Closing the Gap from Uncertainty Quantification to Decision Making: Integrated Prediction-Optimization Modeling of the Critical Infrastructure Flood Resilience

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Abstract

Our research team is involved in several projects that seek to integrate the science-based prediction models of flood-causing events such as hurricanes with the decision-making models for critical infrastructure resilience. To this end, we use the state-of-the-art hydrological models such as WRF-Hydro and ADCIRC to simulate potential realizations of inland and coastal flooding events caused by tropical storms. We use these simulations to generate statistically sound scenarios to populate the inputs of several resilience-based decision making models, all developed using the state-of-the-art scenario-based stochastic and robust optimization methodologies. We identify three time lines where these models can be used to improve the quality of decision making processes: (1) Short-term preemptive resource allocation (preparedness) just before impending tropical storms, (2) Mid-term hardening and resilience investment strategies (mitigation) within a multi-season horizon considering multitudes of potential storms, and (3) Long-term resilience investment and infrastructure design strategy development considering potentially increasing flooding risks due to climate change and sea level rise. We present the overall framework that our team developed relying on the team's in-progress work, particularly for the short- and mid-term prediction-optimization models. We use two specific infrastructures as examples to instantiate our models: (1) Evacuation of patients from healthcare facilities (hospitals and nursing homes), and (2) Substation hardening and preparation for power grids. To create realistic, high-resolution case studies, we consider historical and synthetic storms that impact actual healthcare facilities and power grid for Texas.

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The University of Texas at Austin
Operations Research and Industrial Engineering
Cockrell School of Engineering

CLOSING THE GAP FROM UNCERTAINTY QUANTIFICATION TO DECISION MAKING: INTEGRATED PREDICTION AND OPTIMIZATION FOR INFRASTRUCTURE FLOOD RESILIENCE

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- Operations Research and Industrial Engineering
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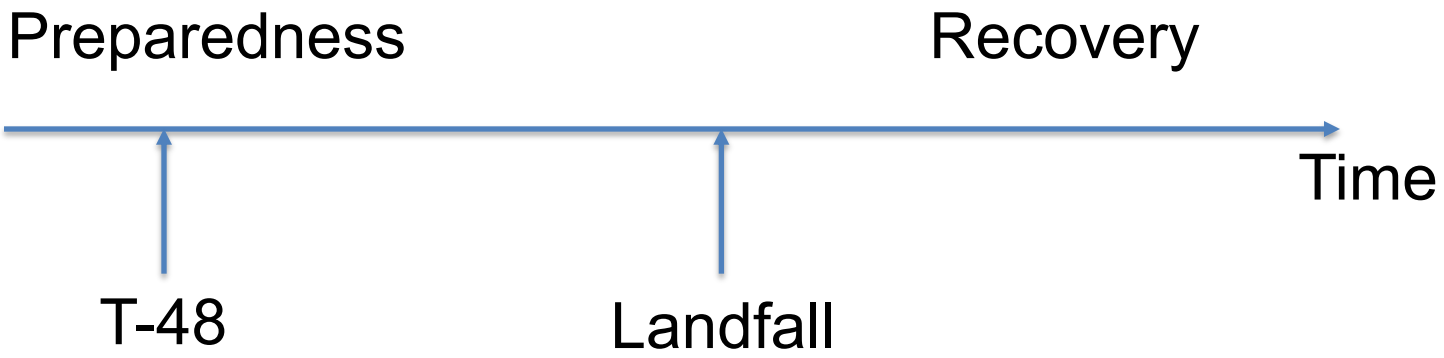
Hurricanes' Impacts

- Infrastructure
  - **Power grid: substations, transformers, power lines**
  - IT: data centers, power sources
  - Road network: bridges, highways
  - **Healthcare: hospitals, nursing homes**
  - Supply chains: chemical plants, ports, retail
- Community and people
  - Housing
  - Patients, nursing home residents, vulnerable communities
- Cascading impacts

Resilience Decision Making Cycle

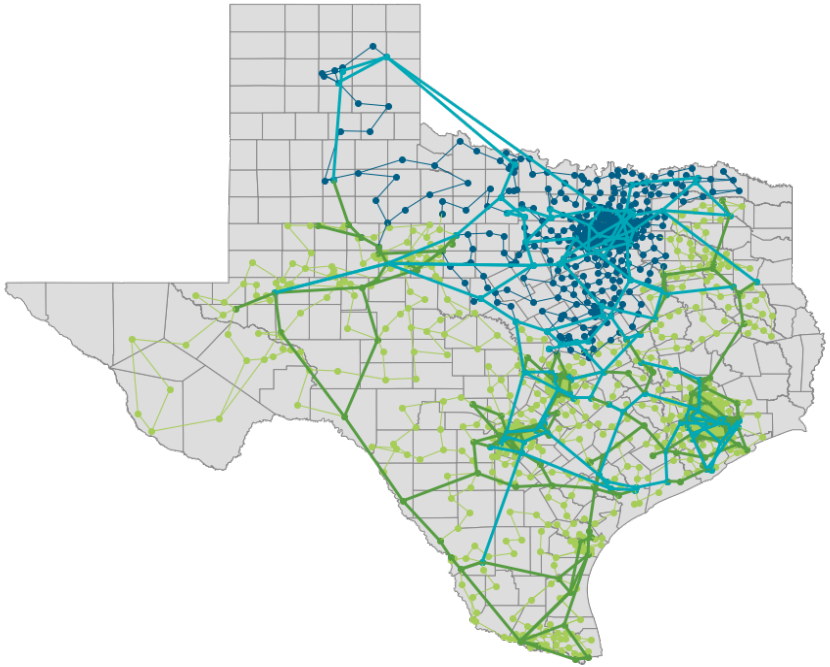
Pre- & Post-Event Decisions



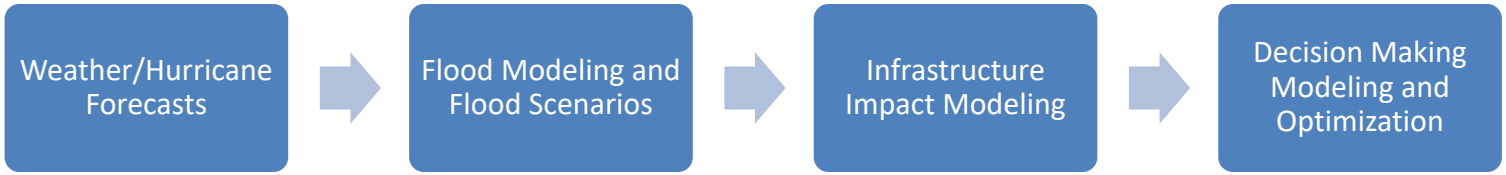
Decide which substations to protect and how much

Decide how to operate the grid to satisfy maximum power demand given the outages due to floods and how to recover flooded substations

Preparing the Power Grid

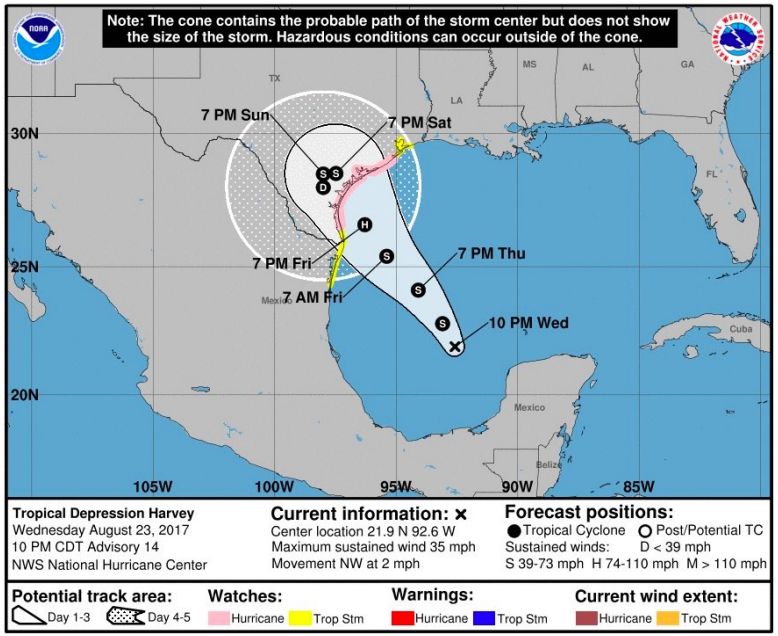


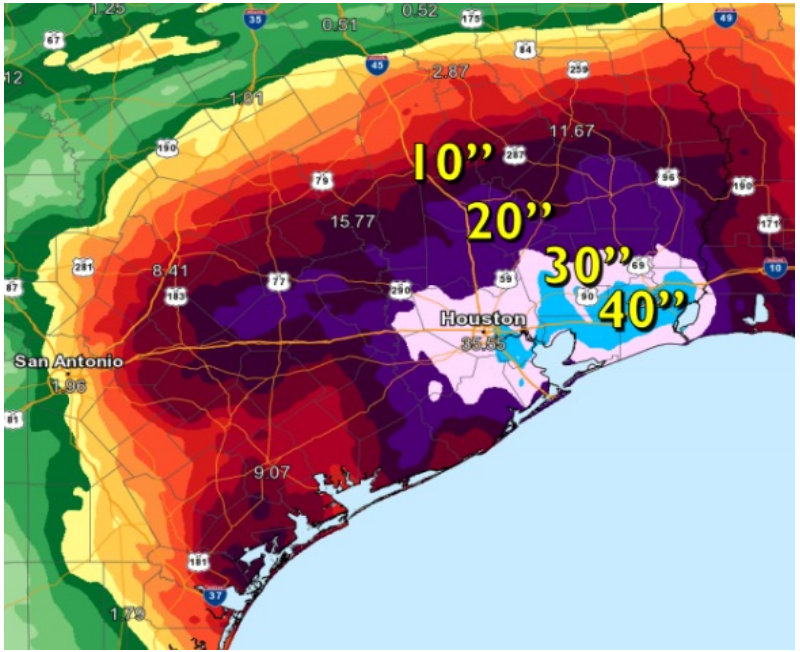
Integration



Integrated Prediction and Optimization-based Decision Support

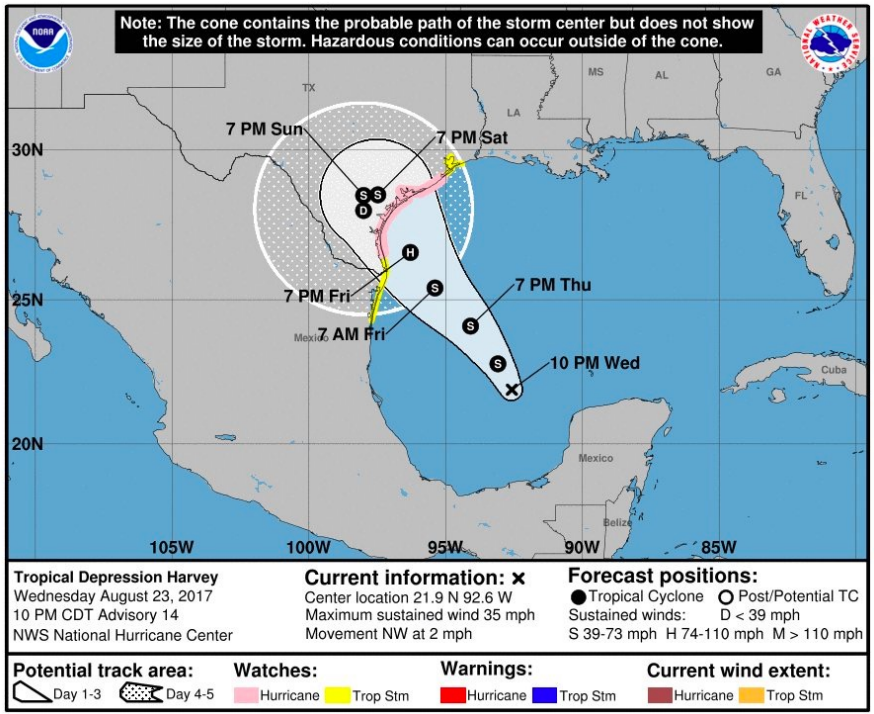
Track and Rainfall Map





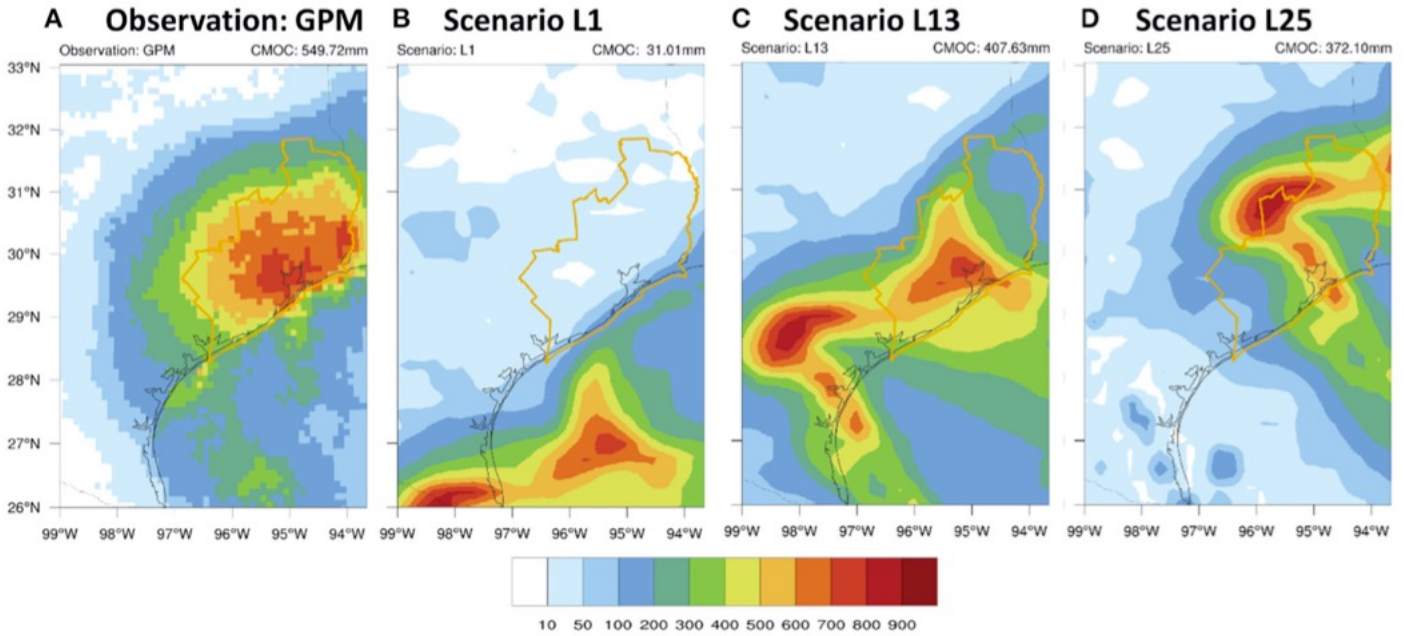
NOAA

Uncertainty Quantification – Scenario Generation

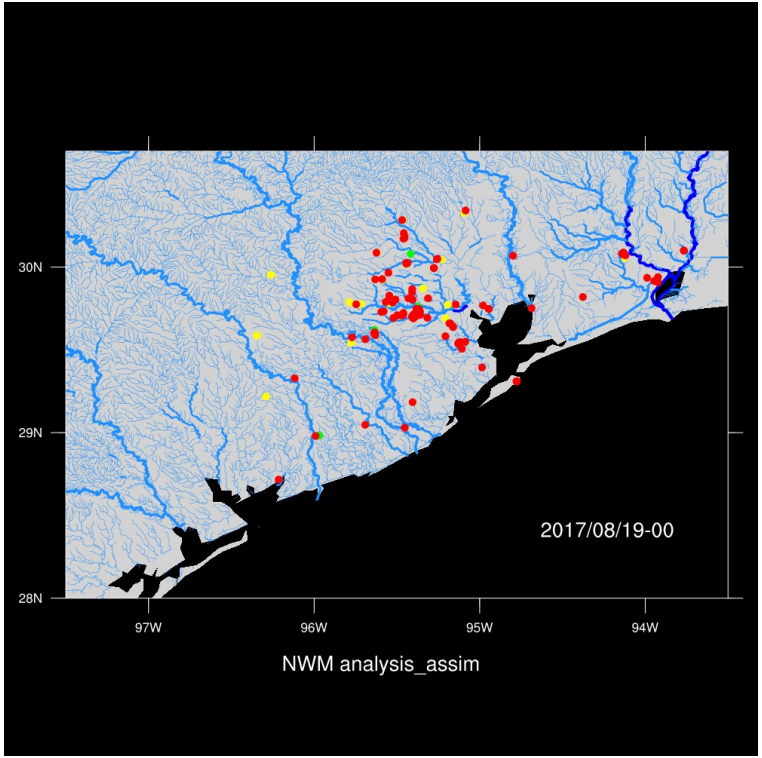


Scenario Generation: One Cone of Uncertainty, Multiple Tracks

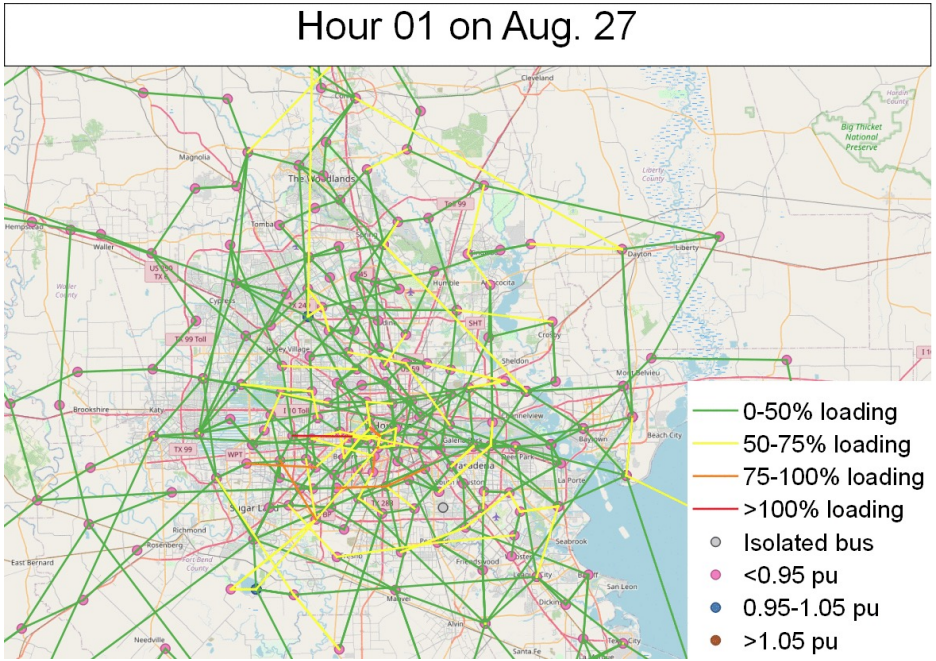
Uncertainty Quantification – Precipitation Shifting



Hurricane/Rain to Flood Modeling

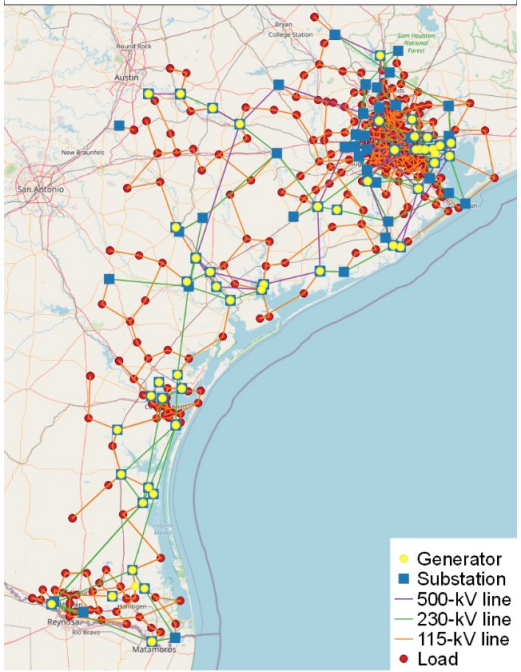


Power Grid Modeling



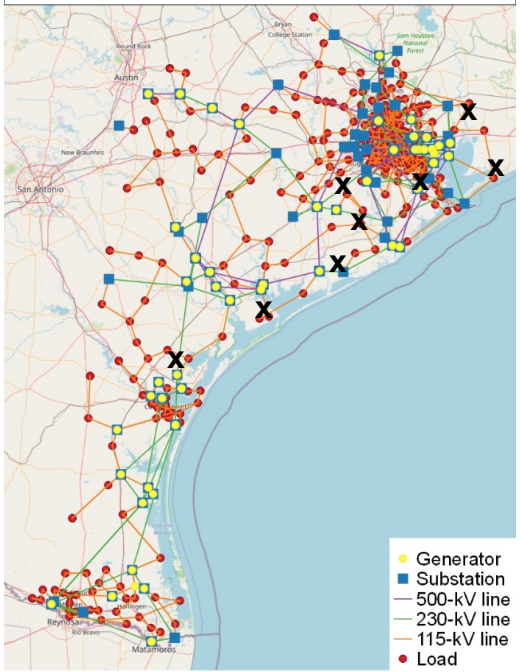
Power Grid Modeling

663-Bus Reduced Network



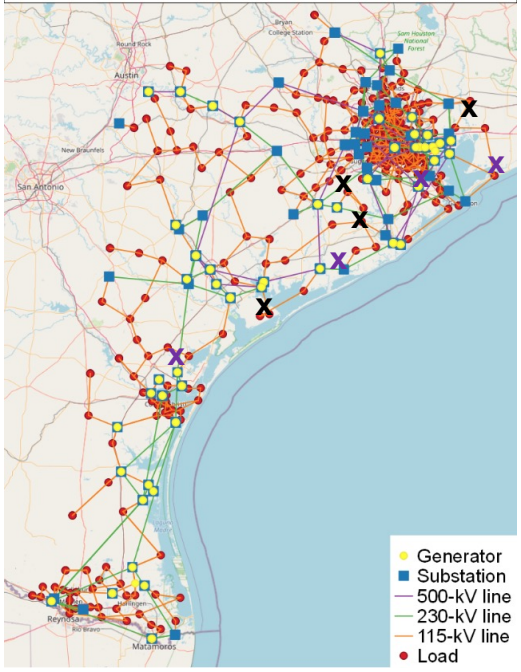
40 GW

663-Bus Reduced Network



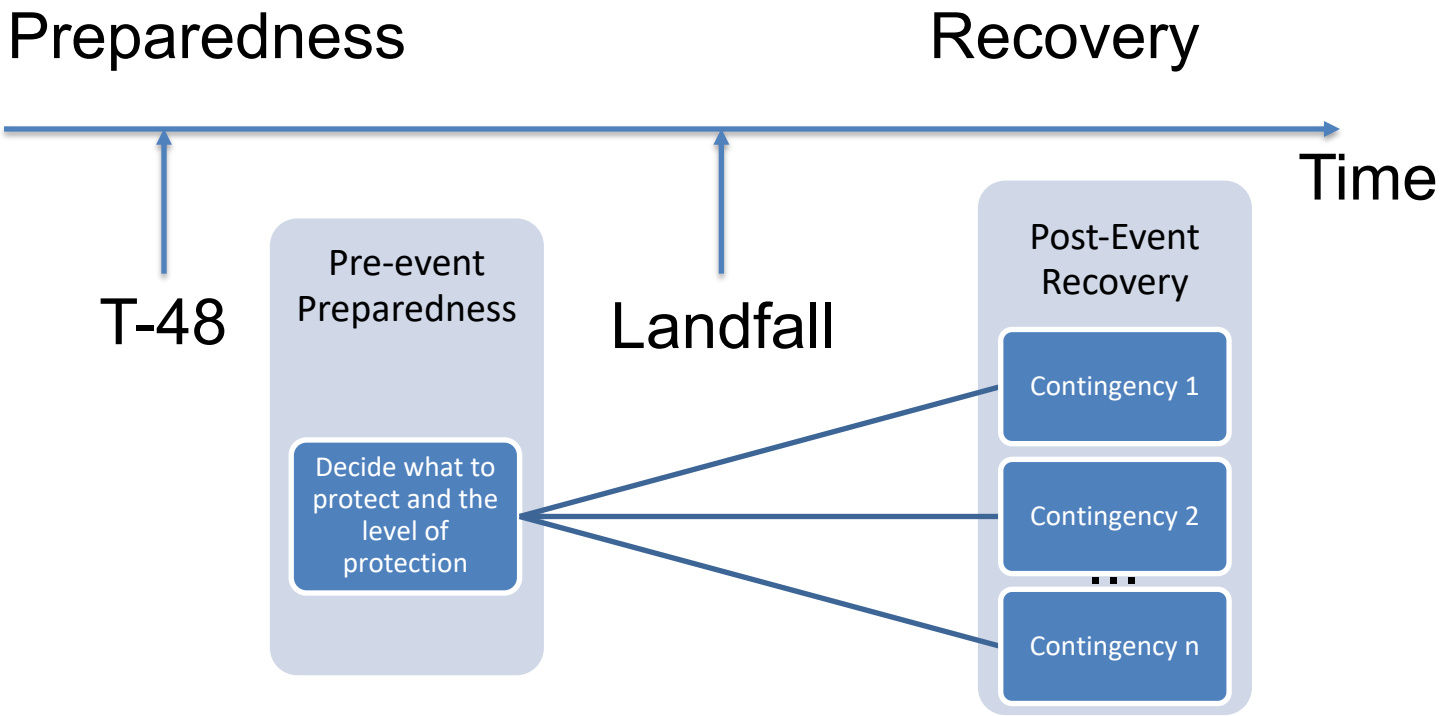
32 GW

663-Bus Reduced Network



38 GW

Coordinating Pre/Post-Event Decisions

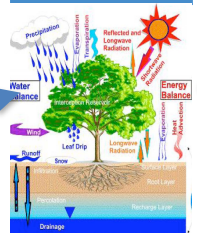


Power Grid Resilience

Weather Forecasts
- Storms/Hurricanes
- Rainfall events

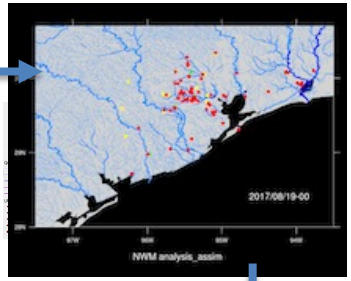
e.g. precipitation, temperature, wind, direction

Hydrology (Noah-MP) → Runoff (R) → Hydraulics (RAPID)

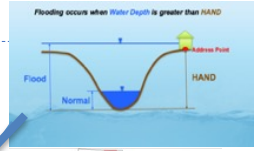


Geoscience Models

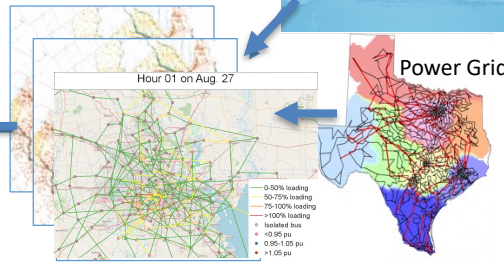
Flood forecast



HAND Analysis



Power Grid Impact Scenarios



Power Grid

Scenario-based Optimization

$$\sum_i f_i z_i + \sum_s p^s \left[\sum_{i,j,v,p} c_{ij}^v x_{ij}^{vps} + \sum_{j,k,v,p} c_{jk}^v x_{jk}^{vps} + \sum_{k,l,v} c_{kl}^v x_{kl}^{vs} \right]$$

$$\sum_k \alpha^v x_{jk}^{0,C,s} = D_j^{C,s} \qquad \forall j \in J, s \in S$$

$$\sum_{v,k} \alpha^v x_{jk}^{v,N,s} = D_j^{N,s} \qquad \forall j \in J, s \in S$$

$$\sum_{i,v} \alpha^v x_{jk}^{vps} \le B_k^p \qquad \forall k \in K, p \in P, s \in S$$

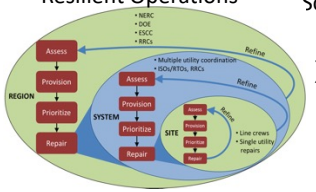
$$\sum_{j,p} x_{ij}^{vps} \le q_i^v \qquad \forall i \in I, v \in V, s \in S$$

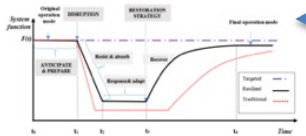
$$\sum_i x_{ij}^{vps} = \sum_k x_{jk}^{vps} \qquad \forall j \in J, v \in V, p \in P, s \in S$$

$$\sum_{j,p} x_{jk}^{vps} = \sum_l x_{kl}^{vs} \qquad \forall k \in K, v \in V, s \in S$$

$$\sum_{i,v \neq 0} q_i^v \le O_{max}$$

Resilient Operations





Resilience is not just about impending events

Days - Weeks

Months – Multiple Hurricane Seasons

Years – Decades – Climate Change Projections

What Comes First? Infrastructure or the resilience?

- How should we **respond to disasters** in the future?
  - Develop a resilience strategy (mitigation, preparedness and recovery) for projected extreme weather events given future climate projections
- How should we **design/adapt the infrastructures of the future for resilience**?
  - Develop a strategy for transitioning the design of the infrastructure (generation mix, batteries, microgrids for power grids) so that it is more resilient by design

Projects

- NSF: CoPe EAGER: Addressing Human-Centric Decision-Making Challenges from Coastal Hazards via Integrated Geosciences Modeling and Stochastic Optimization
- UT EI: Defending the Electricity Infrastructure against Extreme Weather Events, Now and in the Future
- Sandia: Critical Node Identification, Vulnerability Modeling, and Topology Optimization for the Electric Grid
- UT Planet Texas 2050: Hurricane-Resilient Healthcare Infrastructure Modeling with Integrated Flood Prediction and Stochastic Logistics Optimization

energy institute
THE UNIVERSITY OF TEXAS AT AUSTIN

PLANET TEXAS 2050
A UT Grand Challenge

Sandia National Laboratories

NSF

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More UT at AGU

Tue
Dec 14

Presentation
Poster

H25D-1087: Modeling the impacts of tropical storms and hurricanes on watershed …

4:00pm-6:00pm Dec 14 (Central)

Zong-Liang Yang

Presentation
Poster

A25H-1767: Changes in Extreme Rainfall Events under Global Warming: A Case Stu…

4:00pm-6:00pm Dec 14 (Central)

Sabiha Tabassum

Wed
Dec 15

Presentation
Poster

NH35C-0479: Incorporating Hurricane Forecasts into WRF-Hydro for Ensemble Gen…

4:00pm-6:00pm Dec 15 (Central)

Wen-Ying Wu

Presentation
Poster

NH35C-0480: Integrated Intelligence for Electric Grid Resilience using Storm Surge…

4:00pm-6:00pm Dec 15 (Central)

Ashutosh Shukla

Thank you!

Questions, Comments?

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