# Summary of Hurricane Maria NCST Investigation Progress

## *NCST Advisory Committee Meeting*

**September 24, 2026**


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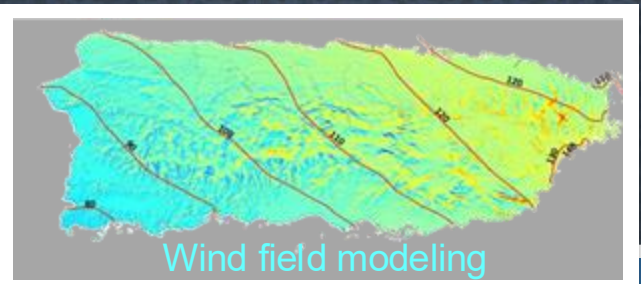
NIST NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

# NIST Hurricane Maria Investigation

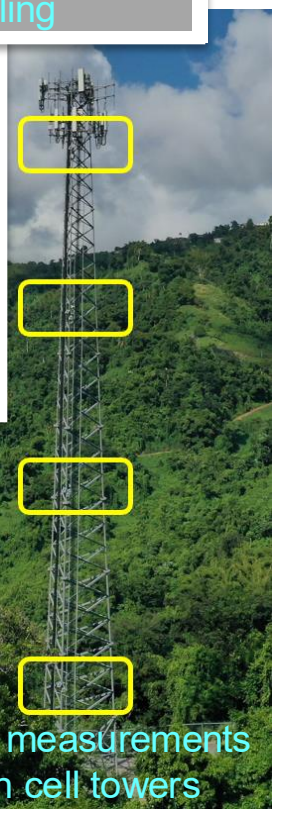
## Event Impacts

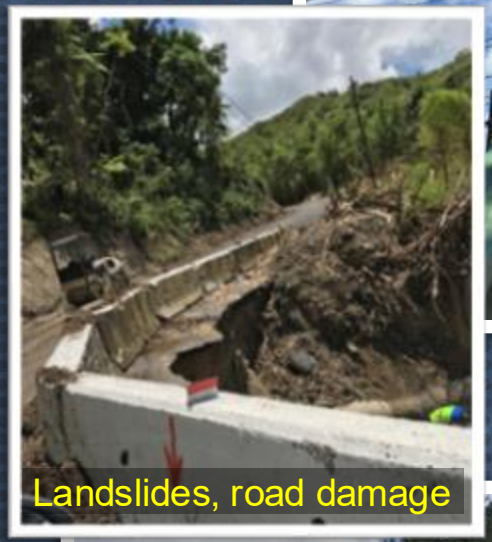

Failure of power & communications


Surveys & interviews

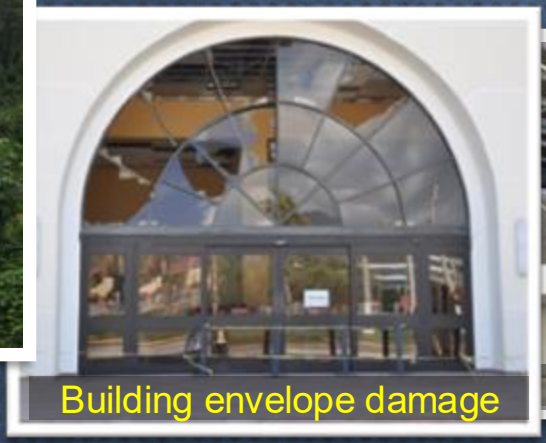

Wind field modeling

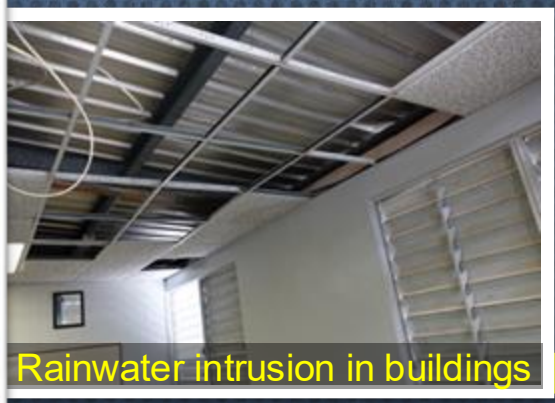

Facility evaluations


Wind measurements on cell towers

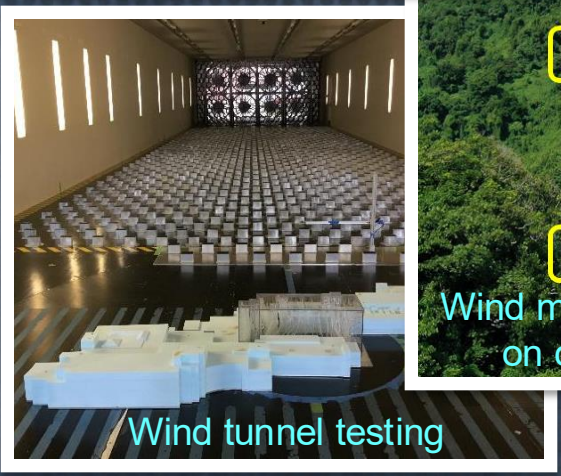

Landslides, road damage


Heavy rain and flooding


Building envelope damage


Rainwater intrusion in buildings

## Recommendations


Wind tunnel testing

## Investigation

1 Program Overview

2 Principal Findings

3 Anticipated Impacts

4 Next Steps

# 1 Program Overview

# 1 NIST Hurricane Maria Program

- **NIST is studying** Hurricane Maria's effects on Puerto Rico and subsequent recovery
- **Goal:** Recommend improved standards, codes, and practices to help communities in Puerto Rico and across the U.S. to be more resilient
- Launched February 2018; authorized by:
  - National Construction Safety Team Act
  - National Windstorm Impact Reduction Act

**Hurricane Maria, September 2017**

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**Hurricane Maria, September 2017**


**NCST Act (Public Law 107-231):** Authorizes NIST 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.*"

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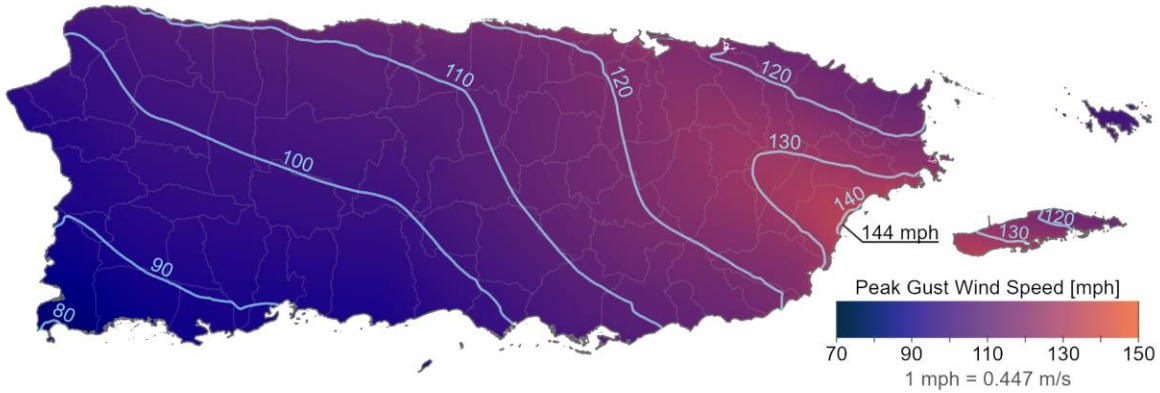
**Hurricane Maria, September 2017**


**NWIR Act (Public Law 114-52):** Designates NIST as lead agency for 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*."

# 1 Hurricane Maria's Impacts on Puerto Rico

- **Hazard Exposure:** Strong Category 4 hurricane, peak gusts near 140 mph (greater with topographic speedup), over 30" rain, extensive flooding, landslides
- **Exposed Population:** Entire Commonwealth (~3.3M people)
- **Mortality:** Challenges attributing hurricane-related deaths; excess mortality est: 2,975
- **Engineered Buildings:** Extensive nonstructural damage, rainwater intrusion, loss of function
- **Emergency Response:** Challenges with rescues in flooded areas, complicated by loss of communications for extended periods

**Peak gust wind speeds without topographic effects**

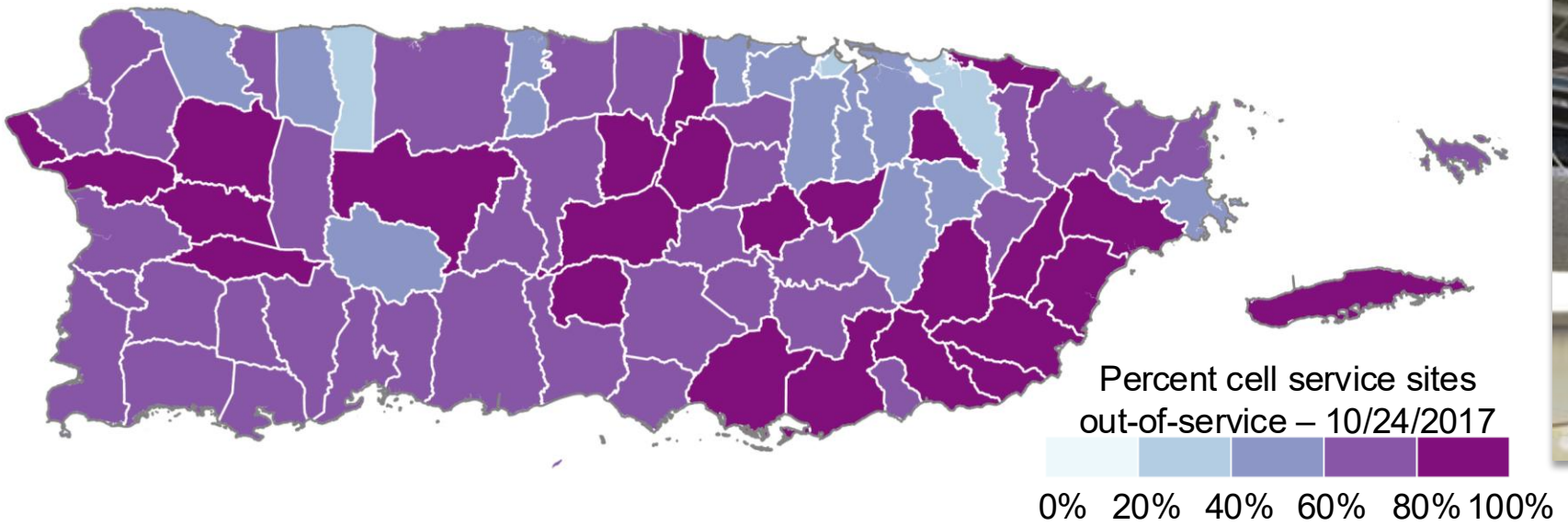




# 1 Impacts on Infrastructure and Recovery

- **Infrastructure Systems:** Severe physical damage and complete/near complete loss of function for electrical and communications systems presented emergency response and recovery challenges
- **Education, Healthcare and Businesses:** Impacts on recovery due to power loss, non-structural building damage, generator failures, road closures

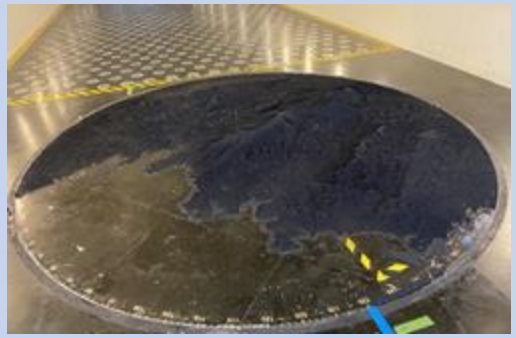
**Wireless communications status at 1 month**



# 1 Hurricane Maria Projects

## National Construction Safety Team (NCST) Technical Investigation

| Hazard Characterization | Performance of Critical Buildings | Public Response to Emergency Communications | Morbidity & Mortality |
|---|---|---|---|





## National Windstorm Impact Reduction Program (NWIRP) Research Study

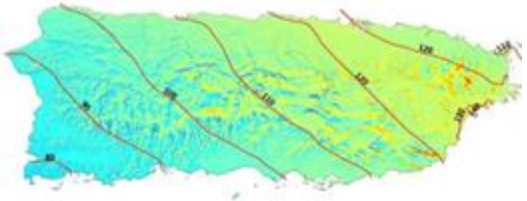
| Recovery of Business & Supply Chains | Recovery of Social Functions | Impacts to & Recovery of Infrastructure Systems |
|---|---|---|



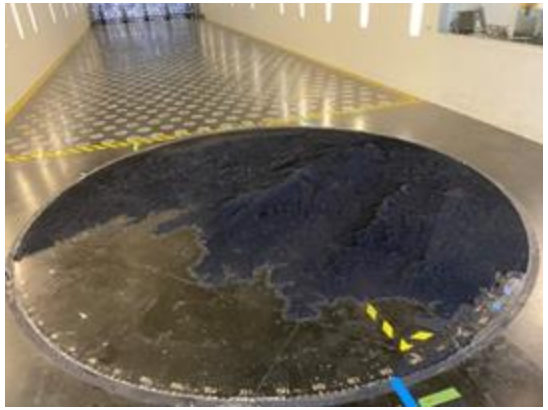
# 1 NIST Hurricane Maria Team

# 1 Supporting Contracts

| Technical Expertise |
| --- |
| Wind Field Modeling and Wind Load Analysis |
| Wind Tunnel Testing and Field Measurement of Winds |
| Engineering Services to Evaluate Critical Building Performance |
| Social Science Data Collection |
| Morbidity and Mortality Assessment |



**Applied Research Associates**



**University of Florida**

**Stantec Consulting**

**Horsley Witten Group**


Source: Bernardo Hernández Prado

**GW/UPR***

*George Washington University / University of Puerto Rico

# 1 Collaborating & Coordinating Agencies

## Federal

Federal Emergency Management Agency
NOAA, National Weather Service
U.S. Army Corps of Engineers
U.S. Geological Survey
Small Business Administration
Dept of Health & Human Services

## Puerto Rico

Depts of Education, Health, Housing, Transportation & Public Works, Economic Development & Commerce
PR Ports Authority, PR Energy and Power Authority
PR Aqueduct & Sewer Authority, Emergency Management
Central Office for Recovery, Reconstruction & Resiliency
Municipalities, universities, businesses, nonprofits
Governor's Federal Affairs Administration
Resident Commissioner's Office

**Collaborate**
**Coordinate**
**Cooperate**

## NIST Engineering Laboratory

Disaster & Failure Studies Program
Community Resilience Group
Structures Group
Earthquake Engineering Group
Applied Economics Office
Data, Security, Technology Group

## Other NIST Units

Public Affairs Office
Office of Chief Counsel
Congressional & Legislative Affairs
Program Coordination
Management & Organization
Acquisition & Agreements Mgt
Statistical Engineering Division of ITL
Research Protections

# 1 NCST Data Collection

## Hazard Characterization

- Wind Tunnel Testing of Topographic Models
- Meteorological Data for Wind Field Model
- Field Measurements of Winds on Cell Towers
- Data on Rainfall, Storm Surge, Flooding and Landslides

## Public Response to Emergency Communications

- Information Provider Interviews
- Household Surveys
- Public Messages for Qualitative Content Analysis
- Household Interviews

## Performance of Critical Buildings

Facility Evaluations: 5 hospitals, 5 shelters

- Phase 1: Document collection & review
- Phase 2: Site visits & interviews

- Wind Tunnel Testing of Two Hospitals

## Morbidity & Mortality

- Verbal Autopsy and Social Environmental Survey
- Integrated Database of Deaths in Puerto Rico
- Medical Records and Hospital Functions Review
- Spatial and Temporal Data for Analysis of Deaths

# 1 NWIRP Data Collection

## Recovery of Social Functions

- Wave 1 School and Hospital Surveys
- Wave 2 School and Hospital Surveys
- Interviews with School and Hospital Administrators

## Recovery of Business and Supply Chains

- Interviews of Shipping and Transportation Representatives
- Surveys of Small and Medium-Sized Manufacturers and Retail/Service Businesses

## Impacts to and Recovery of Infrastructure Systems

- Satellite Remote-Sensing Data on Tree Canopy Cover
- Structured Interviews on Infrastructure Dependencies
- Aerial Imagery of Cell Towers
- Transportation Incident Database

2

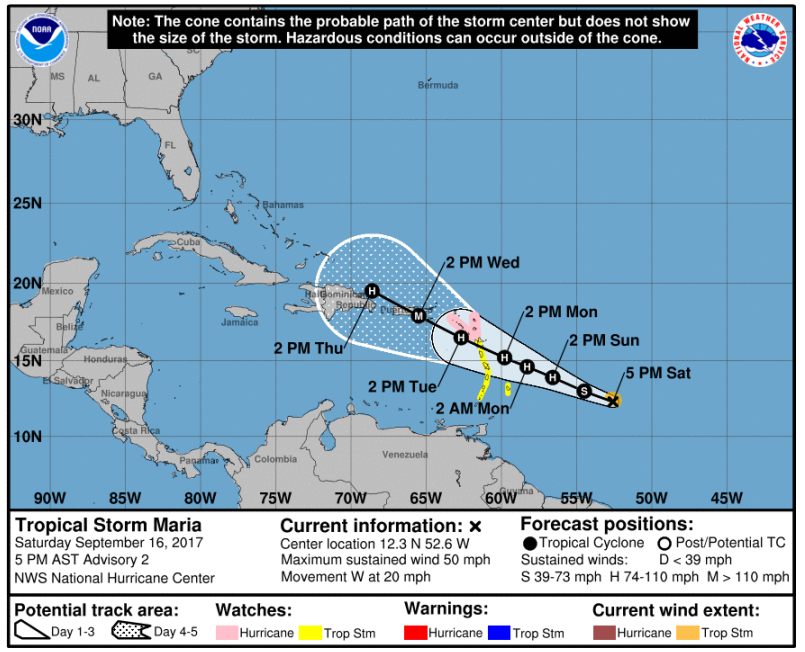
# Principal Findings

Summaries of the principal findings are presented in the following slides. Complete principal findings will be published in NIST's reports for public comment.

# 2 Principal Findings: Preparedness [NCST]

**National Hurricane Center forecasts for Hurricane Maria were skillful and consistent. Access to pre-storm emergency communication messages from multiple sources via multiple channels contributed to broad public understanding of the anticipated hazards associated with Hurricane Maria. However, the public expressed a desire for additional information to support preparedness and protective action decision-making.**

- Household surveys indicated that the public wanted more specific information about the expected performance of buildings and infrastructure, such as homes, utilities, healthcare facilities, workplaces, schools, and childcare facilities. Many residents who perceived their homes to be very safe experienced damage from the hurricane.
- Household surveys indicated a widespread lack of knowledge about how severe the post-storm impacts would be and how long the disruptions and outages would last.




# 2 Principal Findings: Preparedness [NCST]

**Most residents of Puerto Rico reported taking protective measures before Hurricane Maria, including gathering food, water, and medicine; securing their homes; and discussing hurricane preparedness with others. However, these precautions did not address the longer-term, cumulative effects of disruptions and outages.**

- This was particularly true for those with medical needs.
- Within 72 hours of Hurricane Maria, more than one in ten Puerto Ricans reported needing but not having access to medication, medical supplies, and equipment (oxygen, wheelchair, etc.).
- Additionally, one in five Puerto Ricans indicated that within two weeks, someone in their household needed healthcare services.

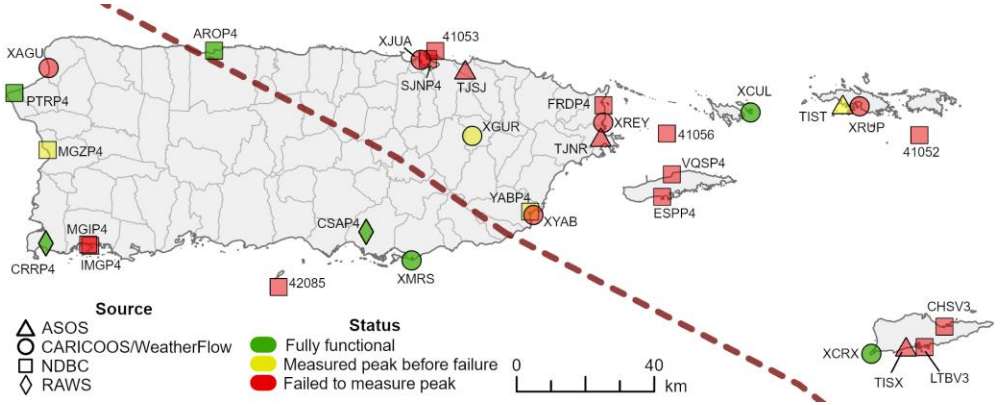
| High Ranking Actions Taken before Hurricanes Irma and Maria | % |
|---|---|
| Set aside food, water, medicine, or other supplies | 92% |
| Talked with others about hurricane preparation | 68% |
| Made a plan for evacuation (such as where to go) | 45% |
| Had insurance coverage for a natural hazard (any) | 34% |

*Emergency Communications Household survey results; sample of n=1,523 is weighted to the adult population of Puerto Rico (2017)*

# 2 Principal Findings: Hazard Exposure [NCST]

**Failures of wind and rainfall measurement and reporting systems posed significant challenges in quantifying the severity of Hurricane Maria's hazard exposure across Puerto Rico, both during the event and in post-storm assessments.**

- Puerto Rico's Doppler weather radar was destroyed by strong winds, the majority of weather stations failed to capture the hurricane's maximum wind speeds, and many rain gauges were damaged or destroyed.
- Reporting failures for weather stations resulted from several factors, including wind damage, loss of electrical power, and limitations in local storage capacity when communications were lost.
- These widespread reporting failures, which are common during landfalling hurricanes in the U.S., left emergency managers with limited information on hazard exposure and increased the likelihood that some of the highest hazard levels were not captured.

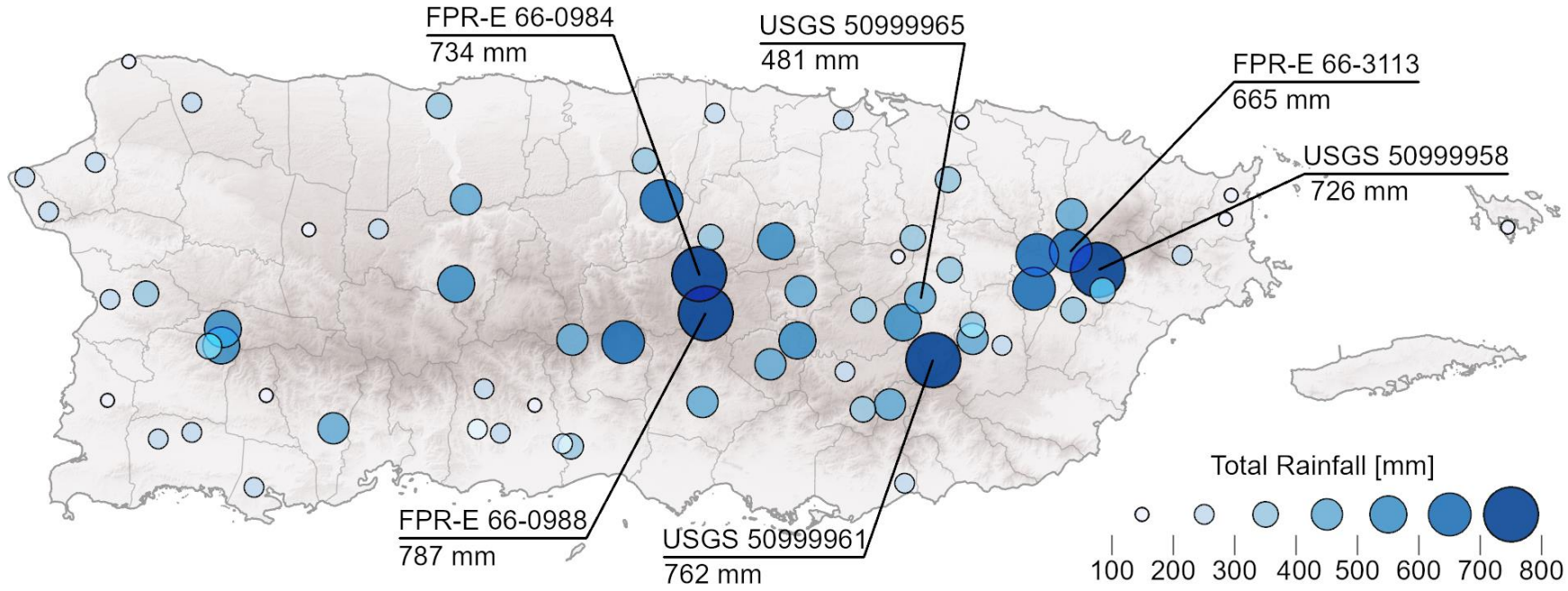



# 2 Principal Findings: Hazard Exposure [NCST]

**Hurricane Maria's rainfall, which was intensified by Puerto Rico's mountainous topography, was extreme relative to historical data. The extreme rainfall led to widespread flooding, and saturated soils were a key factor contributing to more than 70,000 landslides across Puerto Rico.**

- ***Storm-total rainfall*** was evaluated over a three-day period, and the maximum measured value of 787 mm (31.0 in) corresponds to an estimated MRI of 711 years.
- The maximum measured ***hourly rainfall*** was 193 mm (7.6 in), with a corresponding MRI exceeding 1000 years.
- Rainfall accumulations were evaluated from reliable rain-gauge measurements; satellite-based rainfall estimates had difficulty capturing the intense rainfall as influenced by the mountainous topography.

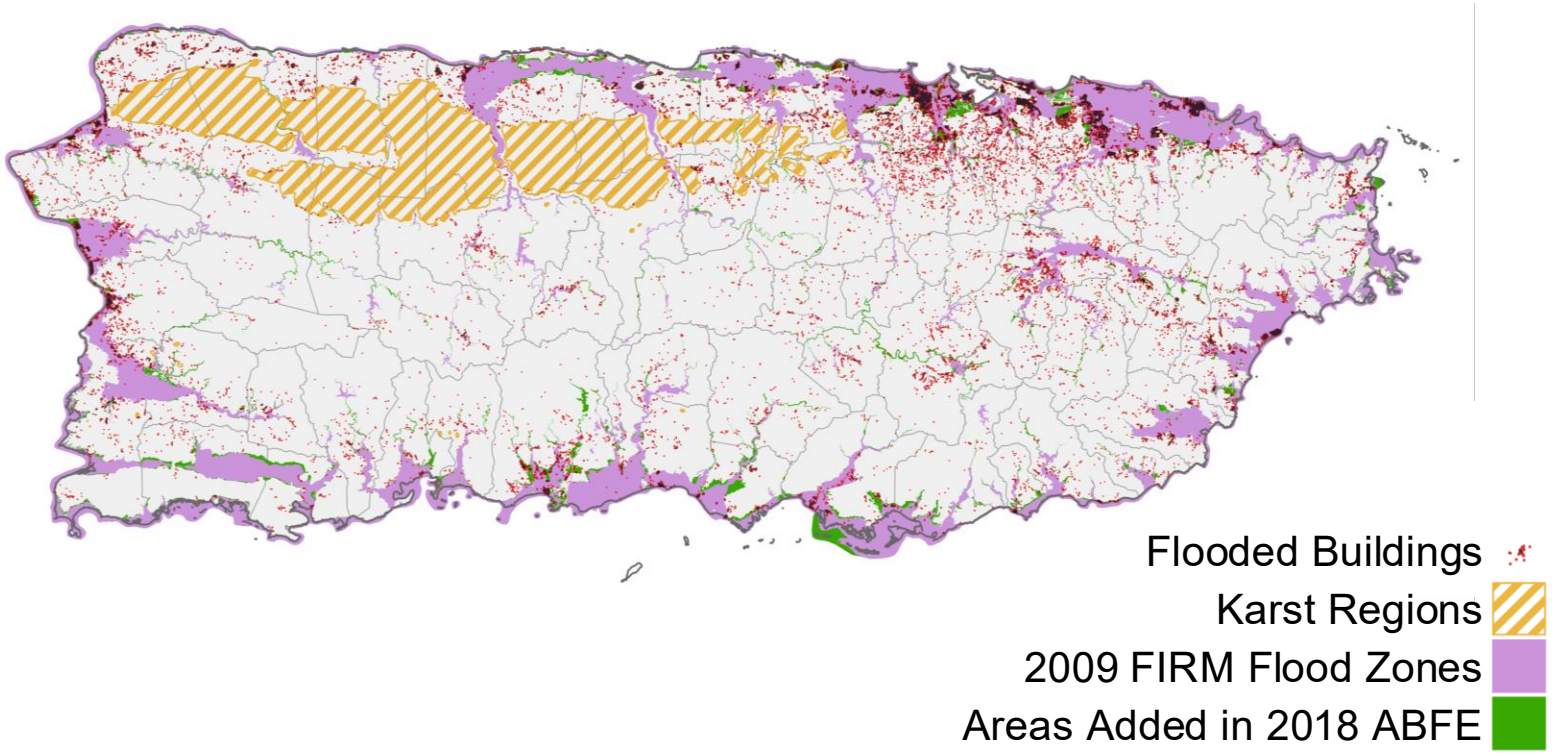
*Rain gauge measurements of storm-total rainfall:*



# 2 Principal Findings: Hazard Exposure [NCST]

**With limited information on the spatial extent and depth of flooding across Puerto Rico's highly variable topography, rainfall-driven flood modeling provided useful estimates of inland flooding to complement the available flood depth measurements. The model results indicated that a significant portion of Hurricane Maria's flooding occurred outside of designated flood zones.**

- Flood model results indicated that 41% of buildings with flood depths greater than 0.3 m (1 ft) were located outside the 100-year and 500-year flood zones from the 2009 FEMA flood insurance rate maps in effect at the time of Hurricane Maria.
- This highlights the risk that during intense rainfall events like Hurricane Maria, rapid accumulation of surface water can lead to runoff-related (pluvial) flooding outside of designated flood zones.
- Current flood zones consider riverine (fluvial) flooding and coastal inundation but generally do not consider pluvial flooding.



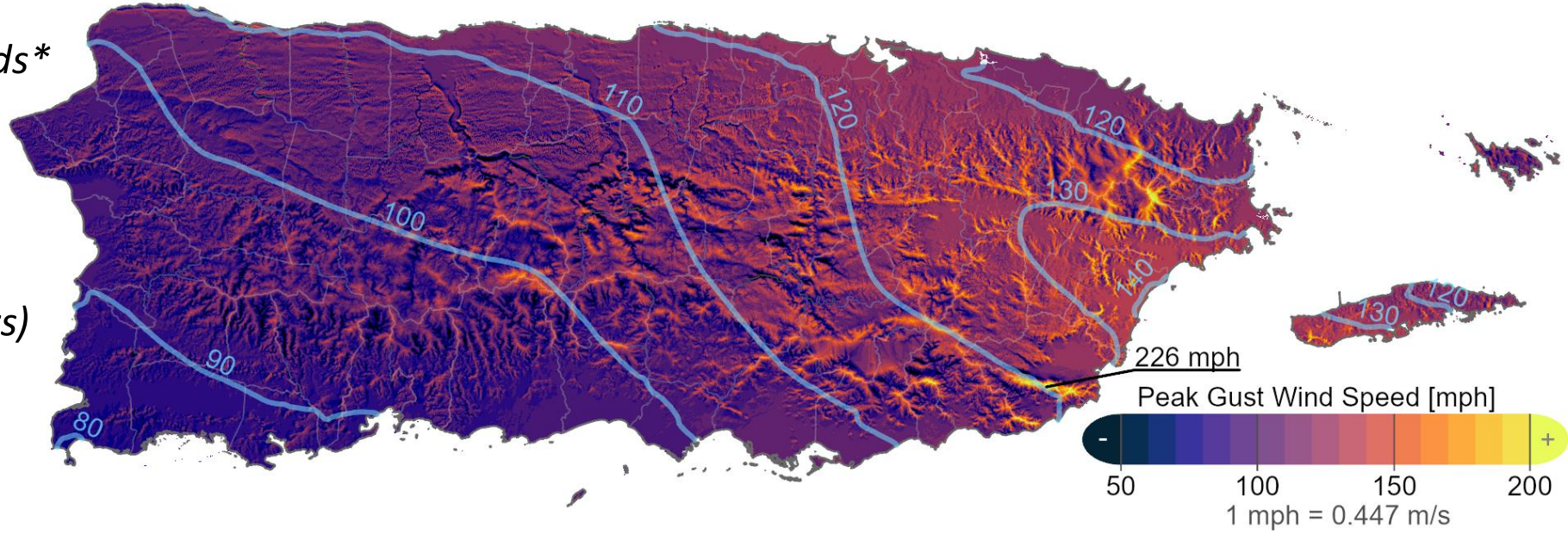
# 2 Principal Findings: Hazard Exposure [NCST]

**Puerto Rico's topography caused significant speedup of winds on hills and mountains, producing increased wind loads on buildings, communication towers, and other structures relative to winds over flat terrain.**

- By fitting a hurricane wind-field model to available meteorological data, NIST estimated the maximum peak gust wind speed* over flat terrain as 144 mph, in the Category 4 range on the Saffir-Simpson scale.
- **However, considering topographic effects using an empirical speedup model, the maximum peak gust wind speed* was estimated as 226 mph, which corresponds to Category 5.**

*Estimated peak gust wind speeds* for Hurricane Maria:*

- *with topographic effects (indicated by color)*
- *without topographic effects (indicated by labeled contours)*



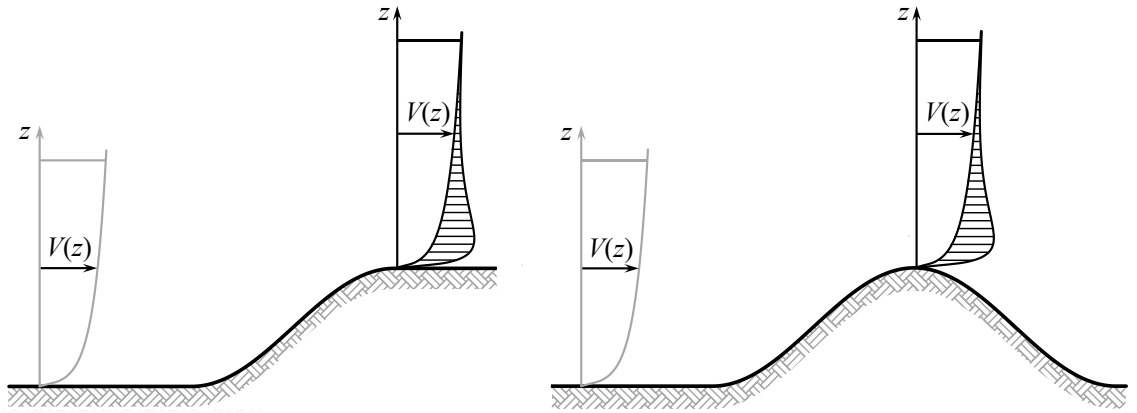

* 3-second gust speed at 10 m above ground over open terrain

# 2 Principal Findings: Hazard Exposure [NCST]

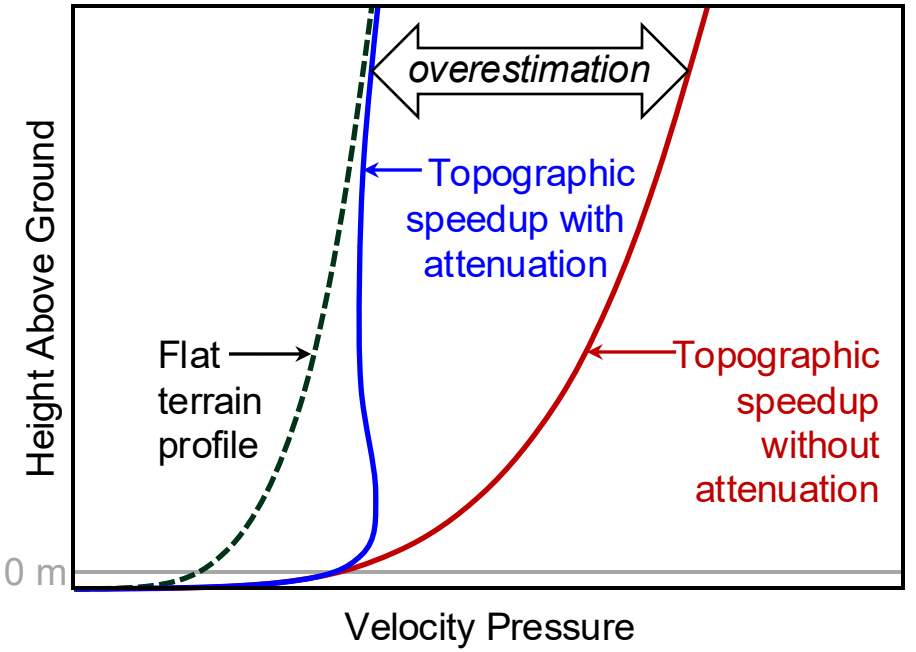
**Applying the current design standard (ASCE 7) to Puerto Rico's mountainous topography underscored the highly approximate and inherently subjective nature of the analytical procedure – and the advantages of microzoned maps to account for the effects of local topography on wind speeds. However, current microzoned maps do not consider reductions in topographic speedup with height; this leads to potentially significant *overestimation* of topographic speedup for structures taller than about 30 m (100 ft).**

- The ASCE 7 analytical procedure requires users to approximate complex, real-world topography using one of three idealized topographic features.
- Microzoned wind speed maps for Puerto Rico (adopted in the 2018 P.R. Building code and in ASCE 7-22) eliminate subjectivity by appropriately representing complex topography using digital elevation data, with the same empirical speedup model used by NIST in the Hurricane Maria wind-field model.

**Idealized Topographic Features in ASCE 7 Analytical Procedure**



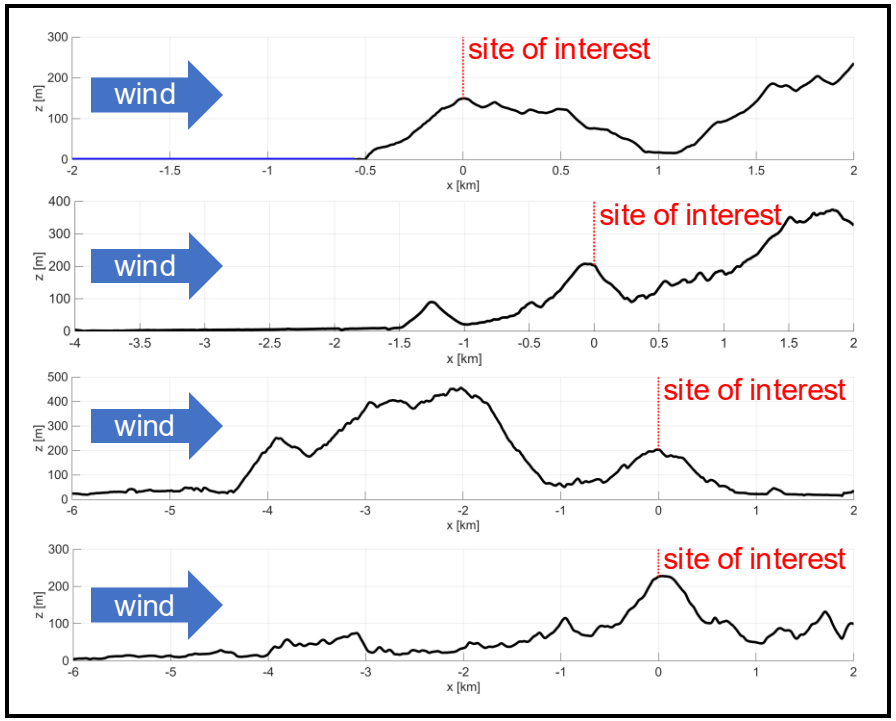

**Overestimation of Topographic Speedup**



# 2 Principal Findings: Hazard Exposure [NCST]

**Standard provisions previously intended to account for sheltering by upwind topography led to significant *underestimation* of topographic speedup in some cases. Upwind topography presents challenges in the evaluation of topographic speedup, because it can decrease the average wind speeds while increasing the turbulent fluctuations. These competing effects can either increase or decrease the resulting gust wind speeds at the site of interest, depending on the location and dimensions of the upwind topography.**

- Prior to 2022, the analytical procedure in ASCE 7 allowed topographic speedup to be neglected if upwind topographic features met certain conditions. These sheltering conditions were found to be *unconservative* through comparisons with wind tunnel data, field measurements, and CFD simulations.
- The sheltering conditions were eliminated in ASCE 7-22. Consequently, the ASCE 7-22 analytical procedure provided conservative estimates of topographic speedup in cases with upwind topography.
- The empirical speedup model (used for the P.R. microzoned maps) also provided conservative estimates, tending to overestimate topographic speedup in cases with distant upwind topography.

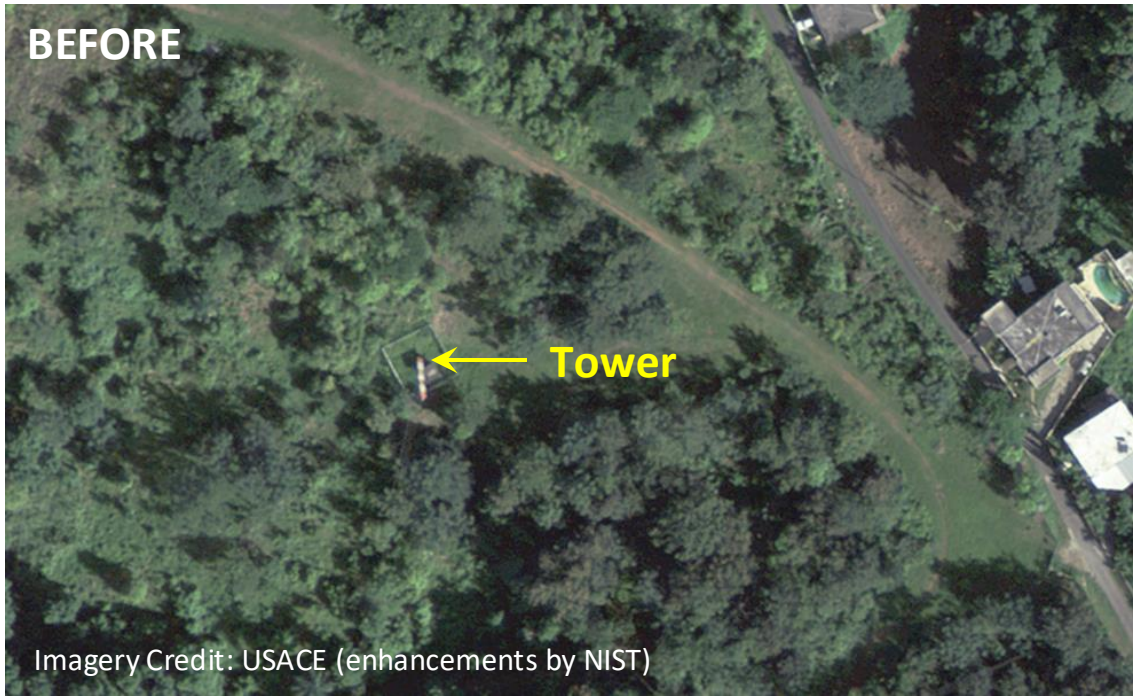


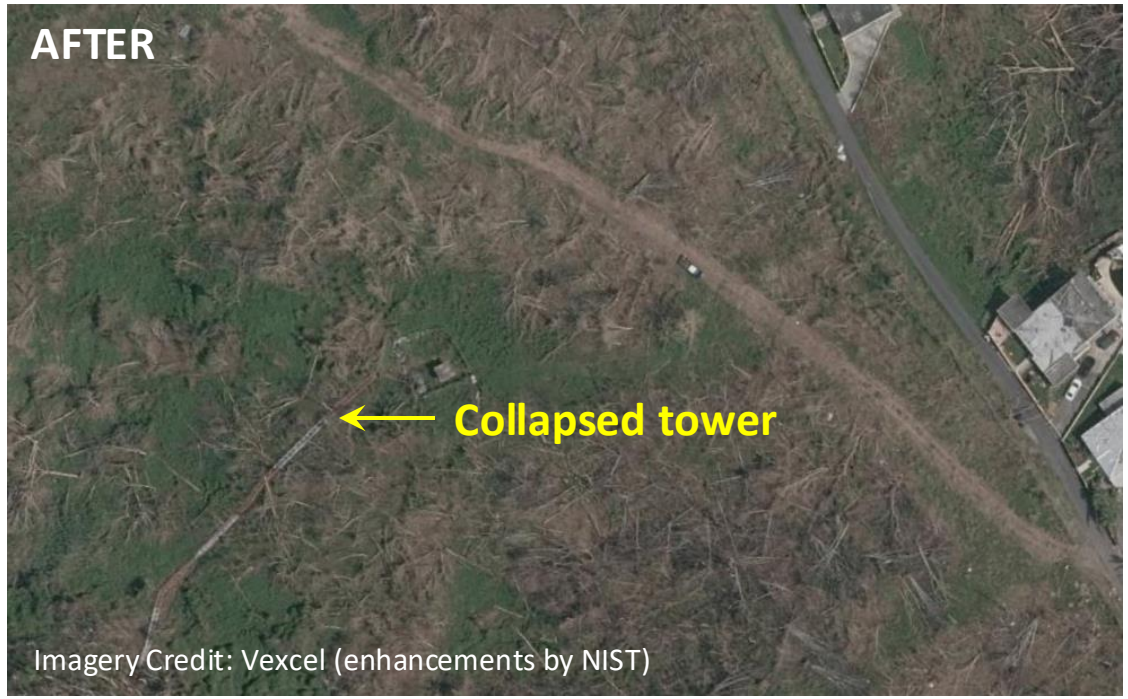

**Puerto Rico Elevation Transects with Varying Upwind Topography**

# 2 Principal Findings: Hazard Exposure [NCST]

**Hurricane winds caused extensive damage to trees, especially on hills and mountains, where winds were intensified by topographic speedup.**

- Tree damage included uprooting, snapping, and defoliation, which reduced the roughness of the terrain, resulting in increased wind speeds near the ground, with corresponding increases in the wind loads on structures.
- Fallen trees also caused disruptions by damaging power lines and blocking roads.



# 2 Principal Findings: Infrastructure [NCST]

**In the immediate aftermath of the hurricane, no single communication channel proved sufficient given the scope of infrastructure damage caused by the hurricane.**

- Amateur radio was one of the only available means of communication initially.
- Information providers found satellite phones to be unreliable.
- When cell phone service was restored, weeks or months after the hurricane, cell phones became the primary means of communication, underscoring their importance to the public.
- Social media was also reported to be a highly utilized channel for information exchange.

Credit: Civil Air Patrol

# 2 Principal Findings: Infrastructure [NWIRP]

**While power outages and damage to the wireline portion of the communications network were the most important factors in the extended duration of wireless communications outages, wind damage to communications towers and equipment played a significant contributing role.**

- Wind and wind-borne debris damage to tower-mounted equipment was common, including damage to and misalignment of antennas and microwave dishes, antenna mounting platforms, and data and power cables.
- Of 594 communications towers in NIST's sample, 27 collapsed (4.5%).
- Severe damage to surrounding trees changed the ASCE 7 wind exposure category for about 50% of the towers in Exposure B (suburban/ wooded) to Exposure C (open) during the storm, resulting in increased wind loads.

# 2 Principal Findings: Infrastructure [NWIRP]

**Modeling of road network disruptions showed that hospital access was impeded for extensive areas across Puerto Rico, with disruptions in some areas persisting for more than a month after the hurricane, particularly in mountainous regions.**

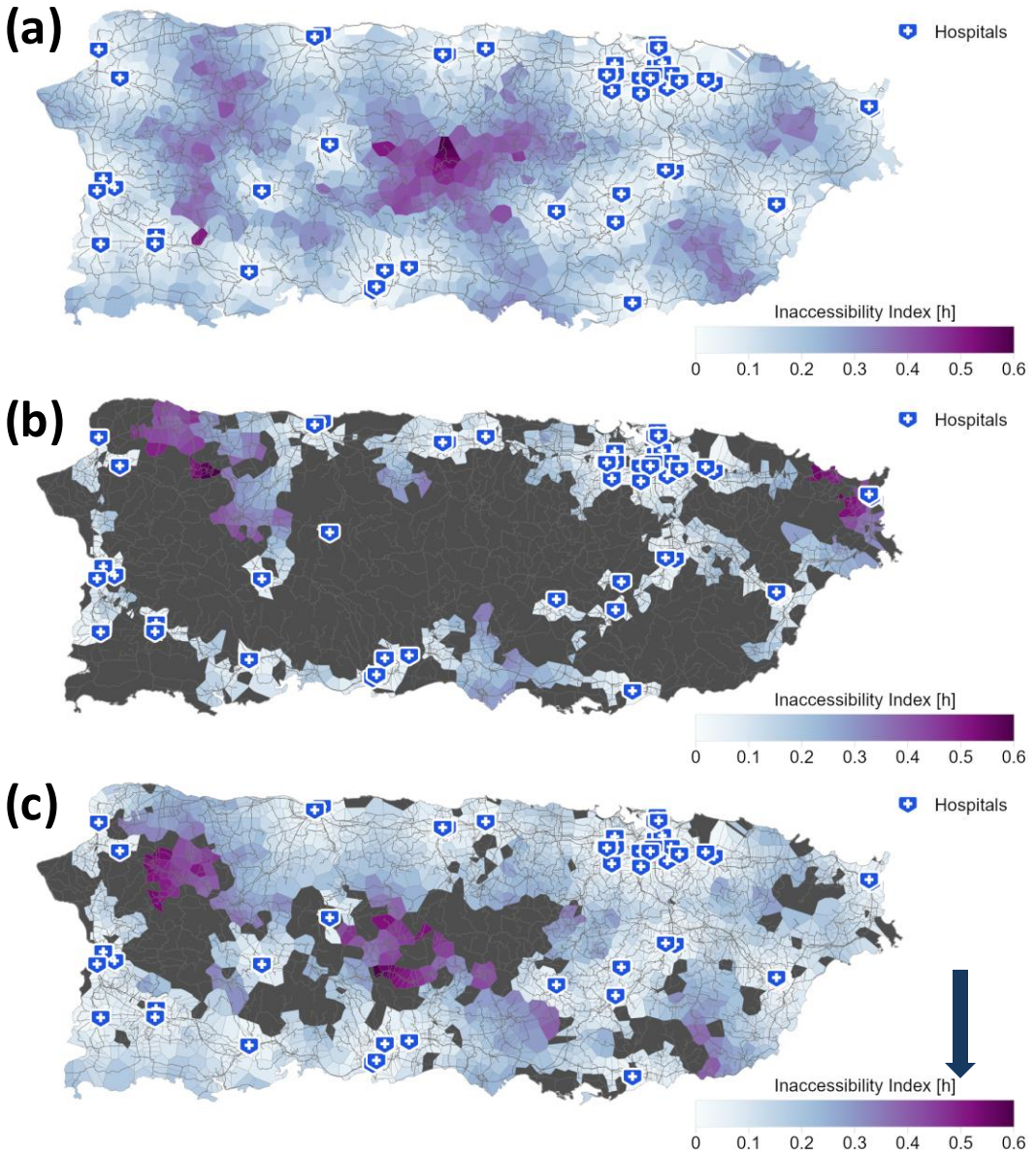
- Disruptions of the road network included landslides, flooding, downed trees, and other debris.
- Further modeling demonstrated that consideration of potential disruptions to the road network can inform planning and decision-making to achieve improved transportation access to healthcare.

*Maps show the hospital inaccessibility index for:*

*(a) fully functional road system*

*(b) road system immediately after Hurricane Maria*

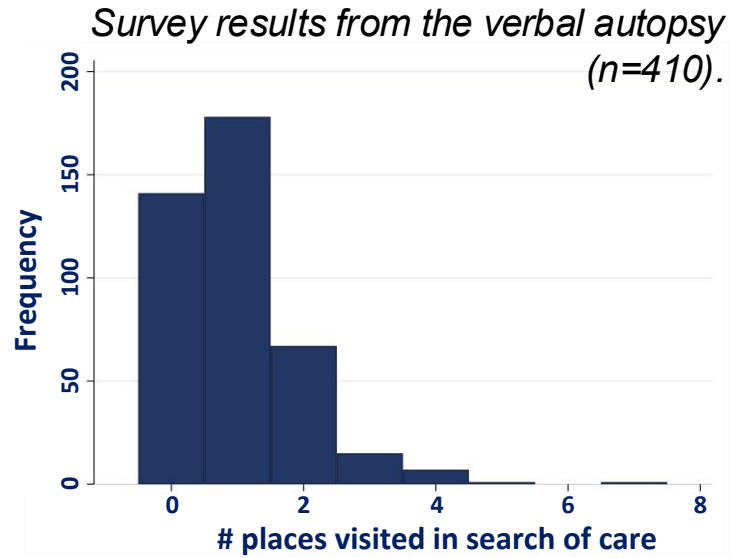
*(c) road system one month after Hurricane Maria*



# 2 Principal Findings: Mortality [NCST]

**Difficulties in accessing medical care following Hurricane Maria included disruption of the road network, limited transportation options (ambulances and public transportation unavailable), closure of clinics and doctors' offices, and communication outages (including 911 services) which blocked access to information on which routes were accessible and which facilities were operational. These difficulties contributed to the extent of mortality following Hurricane Maria.**

- Next of kin of those who died following the hurricane reported that over 20% sought medical care at multiple places (as many as seven) before receiving treatment.
- Most patients arrived at hospitals in poor condition, which may have deteriorated at home or while seeking care.
- Upon arriving at hospitals, patients experienced disruptions caused by storm damage and power outages, and many were exposed to high heat and humidity due to a lack of air conditioning.





Credit: Civil Air Patrol

# 2 Principal Findings: Mortality [NCST]

**Currently, there are no standards for death certification following disasters. Surveillance tools used to study mortality (e.g., death certificates; verbal and social autopsies; event dashboards) lack information on direct and indirect impacts that would allow deaths to be attributed to a disaster such as a hurricane.**

- Surveillance tools also lack the standardized definitions, methodologies, and sources of information necessary to characterize the causes of individual deaths in relation to disasters, and specifically hurricanes and their associated hazards and impacts.


Credit: Bernardo Hernández Prado

# 2 Principal Findings: Building Performance [NCST] NIST

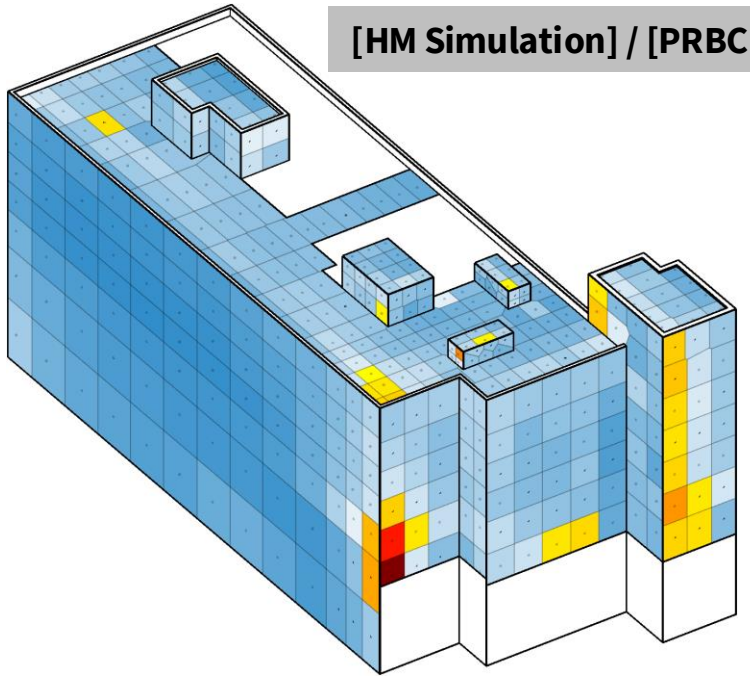
**While most hospital and school buildings in Puerto Rico experienced minimal structural damage during Hurricane Maria, hurricane-force winds and wind-borne debris caused extensive damage to building enclosures, which allowed significant rainwater intrusion.**

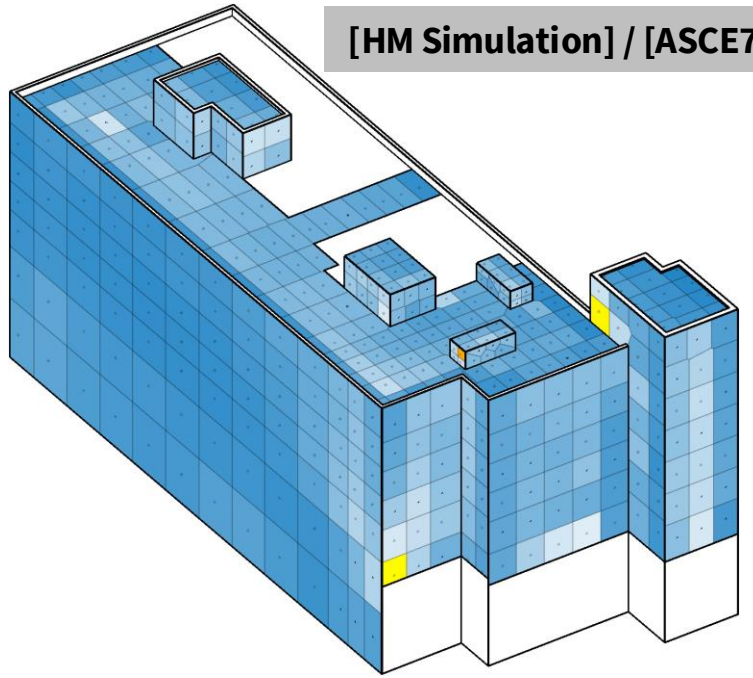
- The most prevalent source of rainwater intrusion in buildings was through damaged roof coverings, with additional rainwater entry through damaged windows, doors, and rooftop equipment.
- Clogging of roof drains by storm-generated debris contributed to increased water retention on flat roofs, exacerbating the intrusion of rainwater through damaged roof coverings.
- Intrusion of wind-driven rain through windows included windows dislodged from the framing and windows with broken glass, as well as intact windows with significant leakage around the seals.
- Wind damage to roof-mounted equipment was widespread across hospitals and some schools. This included shifting and toppling of rooftop units and, in some cases, removal from the roof.
- Damaged and dislodged rooftop equipment not only allowed rainwater intrusion through openings in the roof but also became a source of windborne debris, which punctured roof coverings and created additional pathways for water intrusion.

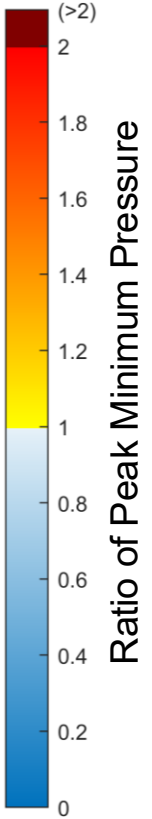
# 2 Principal Findings: Building Performance [NCST]

**Estimated peak local pressures on some hospital and school buildings during Hurricane Maria exceeded the design levels in effect when the buildings were designed (e.g., based on the 1954 or 1968 P.R. Building Code). Estimated wind speeds remained below the levels specified in current codes and standards. However, estimated peak pressures at some locations slightly exceeded even the current design levels for components and cladding, because peak local pressure coefficients from wind tunnel testing significantly exceeded those specified in ASCE 7-22.**

- Design wind pressures based on the 1954 and 1968 PRBC were less stringent than current standards and did not differentiate between components & cladding and the main wind force resisting system.
- Peak pressures on selected hospital buildings were evaluated using wind-field modeling in conjunction with wind-tunnel testing, including the effects of surrounding buildings and topography.



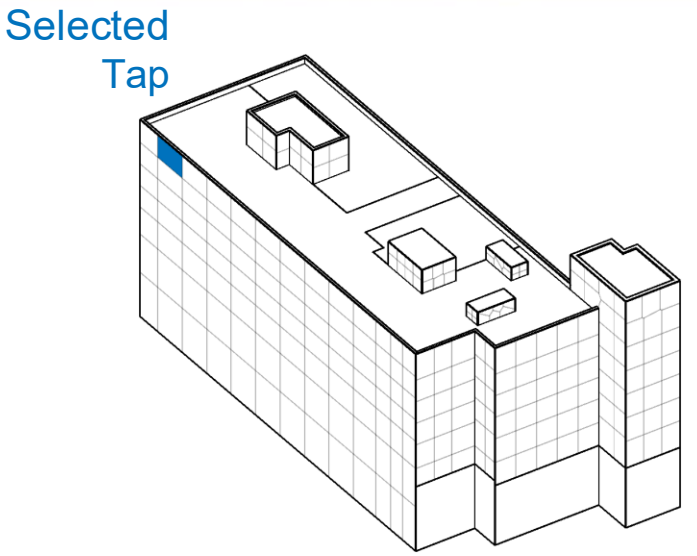



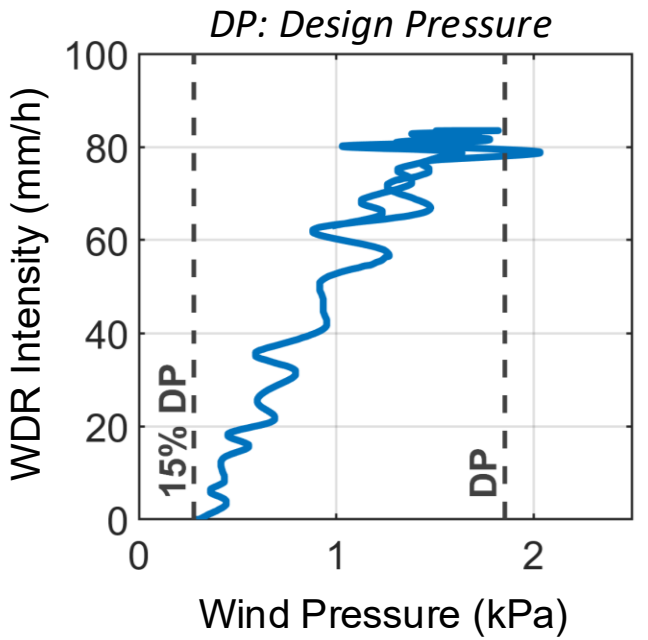



# 2 Principal Findings: Building Performance [NCST] NIST

**The combination of torrential rainfall with hurricane-force winds produced intense wind-driven rain (WDR: i.e., horizontal rain), which penetrated building enclosures, causing extensive interior damage and disrupting the operation of critical facilities across Puerto Rico. Peak WDR intensities occurred in combination with wind pressures that significantly exceeded those used in current standards for water-intrusion testing of fenestration products.**

- WDR rain exposure was evaluated through site-specific analysis of wind and rainfall, and local pressures were evaluated through wind-tunnel testing of a selected hospital building.
- While most buildings evaluated by NIST had older windows, these results indicate that even new windows in compliance with current water-intrusion test standards would not ensure successful performance under WDR conditions like those experienced during Hurricane Maria.
- MRIs associated with Hurricane Maria's WDR intensity could not be determined because historical WDR data are not available and would require a joint analysis of multi-decadal wind and rainfall data to develop.



# 2 Principal Findings: Building Performance [NCST] NIST

**With the loss of utility power, hospitals had to operate on backup power systems for extended periods, and backup power systems at hospitals often did not power air-conditioning systems or elevators.**

- The lack of air-conditioning exposed patients and staff to high heat and humidity, and the lack of elevator service made it difficult to relocate patients from one floor to another (e.g., when required due to flooding).
- Generators typically functioned well during the first three days of operation, but issues were reported with extended generator use, including fuel scarcity and the need for maintenance, as well as damage to generators during operation.

# 2 Principal Findings: Building Performance [NCST] NIST

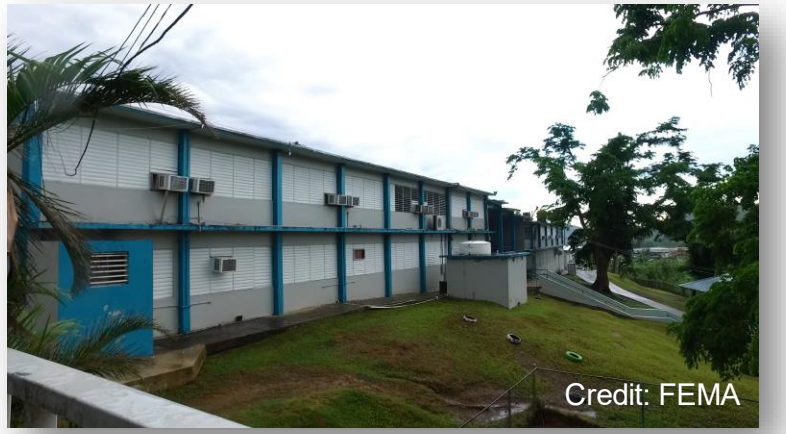
**Refuge areas in designated shelter facilities preserved life safety, successfully protecting occupants from hurricane winds and wind-borne debris. However, occupants were exposed to other hazards, and significant operational challenges were encountered in these facilities.**

- Refuge areas were affected by rainwater intrusion and flooding, especially accessible ground-floor refuge areas, requiring relocation of occupants.
- Shelters generally had higher occupancies than expected and were used far longer than expected.
- Shelter occupants experienced conditions that were not ideal for longer-term occupancy, including lack of air conditioning, mold/mildew exposure, and sanitation problems. These conditions were driven by loss of power, subsequent failure of generators, and lack of water service.
- Multiple groups were involved in managing shelters, and a lack of clear roles and responsibilities exacerbated shelter operational challenges.

# 2 Principal Findings: Building Performance [NWIRP]

**Deferred maintenance, particularly for schools, compounded building and site damage from Hurricane Maria.**

- Older buildings and unaddressed maintenance from before Hurricane Maria represented increased vulnerabilities for existing building stock.
- The resulting damage directly impacted functions served by these buildings such as healthcare, sheltering, education, and business particularly when combined with existing vulnerabilities.
- For both hospitals and schools, resources such as funding and staff for building maintenance were lacking or absent in some facilities.




**Damage Impact on Services: Aggregated to San Juan Municipio**

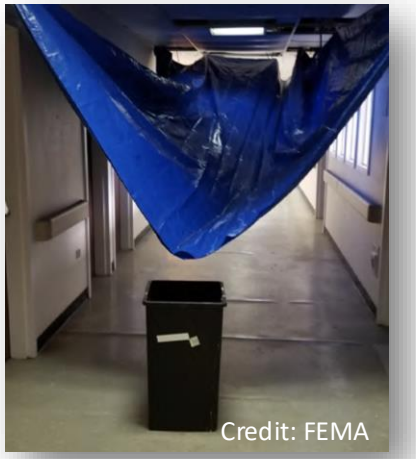
| | Businesses | Schools | Hospitals |
|---|---|---|---|
| None | 39.6 % | 23.9 % | 14.3 % |
| Minor | 24.6 % | 28.3 % | 28.6 % |
| Moderate | 8.4 % | 4.4 % | 57.1 % |
| Severe | 27.2 % | 43.5 % | 0.0 % |

*Survey results for the degree to which damage impacted the provision of service for businesses (n=207), schools (n=49), and hospitals (n=9) in the San Juan Municipio.*

# 2 Principal Findings: Recovery [NWIRP]

**Over the 12 months following Hurricane Maria, the functions of hospitals were disrupted by several factors, including building and site damage, infrastructure service outages, informal sheltering operations, employee issues, patient transfers, and an increase in non-routine functions such as providing post-disaster response assistance for the broader community.**

- Importantly, both physical impacts (e.g., building damage, power loss) and nonphysical impacts (e.g., employee challenges getting to work) contributed to the loss of function of hospitals following Hurricane Maria.



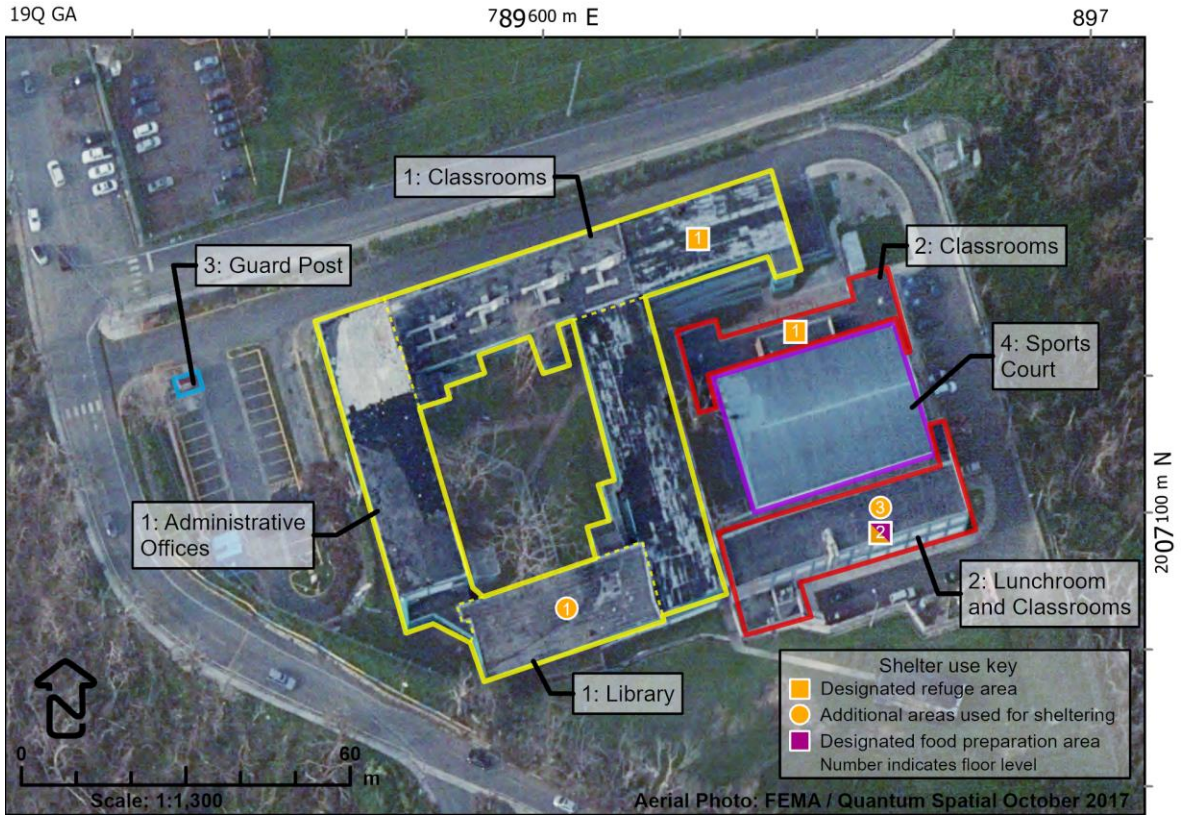


*Survey results on hospital recovery of services and repair progress (n=16) 1 year after Hurricane Maria.*

| Variable | Mean | SD |
|---|---|---|
| Repair Progress (n = 13)[a] | 62% | 33% |
| Primary Service Recovery (n = 16) | 94% | 21% |
| Support Service Recovery (n = 16) | 95% | 19% |
| Transportation Service Recovery (n = 16) | 66% | 47% |
| Community Service Recovery (n = 16) | 58% | 49% |

[a]This summary does not include those that indicated `Not applicable` for repairs and those reporting no building damage but repair values of 0% or 100% (n = 3).

# 2 Principal Findings: Recovery [NWIRP]




Credit: FEMA/Quantum Spatial Imagery; enhancements by NIST

**Public schools used as designated shelters operated for long durations of more than two months, on average, following Hurricane Maria.**

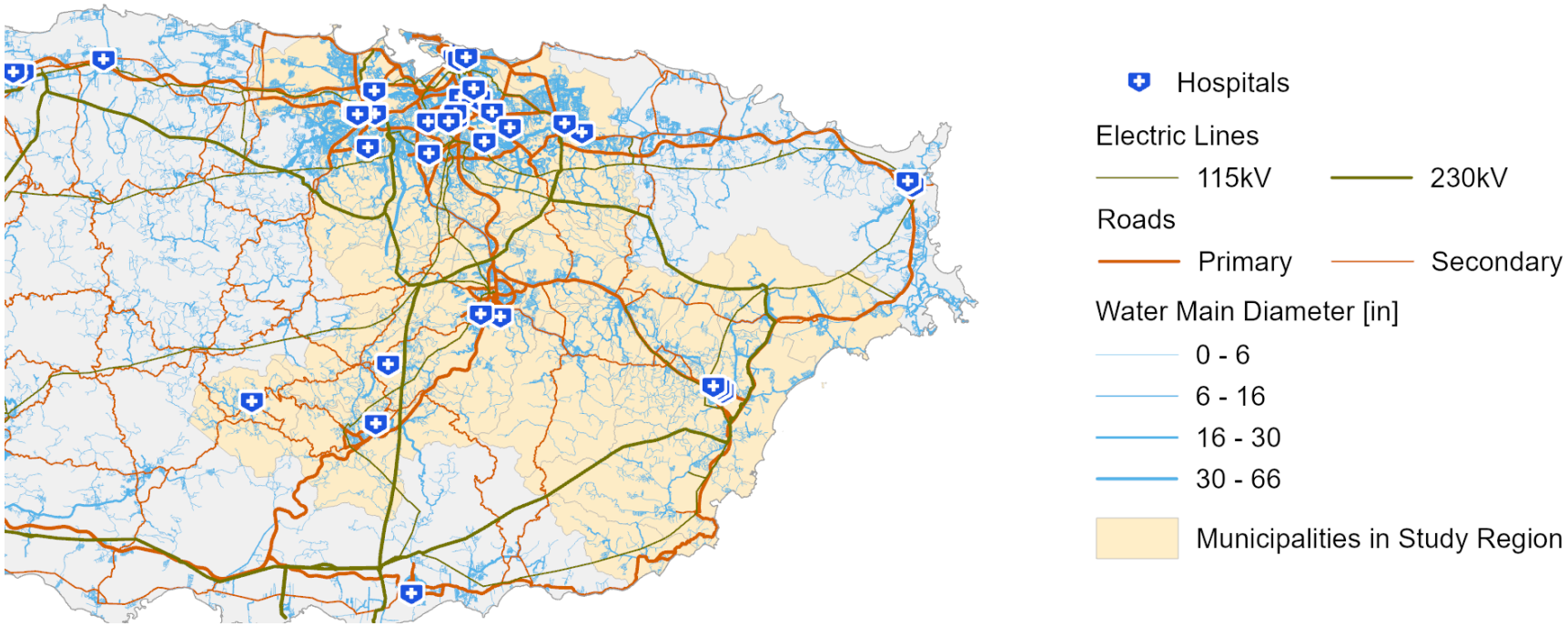
- This duration exceeds design standards and operational guidance, which focus on 24 to 72 hours for hurricane sheltering.
- The long-duration shelter operation impacted the restoration of primary services for schools.

# 2 Principal Findings: Infrastructure [NWIRP]

**Interdependencies across sectors played an important role in the recovery of infrastructure services following Hurricane Maria for communications, power, water, and roads. For example, road access was required for repair of power transmission and communications infrastructure.**

- Cross-sector coordination was hindered by a lack of information on the status and restoration timelines for infrastructure services, which delayed recovery and prolonged the disruption of critical social and economic functions that relied on those services.

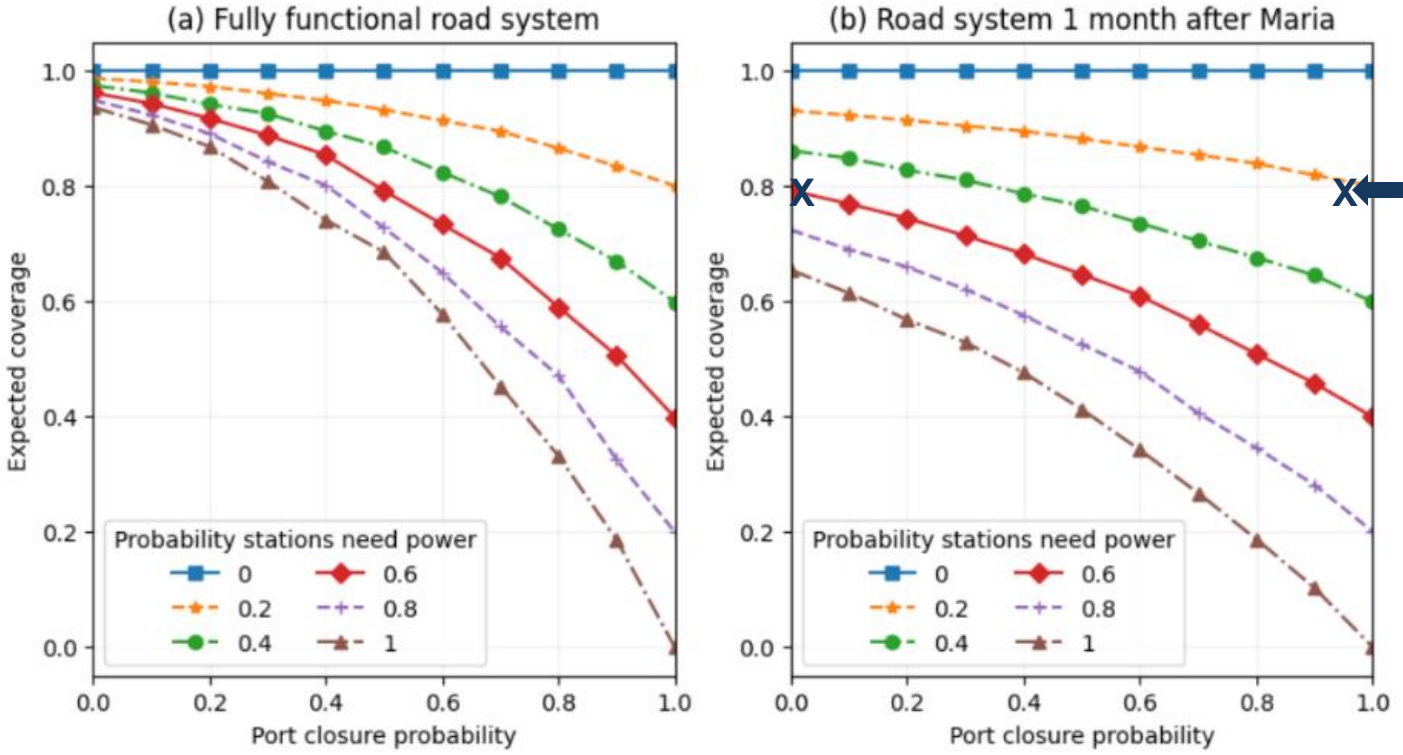
*Spatial distribution of infrastructure system components and hospitals in eastern Puerto Rico*



# 2 Principal Findings: Infrastructure [NWIRP]

**By modeling infrastructure interdependencies, NIST found that cost savings and other benefits can be achieved even through minimal cross-sector coordination in the planning stages.**

- Models demonstrate tradeoffs between solving one sector's disruptions in full (e.g., power) and reducing disruptions across all sectors.
- These results echo FEMA's after-action report and DOE's Puerto Rico energy resilience study.




*Effect of interdependent interruptions to power, port, and road systems on water system functionality for (a) a fully functional road system, (b) a road system one month after Hurricane Maria*

# 2 Principal Findings: Recovery [NWIRP]

**NIST found that preparedness and response actions shaped organizational recovery. Businesses, schools, and hospitals that took specific measures to prepare before Hurricane Maria were able to resume operations more quickly afterward.**

- Preparedness measures and resilience investments that improved recovery outcomes included pre-established emergency plans, diversified suppliers, designated risk mitigation funds, and backup power sources.
- Connections to other organizations in the community, services aimed at meeting employee needs, and resource management strategies played an important role in the response and recovery phases following Hurricane Maria.

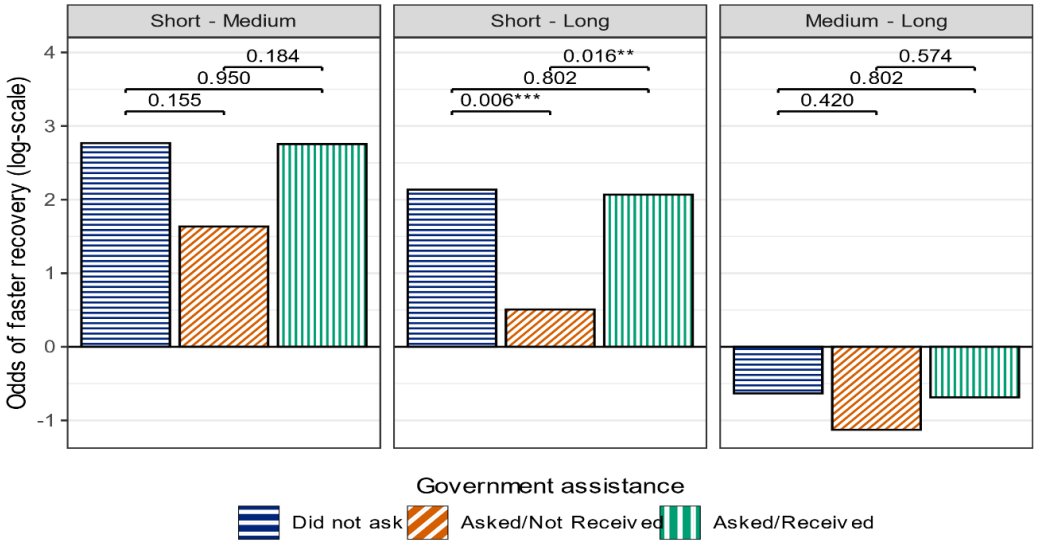
| Organization Type | Lost Electric Power | % Had Backup |
|---|---|---|
| Hospitals | 100% | 100% |
| Schools | 95% | 22% |
| Businesses | 97% | 49% |

*Recovery of Businesses (n=451), Schools (n=284) and Hospitals (n=16) survey results*

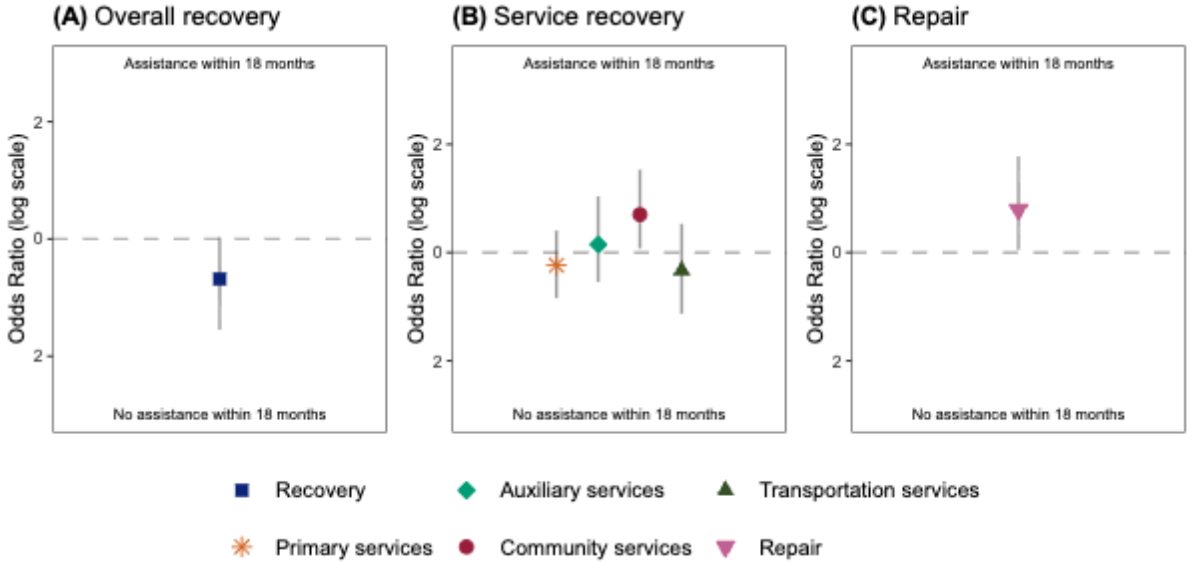
# 2 Principal Findings: Recovery [NWIRP]

**Receipt of financial assistance was a determinant of recovery progress for businesses, schools, and hospitals.**

- The prolonged need for financial assistance is statistically related to slower recovery of businesses and their functions. Businesses that received financial assistance recovered statistically more quickly than those seeking assistance that was not received.
- Schools and hospitals that received financial assistance within 18 months had statistically higher odds of repair progress than those who did not receive assistance within this timeframe.




*(a) Government Assistance Recovery Pairwise Comparison for Businesses (sample n=451; model n's may differ due to missing data)*




*(b) Financial Assistance and Recovery Outcomes Model Results for Schools (sample n=297; model n's may differ due to missing data)*

# 3 Anticipated Impacts

# 3 Recommendations

- Recommendations are expected to include specific improvements to building codes, standards, and practices based on the findings, as well as research to help prevent future building failures, improve emergency communications, and reduce loss of life.
- NIST has a statutory responsibility to promote implementation of recommendations from its NCST investigations.
- By developing and promoting measurements, standards, and technology, NIST is committed to making buildings, infrastructure, and communities more resilient to hurricanes and other hazard events in Puerto Rico and across the United States.

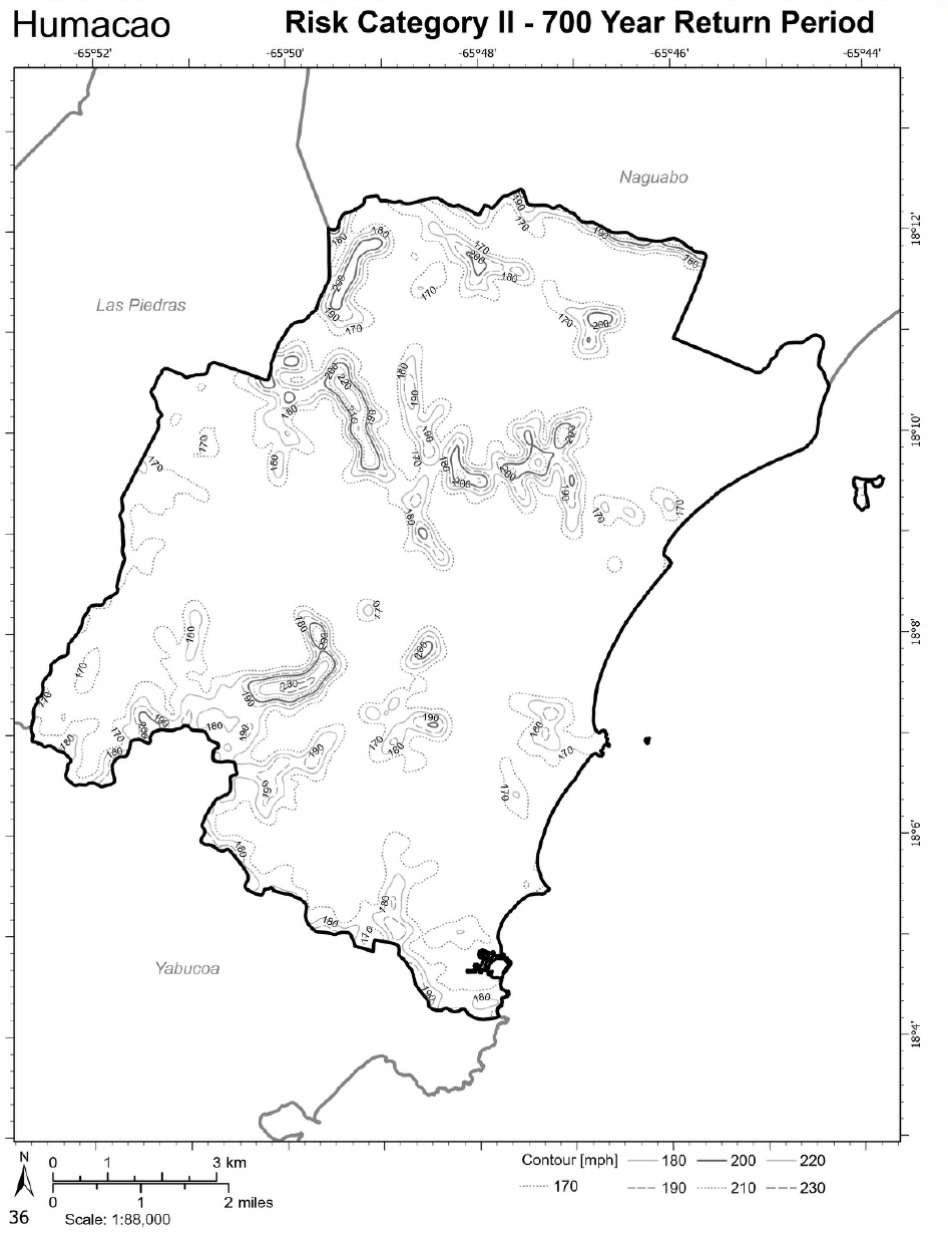
# 3 Recommendation Themes

| | |
|---|---|
| Hazard Exposure | • Improved accounting for hurricane tree damage in wind load standards **[NCST]**<br>• Robust measurement systems for wind, rainfall, and flooding during extreme events **[NCST]**<br>• Improved standards to better account for topographic effects on wind loads **[NCST]** |
| Building Performance | • Performance-based standards for continued operation of essential facilities **[NCST]**<br>• Standards for building enclosures to resist wind-driven rain intrusion **[NCST]**<br>• Standards for condition assessment of existing critical and essential facilities **[NWIRP]** |
| Sheltering | • Best available hurricane refuge areas **[NCST]**<br>• Longer-term occupancy of shelters **[NWIRP]** |
| Infrastructure Dependencies | • Alternative communication modes in anticipation of widespread outages **[NCST]**<br>• Standardized damage assessments and data-sharing across infrastructure sectors **[NWIRP]**<br>• Formal mechanisms for coordination of planning across infrastructure sectors **[NWIRP]** |
| Preparedness, Planning, and Recovery | • Communication about the historical performance of residential building types **[NCST]**<br>• Guidelines on recovery actions for critical social functions **[NWIRP]**<br>• Processes to expedite claims and financial assistance **[NWIRP]** |
| Mortality Surveillance | • Standards for attribution of disaster-related deaths **[NCST]** |

# 3 Proposed Revisions to ASCE 7-28 Standard

**Team members have submitted two proposed revisions to the ASCE 7-28 Standard relevant to findings from the Hurricane Maria Investigation:**

- Limits on the applicability of *Exposure Category B* to wooded areas in hurricane-prone regions, in recognition that strong hurricanes can cause tree damage severe enough to substantially alter landscapes
- Updated ***microzoned wind speed maps*** for Puerto Rico that incorporate topographic effects, along with a new procedure in the Commentary to account for attenuation of topographic speedup with height in conjunction with the microzoned maps



# 4 Next Steps

# 4 NCST Report Hierarchy

## Level 1: Summary Report

**NCSTAR 4**

Overarching Summary Report:
- Principal findings
- Recommendations

## Level 2: Project Reports

**NCSTAR 4-1**

*Hazard Characterization*

**NCSTAR 4-2**

*Performance of Critical Buildings*

**NCSTAR 4-3**

*Public Response to Emergency Communications*

**NCSTAR 4-4**

*Characterization of Morbidity and Mortality*

## Level 3: Contractor Reports

**Examples:**

**NCST GCR 4-1A**
*Wind-Field Modeling*

**NCST GCR 4-1B**
*Wind-Tunnel Testing*

**NCST GCR 4-1C**
*Field Measurements*

*NWIRP Reports will follow a similar structure.*

**NCSTAR:** NCST Act Report

**GCR:** Grant/Contract Report

# 4 Report Review Process

NCST and
NWIRP Reports

Created by khoirul huda from Noun Project

Project Team

Team Lead

*or*

Associate Team Lead

Subject Matter Experts

- NIST Expert
- NIST Statistician
- Outside Expert

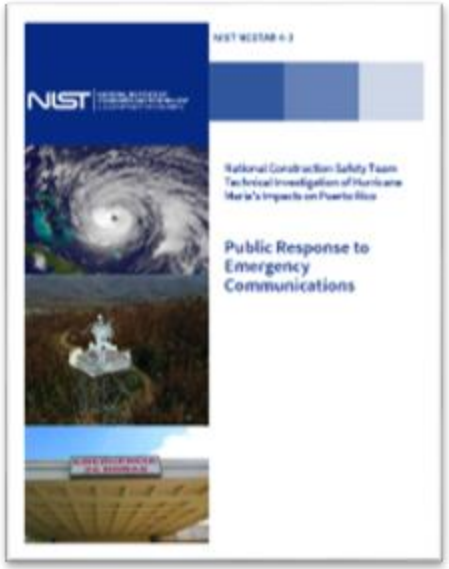
Laboratory Leadership

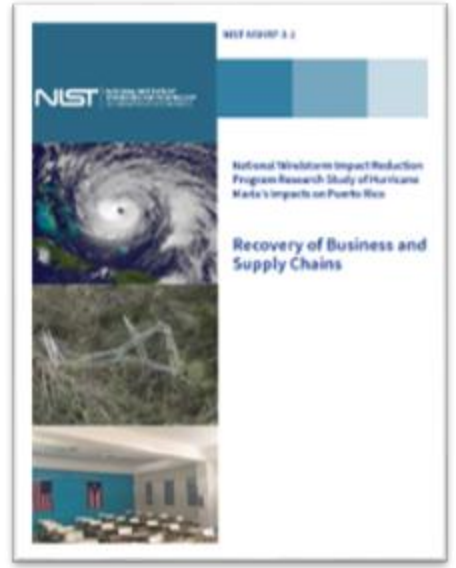
- Division Chief
- Laboratory Director

**Additional NIST and Interagency review steps follow the Engineering Laboratory review and occur prior to the release for public comment.**

# 4 Supporting Contracts

| Service Provided | Contractor | Award Date |
|---|---|---|
| Technical report preparation | FedWriters, Inc. | Dec 2024 |
| Translation/interpretation | Lighthouse Integrated Services Corp. | Jan 2025 |
| Outside expert reviewers | FedWriters, Inc. | Jan 2026 |
| Logistical support for public meetings in Puerto Rico | AECOM | Aug 2026 |



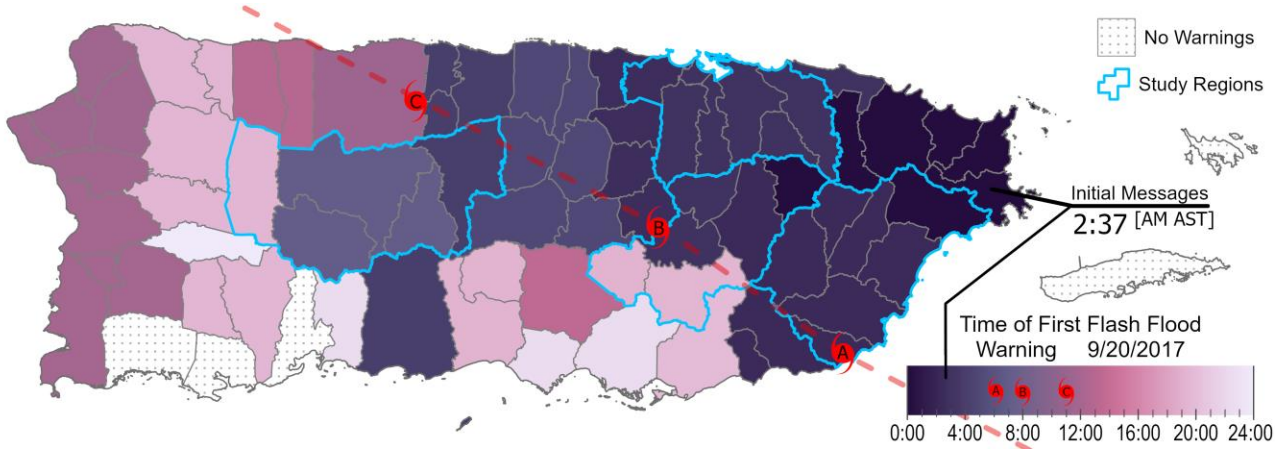
# 4 Communications and Outreach

- Planning for public release of reports is underway
- Products to support communication of technical findings are being developed:
  - **Documentary**

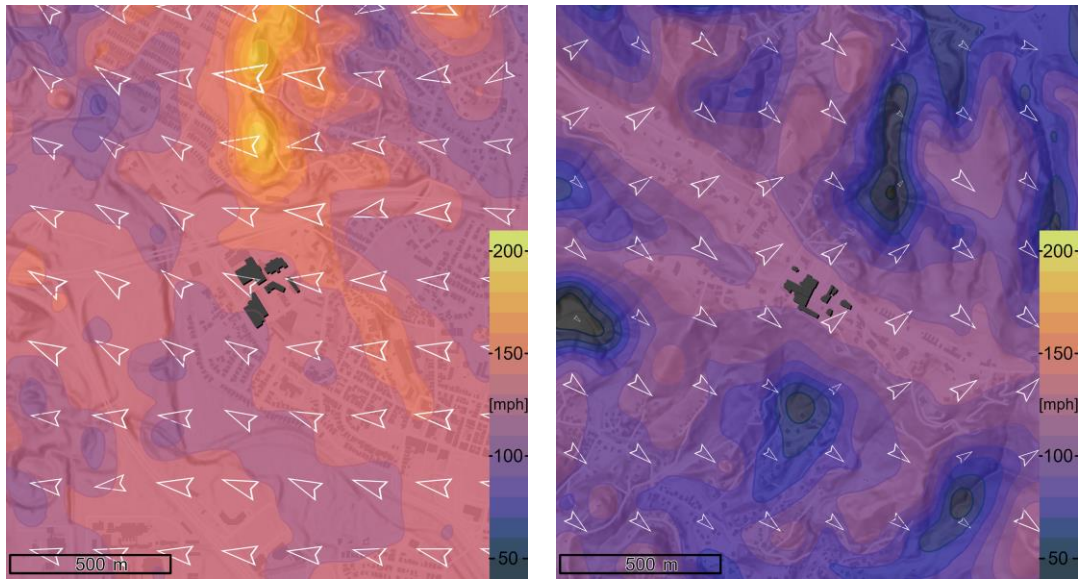
# 4 Communications and Outreach

- Planning for public release of reports is underway
- Products to support communication of technical findings are being developed:
  - Documentary
  - **ESRI StoryMaps**

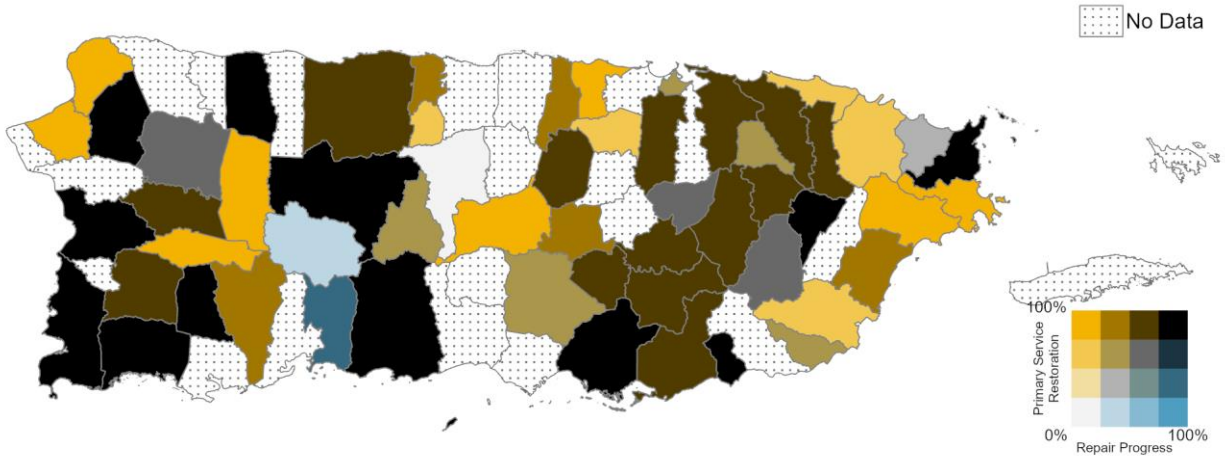
*Time of flash flood warnings*




*Wind hazard exposure at critical building sites*




*Average Primary Service Recovery after 1 year by Average Repair Progress after 1 year for Schools and Hospitals by Municipality*



# Acknowledgments

Following the ninth anniversary of Hurricane Maria's landfall in Puerto Rico, the NIST team acknowledges all those affected by the hurricane.

We especially appreciate:

- Those in Puerto Rico who responded to the data collection requests and shared knowledge, experiences, and lessons learned
- Our many partners in Puerto Rico who supported our data collection efforts
- Our dedicated team, including external experts and contractors

# NIST's Hurricane Maria Investigation

## NIST HM Information

https://www.nist.gov/hurricane-maria

## Public Meeting Videos

https://www.nist.gov/disaster-failure-studies/national-construction-safety-team-ncst/advisory-committee-meetings

## NIST DFS Portal

https://www.nist.gov/disaster-failure-studies/data-submission-portal