NIST National Construction Safety Team Investigation of Hurricane Maria

NCST Advisory Committee Meeting – March 6, 2024

Cross-Project Panel Theme 1: Hazard Exposure

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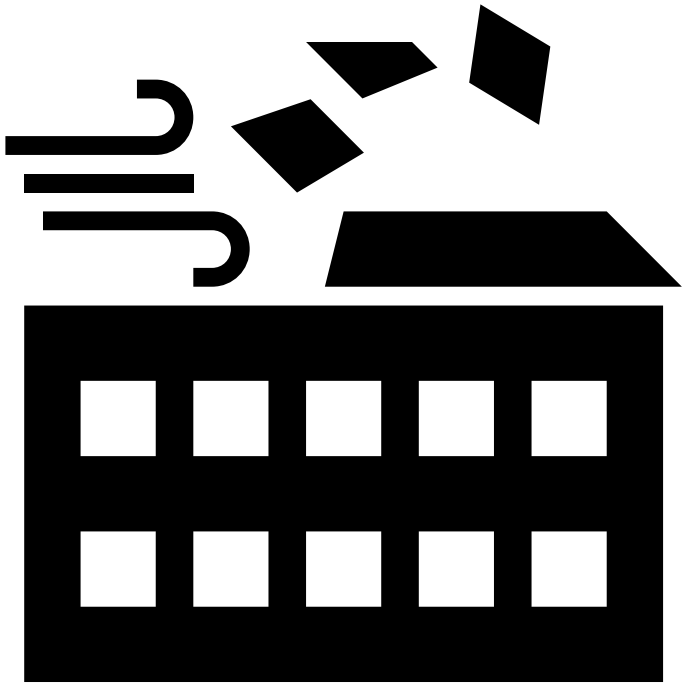
NIST | NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

Motivation

- The Hurricane Maria NCST Investigation goals include characterizing the wind environment and technical conditions associated with deaths and injuries.
- In addition to extreme winds, Hurricane Maria subjected Puerto Rico to heavy rainfall, flooding, and landslides.
- Geospatial linkage of hazard information across projects is important to support analyses of Hurricane Maria's effects on Puerto Rico and the subsequent recovery.



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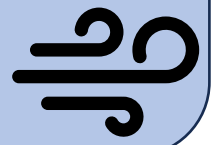
Integration of Data Streams

Data streams featured in Cross-Project Panel Theme 1:

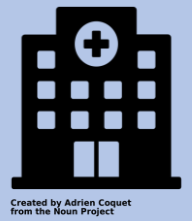
Hazard Characterization
Wind-field model
Rainfall dataset & regression model
Landslide density
Flood model



Emergency Communications
Surveys with households
(1523 households)

Recovery of Social Functions
Surveys with Hospital Administrators
(16 hospitals)

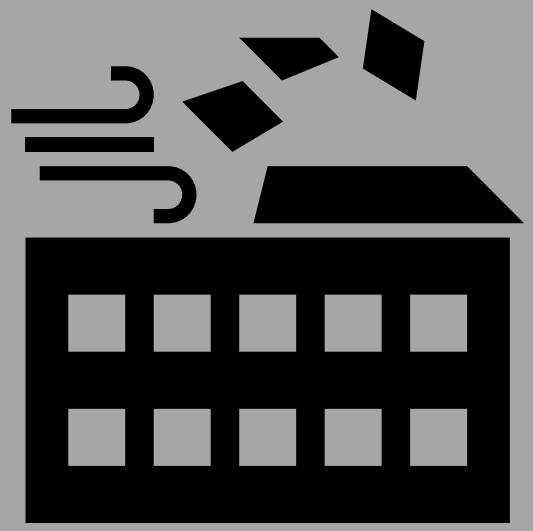
Critical Buildings
Interviews with hospital engineers or administrators
(5 hospitals)
Wind tunnel test data
(2 hospitals)



Recovery of Infrastructure
Aerial imagery for tower sites
(600+ sites)

Recovery of Business
Surveys with businesses
(451 businesses)

Integration of Analysis



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Hazard Data Analysis & Modeling

- How did the wind hazard vary across Puerto Rico during Hurricane Maria?
- How did rainfall vary across Puerto Rico during Hurricane Maria?
- What is the uncertainty associated with these hazard estimates?

Cross-Project Linkages to Hazard Exposure

- How did prior expectations for flooding and landslides align with the hazards experienced during Hurricane Maria?
- What were the wind hazards experienced by critical buildings and infrastructure?
- What role did tree cover play in hazard exposure?

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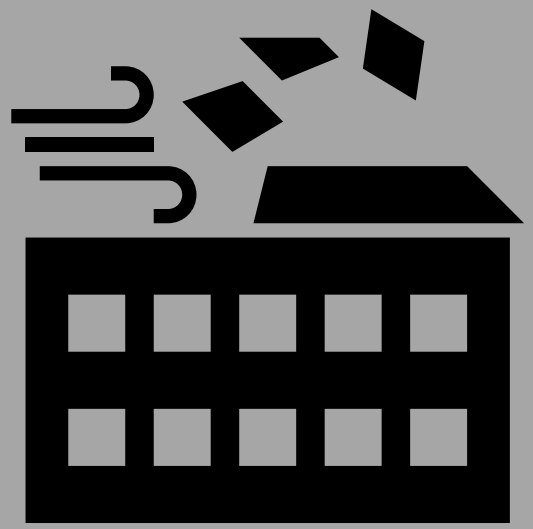

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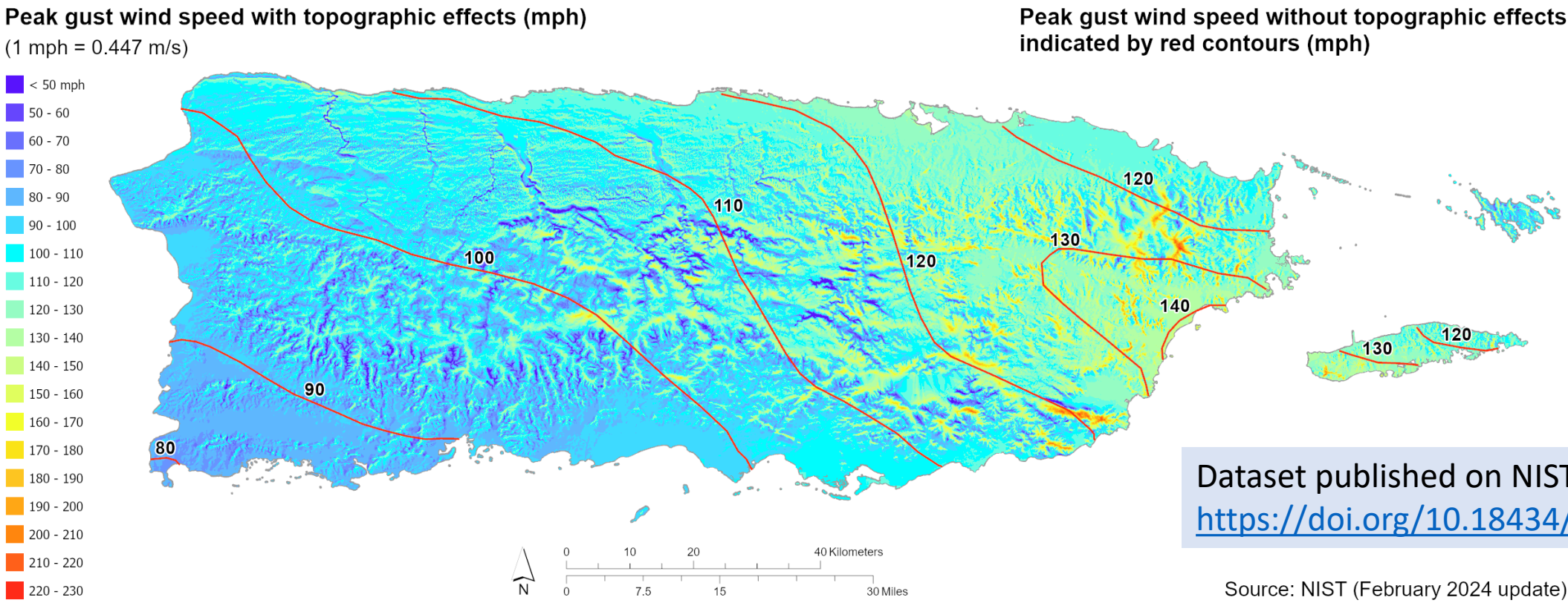
Hurricane Maria Wind-Field Model Update (1/2)

An updated Hurricane Maria wind-field model has been developed that:

- Provides time histories of wind speed/direction (and peak gust speeds) for any location in PR
- Incorporates additional meteorological data and an improved model fitting process
- Accounts for changes in air density associated with variations in atmospheric pressure



Dataset published on NIST MIDAS system: https://doi.org/10.18434/mds2-3184

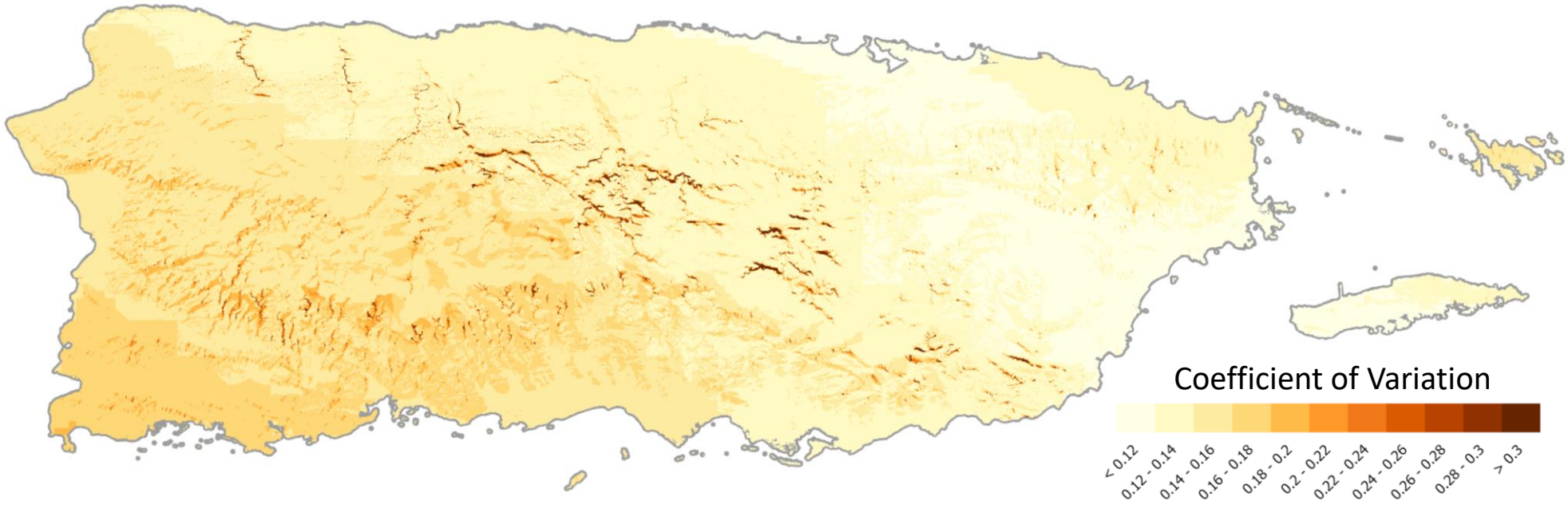
Source: NIST (February 2024 update)

Hurricane Maria Wind-Field Model Update (2/2)

An updated Hurricane Maria wind-field model has been developed that:

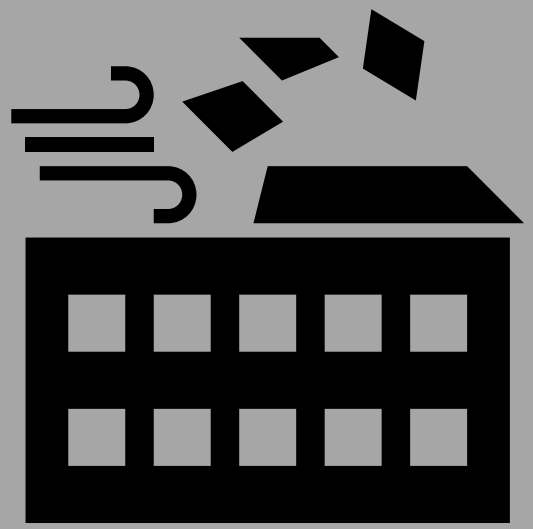
- Provides uncertainty estimates for modeled wind speeds based on:
  - Differences between the wind-field model and peak measured wind speeds over flat terrain (standardized to 3-second peak gusts at 10 m height over open terrain, i.e., ASCE 7 Exposure C)
  - Differences between Topographic Speedup Factors obtained from the wind-field model and from wind tunnel testing of topographic models

Uncertainty in estimated wind speeds



PRELIMINARY ANALYSIS

Integration of Analysis



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Rain Gauge Data Compilation

Rain gauge data compiled for 69 stations, including rainfall totals from Ramos-Scharrón et al. (*doi.org/10.3390/hydrology10020040*)

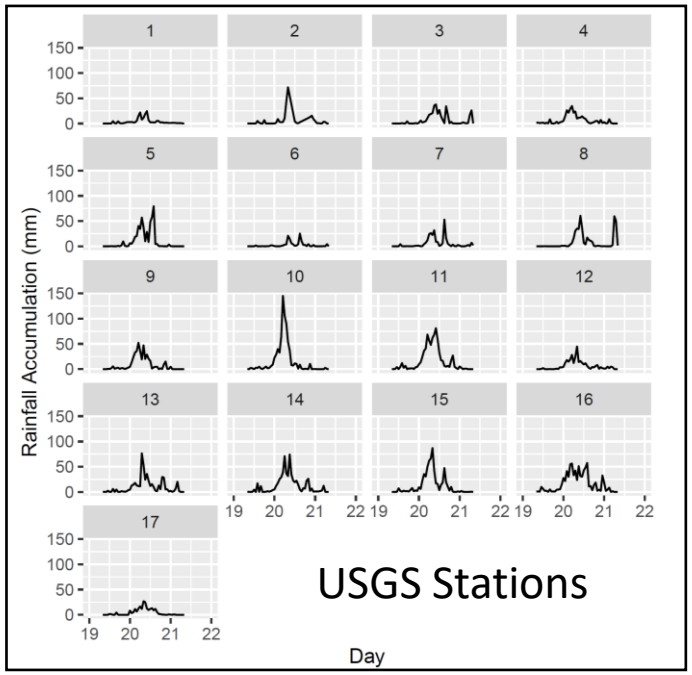
- 39 stations with rainfall totals only
- 30 stations with time series data:
  - 17 USGS stations
  - 13 NWS FPR-E stations (3 with incomplete data)

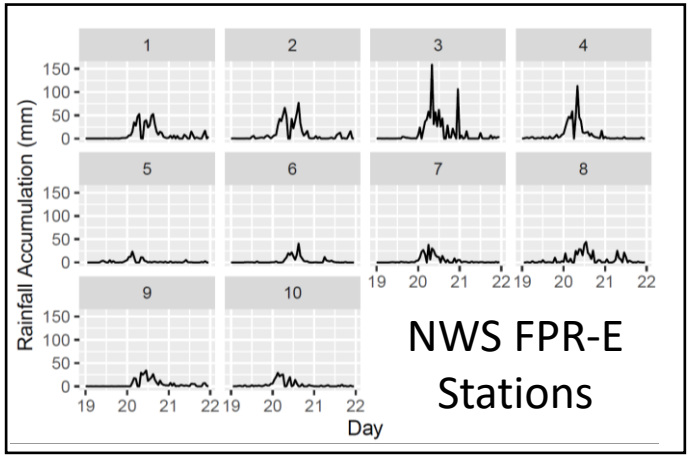
FPR-E data provided by NWS San Juan Weather Forecast Office in Sept 2023

NWS FPR-E* gauge

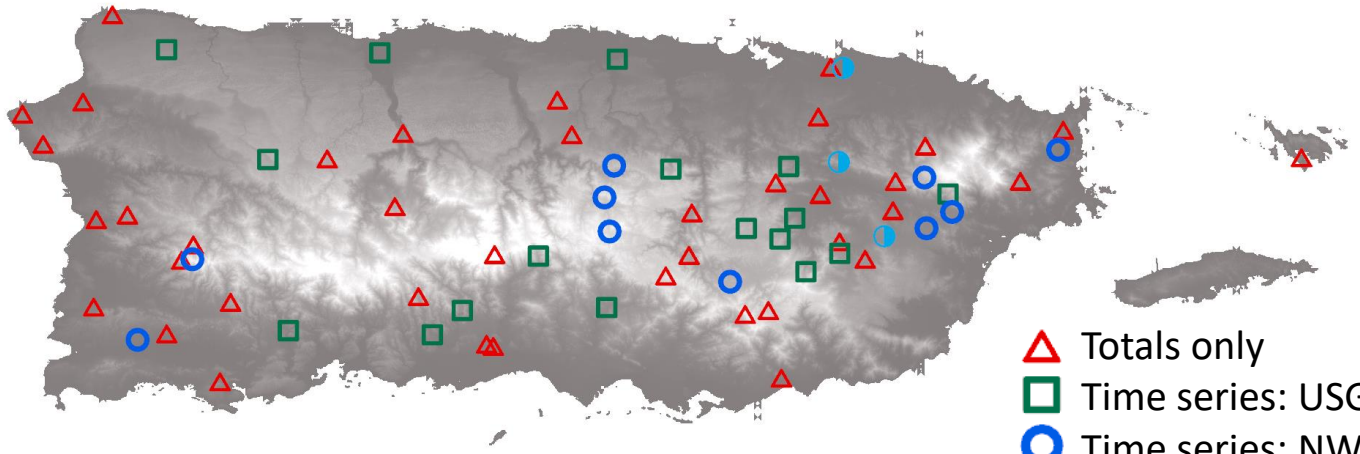
Credit: NOAA

Rainfall time series





Rain gauge locations



*Fischer & Porter Rebuild Recording Rain Gauge

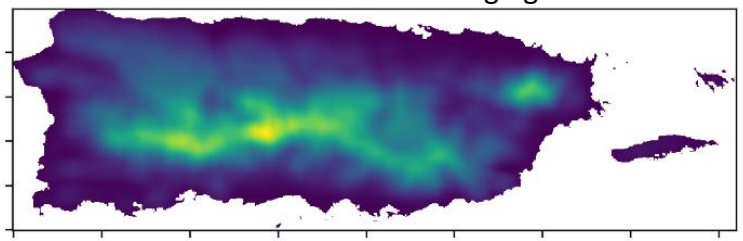
Rain Gauge Data Regression

- Gaussian process regression used for interpolation of rain gauge data and quantification of uncertainty
- Leave-one-out (LOO) cross-validation used to evaluate model predictions:
  - Fit model on data from all stations except one
  - Use model to predict rainfall at the missing station
  - Repeat for all locations and calculate the mean absolute error (MAE)
- Including elevation as a model variable (with spatial smoothing) provided improved predictions relative to location alone
- Gaussian process modeling of time-varying rainfall accumulation is currently underway, using time series data

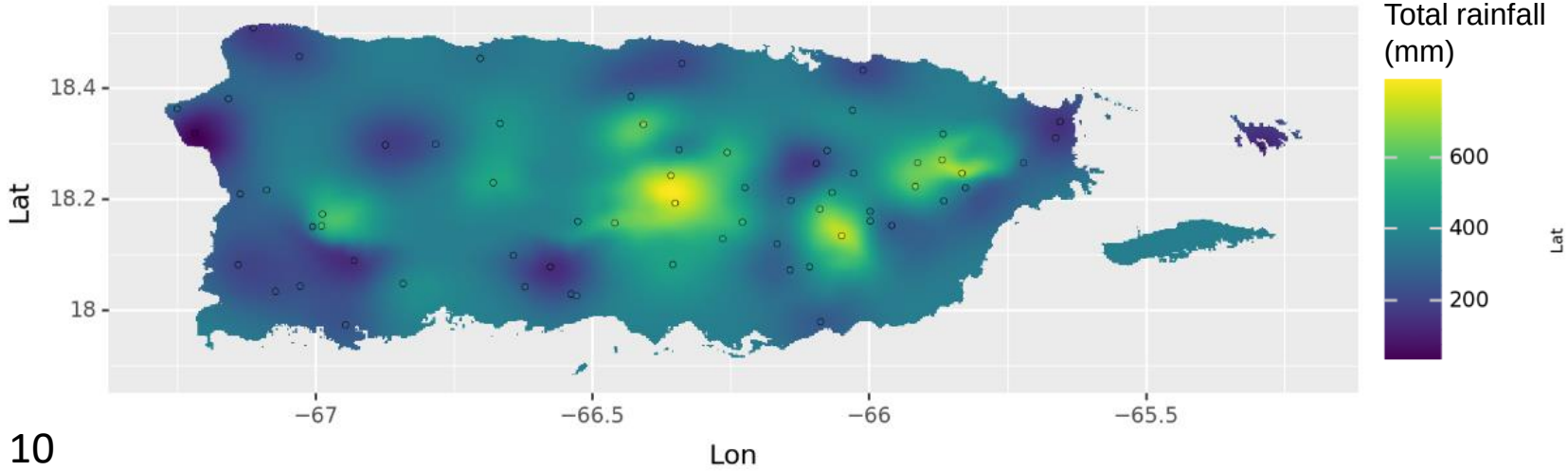
Variables in Model	LOO-MAE
Lat, Long	116.36 mm
Lat, Long, Elevation	114.85 mm

Smoothed elevation data

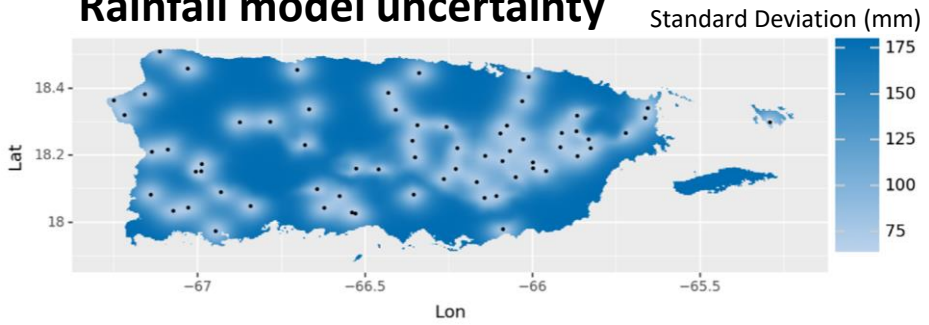
Averaging radius: 2400 m



Gaussian process model for total rainfall

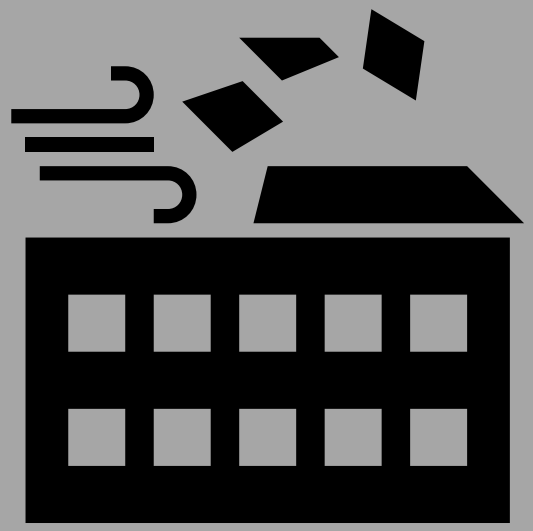


Rainfall model uncertainty



PRELIMINARY ANALYSIS

Integration of Analysis



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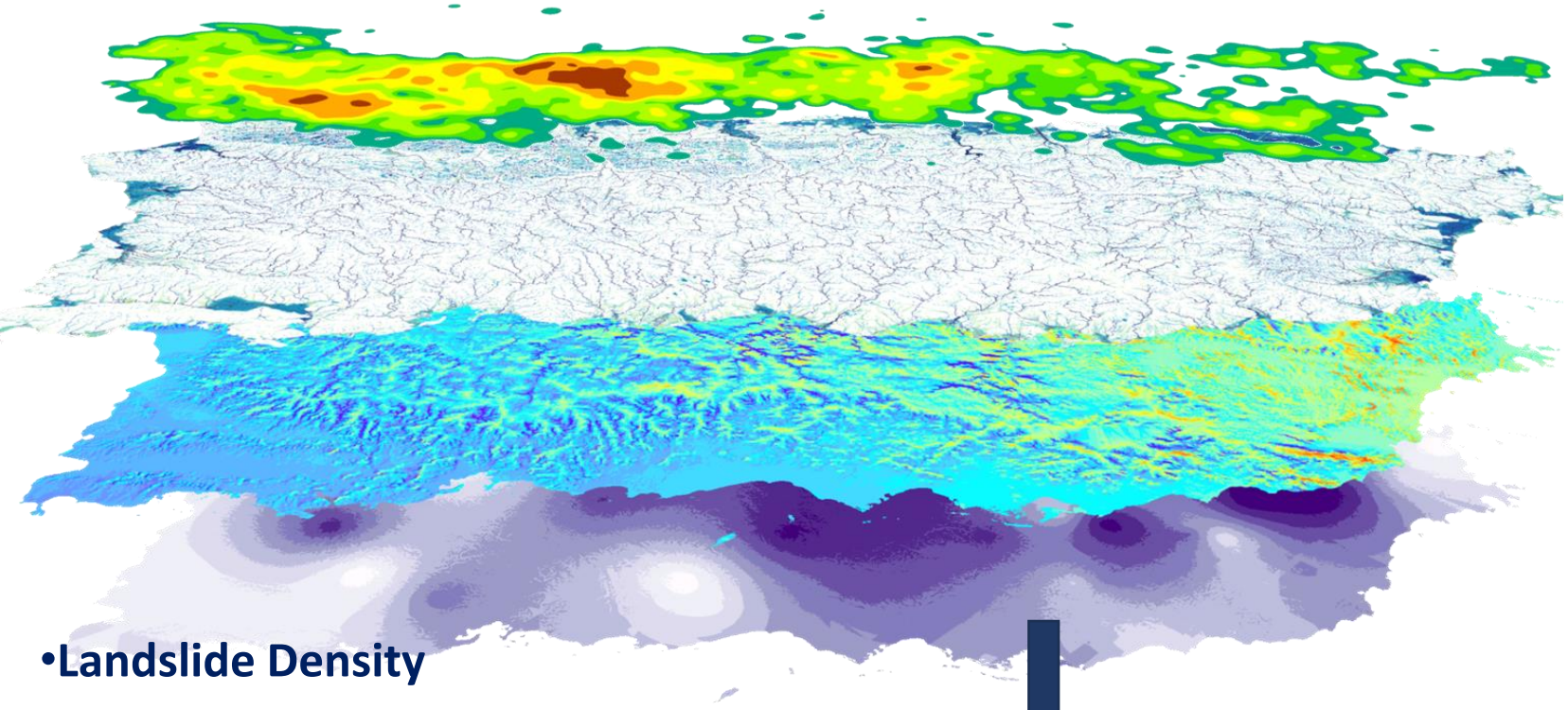
Joining Hazard Data with Survey Data

Geospatial analysis methods are needed for linking various hazard layers with different types of survey data:



- **Landslide Density**
- **Flooding Depth**
- **Peak Windspeed**
- **Total Rainfall**

Hazard Exposure

1500+ Household Surveys

On public response to emergency communications

450+ Business Surveys

On hurricane impacts and recovery

275+ School Surveys

On recovery of social functions

15+ Hospital Surveys

On recovery of social functions

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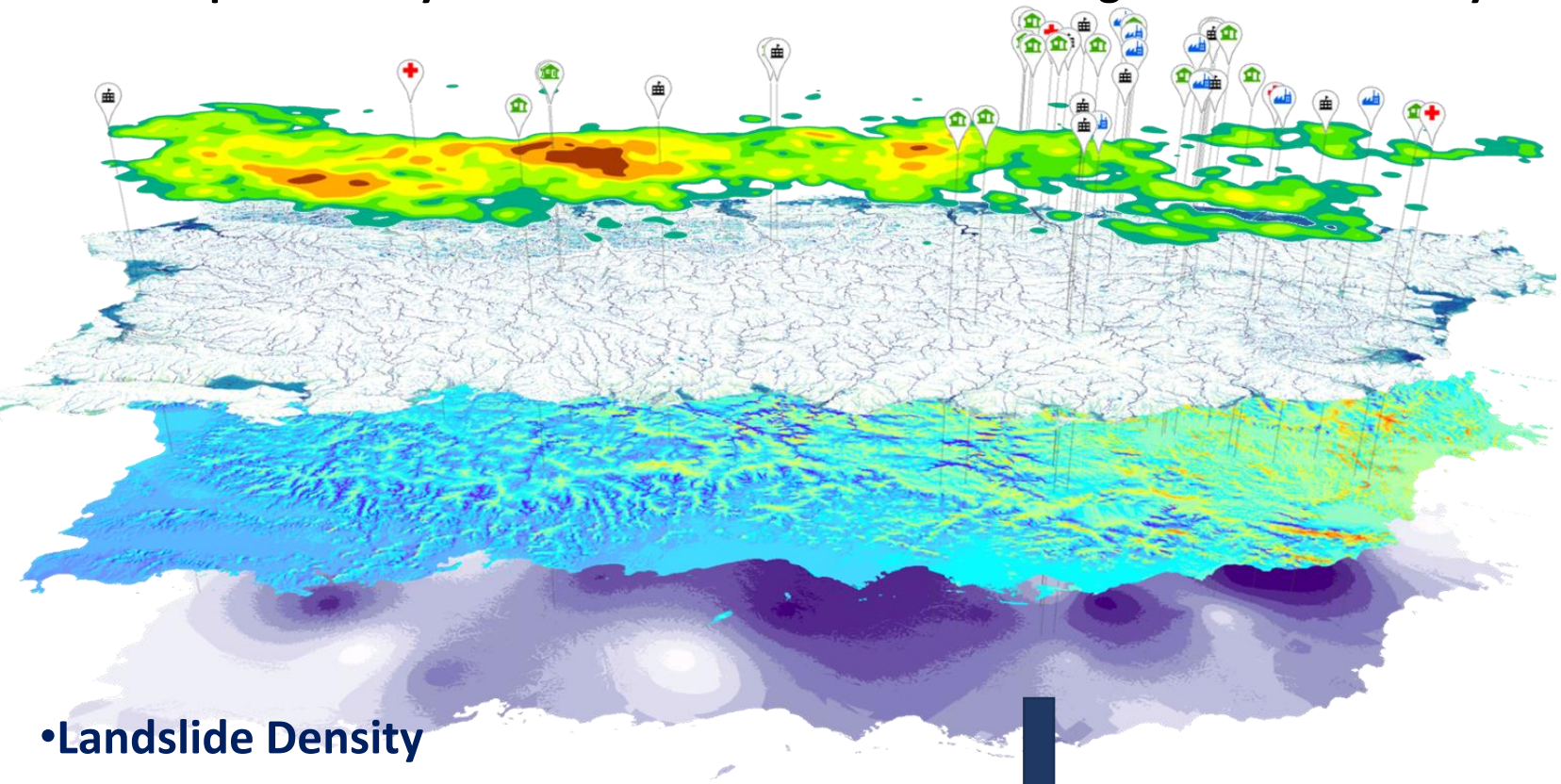

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Geographic Dimensions of the Survey Data

Figure 1: Illustration of Census Block Groups with centroids. (Data Source: US Census Bureau); Figure 2: Illustration of ZIP Codes with centroids. (Data Source: https://gis.pr.gov/)

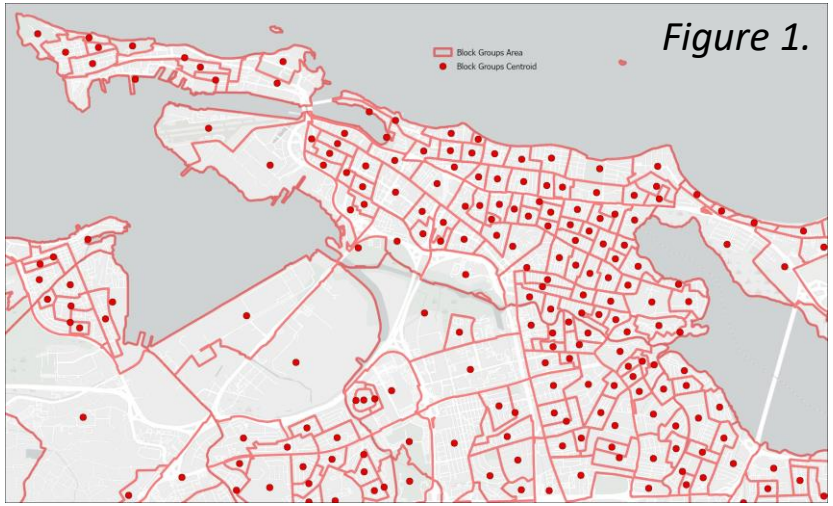


Figure 1.

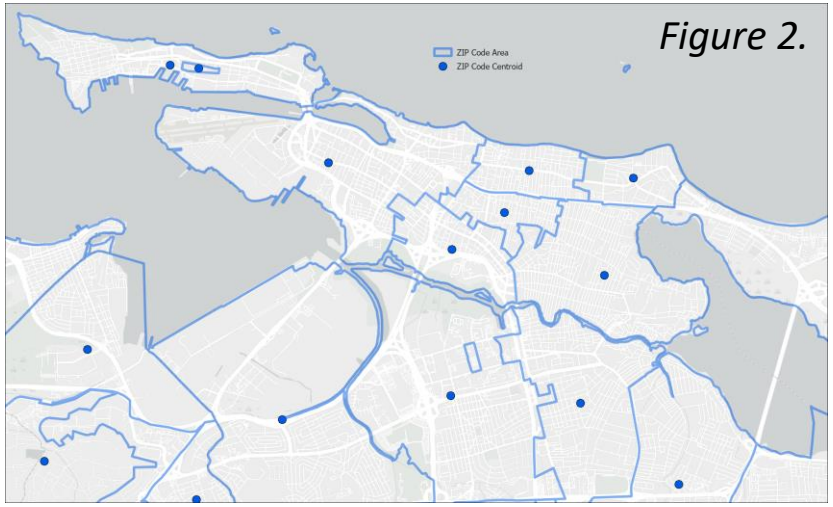
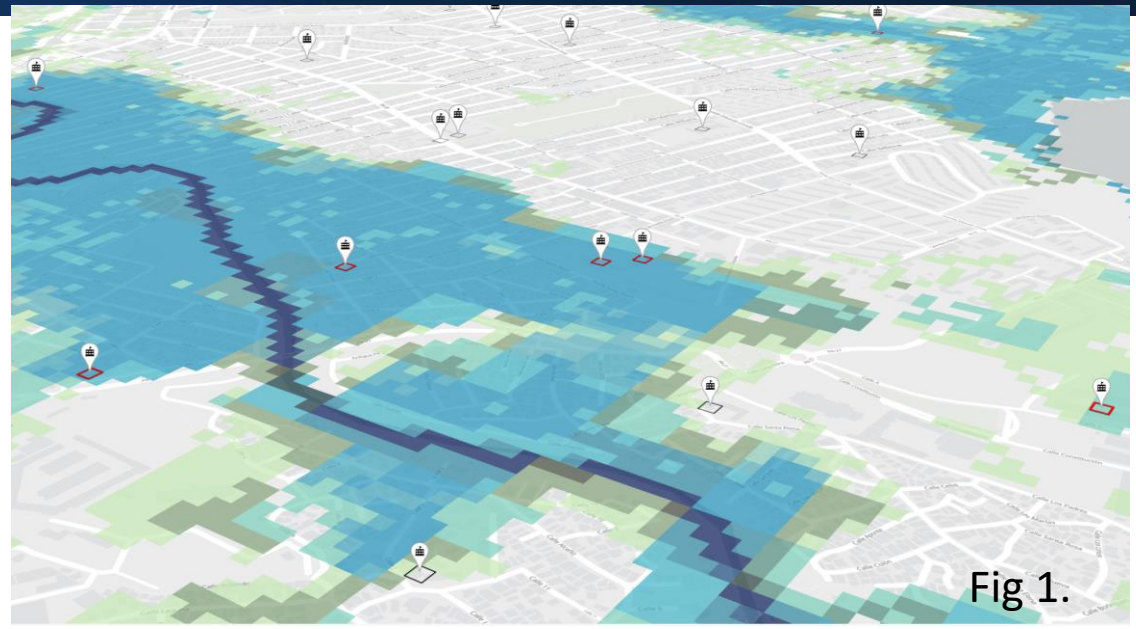


Figure 2.

- Geographic specificity varies for respondents:
  - latitude/longitude for a building (business) or campus (hospital, school)
  - centroid of the census block group (household surveys)
  - ZIP code (business)
- Geocoding (with latitude and longitude) completed for:
  - 100% of clusters used in the sample of households
  - 100% of the sample of schools and hospitals
  - 99% of the sample of businesses

Methods for Joining Data

- Methodological choices will impact the resulting hazard values. The comparison of methods and resulting values is critical to the analyses that follow.
- Options to determine hazard exposure include:
  - Extraction of raster values of peak wind speed grid cells of 100 m (0.00095°) to the respondent points
  - Proximity of landslides and respondent points
  - Aggregation of total rainfall amount to the respondent points using zonal statistics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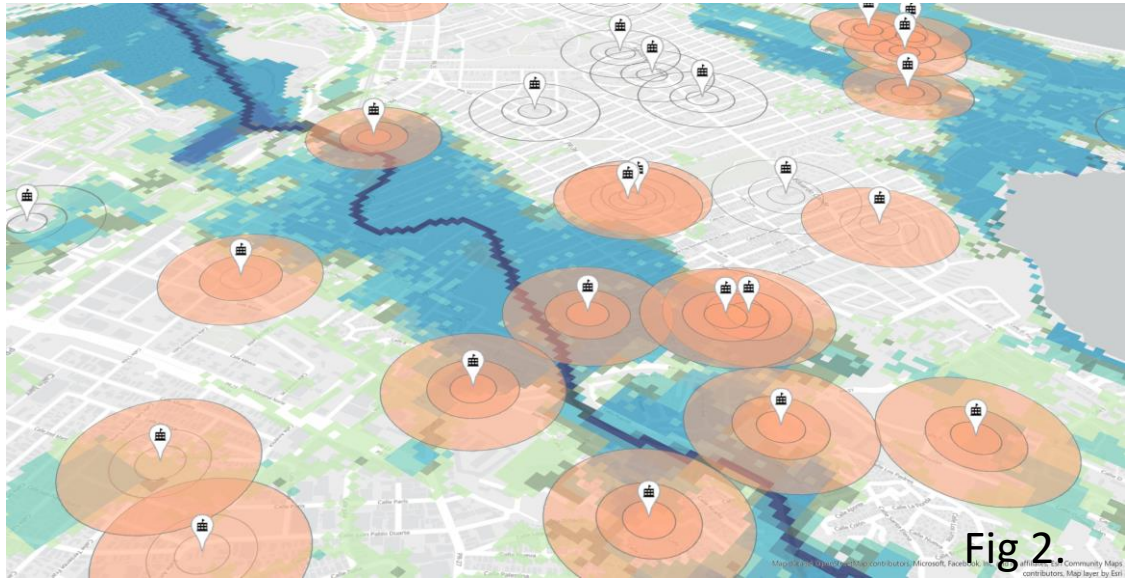


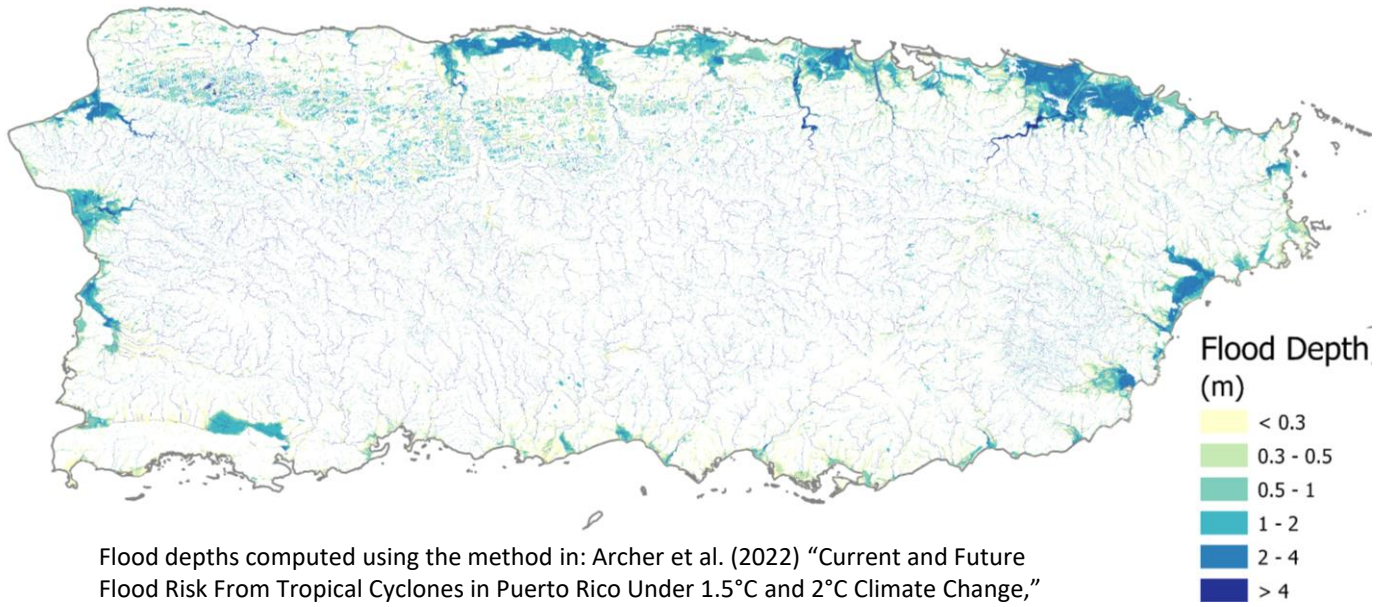
Fig 2.

Figure 1: Illustration of Extraction of Raster Values to Points;
Figure 2: Illustration of Aggregation Using Zonal Statistics

Flood Hazard Exposure: Model vs. Observation

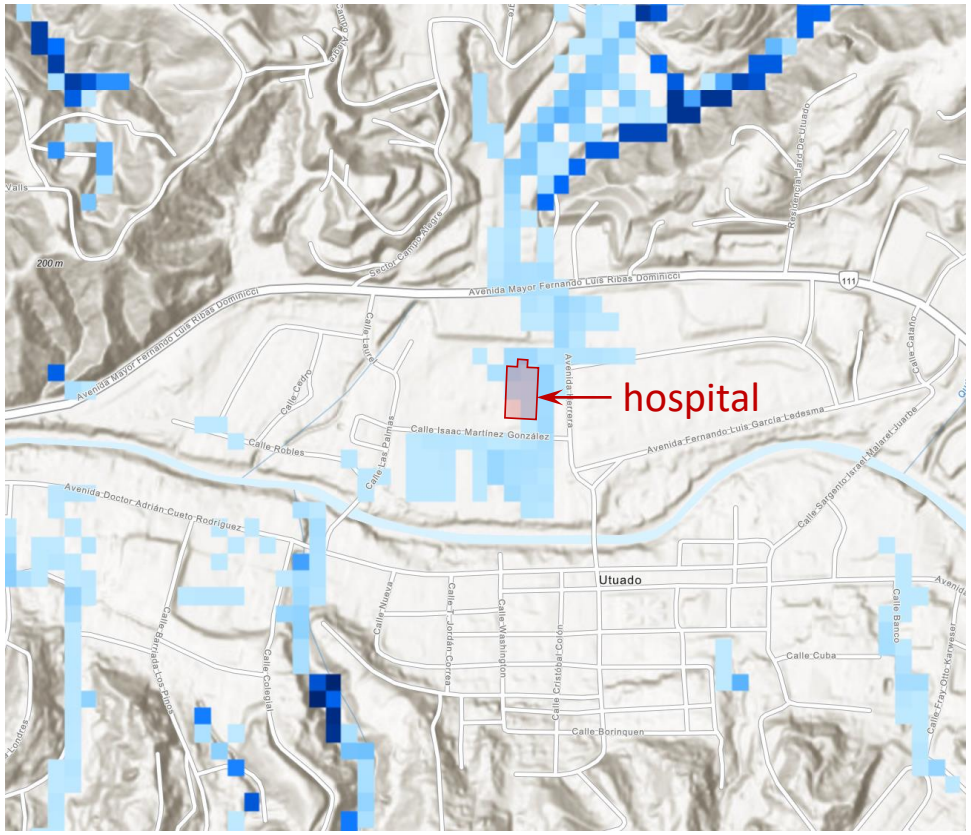
- Flood model results for Hurricane Maria are available through a collaboration with Bristol University, based on rainfall inputs provided by NIST
- Flood model results for a hospital exposed to riverine flooding (at right) show a consistent pattern with descriptions of flooding at the site
- Linkage of flood model results with location information will support analysis of flooding effects across projects

Flood depth modeling (Bristol University)



Flood depths computed using the method in: Archer et al. (2022) "Current and Future Flood Risk From Tropical Cyclones in Puerto Rico Under 1.5°C and 2°C Climate Change," *EGU General Assembly 2022*. <https://doi.org/10.5194/egusphere-egu22-2871>

Modeled flood depth at hospital location



PRELIMINARY ANALYSIS

Methods for Joining Data

- In Figure 3, the comparison of methods and resulting values reflects the potential impact the analyses that follow.
- Use of different sized buffers around a hospital campus results in different values for the maximum flood depth above ground (excluding the nearby river channel):
  - The hospital campus footprint provides a maximum value of 0.337 m
  - The 200m buffer around the campus provides a max value of 0.539 m

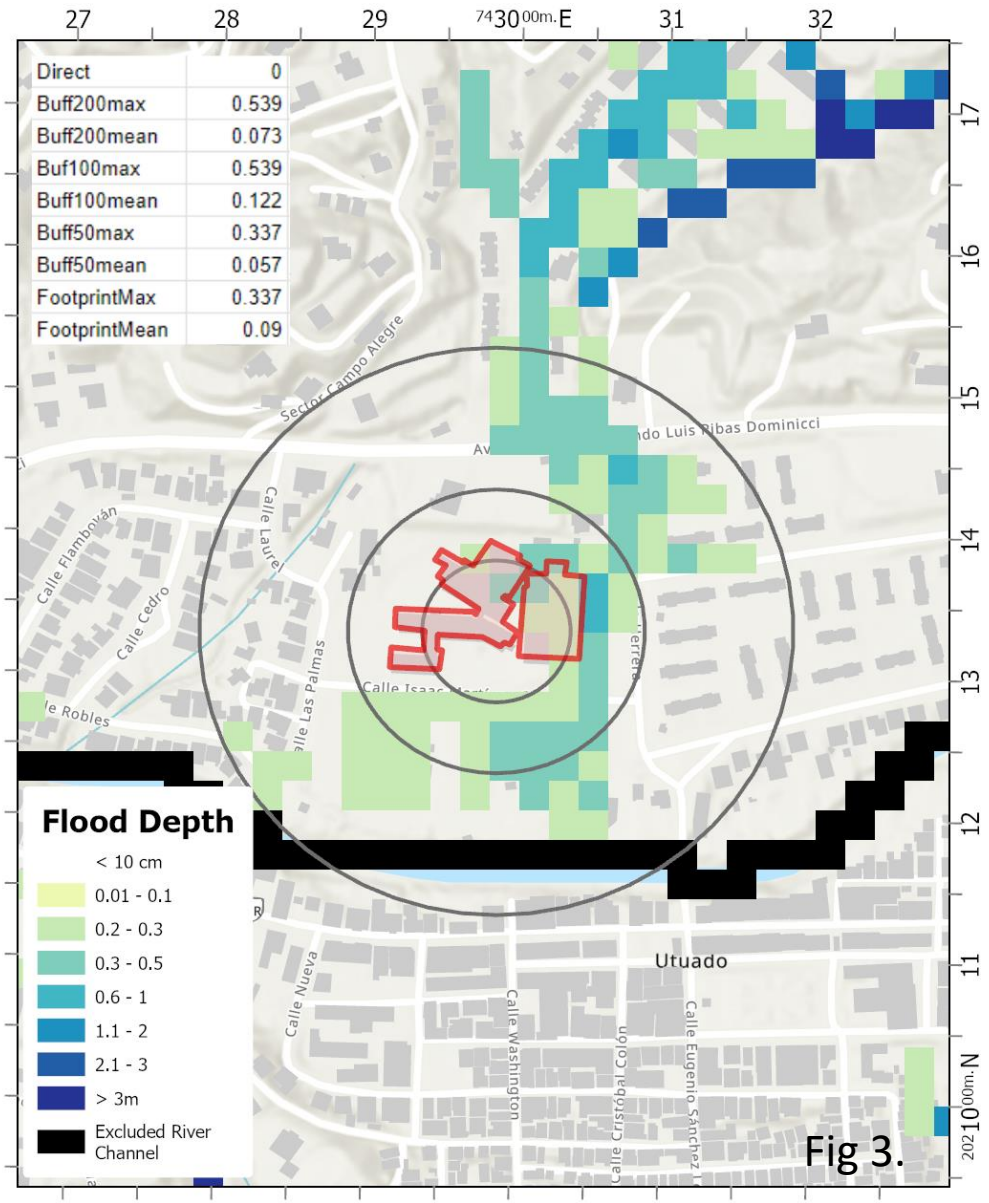
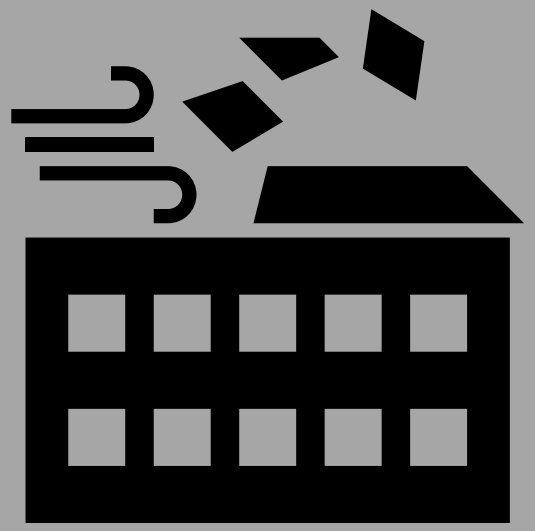


Fig 3.

Figure 3: Illustration of Impact of Methodological Choices

PRELIMINARY ANALYSIS

Integration of Analysis



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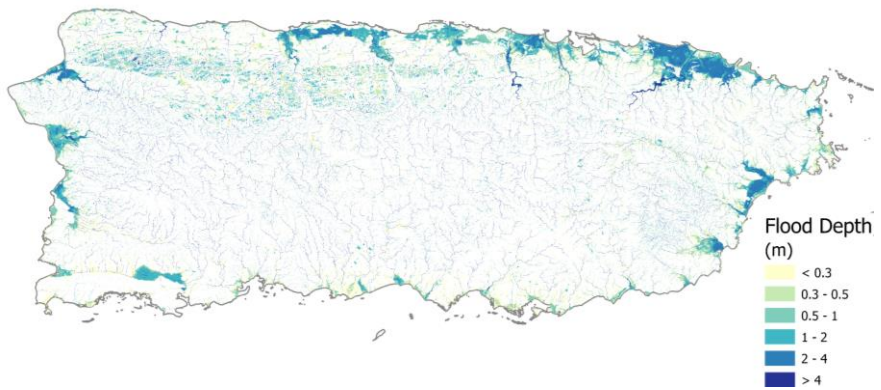
Prior Expectations vs. Hazard Exposure: Flooding

Hazard Characterization

Pre-Maria Flood Hazard Map

Hurricane Maria flood model (Bristol University)



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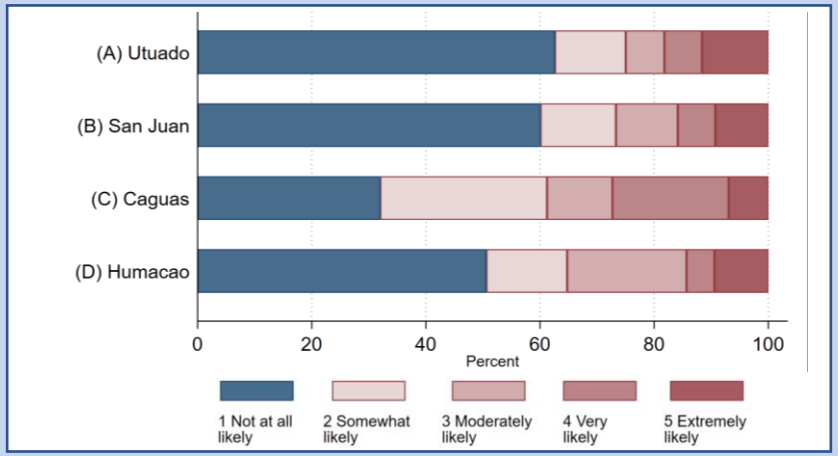
Emergency Communications

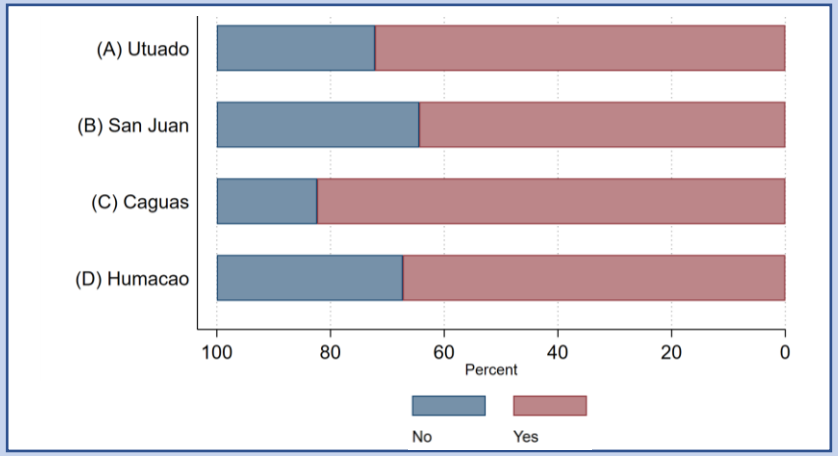
Household survey results:

Created by Rodrigo Ramirez from Noun Project

Expected Flooding of Home (pre-Maria)



Rain/ Floodwater Entered Home (H. Maria)

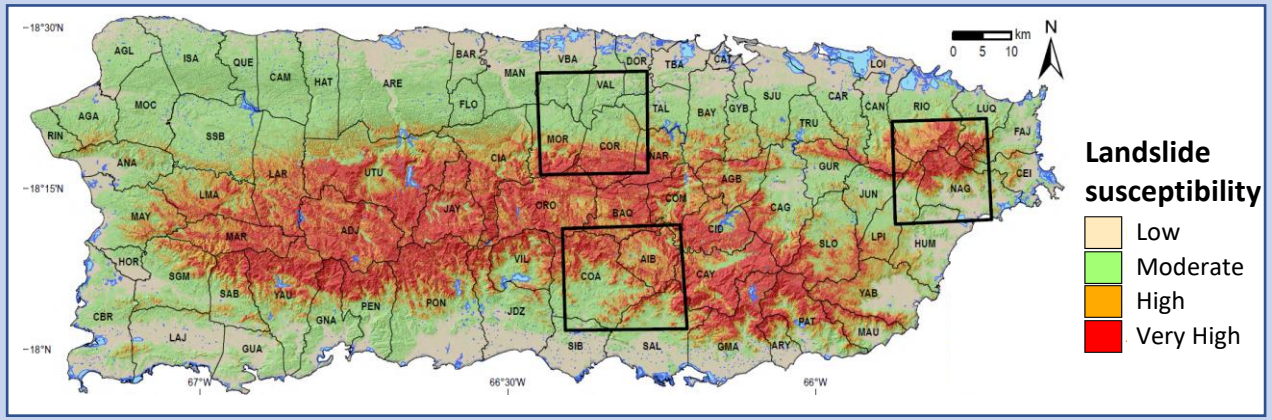


PRELIMINARY ANALYSIS

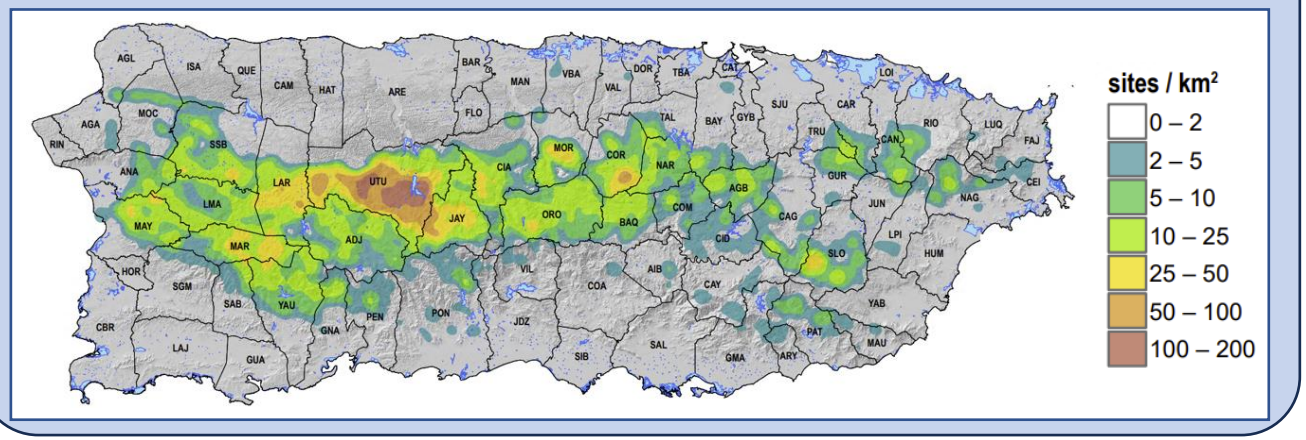
Prior Expectations vs. Hazard Exposure: Landslides

Hazard Characterization

Pre-Maria landslide susceptibility map (USGS)



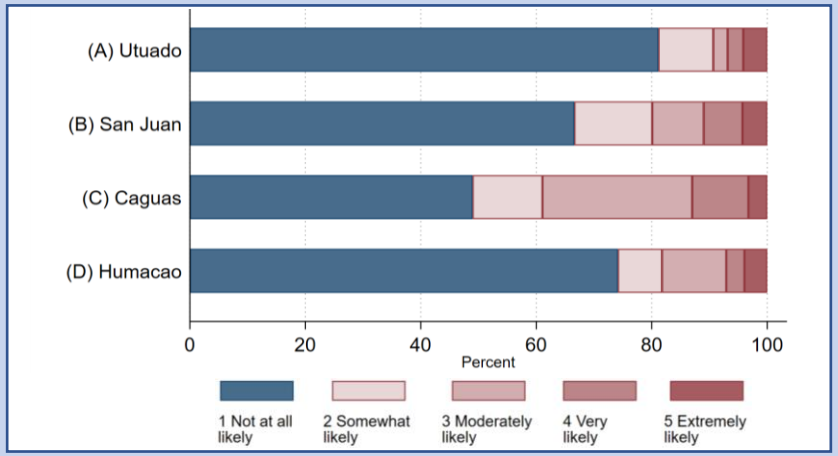
Hurricane Maria landslide density (USGS)



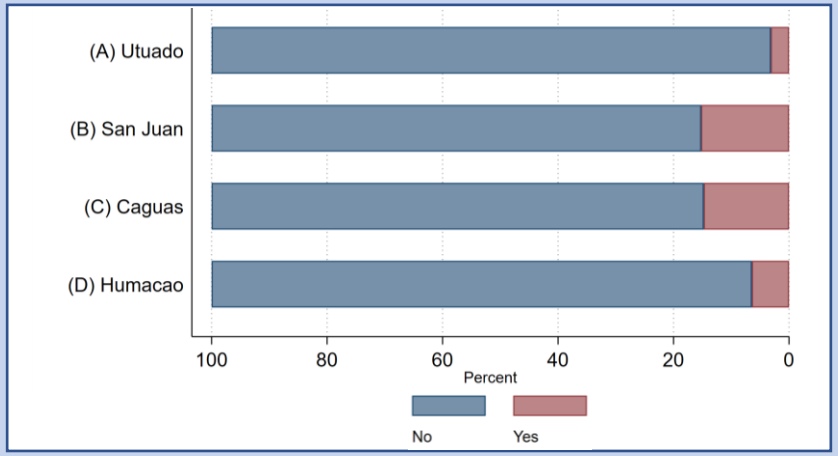
Emergency Communications

Household survey results:

Expected Landslide Impacts on Home (pre-Maria)



Landslide on Property or Impacting Home (H. Maria)



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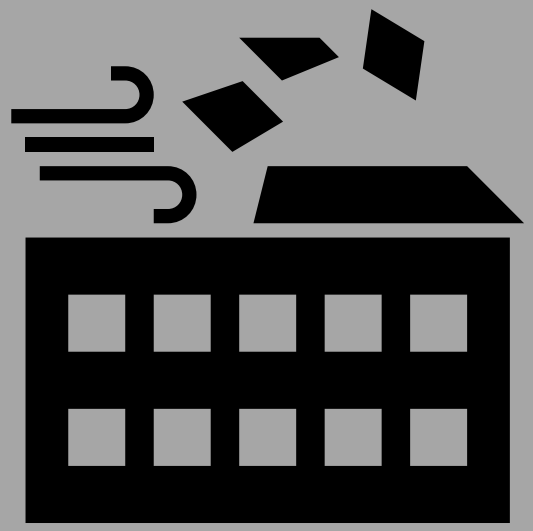

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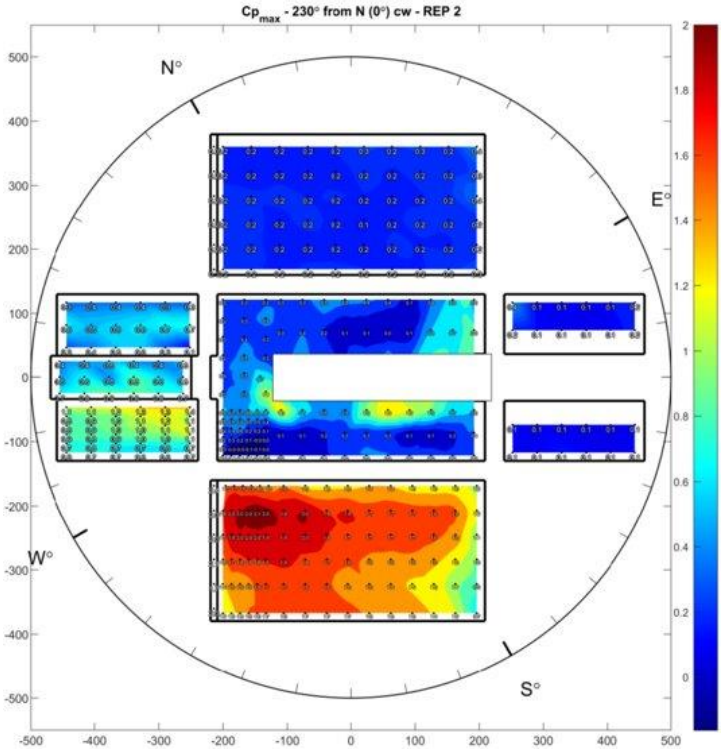
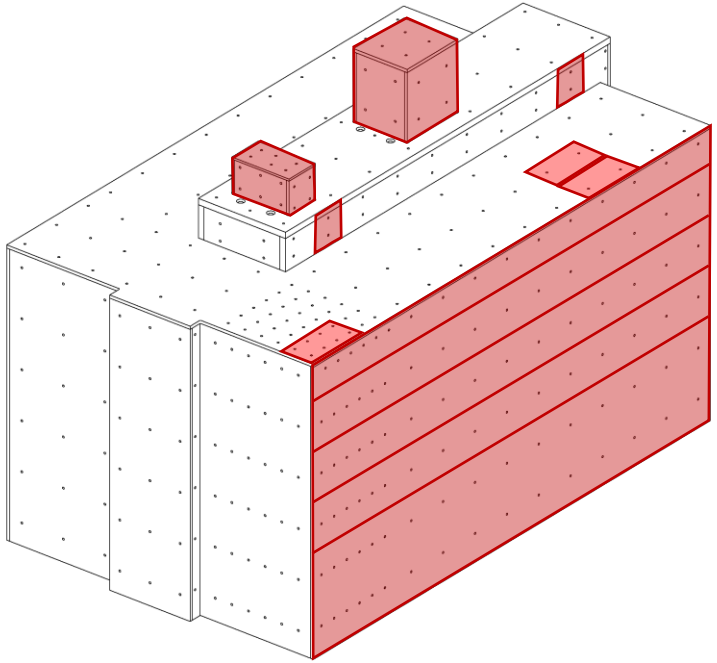
Detailed Analysis of Wind Loads: Two Hospitals

For two hospitals, time histories of wind speed and wind direction obtained from the wind-field model at the hospital locations are being integrated with wind tunnel test data to evaluate time histories of estimated pressures and wind loads during Hurricane Maria.

Measured pressure coefficients

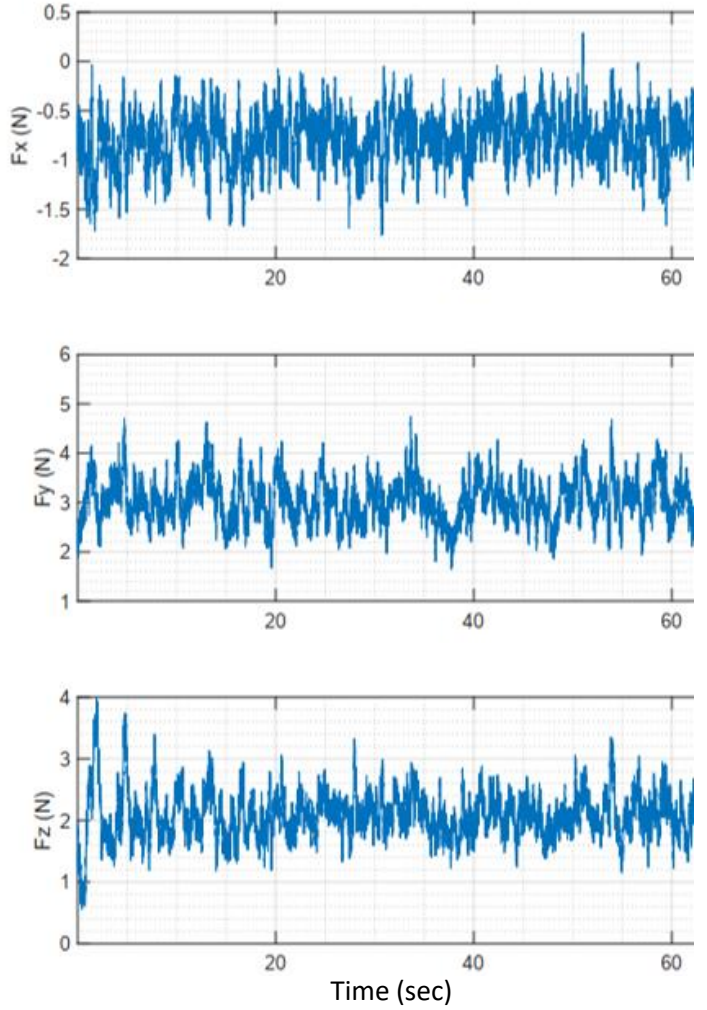


Selected building elements



PRELIMINARY ANALYSIS

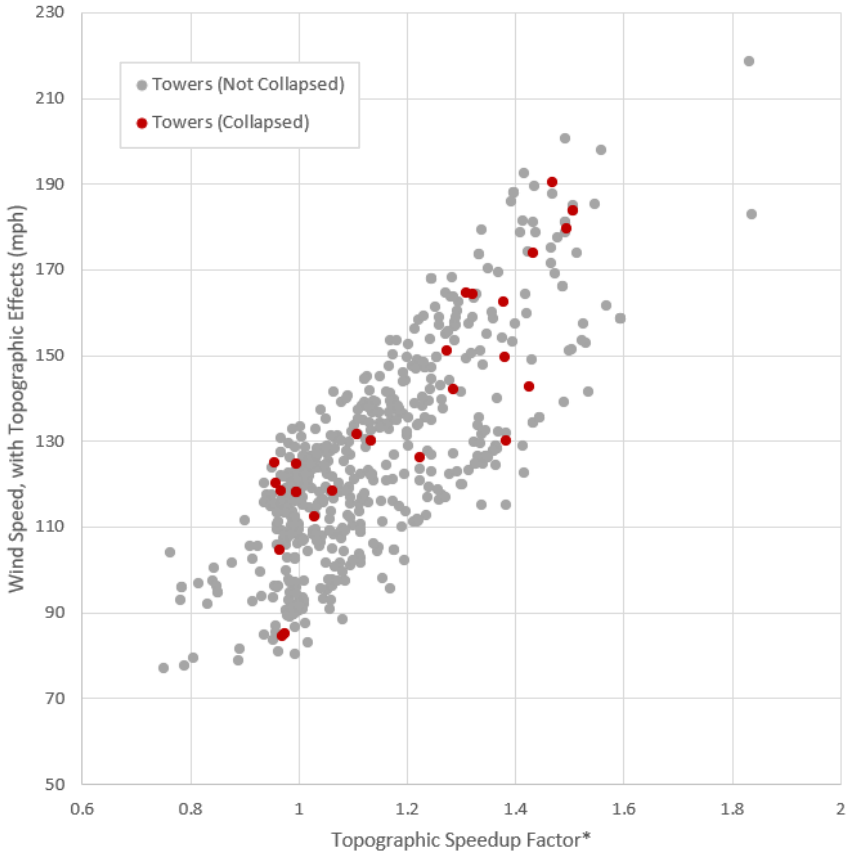
Resultant wind force components



Analysis of Damage to Communication Towers

- Tower damage assessments have been completed for over 600 sites
- Peak wind speeds at tower locations obtained from wind-field model, including topographic speedup effects
- Additional imagery analyzed using 3 pre-event and 4 post-event imagery sources
- Approximately 5% of towers collapsed; antenna misalignment at some locations
- In progress: analysis of tower damage assessments, examining effects of tower type, age, height, and location on performance

PRELIMINARY ANALYSIS



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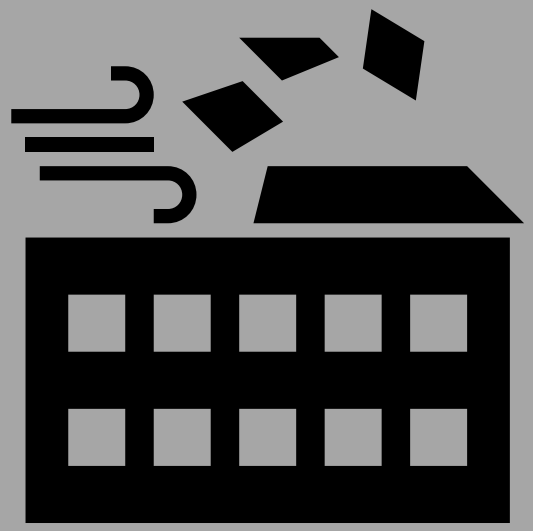

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- How did prior expectations for flooding and landslides align with the hazards experienced during Hurricane Maria?
- What were the wind hazards experienced by critical buildings and infrastructure?
- What role did tree cover play in hazard exposure?

Role of Tree Cover in Hazard Exposure

Hazard Characterization

- Tree canopy slows the wind flow near the ground surface, reducing the wind speeds and corresponding wind loads
- Hurricane winds, particularly when accelerated by topographic effects, can cause significant damage to the tree canopy, reducing its shielding effect
- Computational Fluid Dynamics (CFD) modeling can be used to examine the effects of tree canopy on wind fields
- Point cloud data from LiDAR scanning can provide the information needed for CFD modeling of tree canopy

Recovery of Infrastructure

- Falling trees pose a hazard to infrastructure systems during windstorms and can damage power lines and block roadways
- Vegetation maintenance (i.e., pruning trees) is an important consideration for protection of infrastructure systems
- Documenting the extent of tree cover and its evolution over time is important for understanding the hazard posed to infrastructure systems

Geospatial Analysis: Impact of HM on Vegetation

Objective: To estimate realistic ground roughness of vegetation used for canopy model of CFD simulations

Applications:

- Facilitate a reliable comparison of CFD results with field measurements taken in Yabucoa from March 2021
- Gain insights into topographic wind speed fields over vegetation affected by Hurricane Maria (HM)

Procedure: Utilized USGS LiDAR vegetation data from Yabucoa, captured before and after HM

- Pre-HM data: Collected from May 2016 to January 2017 (far-left image below)
- Post-HM data: Collected from May 2018 to March 2019 (central image below)

PRELIMINARY ANALYSIS

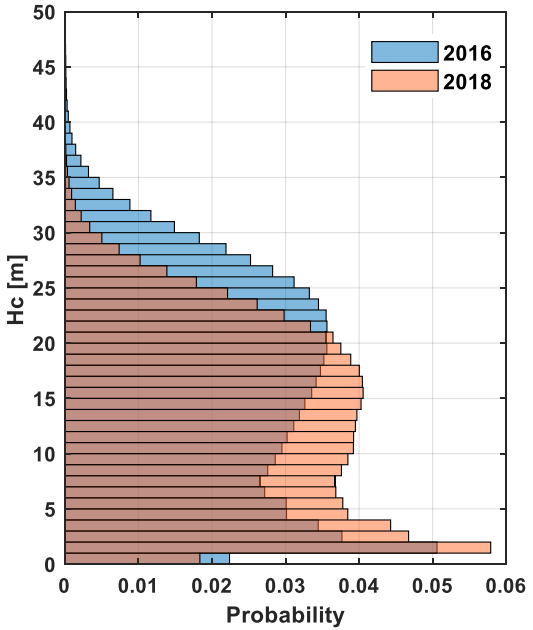
Aerial imagery from Yabucoa showing extensive tree damage caused by HM and subsequent recovery of tree canopy

Credit for Photos: Google Earth

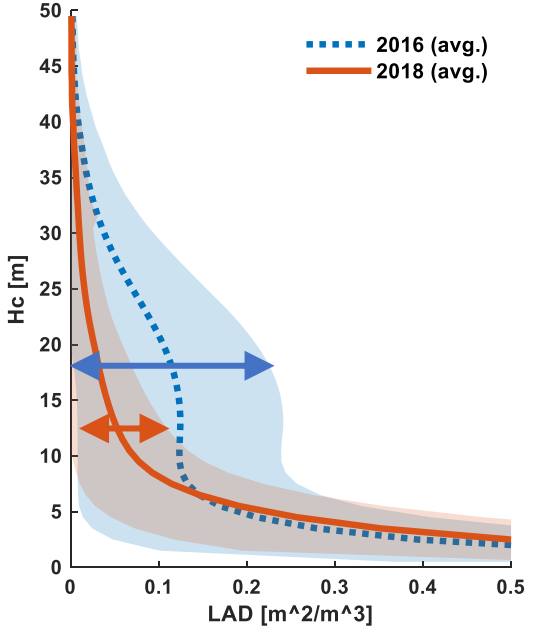
Effects of Hurricane Maria on Vegetation

- Focused on investigation of vegetation characteristics affected by HM:
  - Tree canopy height (H_c), Leaf Area Density (LAD), Leaf Area Index (LAI = sum of LAD values over canopy height)
- HM severely impacted vegetation including trees in Yabucoa:
  - Average reduction of tree canopy heights by 2.7 m and LAI by 16 %
  - Significant damage observed in areas with high topographic speedup of winds

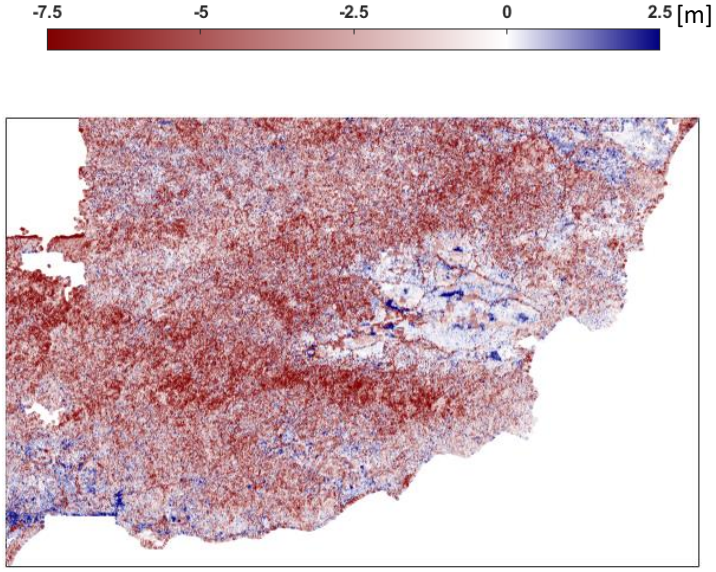
PRELIMINARY ANALYSIS



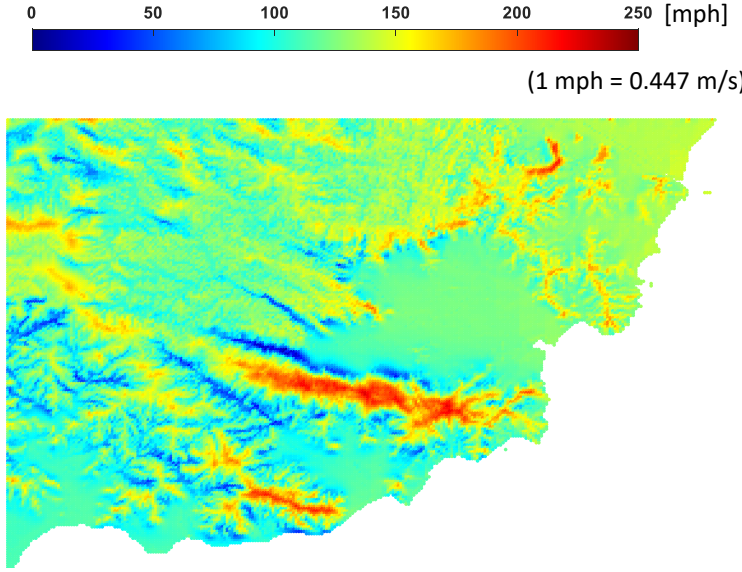
Distribution of tree canopy heights



LAD profiles: Average and variations



Differences in tree canopy heights ($H_{c,2018} - H_{c,2016}$)



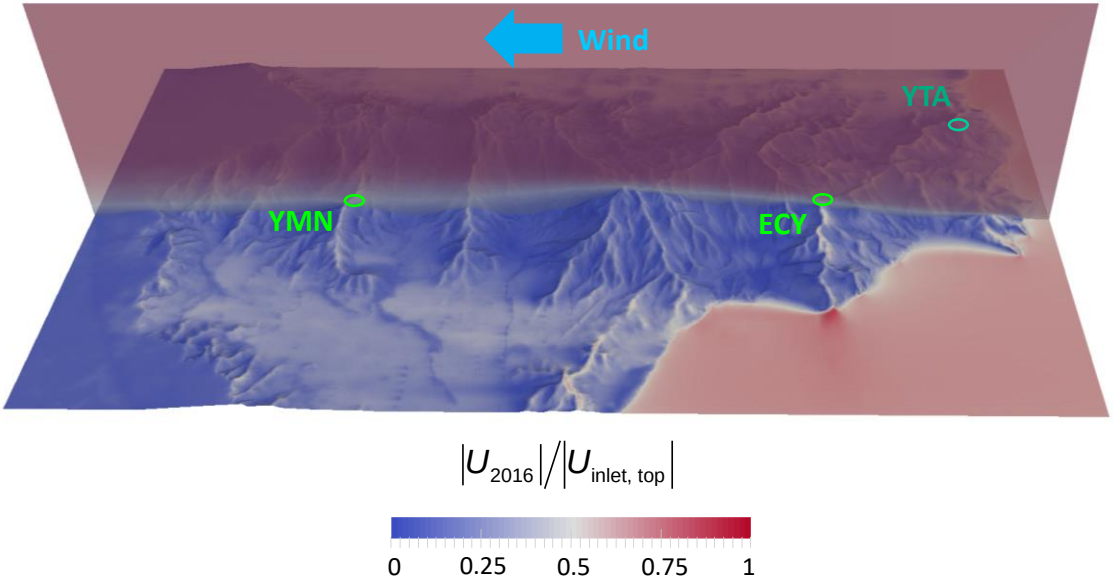
Peak gust wind speeds with topographic effects during HM

Effects of Damaged Vegetation on Winds

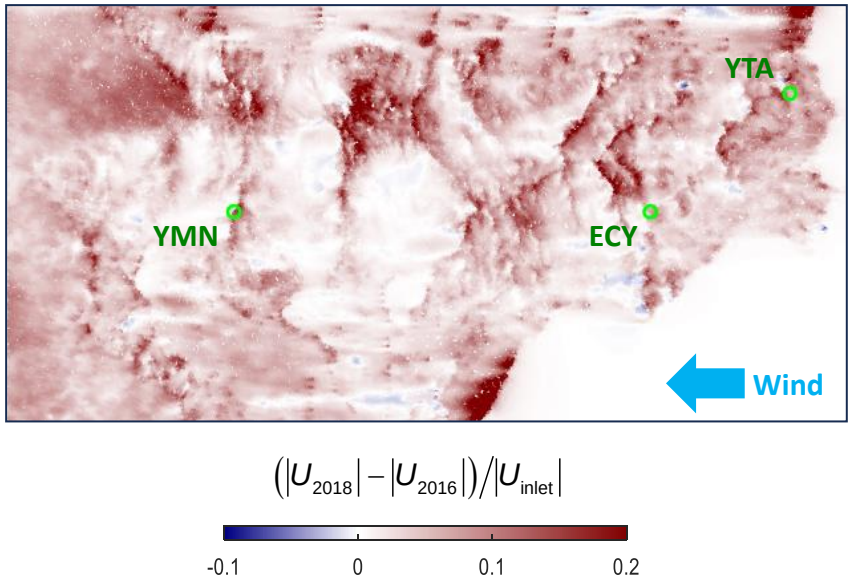
- Employed the pre- and post-HM vegetation data (tree canopy height and LAD) in canopy modeling for CFD:
  - Vegetation plays a role in retarding wind on ground surface
- Vegetation damaged by HM was found to influence topographic wind speeds:
  - Especially noticeable at low elevations in areas with high topographic impact
- Will continue to investigate the effect of damaged vegetation on wind field during HM

PRELIMINARY ANALYSIS

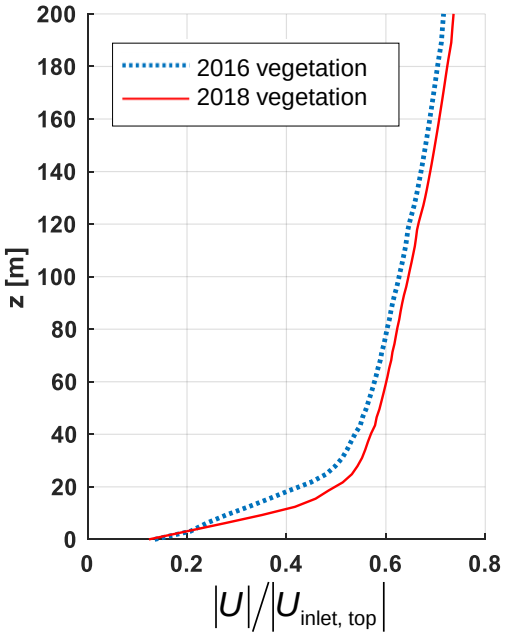
Wind speeds with 2016 vegetation (pre-HM) (wind azimuth: 93°)



Difference ratio of wind speeds with 2016 and 2018 vegetation (15 m above topography)



Comparison of wind speed profiles at YMN

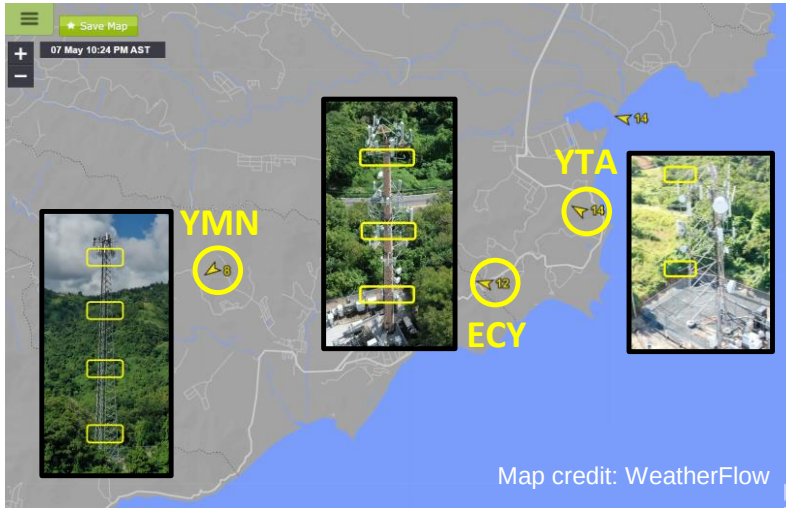


Wind Measurements from Towers: Update

- Completed nearly 3 years of continuous 3-s wind speed/direction measurements from 3 cell towers in Yabucoa
- Addressed maintenance issues for data acquisition systems
  - Repaired anemometers on ECY tower damaged by Hurricane Fiona
  - Replaced dead batteries and fixed malfunctioning electronics of the anemometers on YMN tower
- Compared full-scale measurements from towers with wind tunnel measurements and CFD models (ongoing)

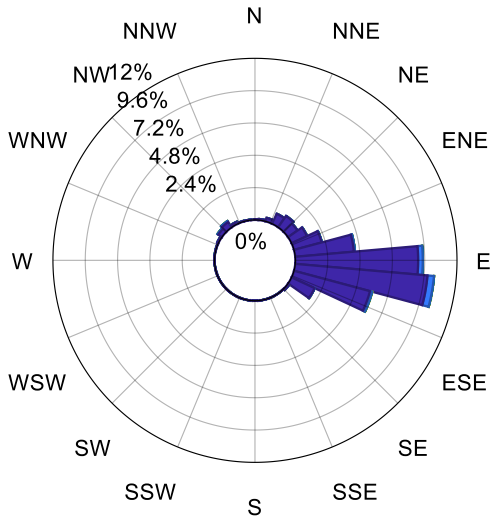
PRELIMINARY ANALYSIS

Locations of three towers in Yabucoa

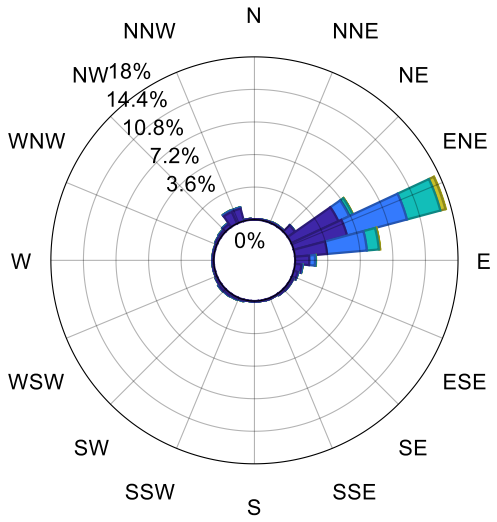


YMN: Yabucoa Manoabo Norte
ECY: El Cocal Yabucoa
YTA: Yabucoa Tanque de Agua

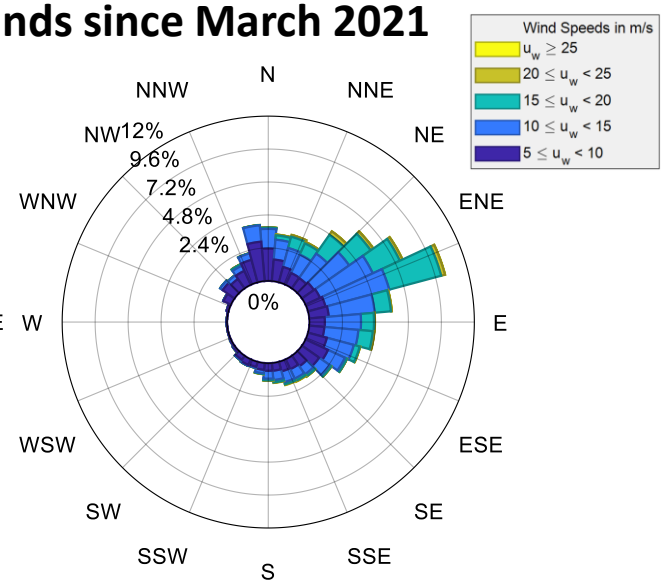
Wind rose plots showing speed and direction of winds since March 2021



YMN tower
(10 m elevation)



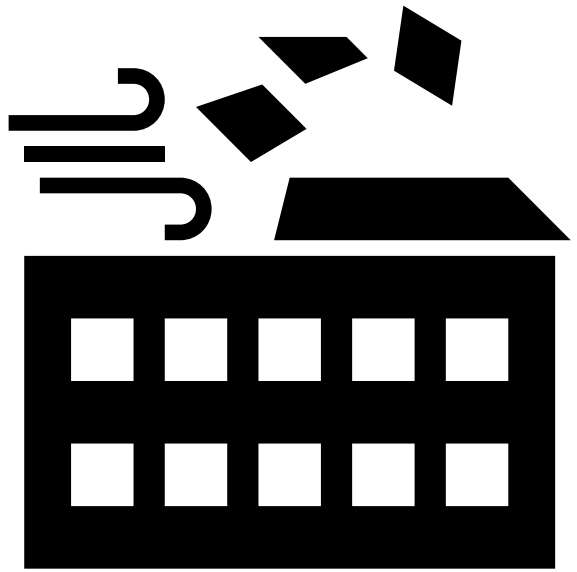
ECY tower
(10 m elevation)



YTA tower
(10 m elevation)

Questions?

Theme 1: *Hazard Exposure*



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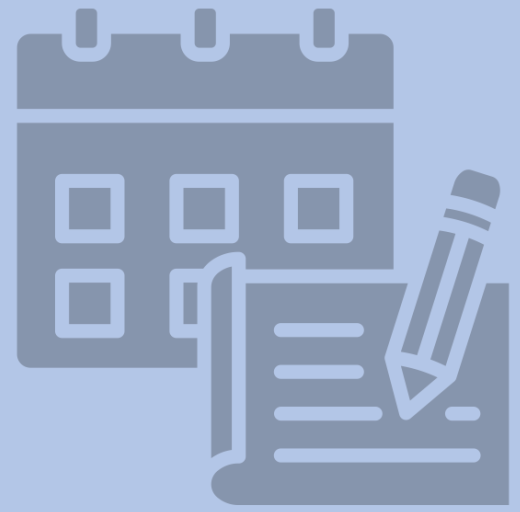
DongHun Yeo, Marc Levitan, Maria Dillard

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

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