

- Information on damages to schools and hospitals has been obtained through Memorandums of Agreement (MOA) established with FEMA. This includes assessments of schools and healthcare facilities performed by the U.S. Army Corps of Engineers (USACE) under mission assignment to FEMA, as well as damage information from the FEMA Public Assistance Program. An initial database of school/shelter characteristics has been developed using data from the USACE school assessments.
- Additional hospital information has been obtained from the HHS and from the PR Department of Health.
- Information on the shelter program has been obtained from the Puerto Rico Department of Housing, including information on shelter population over time.
- Aerial Lidar data has been obtained from MIT Lincoln Laboratory for selected sites in Puerto Rico to characterize the terrain and buildings surrounding selected critical buildings and tower sites (Figure 14).
- GIS information has been obtained from multiple sources for hospitals, schools, and shelters in Puerto Rico. Using this information, hazard levels have been evaluated at selected building sites.

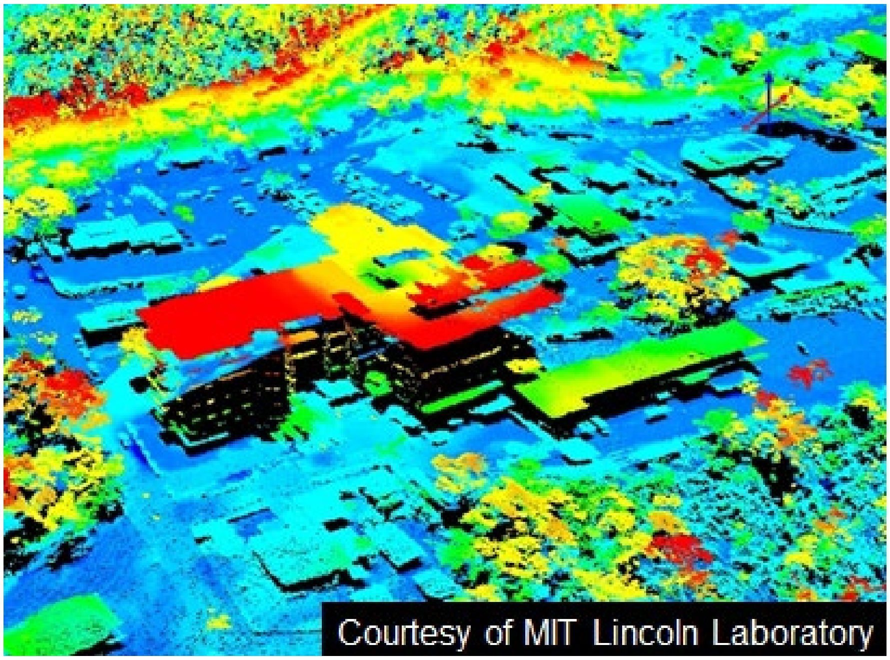


Figure 14. Lidar data for Hospital Bella Vista.

Sample Selection

- A sampling strategy was developed, and five hospitals have been selected for evaluation, with one hospital in each of the four study regions (Figure 4) and one hospital in Mayagüez.
- The selection of a core set of hospital buildings for the Critical Buildings Project provides linkages across multiple projects in the Hurricane Maria Program.
- Selecting hospitals from each of the four study regions provides variation in the hazard exposure, with the lowest wind speeds in the Utuado region and the highest wind speeds in the San Juan region (Figure 15).
- The highest topographic speedup factor (TSF) was observed for Hospital Bella Vista in Mayagüez, with a TSF of approximately 1.5 (Figure 15).
- For the hospitals in the Utuado region, the mountainous topography actually had a sheltering effect, causing a reduction in the wind speeds as indicated by TSF values less than one (Figure 15).

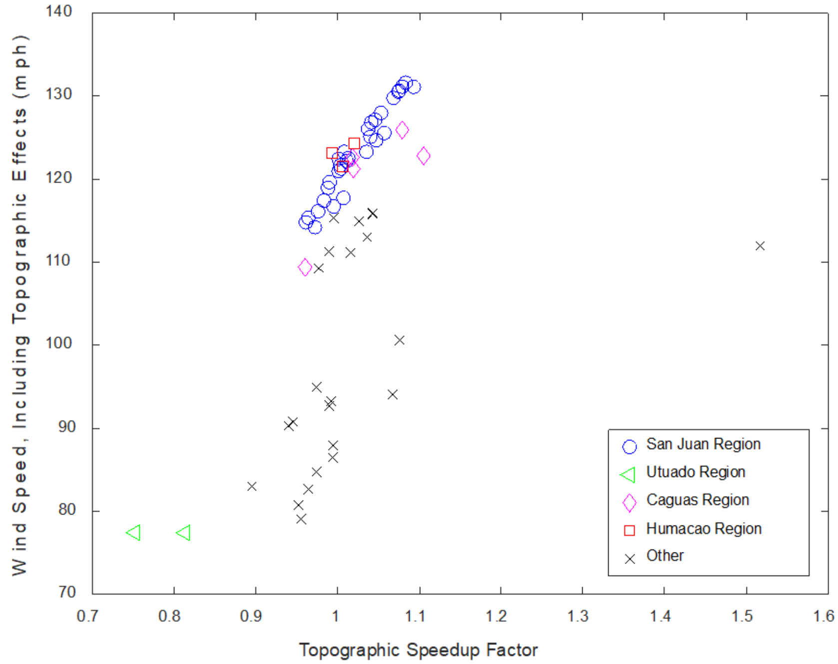


Figure 15. Maximum peak gust wind speed during Hurricane Maria (incorporating topographic effects) versus Topographic Speedup Factor for hospitals in Puerto Rico.

Facility Evaluations

- Site visits and meetings with staff at two hospitals were conducted in October and November of 2019, which included an introduction and overview of the NIST Hurricane Maria Program, as well as facility walkthroughs and discussions of the impact of Hurricane Maria. The two hospitals were University Pediatric Hospital in San Juan and Hospital Bella Vista in Mayagüez.
- The first phase of facility evaluation work, consisting of initial document collection and review, has been initiated for the five selected hospital facilities. Stantec, Inc., (see Section 4.3.3) is supporting NIST in carrying out these evaluations.

Wind Tunnel Testing

- Hospital Bella Vista has been selected as the first facility for wind tunnel testing.
- Plans have been developed to characterize the topographic effects on the incoming flow for this wind tunnel testing work. Incoming flow for wind tunnel testing of the building model (at 1:100 scale) will be based on Particle Image Velocimetry measurements from wind tunnel testing of a topographic model of the Mayagüez region (at 1:3100 scale).
- Drone photography of the Hospital Bella Vista site has been performed to develop a 3D model to support the fabrication of a wind tunnel model. The design of the wind tunnel model, the measurement systems, and the testing plan is in progress.

4.3.3 Public Response to Emergency Communications

Data Collection

- Over 1,000 messages were collected during and after Hurricane Maria in 2017 and 2018.
- Important contacts were made with key individuals in weather prediction and emergency management agencies, both within Puerto Rico and nationally during key site visits, as well as via independent outreach to gather relevant background information.

Methods Development

- NIST narrowed this project's focus to four key study regions within Puerto Rico (see Figure 4). These are the planned regions for distribution of data collection instruments developed for the Emergency Communications and Evacuation project.
- An informal group of experts within the risk communications and severe weather messaging research and operations area at NOAA has assisted with review of data collection instruments.
- A literature review has been completed to identify best practices and important considerations for the creation and distribution of effective emergency messages as well as factors relevant to protective action decision making (evacuation).
- Drafts of preliminary interview and survey guides and related distribution and analysis plans have been developed for the collection of information on the dissemination and effectiveness of emergency communications. Public data on factors influencing risk perception and decision-making processes regarding protective action have been reviewed.
- A list of possible interviewees has been created for the information provider interviews.
- A sampling plan has been developed for the deployment of the household survey (1,500 respondents) in the four study areas to ensure appropriate response across demographic variables as well as risk exposure to flooding and landslide conditions.
- The project team is working through the final stages of required approvals for deployment of the household survey pilot test and for interviews with information providers, including review by subject matter experts and contractor personnel and translation to Spanish.

Analysis

- Coordination across the Hurricane Maria projects is ongoing to identify key areas of mutual interest and to support the best overall analysis to achieve the goals of the program.
- Transcription and cataloging of emergency communication messages have continued to support the ongoing qualitative content analysis.

4.3.4 Characterization of Morbidity and Mortality

Initial Data Collection

- The project team conducted meetings with scientists and doctors on and off the island to accurately capture the data that already exists and that can be readily used by NIST.

Methods Development

- The project team presented the Hurricane Maria Program and received input from the public health and disasters community at the Disasters and Health Workshop hosted by the NCDMPH in April 2019.
- The project team participated in all public meetings of the National Academies Committee on *Best Practices for Assessing Mortality and Significant Morbidity Following Large-Scale Disasters*, a study funded by FEMA. Additionally, NIST presented at one of the meetings, alongside physicians and public-health experts from Puerto Rico, to inform the National Academies study.
- A literature review to inform the verbal autopsy (VA) instrument development has been conducted under an interagency agreement (IAA) with the NCDMPH.
- Questions relevant to the mortality project were developed to include in the survey instruments of other projects (including Emergency Communications and Recovery of Social Functions).

4.3.5 Recovery of Business and Supply Chains

Methods Development

- The sampling frame was finalized in June 2020. The frame includes lists of SMEs created using data from InfoUSA for the complete geographic scope and all in-scope industries in service, retail, and manufacturing. Records were also pulled for businesses in the transportation/shipping industry for all of Puerto Rico (to inform the selection of the transportation/shipping entity interviews).
- The list of SMEs will be compared to the PRiMEX SMEs (primarily consisting of SMMs) to ensure no additional burden to respondents.
- The sample design for the Recovery of Business and Supply Chain Project has been refined to directly link to the sample for the Recovery of Social Functions Project. For all ZIP codes in the NIST study, areas containing hospitals will be included via a random sampling of businesses proportional to the count of specified business types in that ZIP code compared to those of the same business types in all in-scope ZIP codes. Within ZIP codes that do not contain hospitals, a sample of SMEs proportionate to the number within each category will be selected.

Data Collection

- Data were obtained from the Puerto Rico Manufacturing Extension (PRiMEX), PR Ports Authority, and PR Department of Labor and Human Resources.

- The project team discussed business preparedness, mitigation, and recovery with multiple companies and government agencies. Data on the recovery of key businesses within the Food Preparation Manufacturing sector and Medical Device Manufacturing sector were collected through site visits in conjunction with PRiMEX and NIST Manufacturing Extension Partnership (MEP) in the summer of 2019.
- Data on initial SME recovery, collected from field observations and other sources, have been compiled to support future analyses.
- The project team has developed drafts of all survey and interview instruments for data collection on the recovery of SMEs. Figure 16 provides an overview of the types of data to be collected via these tools to allow for analysis of recovery. Major categories include: (1) prior resilience state/capacity, (2) impacts (direct and indirect), (3) response and recovery, and (4) future resilience state/capacity. Two tools related to manufacturing have been drafted, namely the Manufacturing Continuity Business Survey and the Manufacturing Supply Chain Interview Guide. Two tools related to small retailers and service sector businesses have been drafted, namely the Retail and Services Continuity Business Survey and the Business Continuity Interview Guide.
- The project team is aligning questions with the Recovery of Social Functions Project and modifying questions and survey mode due to COVID-19 limitations.

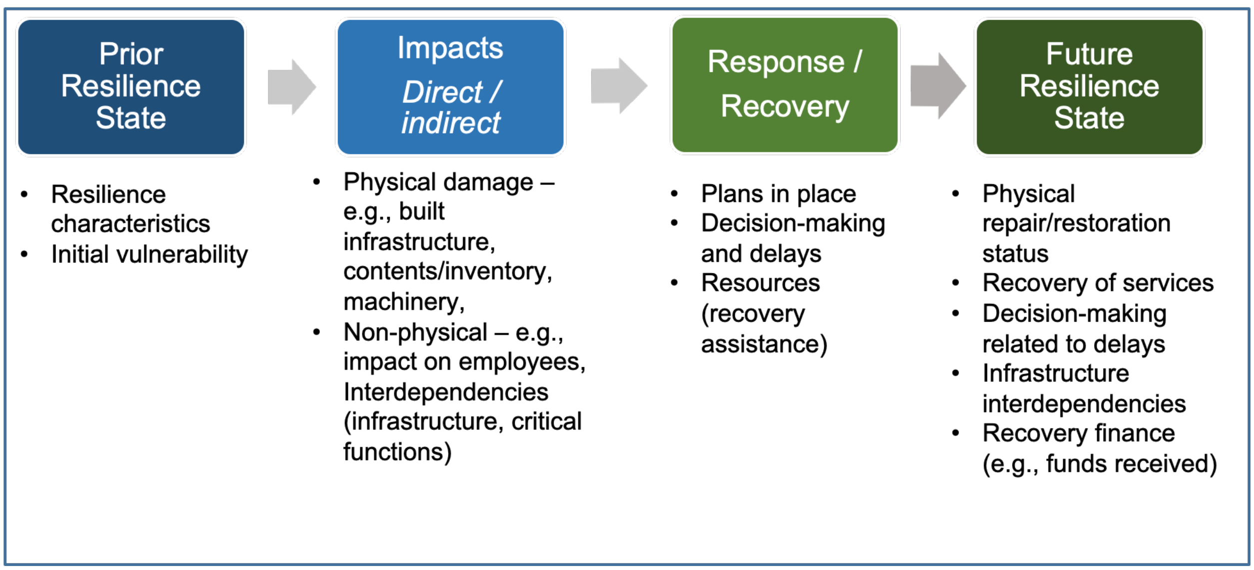


Figure 16. Overview of survey considerations for small and medium-sized enterprise recovery.

Analysis

- Spatial analyses of publicly available data for transportation networks and socio-economic data have been conducted to inform sampling and analysis plans. The focus of these analyses has been to identify clusters of SME sectors relative to major roadways and key port facilities.
- Basic descriptive analyses have been conducted to understand the immediate needs of SMMs determined through a short-form survey conducted by PRiMEX through the NIST MEP Manufacturing Disaster Assessment Program (MDAP).
- Preliminary models based on Discrete Event Simulation (DES) and Complex Network Theory (CNT) were developed for the two key sectors (Medical Device Manufacturing and Food Preparation Manufacturing) using information from company discussions and manufacturing facility tours. Figure 17 provides an overview of the general framework employed to assess network resilience through CNT. In particular, the completion of these analyses has improved the question and sample frame development for the data collection instruments focused on recovery of individual SMEs.

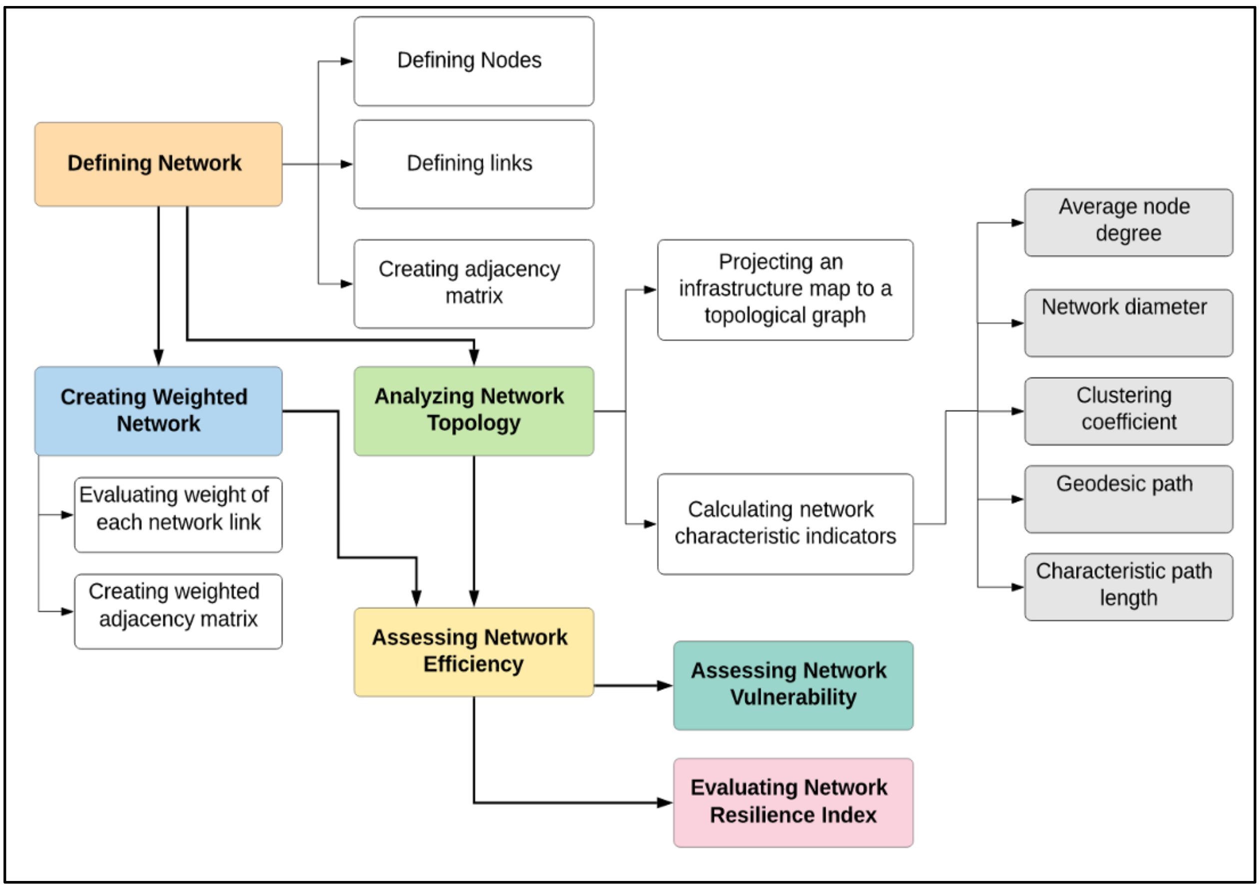


Figure 17. CNT assessment process

4.3.6 Recovery of Social Functions

Methods Development

- The sampling frame was finalized in May 2020. It includes full lists of K-12 schools and hospitals created using public data from a variety of sources, including the Asociación de Hospitales de Puerto Rico, American Hospital Directory, National Center for Educational Statistics, and PR Department of Education.
- The sample design for the Recovery of Social Functions Project has been refined to reflect alignment with the Critical Buildings Project, coordination with the Morbidity and Mortality Project and the Recovery of Infrastructure Project, and direct linkage through sequential sampling with the Recovery of Business and Supply Chains Project.
- The project will be conducted by collecting data at three time points, which are referred to as "waves" below. The project team has selected a longitudinal design in order to understand the over time recovery of the same sample of institutions.

Data Collection

- Data were obtained from FEMA, HHS, and the PR Department of Health to support decisions about sampling stratification.
- Data on hospitals, schools, shelters, and school closures have been compiled to support future analyses.
- Secondary data are being collected on the recovery of hospitals and schools, which includes documentation of the timing and flow of recovery assistance and recovery plans.
- Drafts of the Wave 1 survey instruments have been developed for data collection on the recovery of schools and hospitals; the project team is working on modifications to questions and survey mode due to COVID-19 limitations.

Analysis

- Spatial analyses of publicly available data for schools and hospitals have been conducted to inform sampling and analysis plans. The focus of these analyses was to identify clusters of schools based on the distance to hospitals, as well as to examine differences between schools located near hospitals versus those further away (Figure 18).
- Basic descriptive analyses have been completed to understand the population of K-12 schools and hospitals in Puerto Rico, as well as the characteristics of those institutions within the study area.

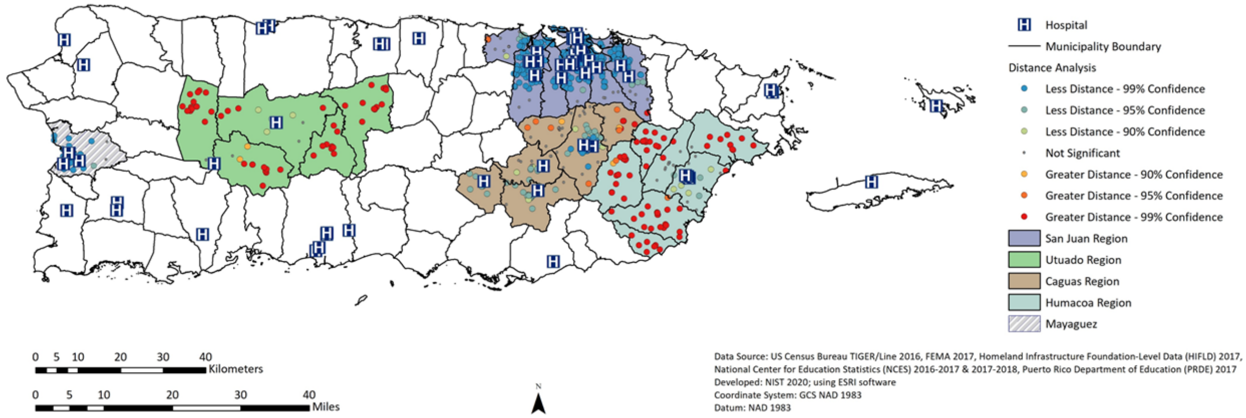


Figure 18. Preliminary results of spatial analysis of secondary data for schools and hospitals.

4.3.7 Recovery of Infrastructure Systems

Data collection

- From NIST visits to Puerto Rico to meet with PREPA (power), PRASA (water), and DTOP (transportation) and through subsequent communications, agency points of contacts were confirmed, and contextual information was provided to inform the infrastructure interview instrument design and model development.
- GIS datasets for the power, water, and transportation infrastructure systems have been obtained. In Figure 19, a subset of the data is plotted. The figure shows high-capacity links of the power, transportation, and water systems along with the locations of hospitals in the Homeland Infrastructure Foundation-Level Data (HIFLD) database.

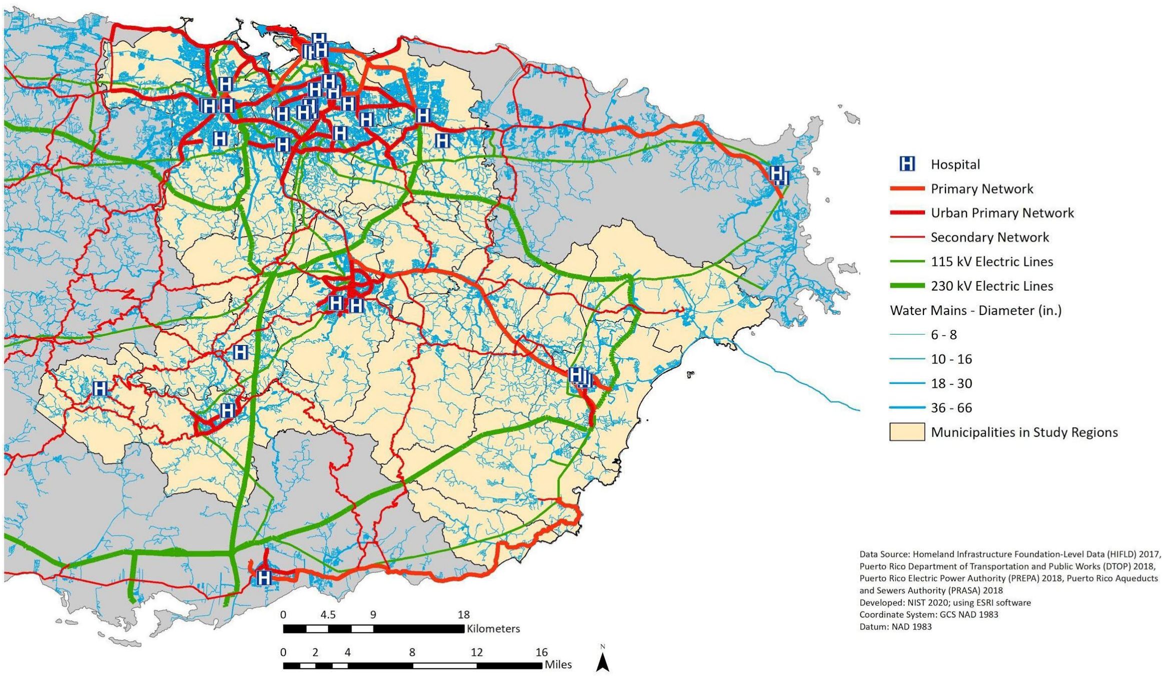


Figure 19. High-capacity links of the water, power, and transportation infrastructure systems, shown with hospital locations for a subset of the municipalities targeted by the infrastructure project.

- From the PR DTOP, NIST obtained the road system classification log for Puerto Rico and event databases for Hurricanes Maria and Irma. The reported event locations are plotted in Figure 20 alongside primary and secondary roads. The widespread nature of the events across the region is indicated, with events reported for many primary, secondary, and tertiary roads. For each event, detailed information is given, for example, a classification of the incident, its location and date, and its status (e.g., closed, partially closed, closed) at given times, in addition to the information source.

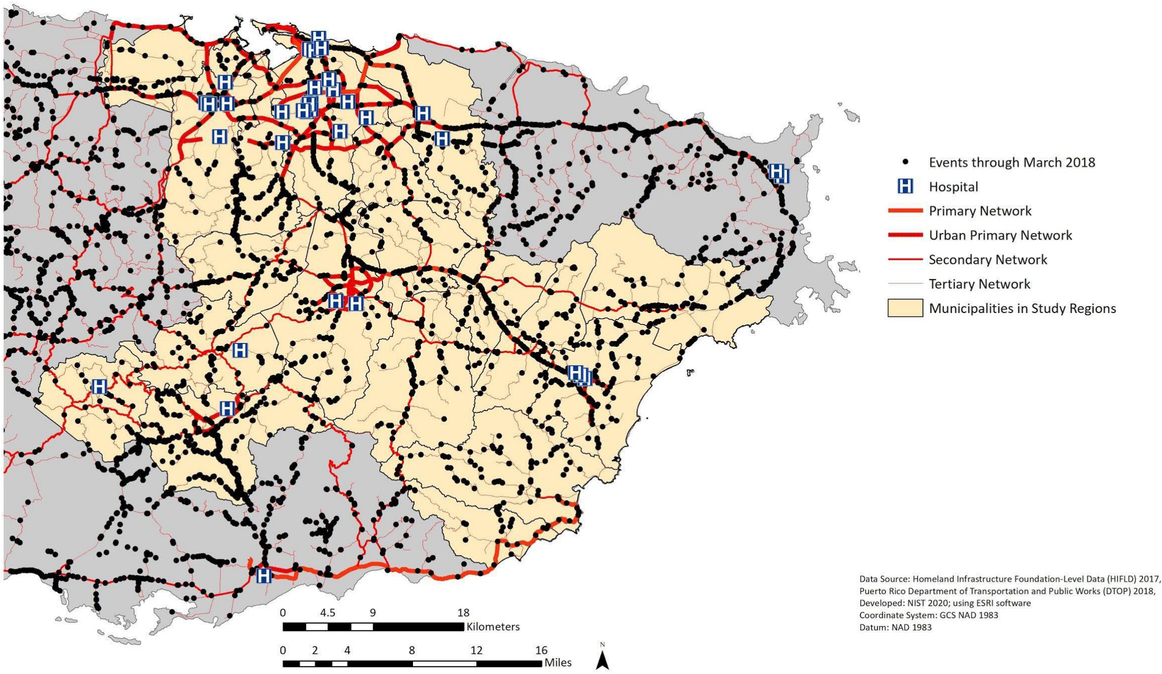


Figure 20. Transportation system events associated with Hurricanes Irma and Maria as reported through March of 2018 for roads/bridges, shown with hospital locations for a subset of the municipalities targeted in the infrastructure project.

- Preliminary survey and interview guides for data collection on infrastructure support of critical buildings have been drafted.
- Data collection opportunities have been identified to provide improved insights about the causes of the loss of functionality and extended-duration outage of the wireless communication system in Puerto Rico following Hurricane Maria. Information was also provided by wireless communications service and infrastructure providers.
- NIST established an agreement with American Tower Corporation, allowing for data sharing. Subsequently, NIST received a post-storm photo library documenting conditions at over 100 tower sites.
- A data collection trip to Puerto Rico in October 2019 included field visits to four tower sites and one roof-mounted tower and meetings with the Telecommunications Regulatory Board and PR Wireless.
- Building codes and standards for telecommunication structures adopted by Puerto Rico from 1968 to the present have been collected.
- The history of wind load provisions in building standards to provide context to the date of construction of any tower or building studied have been documented.

4.4 Advisory Committee Meetings and Reports

Since the establishment of the Hurricane Maria National Construction Safety Team in February 2018, NIST has been receiving advice and observations from internationally respected experts in a variety of fields who serve on the agency's NCST Advisory Committee.[44] The Committee provides advice on the functions of National Construction Safety Teams, the composition of Teams, the exercise of authorities enumerated by the Act, and other items as necessary to enable the NIST Director to carry out the Act. Additionally, both the Committee and NIST are responsible for annual reports to Congress. The Committee report includes an evaluation of Team activities, along with recommendations to improve the operation and effectiveness of Teams and an assessment of the implementation of the recommendations of Teams and of the Advisory Committee. The NIST report includes a response to the Committee's advice, as well as updates on NCST activities. The Hurricane Maria NCST investigation is addressed in the Committee's reports to Congress submitted in December 2018[45] and December 2019[46] and in the NIST reports to Congress for fiscal years 2018[47] and 2019.[48] The following is an excerpt from the Committee's Report to Congress in December 2019:

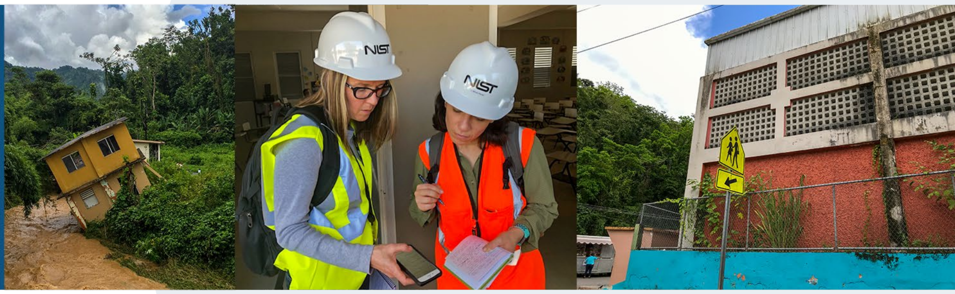
> NIST is to be complimented on assembling a diverse team of highly qualified researchers in a range of critical areas, including hazard characterization (wind and flooding), performance of buildings and critical infrastructure, risk communication, business and supply chain logistics, and health and medicine. Furthermore, they have successfully involved professionals, including social scientists and engineers, from the affected area. We believe inclusion of local professionals was particularly important for this study. The breadth of the team resulted in a requirement for a considerable level of communication and project management support, which NIST has done very well.
>
> We applaud the actions of linking the disparate parts of this study together. In particular, the combined efforts of social science and engineering are likely to offer new insights that could not be accomplished without collaboration of the two disciplines.

The Team has provided multiple public briefings to the Advisory Committee on the plans and progress of the investigation. All NIST presentations to this committee have been held in open sessions and are available on NIST's Hurricane Maria website. Observations from preliminary reconnaissance of Hurricane Maria's impacts on Puerto Rico were presented to the Advisory

[44] www.nist.gov/topics/disaster-failure-studies/national-construction-safety-team-ncst/advisory-committee
[45] www.nist.gov/system/files/documents/2019/02/04/ncstac_2018_report_to_congress.pdf
[46] www.nist.gov/system/files/documents/2020/03/13/2019_NCSTAC_ReporttoCongress.pdf
[47] www.nist.gov/system/files/documents/2019/10/31/nist_ncst_fy18_annual_report_to_congress_10-8-19.pdf
[48] www.nist.gov/system/files/documents/2020/07/27/NIST_NCST_FY19_Annual_Report_to_Congress%207-10-2020.pdf

Committee on February 20, 2018.[49] On May 16, 2018,[50] August 18, 2018,[51] September 6, 2019,[52] and June 30, 2020,[53] the NCST Advisory Committee received updates on the plans and progress of projects conducted under the Hurricane Maria Program. Consistent with the committee charter, members of the Advisory Committee provided observations and advice on the NCST projects. The Advisory Committee was also presented with information about Hurricane Maria projects that fall under the NWIRP statutory authority, although they are not authorized to make consensus recommendations relating specifically to these activities.

49 www.nist.gov/topics/disaster-failure-studies/ncstac-february-20th-2018-presentations
50 www.nist.gov/topics/disaster-failure-studies/ncstac-may-16-2018-presentations
51 www.nist.gov/topics/disaster-failure-studies/ncstac-meeting-august-2018-agenda-and-presentations
52 www.nist.gov/topics/disaster-failure-studies/ncstac-meeting-september-2019-agenda-and-presentations
53 www.nist.gov/system/files/documents/2020/06/24/NCSTAC_Meeting_Agenda_2020June30_July01.pdf



5. Final Reports and Recommendations

Following data collection and analysis for the seven technical projects, NIST will issue public reports describing the analysis, findings, and recommendations resulting from the NCST investigation and the NWIRP research study. Recommendations from the NCST investigation are expected to include specific improvements to building codes, standards, and practices based on the findings, as well as recommendations for research needed to help prevent future building failures, improve emergency communications, and reduce loss of life. NIST may also make recommendations from the NWIRP research study; these recommendations will focus on resilience planning and other actions that can improve the recovery process before, during, or after a wind hazard event, as well as recommendations for further research needed to support community resilience. NIST will widely disseminate its draft and final reports with findings and recommendations.

NIST has a statutory obligation to oversee the implementation of the recommendations of its NCST investigations. In addition to taking action on any NCST recommendations within its own purview for follow-up research or other activities, NIST will reach out to all relevant federal agencies as well as the Puerto Rico government and others in the public and private sectors to encourage leadership in driving voluntary implementation of the NCST recommendations. Individual briefings also will be offered to agencies and other organizations. As with its previous investigations, NIST will track and regularly report publicly on the progress that the agency and others are making to implement its NCST recommendations. This statutory requirement stands as an enduring commitment to improving the safety and structural integrity of buildings in Puerto Rico and throughout the United States through the development and promotion of measurements, standards, and technology that will make buildings, infrastructure, and communities more resilient to hurricanes and other hazard events.

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