NIST National Construction Safety Team
Investigation of Hurricane Maria

N CST Advisory Committee Meeting – March 6, 2024

Cross-Project Panel Theme 2:
Hospital Functionality & Infrastructure Dependencies

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The Hurricane Maria NCST Investigation goals include characterizing the performance of representative critical buildings, and designated safe areas in those buildings, including their dependence on lifelines.

Hurricane Maria impacted hospital functionality through:
- Damage to building components and systems
- Disruption of supporting infrastructure

Functionality is a measure of how well a building or lifeline infrastructure system operates, delivers its required services, or meets its intended purpose (NIST SP-1254*).

Dependence on infrastructure was a major theme, both for the hospitals’ ability to provide services as well as the ability of people to access healthcare.

* https://doi.org/10.6028/NIST.SP.1254
Emergency Communications
Surveys with households (1523 households)
Interviews with information providers (35 providers)

Morbidity and Mortality
Interviews with hospital administrators and clinical staff (6 hospitals; 30 respondents)

Critical Buildings
Interviews with hospital engineers or administrators (5 hospitals)

Recovery of Social Functions
Surveys with hospital administrators (16 hospitals)
Interviews with hospital administrators (ongoing)

Recovery of Infrastructure
PR DTOP road network & events (6710 events)
NASA Black Marble nighttime lights product for PR

Recovery of Business
Surveys with businesses (451 businesses)
Interviews with shipping and transportation operators (30 respondents)
Hospital Building Performance & Functionality

What were the prevalent types of damage and sources of water intrusion in hospital buildings?

How did water intrusion impact hospital functionality?

Infrastructure Dependencies for Hospitals & Healthcare Access

How did disruptions of the transportation network affect hospital functionality and healthcare access?

How did disruptions of the electric power network affect hospital functionality and healthcare access?
Common themes observed across projects:

- Wind and wind-borne debris caused damage to building envelopes
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- Wind and wind-borne debris caused damage to building envelopes
- Damage to building envelopes allowed intrusion of rainwater
Common themes observed across projects:

- Wind and wind-borne debris caused damage to building envelopes
- Damage to building envelopes allowed intrusion of rainwater
- Water intrusion damaged equipment/contents and forced relocation of patients/staff
Hospital Building Performance and Functionality

Common themes observed across projects:

- envelope damage
- rainwater intrusion
- equipment damage

Morbidity and Mortality

Hospital personnel interviews:

All hospital personnel, across most sampled facilities, reported significant physical and structural damage to the facilities, particularly window and door damages, roof sheathing failures, and significant parts of the roofs being blown off, which in most buildings allowed substantial rainwater leakage and winds to impact patient rooms, and flooding and destruction in various parts of the hospital, including in ICUs and EDs. This forced the emergency transfer of patients, some in critical condition, to the hallways and other floors.
Hospital Building Performance & Functionality

What were the prevalent types of damage and sources of water intrusion in hospital buildings?

How did water intrusion impact hospital functionality?

Infrastructure Dependencies for Hospitals & Healthcare Access

How did disruptions of the transportation network affect hospital functionality and healthcare access?

How did disruptions of the electric power network affect hospital functionality and healthcare access?
Sources of Rainwater Intrusion

Critical Buildings

*Hospital personnel interviews:*

- All 5 hospitals experienced significant rainwater intrusion
- Most prevalent sources of rainwater intrusion:
  - Leaking roof covering and/or decking
  - Windows or doors with broken glass
  - Damaged or dislodged rooftop equipment
- Less prevalent pathways:
  - Windows or doors with leaking seals
  - Windows or doors with damage that prevented closure
  - Undamaged windows or doors (e.g., jalousie windows)
  - Damaged walls
Critical Buildings

Hospital personnel interviews:

All 4 of the responding hospitals reported a “large” amount of rainwater intrusion through leaking roof covering and/or decking.

<table>
<thead>
<tr>
<th>Source of Rainwater Entry</th>
<th>Amount of Rainwater Intrusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leaking Roof Covering and/or Decking</td>
<td>small</td>
</tr>
</tbody>
</table>

(H-5 experienced riverine flooding; staff could not identify sources of rainwater intrusion.)

H-4: Due to the wind speed at the roof, the membrane, and the thermal insulation of the main building with its metal roof were torn off, facilitating the entry of rainwater into the building.

Morbidity and Mortality

Hospital personnel interviews:

H-21: Hurricane Maria severely impacted the hospital roof; the waterproofing layer was blown off and rainwater entered in large quantities.
Sources of Rainwater Intrusion
Damage to Roof Covering and/or Decking

Recovery of Social Functions

*Hospital survey results:*

More than two-thirds of hospital respondents indicated roof cover damage affecting 25% or more of the total area

Recovery of Business

*Business recovery survey results:*

70% of retail service firms reported that water entered through the roof:

- Any part of the roof gone**: 40%
- Roof need to be patched or replaced: 58%
- Water entered through the roof: 70%

**of yes responses, 57% “could see the sky”

82% of manufacturing firms (n = 17) reported roof damage

PRELIMINARY ANALYSIS
Critical Buildings
*Hospital personnel interviews:*

2 of the 4 responding hospitals reported a “large” amount of rainwater intrusion through windows or doors with broken glass:

<table>
<thead>
<tr>
<th>Source of Rainwater Entry</th>
<th>Amount of Rainwater Intrusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windows or Doors with Broken Glass</td>
<td><img src="chart.png" alt="Chart" /></td>
</tr>
</tbody>
</table>

(H-5 experienced riverine flooding; staff could not identify sources of rainwater intrusion.)

Morbidity and Mortality
*Hospital personnel interviews:*

H-17: The hospital suffered considerable physical damage; the wind broke many windows and impacted emergency doors, which caused rooms and various hospital areas to be flooded

Recovery of Social Functions
*Hospital survey results:*

More than half of the surveyed hospitals had “several” windows/doors damaged by Hurricane Maria; the remainder had a “few.”

<table>
<thead>
<tr>
<th>Recovery Level</th>
<th>None</th>
<th>Few</th>
<th>Several</th>
<th>Most or All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Hospitals</td>
<td>0%</td>
<td>46%</td>
<td>54%</td>
<td>0%</td>
</tr>
</tbody>
</table>
Critical Buildings

Hospital personnel interviews:

All 4 of the responding hospitals reported a “moderate” amount of rainwater intrusion through damaged or dislodged rooftop equipment:

<table>
<thead>
<tr>
<th>Source of Rainwater Entry</th>
<th>Amount of Rainwater Intrusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage or Dislodged</td>
<td>small</td>
</tr>
<tr>
<td>Rooftop Equipment</td>
<td></td>
</tr>
</tbody>
</table>

(H-5 experienced riverine flooding; staff could not identify sources of rainwater intrusion.)

Rooftop equipment observations for businesses:

Recovery of Business

Business recovery survey results:

58% of manufacturing firms (n = 17) reported damaged or dislodged rooftop equipment
Hospital Building Performance & Functionality

What were the prevalent types of damage and sources of water intrusion in hospital buildings?

How did water intrusion impact hospital functionality?

Infrastructure Dependencies for Hospitals & Healthcare Access

How did disruptions of the transportation network affect hospital functionality and healthcare access?

How did disruptions of the electric power network affect hospital functionality and healthcare access?
**Impacts of Water Intrusion**

**Forced Relocation of Patients and Staff**

**Critical Buildings**

*Hospital personnel interviews:*

- 3 of the 5 hospitals indicated that penetration of physical hazards had a “severe” impact on hospital functionality.
- 3 of the 5 hospitals indicated that patients had to be moved from one part of the facility to another because of floodwater.

**Contributing Factor**

<table>
<thead>
<tr>
<th>Penetration of Physical Hazards</th>
<th>Severity of Impact on Functionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-1, H-2, H-3, H-4, H-5</td>
<td>none, minor, moderate, severe</td>
</tr>
</tbody>
</table>

**H-1**: Due to excessive water ingress into the emergency area, all ER occupants moved to areas where work could be done. Rainwater entered all areas within the facility.

**Morbidity and Mortality**

*Hospital personnel interviews:*

- H-19: The roof was unable to withstand HM winds and rain; this led to flooding of the upper floors and forced the closure of the ICU and other areas and evacuation of patients to lower floors and the ED.
Impacts of Water Intrusion
Damage to Interior Contents and Equipment

Critical Buildings
*Hospital personnel interviews:*

- 4 of the 5 hospitals reported loss of function for elevators, making it challenging to move patients when required
- 2 of the 5 hospitals reported that damage to electrical/mechanical systems had a “severe” impact on functionality
- 1 of the hospitals reported that damage to interior finishes and contents had a “severe” impact on functionality

Morbidity and Mortality
*Hospital personnel interviews:*

Patient movement was very difficult for four of the hospitals because they had problems with their elevators, due to limited electric power generator capacity, flooding in the elevator machine room, or due to a fire causing temporary loss of electrical power.

H-10: The major infrastructure problem was the breakage of a door on the roof, which caused the elevator machine room to flood, causing the elevators to stop working.

<table>
<thead>
<tr>
<th>Contributing Factor</th>
<th>Severity of Impact on Functionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage to Electrical/Mechanical Systems</td>
<td>none minor moderate severe</td>
</tr>
<tr>
<td>H-1</td>
<td>none</td>
</tr>
<tr>
<td>H-2</td>
<td>minor</td>
</tr>
<tr>
<td>H-3</td>
<td>moderate</td>
</tr>
<tr>
<td>H-4</td>
<td>severe</td>
</tr>
<tr>
<td>H-5</td>
<td>severe</td>
</tr>
<tr>
<td>Damage to Interior Finishes and Contents</td>
<td>none minor moderate severe</td>
</tr>
<tr>
<td>H-1</td>
<td>none</td>
</tr>
<tr>
<td>H-2</td>
<td>minor</td>
</tr>
<tr>
<td>H-3</td>
<td>moderate</td>
</tr>
<tr>
<td>H-4</td>
<td>severe</td>
</tr>
<tr>
<td>H-5</td>
<td>severe</td>
</tr>
</tbody>
</table>
Impacts of Water Intrusion
Damage to Interior Contents and Equipment

Recovery of Social Functions
Hospital survey results:

• 61% of surveyed hospitals reported damage to interior contents and inventory as either “moderate,” “severe,” or “complete loss”
• 62% of surveyed hospitals reported damage to machinery/equipment as either “moderate,” “severe,” or “complete loss”

<table>
<thead>
<tr>
<th>Damage Category</th>
<th>Minor</th>
<th>Moderate</th>
<th>Severe</th>
<th>Complete Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contents/inventory</td>
<td>31%</td>
<td>38%</td>
<td>8%</td>
<td>15%</td>
</tr>
<tr>
<td>Machinery/equipment</td>
<td>15%</td>
<td>23%</td>
<td>31%</td>
<td>8%</td>
</tr>
</tbody>
</table>

Recovery of Social Functions
Hospital interview responses:

H154: “There was an electrical issue caused by the river water because, when it got flooded, we had floating pumps, but when E1 and E2 flooded, the pumps were submerged under water, something we didn’t expect either, and we lost power. ...Running out of electricity at six o’clock in the evening was already a disaster because we had neither electricity nor running water.”

H154: “What we did not have was, obviously, due to the water damage in the operating room, the medical gas system ...since the medical gas system was flooded, we could not offer the service...”
Hospital Building Performance & Functionality

What were the prevalent types of damage and sources of water intrusion in hospital buildings?

How did water intrusion impact hospital functionality?

Infrastructure Dependencies for Hospitals & Healthcare Access

How did disruptions of the transportation network affect hospital functionality and healthcare access?

How did disruptions of the electric power network affect hospital functionality and healthcare access?
Recovery of Infrastructure

Network Modeling:

- Using PR DTOP road database (left figure), an *inaccessibility index* was computed for hospitals (right figure).
  - Index calculated based on estimated minimum travel time to hospital with assumed travel speeds for each road segment, and ideal conditions with no congestion.
  - *Hospital access* is equated with connectivity to hospitals; 0% of roads, it is assumed, were disrupted before Maria.
  - “Poor” hospital access here is inaccessibility index greater than 1 (an index of 1 is a travel time of 1 h in ideal conditions).
  - Pre-Maria % of road segments disrupted and % of the population with no or poor access are computed.

Pre-Maria

Puerto Rico road network (Source: PR DTOP)

Inaccessibility index

- 0% of road segments disrupted
- 1.5% have poor to no access
  - No (0.0%)
  - Poor (1.5%)
Recovery of Infrastructure

Network Modeling:

- Network disruptions are simulated by breaking road segments based on events; then connectivity and hospital access are recalculated
  - For "immediately" after landfall, events are drawn from the PR DTOP Transportation Event Database
  - For one month after, road status is taken from PR DTOP Road Status database

Immediately after Maria

- 30% of road segments disrupted
- 54% have poor to no access
  - No (51%)
  - Poor (2.7%)

1 month after Maria

- 20% of road segments disrupted
- 16% have poor to no access
  - No (12%)
  - Poor (4.4%)
Transportation Disruptions: Local Perspective

Critical Buildings
Hospital personnel interviews:
- 4 of the 5 hospitals experienced disruption of roadway access
- Factors contributing to the disruption of road access included:
  - Flooding of Roadways (3 of 5)
  - Fallen Trees & Other Debris (3 of 5)
  - Landslides (2 of 5)
- 3 of 5 hospitals reported that disruption of road access had a severe effect on functionality:

<table>
<thead>
<tr>
<th>Contributing Factor</th>
<th>Severity of Impact on Functionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disruption of Road Access</td>
<td>none</td>
</tr>
<tr>
<td>H-1</td>
<td></td>
</tr>
<tr>
<td>H-2</td>
<td></td>
</tr>
<tr>
<td>H-3</td>
<td></td>
</tr>
<tr>
<td>H-4</td>
<td></td>
</tr>
<tr>
<td>H-5</td>
<td></td>
</tr>
</tbody>
</table>

Morbidity and Mortality
Hospital personnel interviews:

H-4: Due to the damage caused by HM to the roads and communication system, many patients in the mountainous region did not have access to the hospital.

H-10: During HM’s landfall, the implementation of the emergency plan faced difficulties; due to road damage, landslides and floods, since some personnel were unable to get to the hospital in time to relieve their colleagues.

H-34: Access roads to the hospital were blocked, due to flooding and downed power lines; it was impossible for patients to enter or leave; staff went out to the road to pick up patients to take them into the ED.
Hospital Building Performance & Functionality

What were the prevalent types of damage and sources of water intrusion in hospital buildings?

How did water intrusion impact hospital functionality?

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How did disruptions of the electric power network affect hospital functionality and healthcare access?
Electric Power Disruptions: Island-Wide Perspective

Recovery of Infrastructure

*NASA Black Marble dataset:*

Hospitals were located in barrios that experienced an average of 100 days without electricity, lower than the island-wide average of 115 days.

Barrio-level estimate of the Number of Days Without Electricity (NDWE), based on NASA’s Black Marble nighttime lights product suite (VNP46)


Power disruptions for businesses:

**Recovery of Business**

*Business recovery survey:*

97.1% of surveyed businesses lost electrical power (n = 451)

Days until electric power was restored:
- Mean: 98.2 days
- Median: 90.0 days
Electric Power Disruptions: Local Perspective

Critical Buildings
Hospital personnel interviews:
- All 5 hospitals experienced disruption of electric power service
- All 5 hospitals reported that loss of electric power had a “severe” impact on functionality

**Contributing Factor**

<table>
<thead>
<tr>
<th>Loss of electric power</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-1</td>
</tr>
</tbody>
</table>

**Severity of Impact on Functionality**

- none
- minor
- moderate
- severe

H-5: The loss of electrical power affected the operation and comfort of the facility's operations... The generators are only used to power the lighting circuits and some small air conditioners located in certain offices, as they lack the capacity to power the hospital's air conditioning systems or operate the elevators, leaving the hospital without vertical movement. As a result, the hospital operates without air conditioning, and the movement of ... patients located on the second floor is hampered.

Morbidity and Mortality
Hospital personnel interviews:
- 2 of 6 the hospitals reported insufficient power generation capacity that affected air conditioning systems, exposing patients and staff to high heat and humidity
- The other 4 hospitals largely maintained functioning power generation systems throughout Hurricane Maria's landfall and for the two weeks after, with some temporary interruptions

H-34: After the impact of HM, the need to transfer patients out of the hospital increased, due to lack of electric power generation and air conditioning causing a very difficult environmental situation of high heat and humidity.
Emergency Communications

Household survey results:

Survey question: Within the first two weeks after Hurricane Maria, did you or anyone in your household have difficulty accessing healthcare services for any of the following reasons? About 14% said yes.

Among those, two reasons for difficulty include:

<table>
<thead>
<tr>
<th>Reason</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hospital closed</td>
<td>15-20%</td>
</tr>
<tr>
<td>Hospital not accepting patients/lacking key services</td>
<td>40-45%</td>
</tr>
</tbody>
</table>

Emergency Communications

Information provider interview quotes:

"Being able to communicate which facilities were available and which were not became a matter of life or death. We needed to inform the audience about the actual situation in hospitals."

"...when there’s heat and no electricity, we must try to avoid health complications, because going to a hospital in the midst of an emergency like that is almost the worst thing you can do. For example, we found that hospitals became hotbeds for sepsis because there was no air conditioning and bacteria spread."

From respondent #16
Questions?

Theme 1: Hazard Exposure

Theme 2: Hospital Functionality & Infrastructure Dependencies

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Theme 3: Protective Action & Preparedness

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