

# NIST National Construction Safety Team Investigation of Hurricane Maria

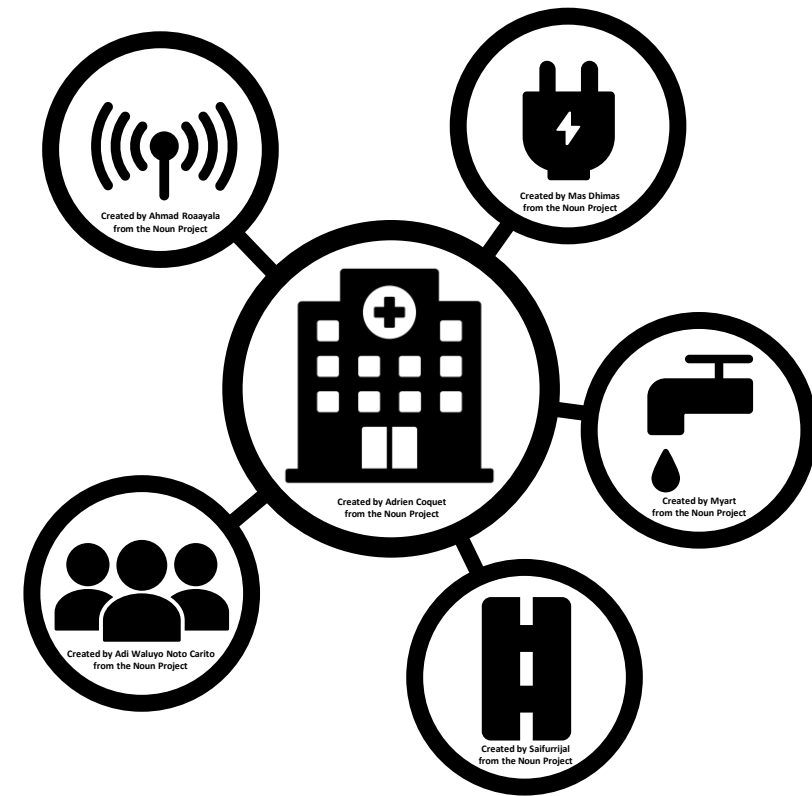
*NCST Advisory Committee Meeting – March 6, 2024*

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

*Maria Dillard, Joseph Main, Ken Harrison*

## Motivation

- 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>

# Hospital Functionality & Infrastructure Dependencies

## Integration of Data Streams

### Data streams featured in Cross-Project Panel Theme 2:

#### Emergency Communications

Surveys with households  
(1523 households)  
Interviews with information  
providers (35 providers)



Created by Rodrigo Ramirez  
from Noun Project

#### Morbidity and Mortality

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



Created by Karim Tegalsari  
from Noun Project

#### Recovery of Social Functions

Surveys with hospital administrators  
(16 hospitals)  
Interviews with hospital  
administrators (ongoing)



Created by Matthias Hartmann  
from Noun Project

#### Critical Buildings

Interviews with hospital engineers or  
administrators  
(5 hospitals)



Created by Adrien Coquet  
from the Noun Project

#### Recovery of Infrastructure

PR DTOP road network & events  
(6710 events)  
NASA Black Marble night-  
time lights product for PR



#### Recovery of Business

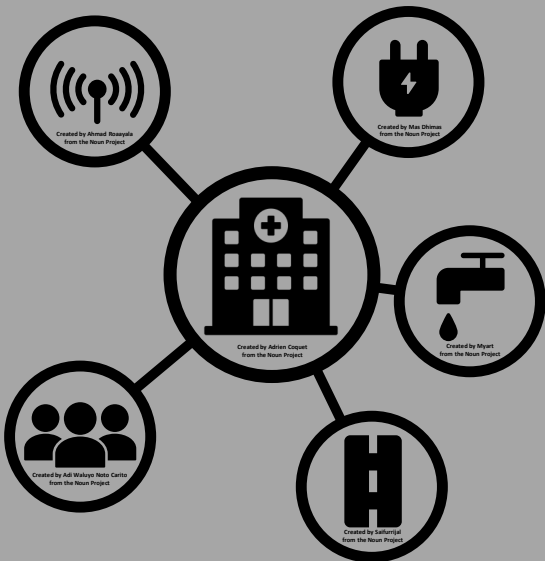
Surveys with businesses  
(451 businesses)  
Interviews with shipping and  
transportation operators  
(30 respondents)



Created by Matthias Hartmann  
from Noun Project

# Hospital Functionality & Infrastructure Dependencies

## Integration of Analysis



### Hospital Building Performance & Functionality

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

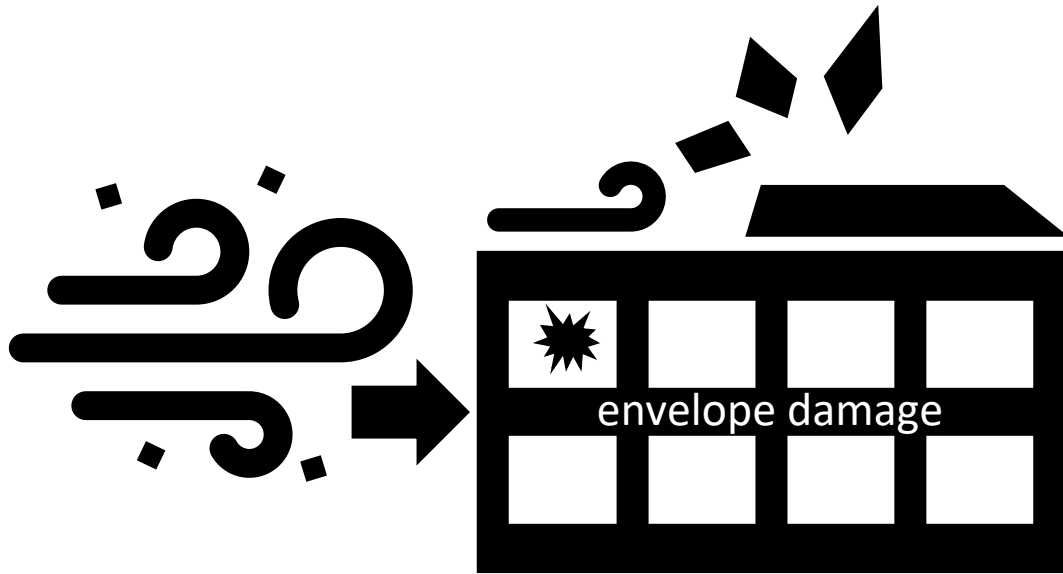
How did water intrusion impact hospital functionality?

### Infrastructure Dependencies for Hospitals & Healthcare Access

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

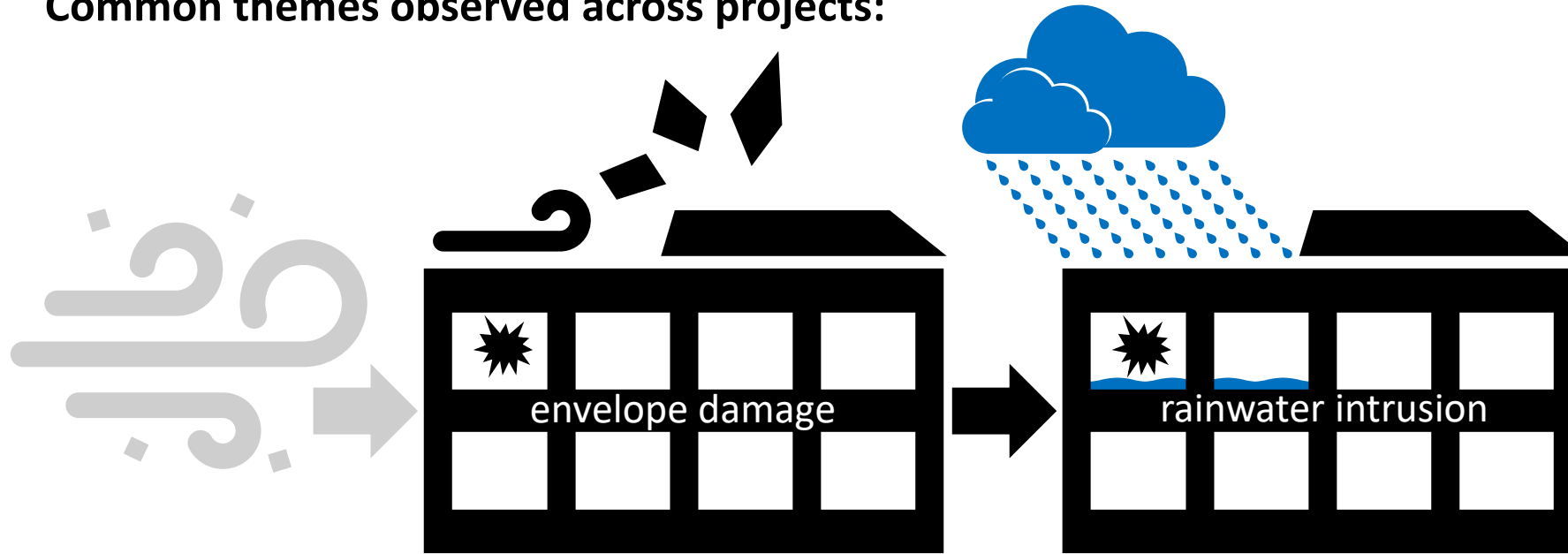
How did disruptions of the electric power network affect hospital functionality and healthcare access?

Common themes observed across projects:



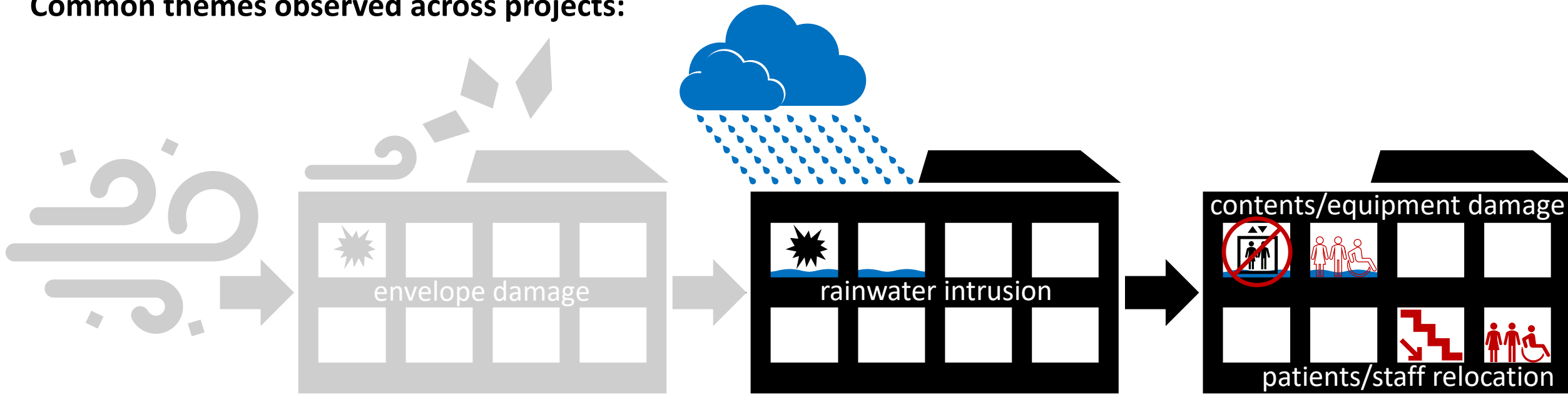
- Wind and wind-borne debris caused damage to building envelopes

Common themes observed across projects:



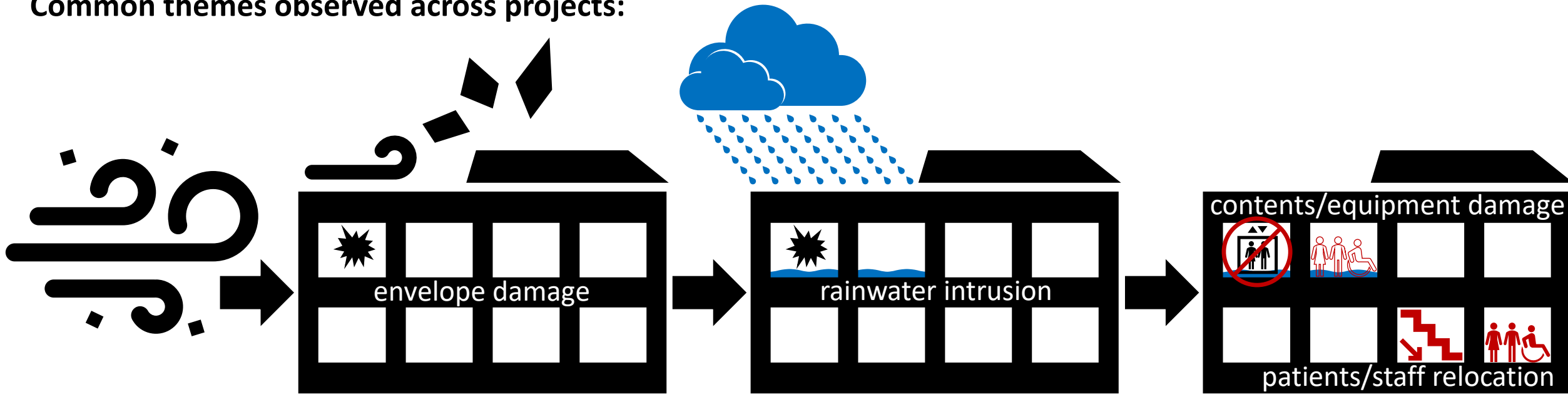
- Wind and wind-borne debris caused damage to building envelopes
- **Damage to building envelopes allowed intrusion of rainwater**

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**

Common themes observed across projects:



## Morbidity and Mortality

### *Hospital personnel interviews:*

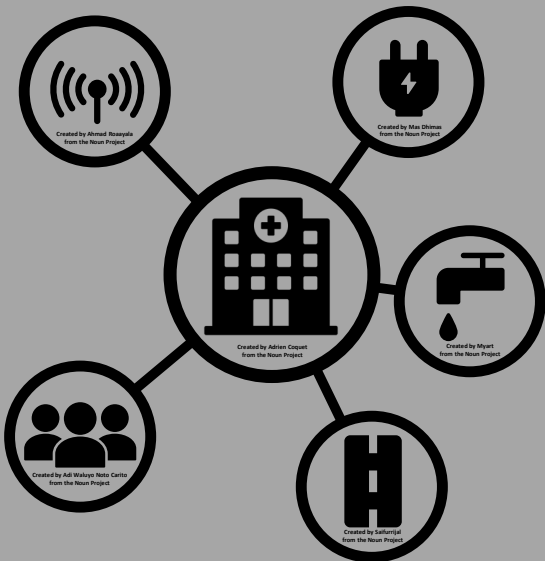
All hospital personnel, across most sampled facilities, reported significant physical and structural damage to the facilities, particularly window and door damages, roof sheathing failures, and significant parts of the roofs being blown off, which in most buildings allowed substantial rainwater leakage 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.



Created by Karim Teghan  
from NIST Project



## Integration of Analysis



### 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

Damaged  
Roof Covering



Windows with  
Broken Glass



Damaged/Dislodged  
Rooftop Equipment



# Sources of Rainwater Intrusion

## Damage to Roof Covering and/or Decking

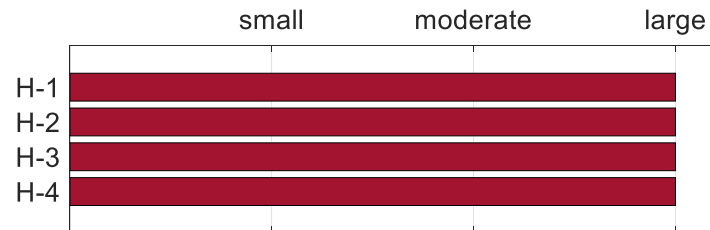
### Critical Buildings

#### Hospital personnel interviews:



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

Source of Rainwater Entry	Amount of Rainwater Intrusion
Leaking Roof Covering and/or Decking	small
	moderate
	large
	H-1
	H-2
H-3	
H-4	



(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

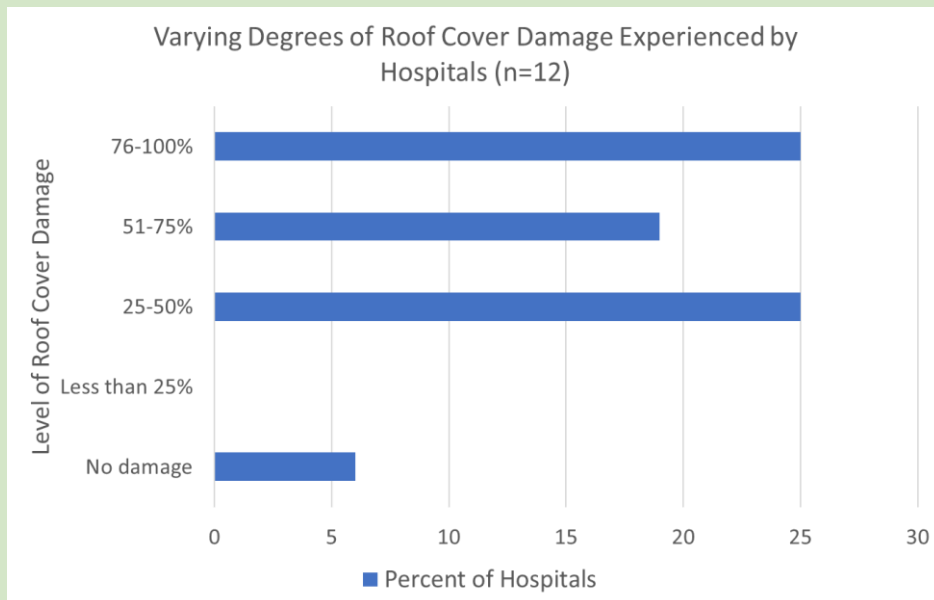
## Damage to Roof Covering and/or Decking

### 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



### Roof damage observations for businesses:

### Recovery of Business

#### Business recovery survey results:



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

Retail/Service firms (n=272)	
	Responding 'yes'
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

# Sources of Rainwater Intrusion

## Damage to Windows and Doors

### Critical Buildings

#### Hospital personnel interviews:



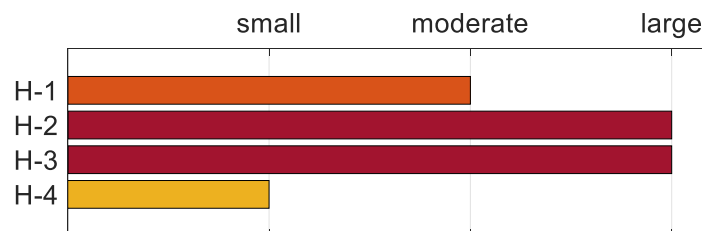
Created by Adrien Coquet from the Noun Project

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

#### Source of Rainwater Entry

#### Amount of Rainwater Intrusion

Windows or Doors with Broken Glass



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



### Morbidity and Mortality

#### Hospital personnel interviews:



Created by Karim Tegabari from Noun Project

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:



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

None	Few	Several	Most or All
0%	46%	54%	0%

**PRELIMINARY ANALYSIS**

# Sources of Rainwater Intrusion

## Damage to Rooftop Equipment

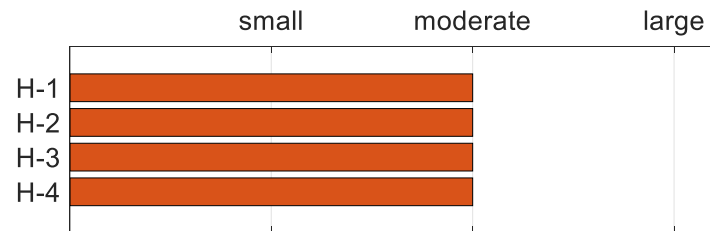
### Critical Buildings

#### *Hospital personnel interviews:*



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

Source of Rainwater Entry	Amount of Rainwater Intrusion		
	small	moderate	large
Damage or Dislodged Rooftop Equipment	H-1	[Orange bar]	
	H-2	[Orange bar]	
	H-3	[Orange bar]	
	H-4	[Orange bar]	



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



### Rooftop equipment observations for businesses:

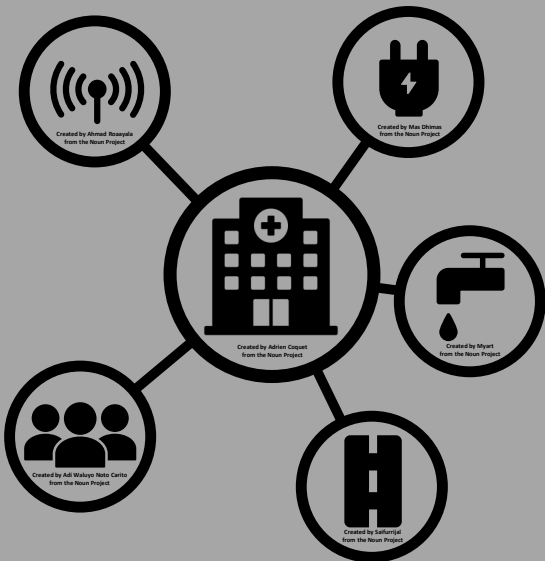
#### Recovery of Business

#### *Business recovery survey results:*



58% of manufacturing firms (n = 17) reported damaged or dislodged rooftop equipment

## Integration of Analysis



### 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?

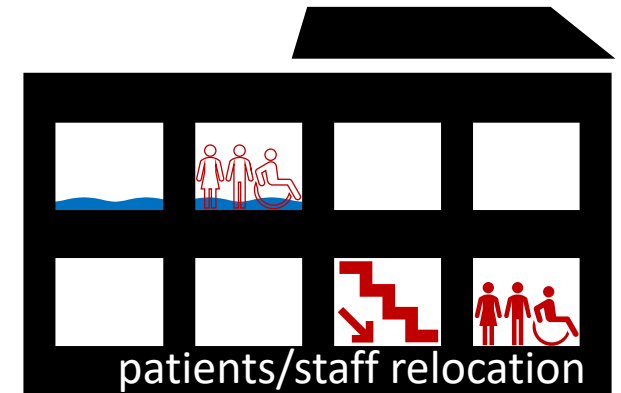
How did disruptions of the electric power network affect hospital functionality and healthcare access?

### Critical Buildings

#### Hospital personnel interviews:

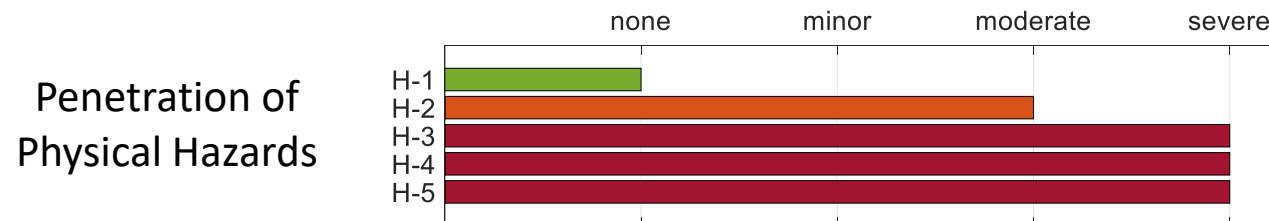


- 3 of the 5 hospitals indicated that penetration of physical hazards had a “severe” impact on hospital functionality
- 3 of the 5 hospitals indicated that patients had to be moved from one part of the facility to another because of floodwater



#### Contributing Factor

#### Severity of Impact on Functionality



*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.*



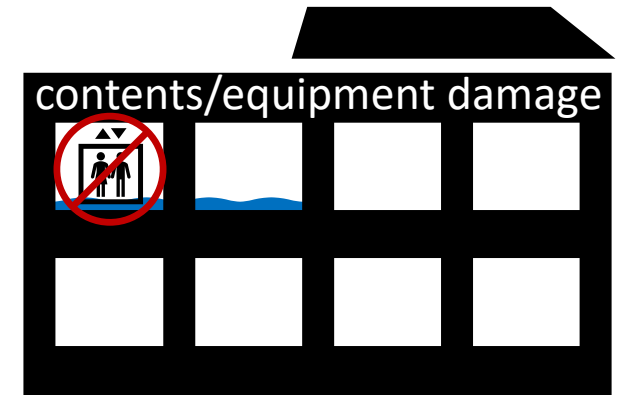
### Critical Buildings

#### 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

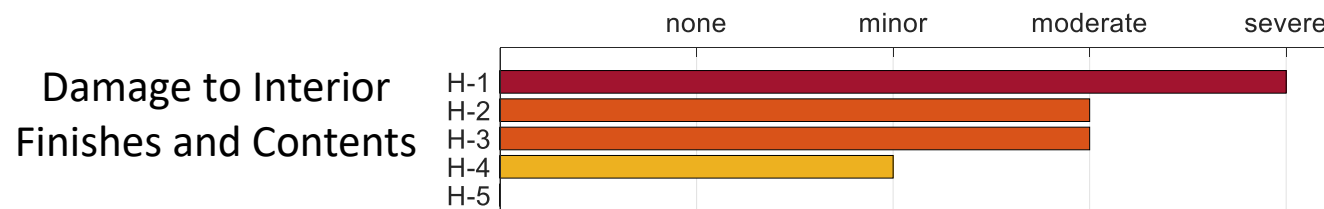
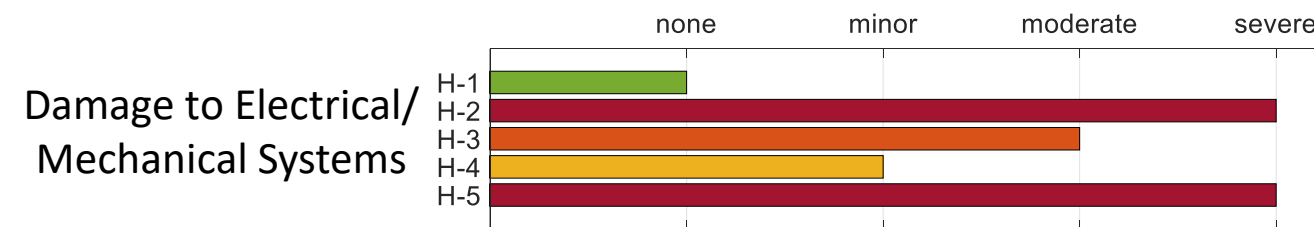


Created by Adrian Coquet from the Hour Project



#### Contributing Factor

#### Severity of Impact on Functionality



### Morbidity and Mortality

#### Hospital personnel interviews:



Created by Kantor Tegahan from the Hour Project

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.*

### Recovery of Social Functions

#### *Hospital survey results:*



Created by Matthias Hartmann  
from Nost Project

- 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”

<i>Damage Category</i>	<i>Minor</i>	<i>Moderate</i>	<i>Severe</i>	<i>Complete Loss</i>
<b>Contents/inventory</b>	31%	38%	8%	15%
<b>Machinery/equipment</b>	15%	23%	31%	8%

### Recovery of Social Functions

#### *Hospital interview responses:*



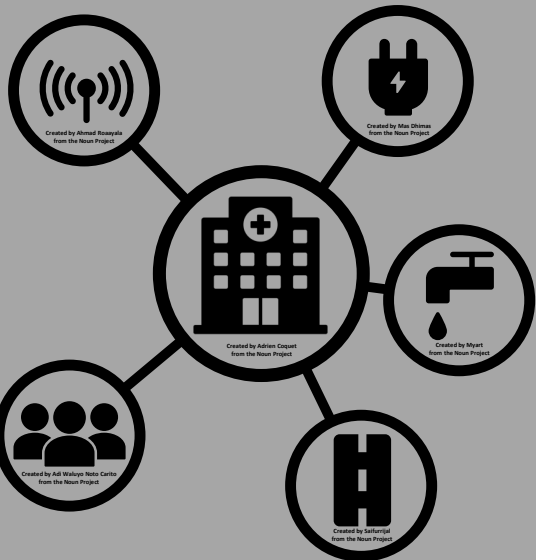
Created by Matthias Hartmann  
from Nost Project

*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 Functionality & Infrastructure Dependencies

## Integration of Analysis



### 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?

# Transportation Disruptions: Network Perspective

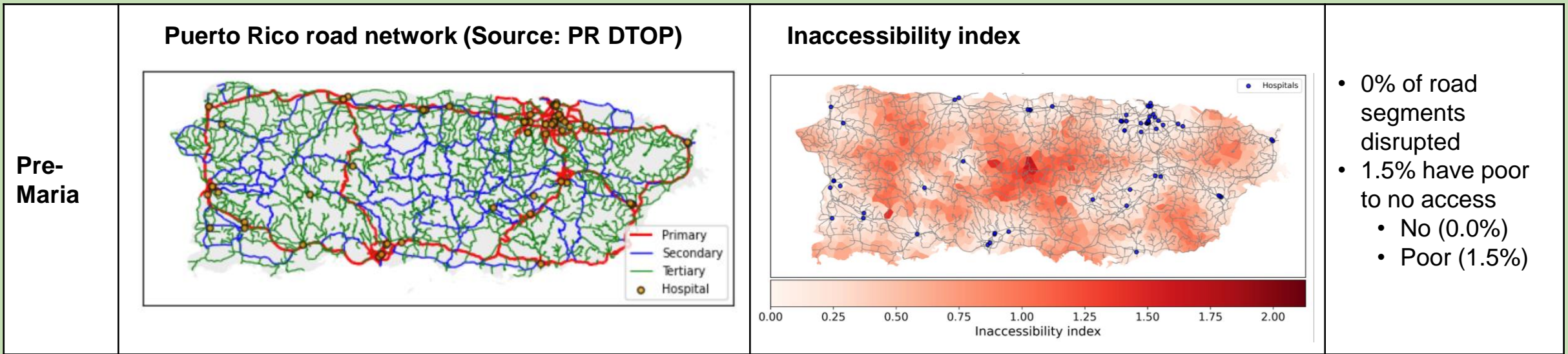
## Recovery of Infrastructure

### 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



PRELIMINARY ANALYSIS



# Transportation Disruptions: Network Perspective



## 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

**PRELIMINARY ANALYSIS**

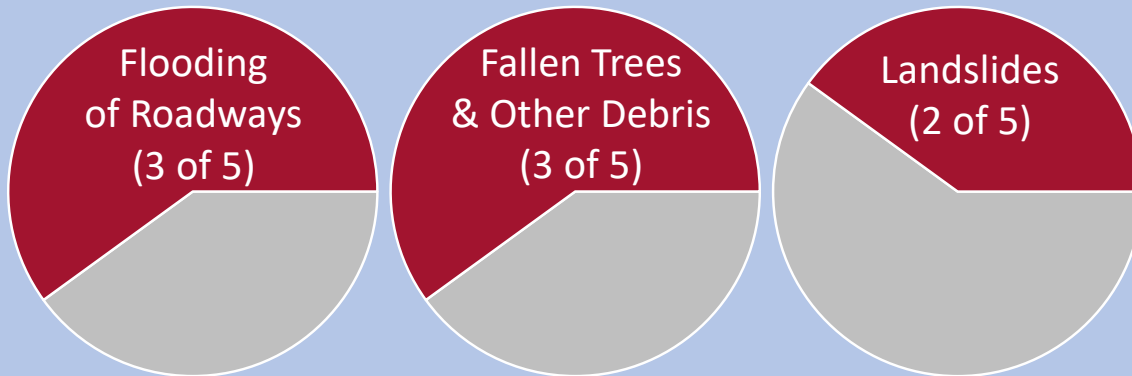
<p><b>Immediately after Maria</b></p>			<ul style="list-style-type: none"> <li>• 30% of road segments disrupted</li> <li>• 54% have poor to no access                             <ul style="list-style-type: none"> <li>• No (51%)</li> <li>• Poor (2.7%)</li> </ul> </li> </ul>
<p><b>1 month after Maria</b></p>			<ul style="list-style-type: none"> <li>• 20% of road segments disrupted</li> <li>• 16% have poor to no access                             <ul style="list-style-type: none"> <li>• No (12%)</li> <li>• Poor (4.4%)</li> </ul> </li> </ul>

# 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:



- 3 of 5 hospitals reported that disruption of road access had a severe effect on functionality:

Contributing Factor	Severity of Impact on Functionality			
	none	minor	moderate	severe
Disruption of Road Access	H-1	Severe		
	H-2	Severe		
	H-3	Moderate		Severe
	H-4	Minor	Severe	
	H-5	Severe		



Created by Adrien Couquet from the Noun Project

## Morbidity and Mortality

### Hospital personnel interviews:



Created by Kenfor Tegabart from Noun Project

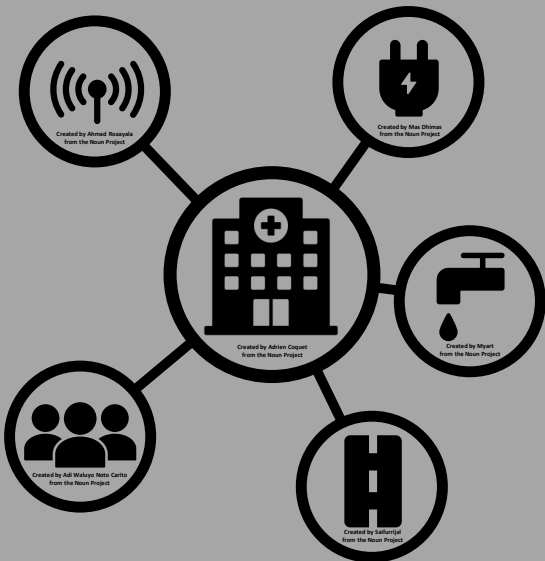
*H-4: Due to the damage caused by HM to the roads and communication system, many patients in the mountainous region did not have access to the hospital.*

*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 Functionality & Infrastructure Dependencies

## Integration of Analysis



### 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

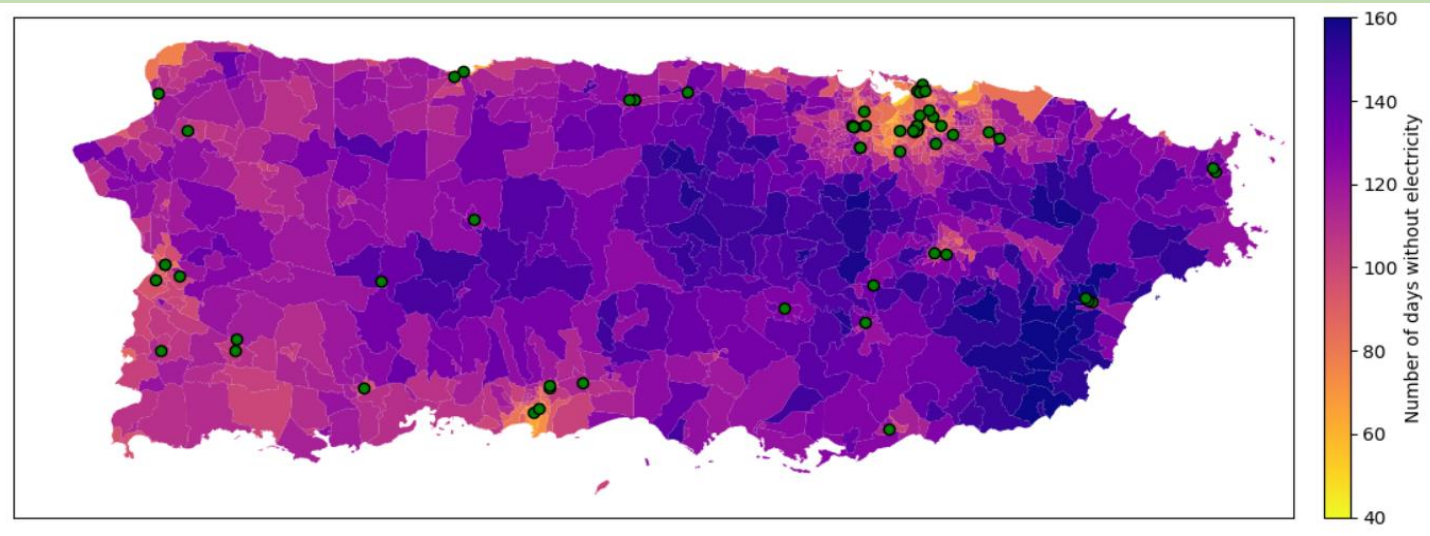
How did disruptions of the transportation network affect hospital functionality and healthcare access?

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

## Recovery of Infrastructure

*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)

Román MO, Stokes EC, Shrestha R, Wang Z, Schultz L, Carlo EAS, Sun Q, Bell J, Molthan A, Kalb V, Ji C, Seto KC, McClain SN, Enenkel M (2019) Satellite-based assessment of electricity restoration efforts in Puerto Rico after Hurricane Maria. PLOS ONE 14(6):e0218883. <https://doi.org/10.1371/journal.pone.0218883>

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



## 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



Created by Adrian Coquet from the Noun Project

### Contributing Factor

### Severity of Impact on Functionality

	none	minor	moderate	severe
Loss of electric power				████████████████████
H-1				████████████████████
H-2				████████████████████
H-3				████████████████████
H-4				████████████████████
H-5				████████████████████

*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:



Created by Karim Teghaoui from Noun Project

- 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:*



Created by Rodrigo Ramirez from Noun Project

**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:**

Hospital closed	15-20 %
Hospital not accepting patients/ lacking key services	40-45%

## Emergency Communications

### *Information provider interview quotes:*



Created by Rodrigo Ramirez from Noun Project

*"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?

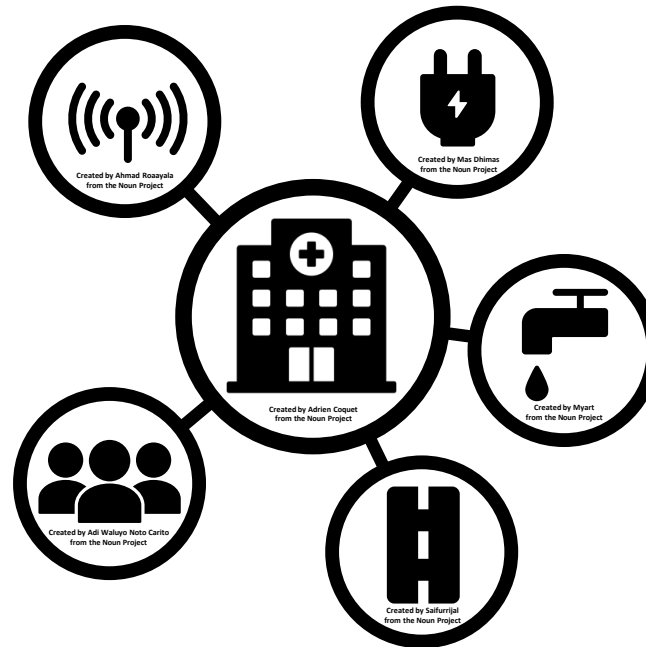
## Theme 1: Hazard Exposure



Created by Arthur Shlain  
from the Noun Project

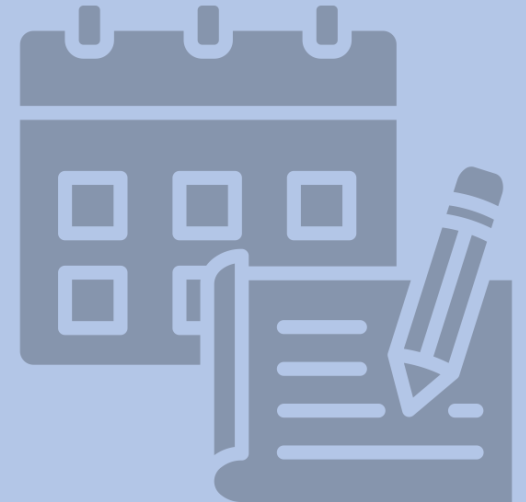
*DongHun Yeo, Marc Levitan,  
Maria Dillard*

## Theme 2: Hospital Functionality & Infrastructure Dependencies



*Maria Dillard, Joseph Main,  
Ken Harrison*

## Theme 3: Protective Action & Preparedness



Created by Good Father  
from Noun Project

*Jennifer Helgeson, Katherine Johnson,  
Marc Levitan, Judith Mitrani-Reiser*