Regional Risk and Resilience Analysis

Definition of Testbeds, Analyses, Footprints, Resolution/Granularity and Data

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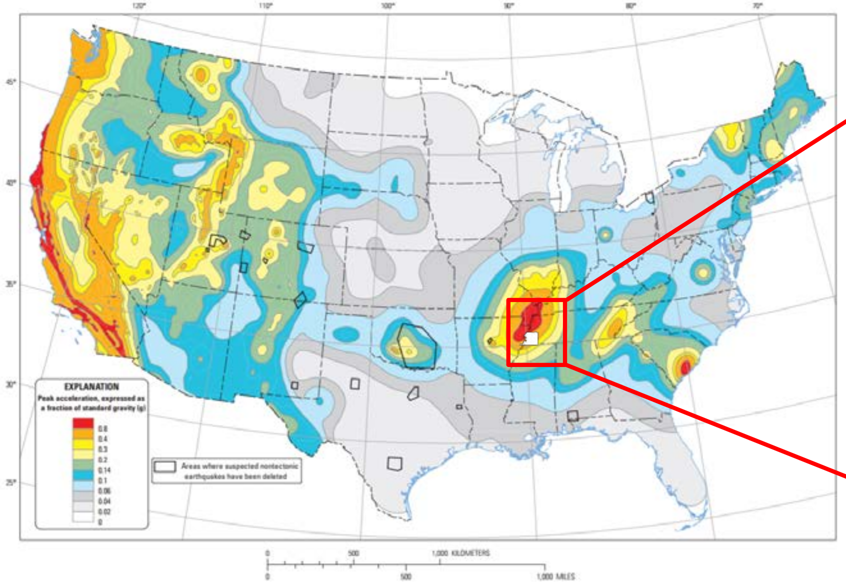
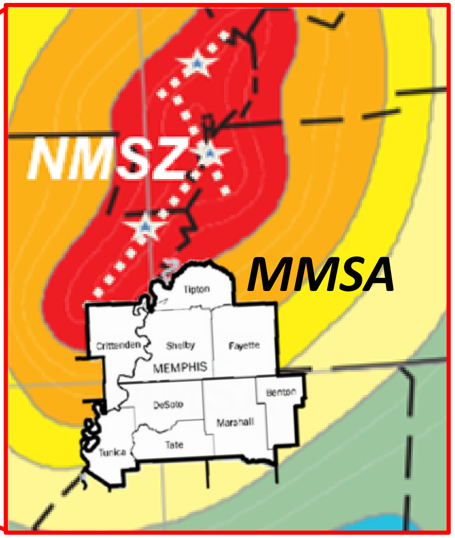
Introduction

- Testbeds allow us to test and verify algorithms for risk and resilience analysis
- One of the testbed we developed is the Memphis Metropolitan Statistical Area (MMSA) that could be subject to earthquake scenarios originating from the New Madrid Seismic Zone





- Other testbeds include Centerville (a virtual community), Seaside OR, and Houston/Galveston
- All the testbeds will be included in IN-CORE for researchers to learn, expand upon, and validate their own algorithms

Objectives

- Considering the MMSA testbed as an example, I will talk about the
  - Rationale for selecting a testbed
  - Definition of the hazard and network footprints
  - Definition of the hazard and network resolution/granularity
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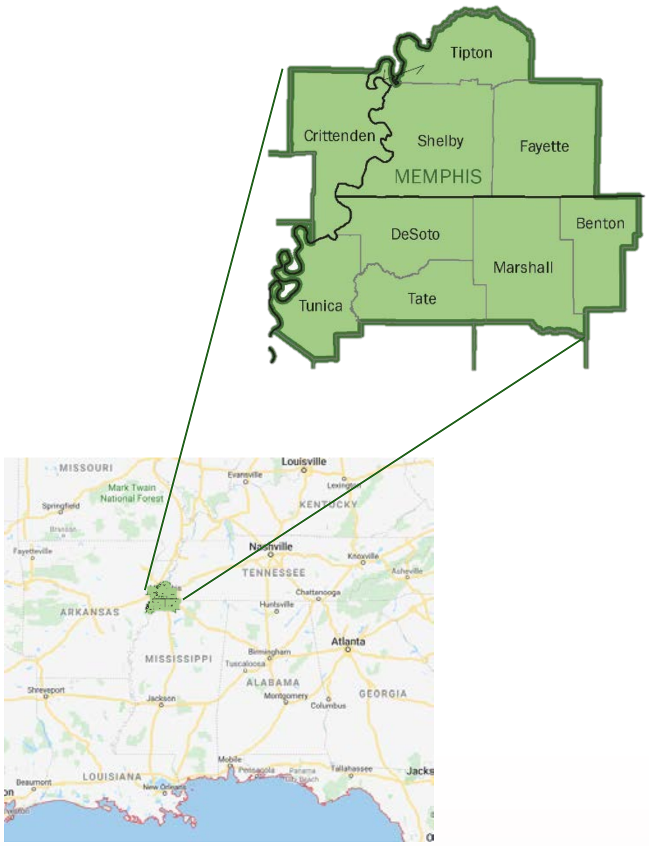
Planning was initiated on the Memphis Metropolitan Statistical Area (MMSA) Testbed in November, 2016

- This testbed was selected for several reasons
  - We wanted to ensure the scalability of the models and solution algorithms to a large urban area (MMSA, including Shelby County, TN and will be the largest testbed we consider)
  - We found that there are challenges in doing **functionality** analyses (e.g., water, power and traffic **flow** analyses) when we consider small testbeds because the footprint of infrastructure is typically larger than the footprint of a small testbed
    - So when we consider a small testbed, we either do not do the functionality analysis (like we did not do a power flow analysis for Centerville) or we make some assumptions on the “boundary conditions” (which are not always easy to make and are likely to affect the results)
    - Considering a testbed with a large footprint allows us to do more realistic functionality analyses and a more complete coupling among physical, social, and economic systems
  - A high-resolution topological model of the community, its physical and social infrastructure, and the seismic hazards from the New Madrid Zone had already been developed (at least in part) for the Shelby County Testbed developed by the MAE Center

The footprint of the MMSA testbed includes nine counties across three states

- Memphis has about 700,000 people; Shelby County about 1M; and MMSA about 1.4M
- Physical infrastructure includes
  - buildings (residential, schools and hospitals)
  - potable water network
  - electric power network
  - transportation network (roads and railways)
- The target community metrics are
  - population stability
  - economic stability
  - social services stability
  - physical services stability



The objectives of the MMSA testbed are to

- **Demonstrate that the developed assessment algorithms can be scaled to a large urban area**, and examine the degree to which the modeling and analysis developed based on smaller testbeds scale to a real urban area
- **Understand challenges in performing realistic functionality/recovery analyses** (e.g., for the water, power and traffic flow analyses) at different scales
- **Examine the impact on urban resilience of the support from the surrounding communities**
- **Develop high-resolution, 3-dimensional (3D), physics-based models for the seismic wave propagation** under realistic tectonic and geo-morphological conditions (Tier 2 hazard analysis), suitable for the assessment of spatially distributed earthquake demands on distributed infrastructure situated in regions of potential liquefaction
- **Study the impact of riverine flooding** on urban communities under climate change using coupled hydrologic-hydraulic models
- **Integrate the physical damage to buildings with utility disruptions** predicted by a cascading failure model of interdependent utility networks to estimate the post-event functionality loss ratio of building portfolios probabilistically at the community scale
- **Model interfaces and information flow between physical, social and economic systems during the recovery process** with the ultimate goal of informing the development of efficient decision support algorithms

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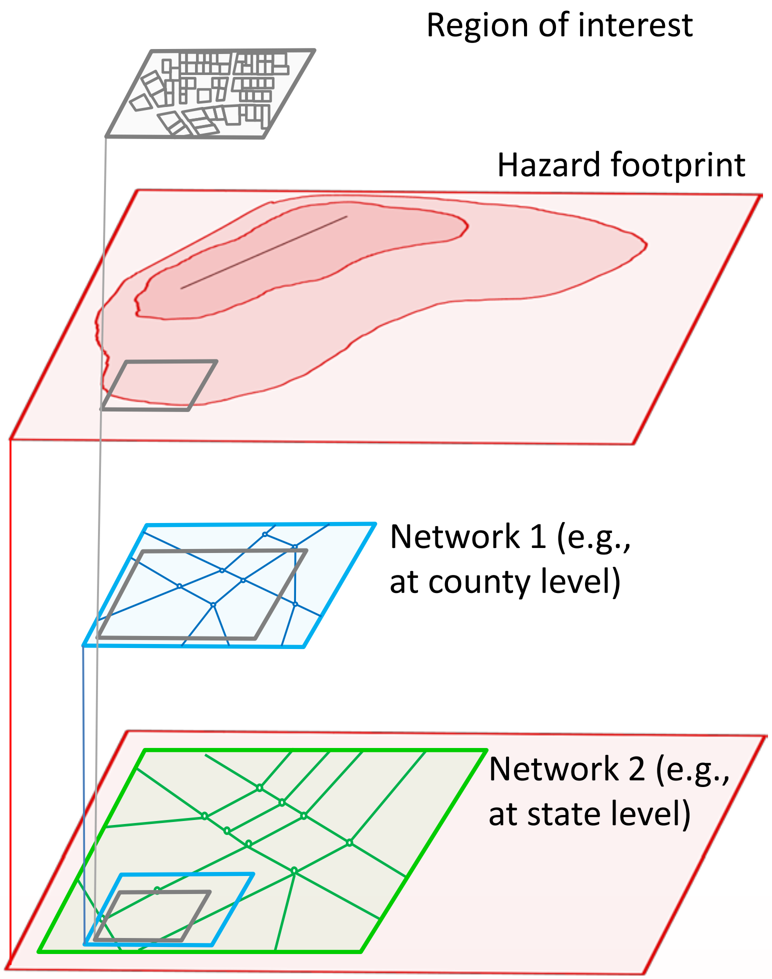
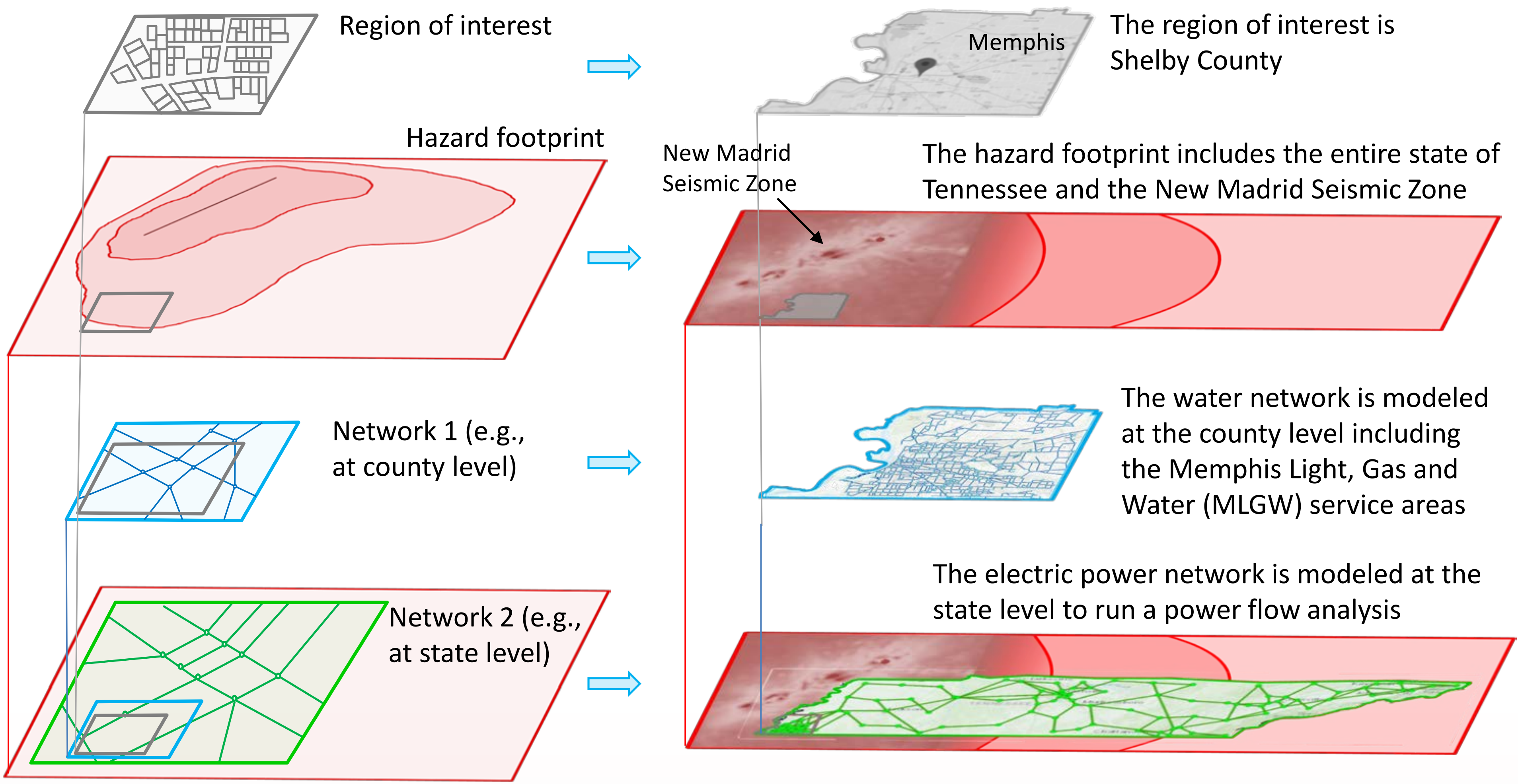
Before doing any analyses, for a given region of interest, we need to define the footprint of the hazard and of each network

- The footprint of the hazard and of each network might exceed the footprint of the region of interest
- The hazard and the different networks might have different footprints
- The hazard footprint has to be at least as big as the largest network footprint and in general has to include the source
- The definition of the footprint of each network depends on four key factors
  - The type of information of interest (physical damage vs. functionality)
  - Existence of easily-recognizable physical boundaries and possibility to model the boundary conditions
  - Existence and location of strategic elements that need to be included like generation nodes (depending on the purpose of the analysis)
  - Modeling of the damage propagation among infrastructure systems



Sharma, N., Tabandeh, A., Gardoni, P., Murphy, C. (2019). "Modeling and evaluating the impact of natural hazards on communities and their recovery," *Structure and Infrastructure Engineering* (under review).

If we consider Shelby County as the region of interest, the hazard and network footprints might actually be different from the MMSA



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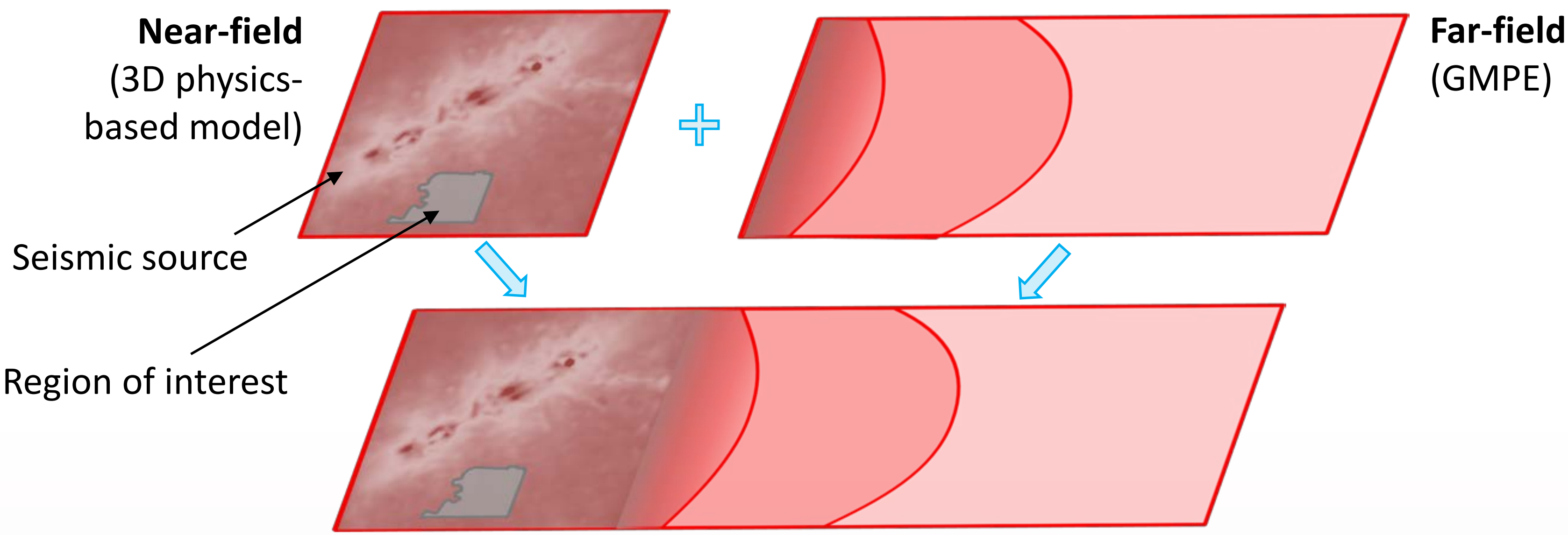
Once we defined the footprint of the hazard, we need to define the model resolution

- In the near-field, we can increase the resolution of the seismic hazard model considering a 3D physics-based model
- In the far-field, we can use the traditional ground motion prediction equations
- In terms of modeling, different resolutions of the footprint affect the ability to describe
  - the spatial variability of hazard over the area of interest (including directivity effects)
  - the amplification phenomena due to local basin effects



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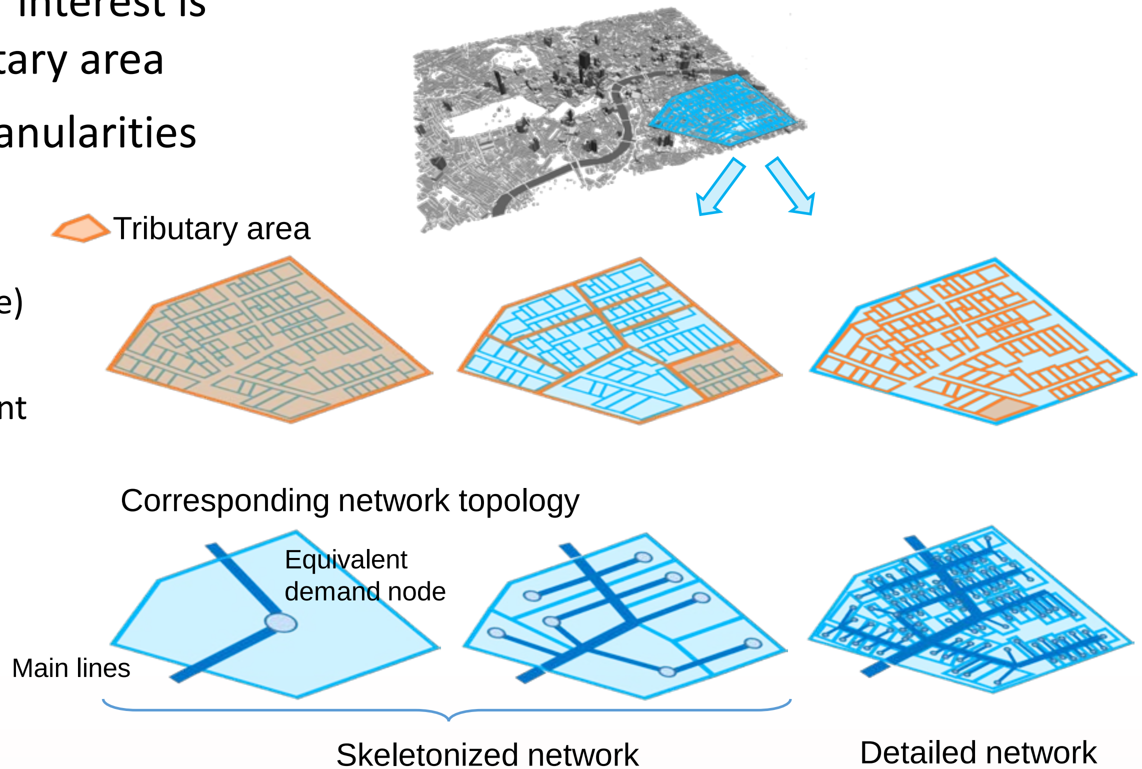
Similarly, once we defined the footprint of a network, we need to define its granularity (i.e., the resolution of the model)

- We define a tributary area as the area served by a single network node
  - By changing the tributary area we can define networks with different levels of granularity
  - In the limit, the most refined model considers each single parcel (house lot) as the tributary area
- The nodal value of the quantity of interest is the spatial average over the tributary area
- In terms of modeling, different granularities affect the ability to describe
  - the spatial variability of the impact over the area of interest (more next slide)
  - the changes in the network capacities and demands following a disrupting event
  - the recovery process, as skeletonized networks include only main lines (not small distribution lines)

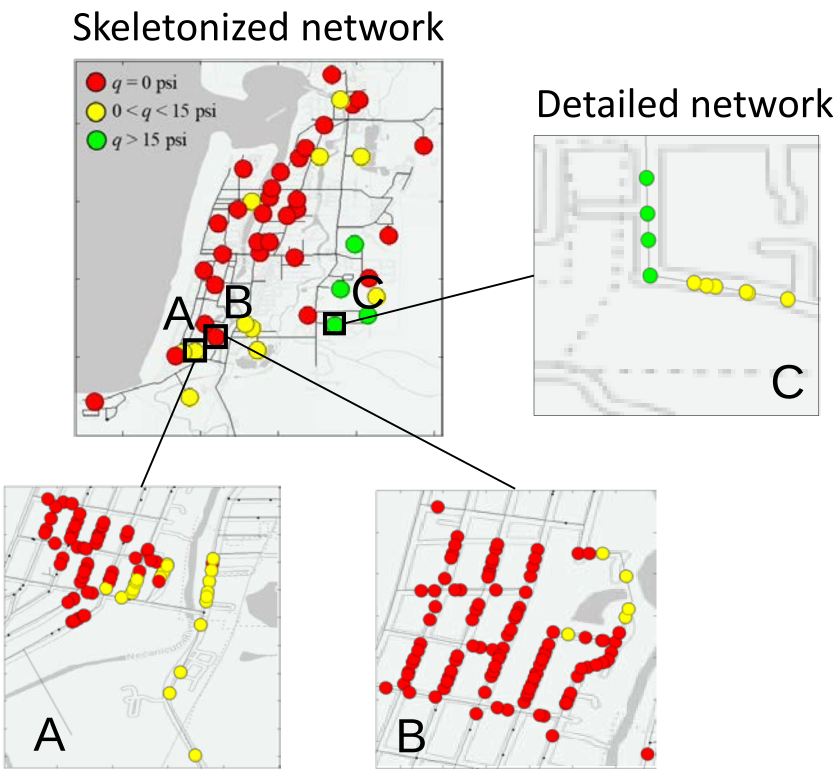


Guidotti, R., Gardoni, P., and Rosenheim, N. (2019) "Integration of physical infrastructure and social systems in communities' reliability and resilience analysis," *Reliability Engineering & System Safety,* 185, 476-492.

It is important to capture the spatial variability of the impact over the area of interest

… because certain population groups may be more impacted than others or recover more slowly, and tributary areas that are too large would underestimate the actual societal impact (Gardoni and Murphy, 2020)

- The detailed network allows us to capture the variability within the larger tributary areas used for the skeletonized networks (Guidotti et al. 2018)



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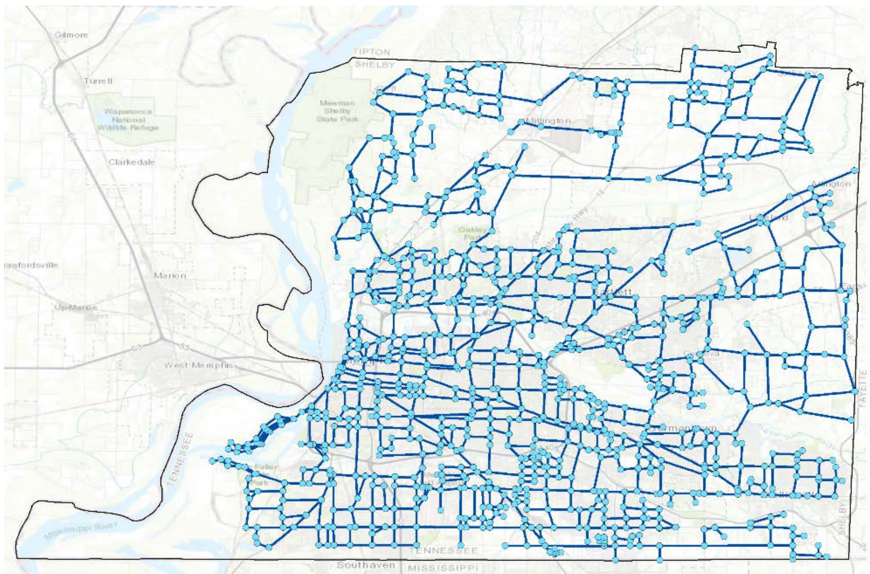
Gardoni, P., and Murphy, C., (2020). “Society-based design: developing sustainable and resilient communities,” *Sustainable and Resilient Infrastructure,* 5(1), 4-19.

For example, we modeled the potable water network of Shelby County with two levels of granularity

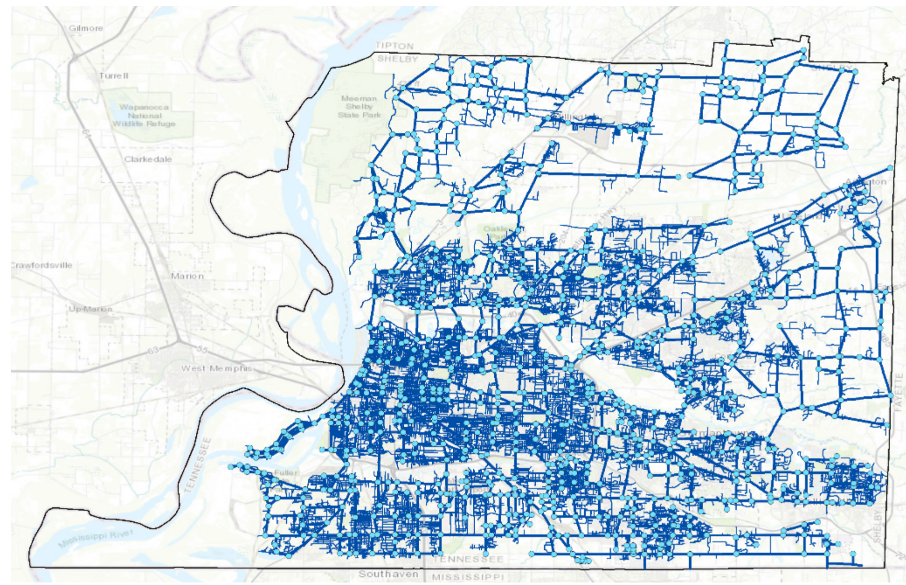
- A **skeletonized** model of the network
  - is able to provide a preliminary assessment of the network reliability and resilience
  - typically requires fewer input data and a lower computational costs than a detailed network
- A **detailed** model of the network
  - is required to capture the variability of the impact at the house lot level
  - typically requires a large amount of input data, and large computational cost



Skeletonized Model

Number of Junctions: 965

Number of Pipes: 1,346



Detailed Model

Number of Junctions: 10,868

Number of Pipes: 12,703

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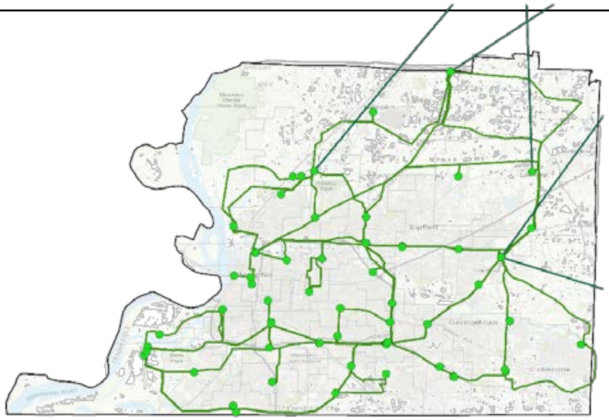
We modeled the electric power network with two levels of granularity based on the area of interest

- We developed a **detailed** model for the power network of Shelby County
  - to capture the variability of the impact within the county
  - to estimate the timeline of power outage affecting dependent areas

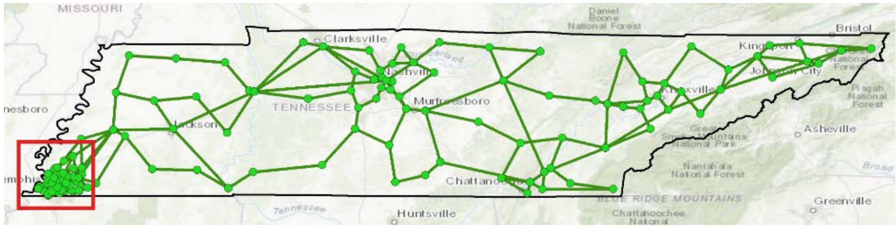


Detailed Model in Shelby

Number of Buses: 69

Number of Lines: 107

- We developed a **skeletonized** model for the power network outside of Shelby County
  - to model the effects of damage to the external grid (i.e., generators, major transmission lines) supplying power to Shelby County
  - which is sufficient to perform accurate power flow analyses



Skeletonized Model for TN

Number of Buses: 150

Number of Lines: 146

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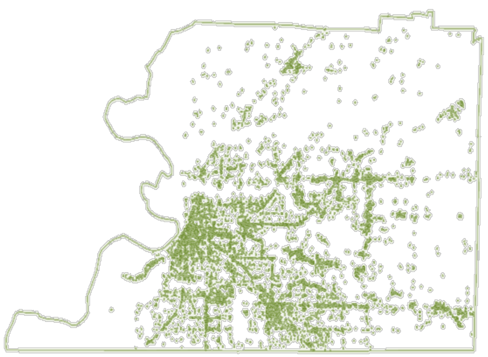
We collected all the required physical and demographic data for each individual building in Shelby County

- Structure type, occupancy type, and number of stories are required for the damage assessment
- Demographics and population size are needed along with the predicted physical damage to predict possible population dislocation and model the time-varying demand on the water and electric power networks

Residential Buildings

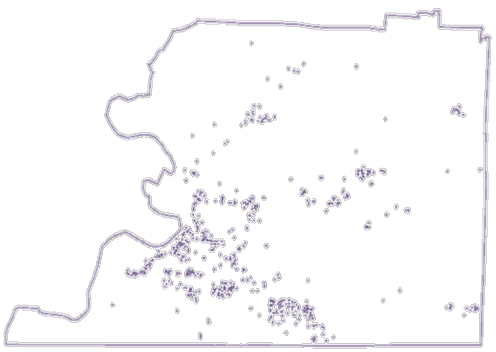
Number of buildings: 288,097
Single family houses: 93.5%
Wood structure: 98.6%

Commercial Buildings



Number of buildings: 16,832
Retail and Wholesale: 52.94%
Steel structure: 35.25%
Unreinforced masonry: 21.47%

Industrial Buildings



Number of buildings: 1,076
Heavy Industrial: 65.9%
Steel structure: 58.8%

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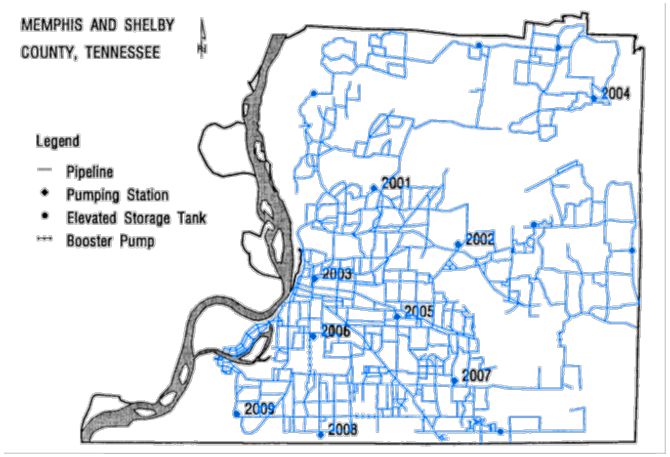
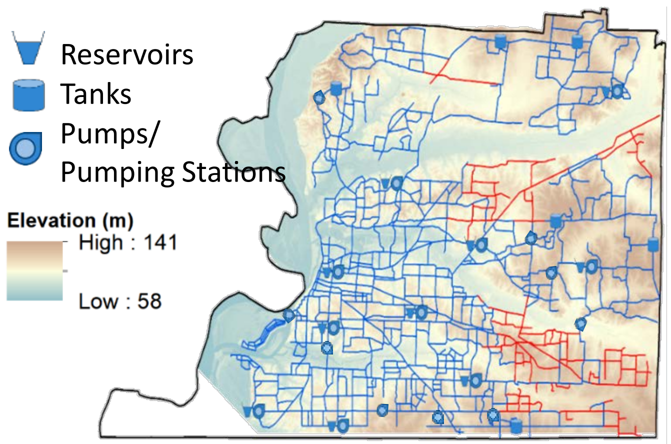
However, the majority of the national critical infrastructure are owned and operated by private companies

- As a result, information on network topology and operation is often missing or incomplete

- We had to collected additional information and design the missing portions of the infrastructure using general inference techniques and engineering principles
  - Added the elevation from the USGS raster maps
  - Completed the topology based on street maps and building access
  - Designed the pipe diameters and pump capacities by satisfying flow constraints in normal operating conditions
  - Defined tank capacities from published work and general search



After Hwang et al. (1998)



After Sharma et al. (2019)

Hwang, H.H.M., Lin, H. and Shinozuka, M. (1998) "Seismic Performance Assessment of Water Delivery Systems," *Journal of Infrastructure Systems*, 4(3), 118-125.

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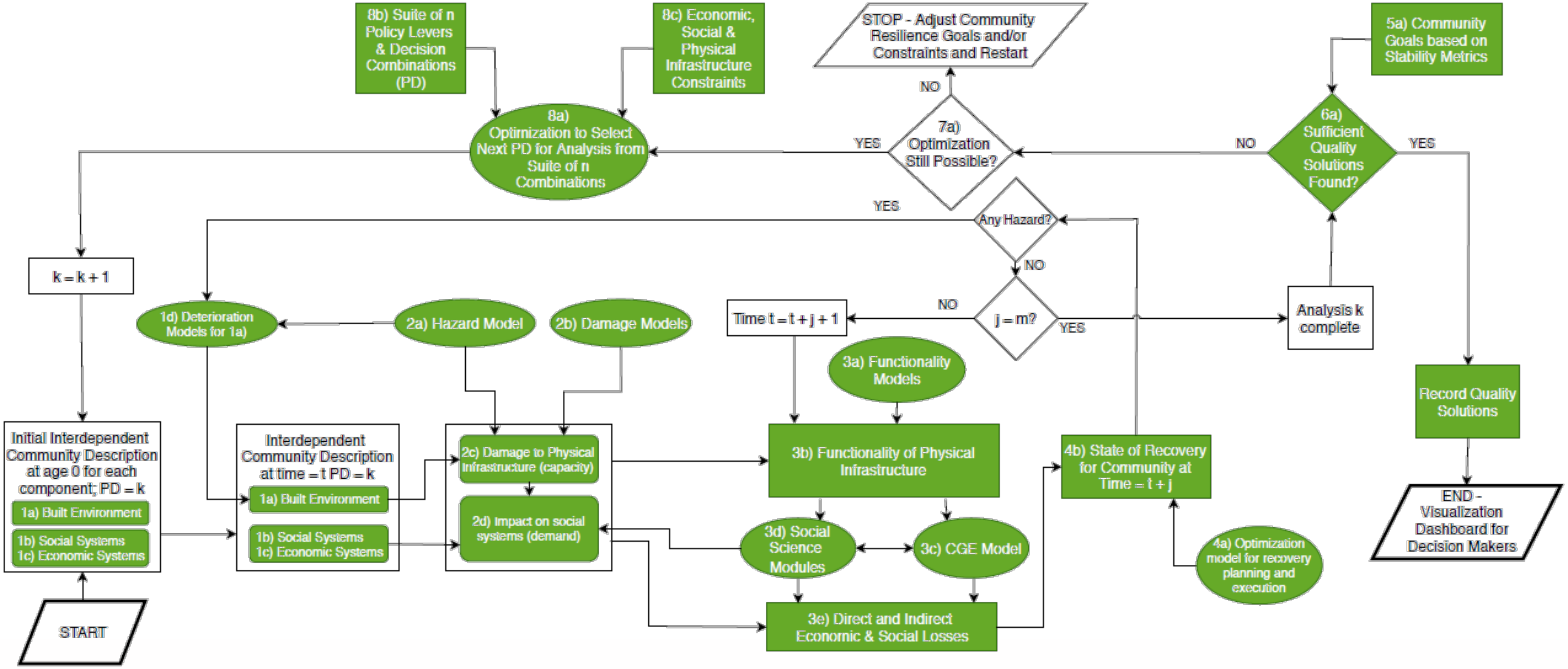
The MMSA testbed is comprehensive and tests most of the models and analyses that are available or are being developed for IN-CORE

Flowchart of the analyses in IN-CORE



= Models and analyses included in the MMSA testbed

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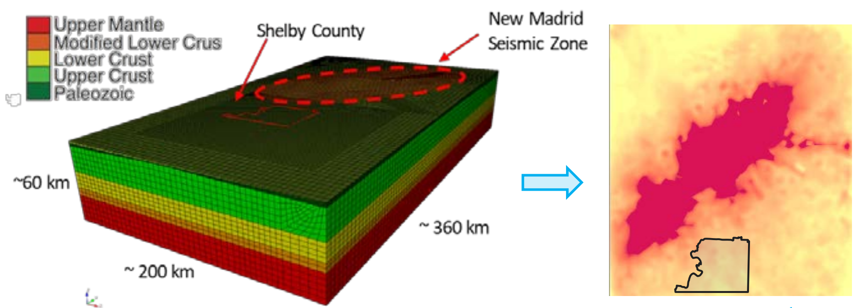
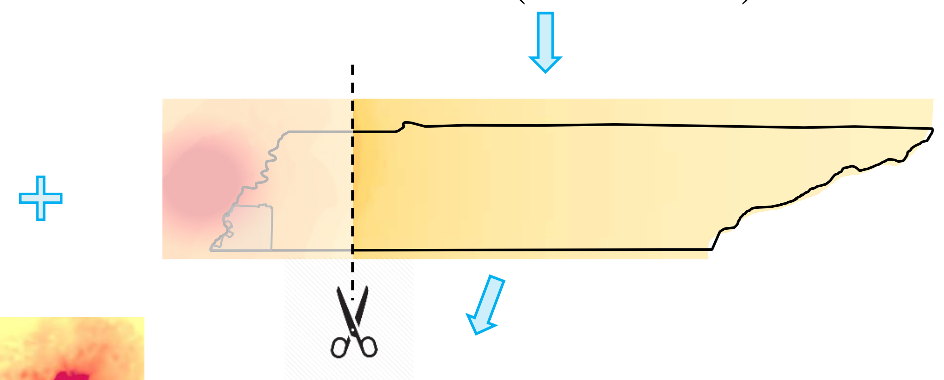
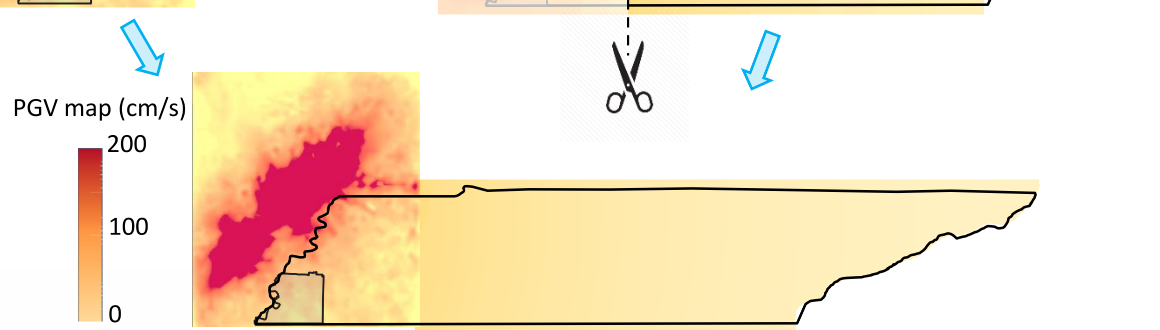
We propagated an hypothetical earthquake with 7.7M and hypocenter at a depth of 14 km with the two levels of resolution

- A high-resolution model in the near-field
  - Requires a 3D physics-based model and a numerical software (e.g., SPEED)
  - Is able to capture the amplification effect due to the thick layer of sediments beneath Shelby County
- A low-resolution model in the far-field
  - Is based on GMPE (e.g., Steelman et al., 2007)
  - The intensity measure of interest is empirically provided as a function of earthquake characteristics (e.g. magnitude M, epicentral distance R, fault F and soil S characteristics)



$$IM = IM(M, R, F, S)$$





Steelman, J., Song, J., and Jerome, F. (2007). Integrated data flow and risk aggregation for consequence-based risk management of seismic regional losses. MAE Center report (available at http://mae.cee.illinois.edu).
Guidotti, R., Tian, S., and Gardoni, P. (2020). "Simulation of seismic wave propagation in the Metro Memphis Statistical Area (MMSA)," (in preparation).

We used the earthquake intensity measures and fragility functions to estimate the damage of individual buildings

- Low damage
- Medium damage
- High damage

Most likely damage state for <u>residential</u> buildings | **Most likely damage state for <u>commercial</u> buildings** | **Most likely damage state for <u>industrial</u> buildings**

Estimated damage state, using the <u>GMPE</u> for hazard

Estimated damage state, using the <u>3D physics-based model</u> of the hazard

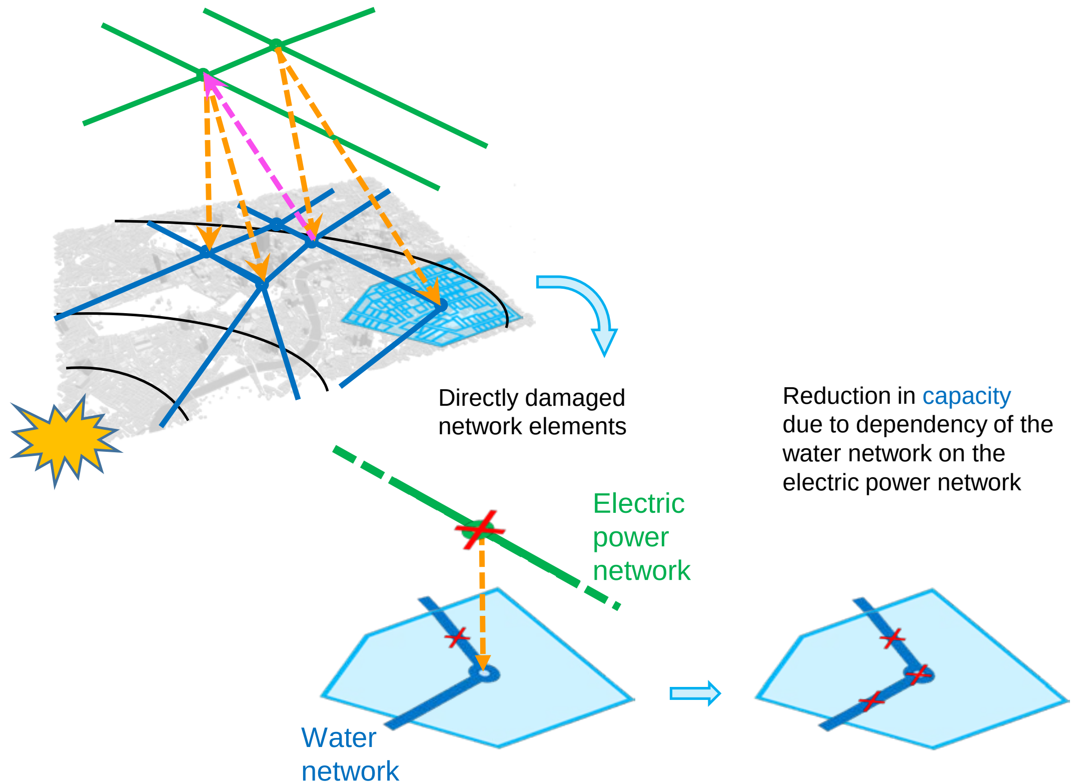
- We observe
  - localized high damage due to the hazard amplifications in certain areas, which is not captured by the GMPE
  - on average less structural damage in residential buildings but more structural damage in industrial buildings (given their specific locations)

Sharma, N., Tabandeh, A., Gardoni, P., Murphy, C. (2019). “Modeling and evaluating the impact of natural hazards on communities and their recovery,” *Structure and Infrastructure Engineering* (under review).

Physical infrastructure often depend on each other and such dependencies might indirectly affect a network capacity

Some examples

- Buildings need the service provided by the water and power networks
- The water network depends on the power network because it needs power at the pumping stations and control systems
- The electric power network needs fuel for generators and water for cooling
- The transportation network needs power for signaling
- The water network needs the transportation network to access the locations of critical elements



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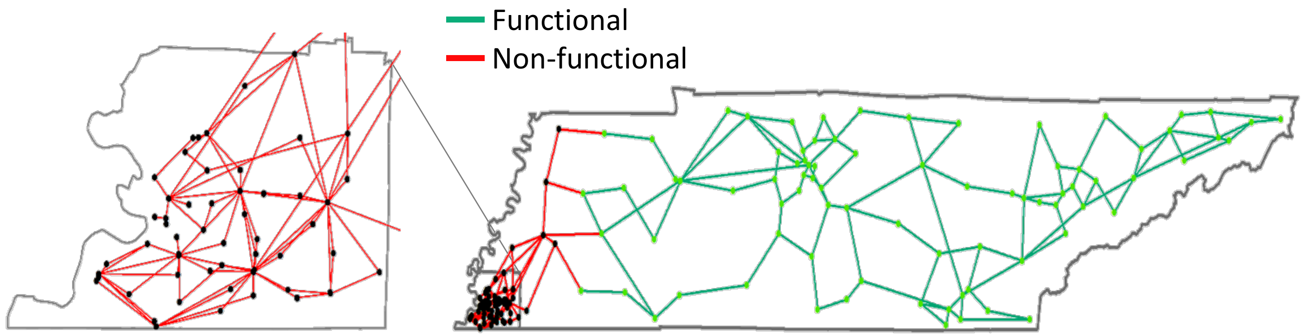
Sharma, N., Nocera, F., and Gardoni, P. (2019). “Classification and mathematical modeling of infrastructure interdependencies,” *Sustainable and Resilience Infrastructure* (under review).

First we estimated the impact of the earthquake on the power network capacity

- The components of the electric power network can lose functionality due to direct structural damage, disconnection, or overloading
- We modeled the direct structural damage
  - on substations and power lines, using component fragilities in a system reliability analysis
  - on secondary distribution circuits, using service area damage ratios and further statistical analyses
- To run the power flow analysis
  - we detected disconnected components using a network cleaning process
  - we detected overloading and check for power balance using an optimized power flow analysis

Impact on Shelby County power network

Buses damaged:	28.3%
Buses not functional:	100%
Lines disconnected:	45.4%
Lines not functional:	100%
Transformers damaged:	59.5%
Service areas damaged:	76%
Service areas blacked out:	100%



- We estimated a complete power blackout for Shelby County

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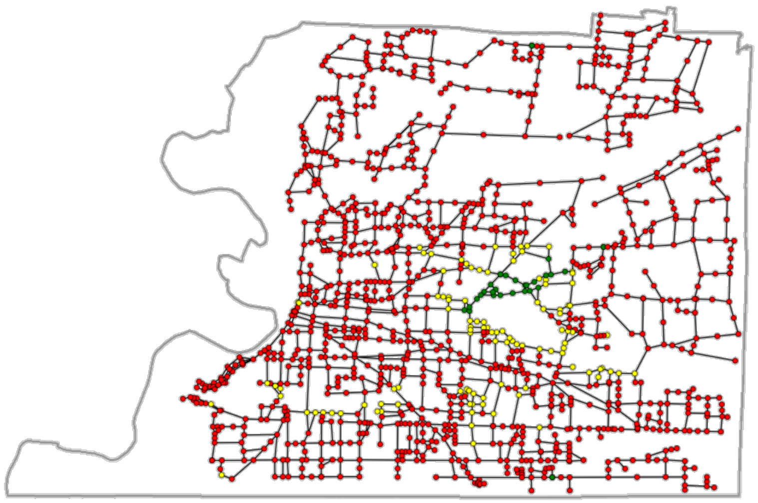
Then we estimated the impact of the earthquake on the water network capacity…

Water Network <u>without</u> dependency on the Electric Power Network



- Pressure ≥ 15 psi
- 15 psi > Pressure ≥ 10 psi
- Pressure < 10 psi

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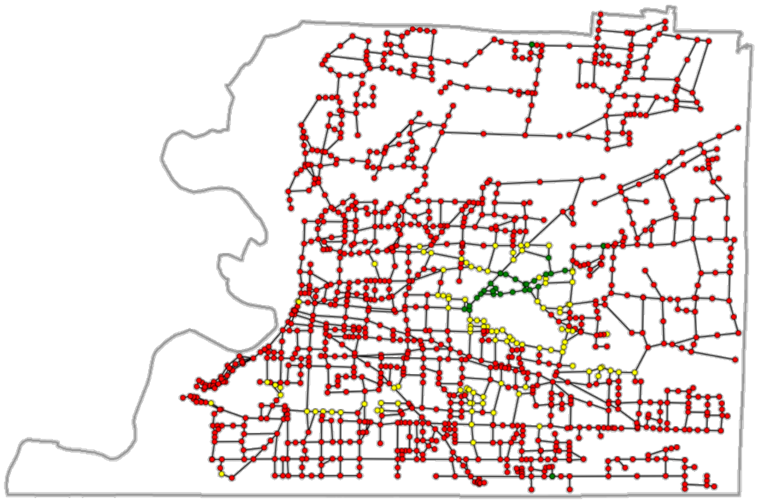
Then we estimated the impact of the earthquake on the water network capacity…

… and considered the dependency on the electric power network

Water Network <u>without</u> dependency on the Electric Power Network



- Pressure ≥ 15 psi
- 15 psi > Pressure ≥ 10 psi
- Pressure < 10 psi

The dependency on power exacerbates the impact by causing additional pumps to go offline

Water Network <u>with</u> dependency on the Electric Power Network

- We see that accounting for the dependency of the water network on the power network significantly reduces the ability of the water network to deliver water

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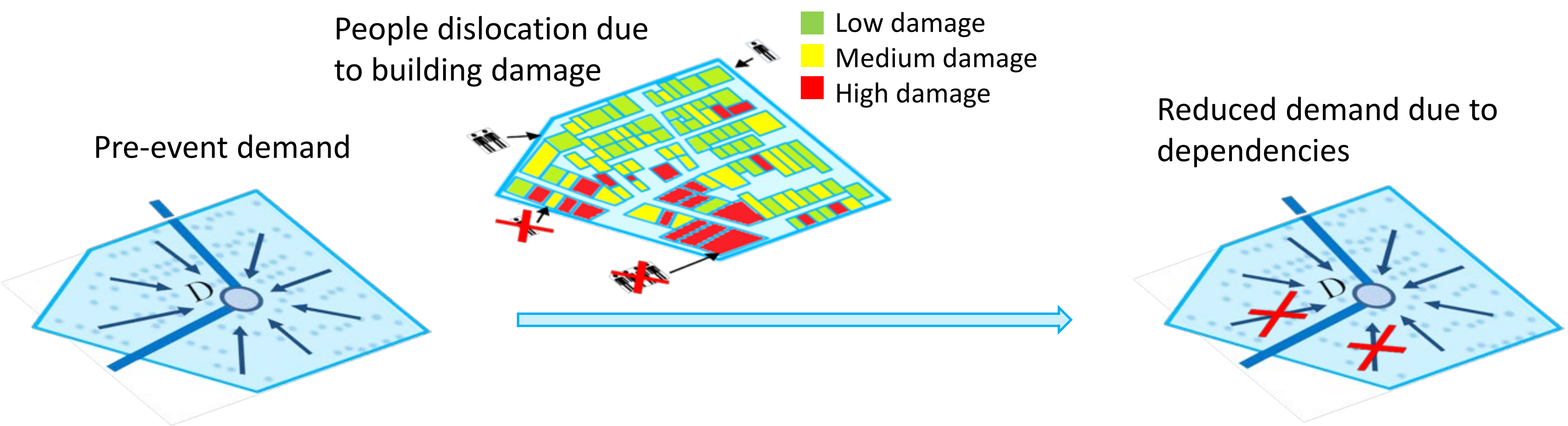
Not only the capacity, but also the demand can be affected by dependencies

- For example, building damage can lead to people dislocation or business interruption that affect the post-event water network **demand**



- The updated network **capacity** and **demand** can then be used in a flow-based network analysis to assess the functionality and reliability of the network

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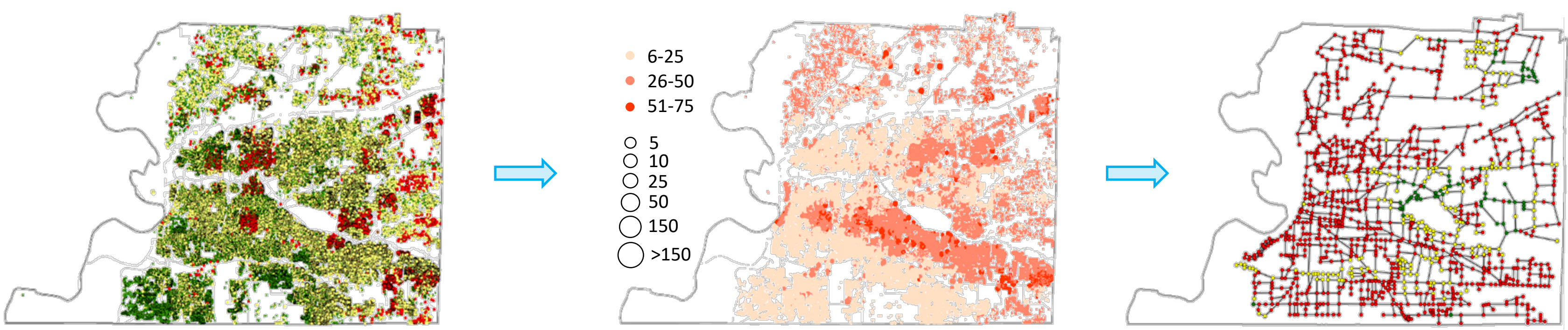
We studied the effects on the water demand of people dislocation due to a seismic event

- People dislocation is estimated using a logistic model based on the PMF of the residential structural damage and other socioeconomic factors (i.e., income and race)
  - Individuals with a higher income are more likely to dislocate in case of structural damage
- (External) people dislocation results in a <u>decrease</u> in the water demand at the nodes of the water network
- The assessed physical damage to the water network and the reduced demand due to people dislocation are then used in a water-flow analysis to see if the new water demand is met

Most likely damage state for residential buildings | **People dislocation due to building damage [%]** | **Water demand met after dislocation**



- Thanks to the reduction in water demand, the water network performs better than if we did not consider people dislocation

Sharma, N., Tabandeh, A., Gardoni, P., Murphy, C. (2019). “Modeling and evaluating the impact of natural hazards on communities and their recovery,” *Structure and Infrastructure Engineering* (under review).

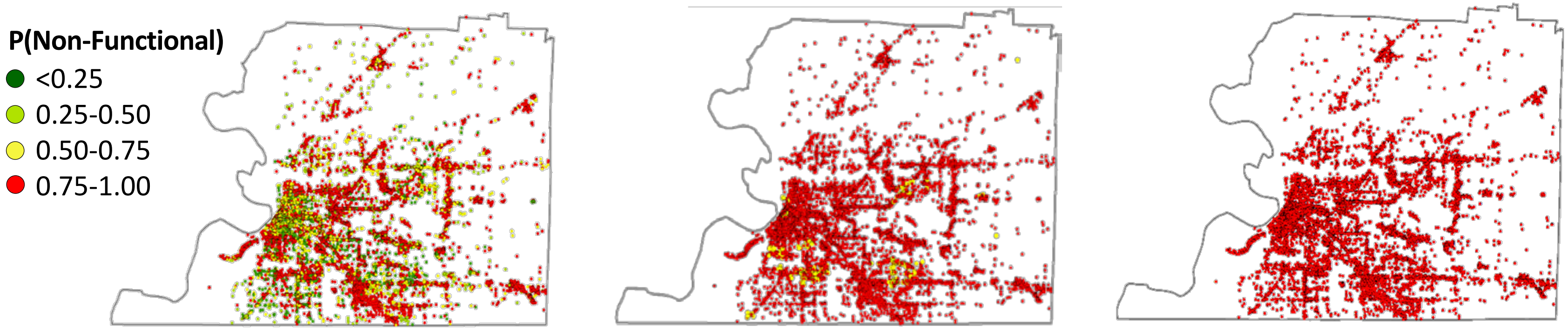
The service provided by the supporting infrastructure affects the building functionality

- As an example, we estimated the probability that each commercial building is not functional considering structural damage as well as access to water and power

Probability of being non functional due to only structural damage

Probability of being non functional due to structural damage or lack of water

Probability of being non functional due to structural damage, or lack of water or power

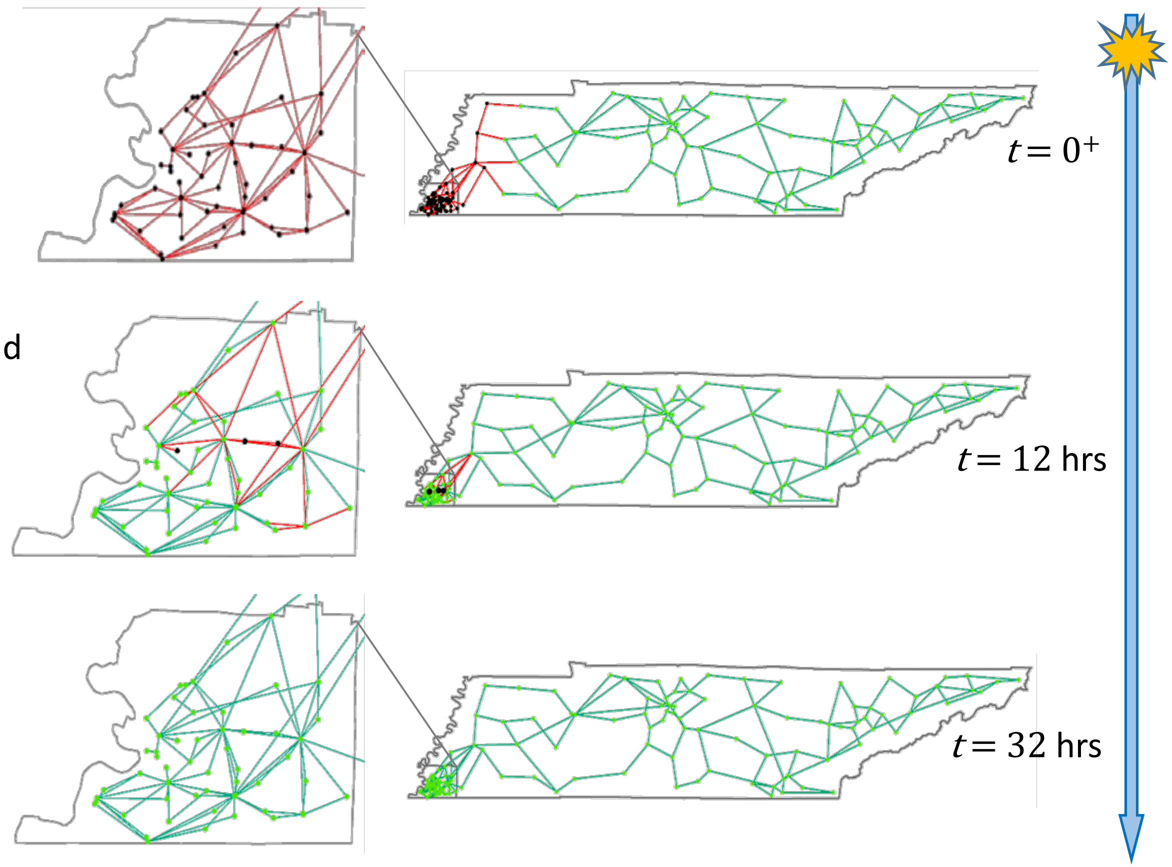


- Considering only the structural damage, we significantly underestimate the lack of functionality of buildings
- In this example, due to a likely power blackout in Shelby County (with a probability 0.98) in the immediate aftermath of the earthquake, the most likely functionality state of the buildings is 'Non-Functional' (considering no power backups)

Sharma, N., Tabandeh, A., Gardoni, P., Murphy, C. (2019). "Modeling and evaluating the impact of natural hazards on communities and their recovery," *Structure and Infrastructure Engineering* (under review).

We modeled the recovery of the power network considering the actual priorities in a real post-disaster recovery

- We can see that
  - Immediately after the earthquake the damaged network has a blackout in Shelby County
  - With nominally assumed crew sizes and corresponding scheduling constraints, power network starts recovering fairly quickly
  - After about 32 hrs of repair work, all critical components have recovered, however non critical repairs continue

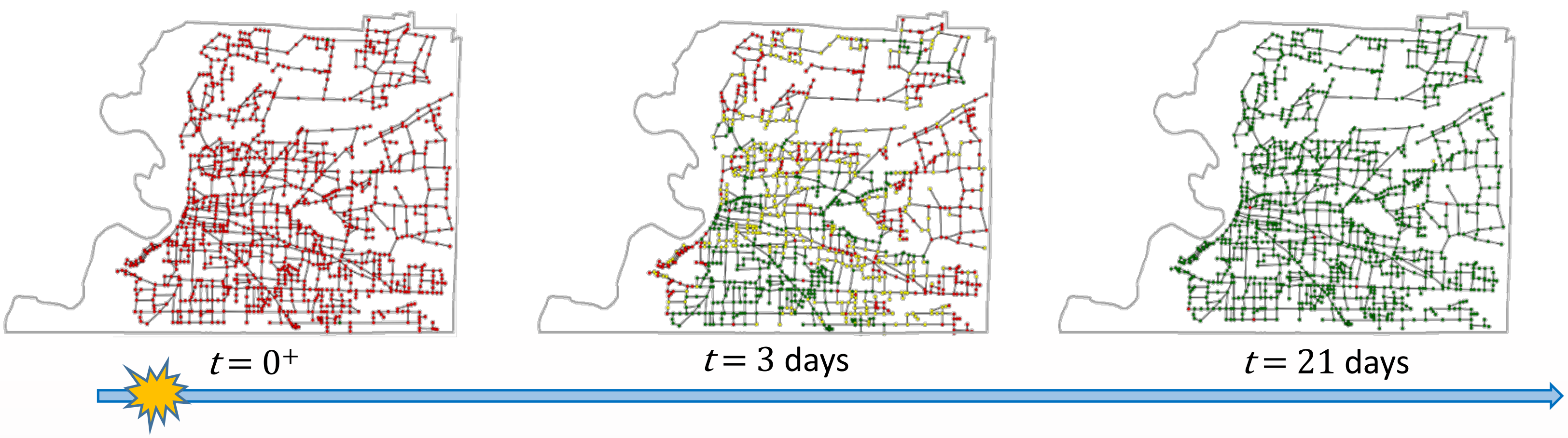


Memphis Light Gas and Water. (2017, May 28). *How MLGW Restores Power* [Press release]. Retrieved from http://www.mlgw.com/news/how-mlgw-restores-power-5-2017.

Sharma, N., Tabandeh, A., Gardoni, P., Murphy, C. (2019). "Modeling and evaluating the impact of natural hazards on communities and their recovery," *Structure and Infrastructure Engineering* (under review).

We then modeled the recovery of the water network

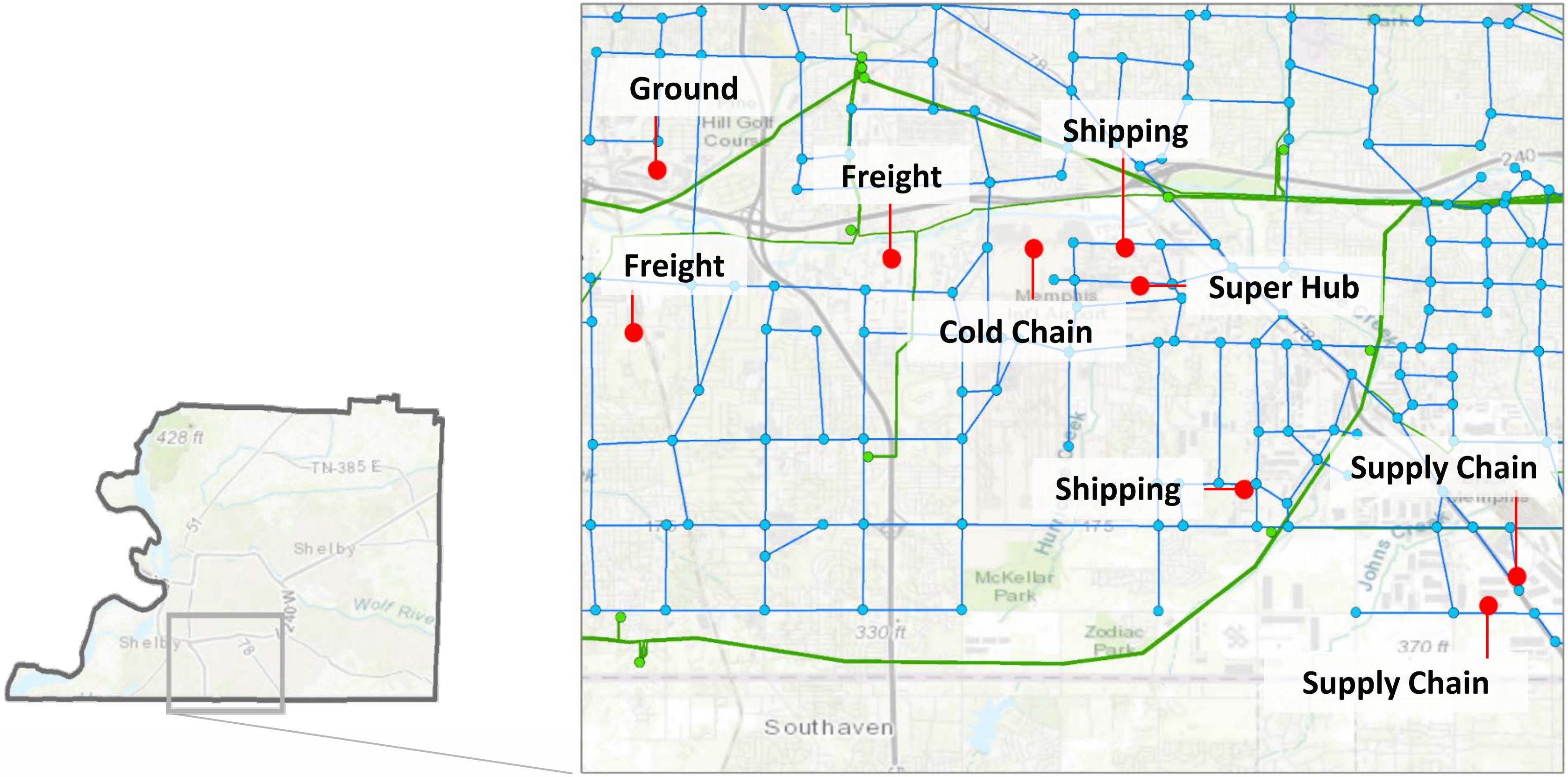
- A flow analysis of the water network with state variables $\mathbf{x}(t)$, considering reduced water capacity (due to power outage) and reduced water demand (due to dislocation) allows us to assess the availability of water at any nodes over time
- We can see that
  - Immediately after an earthquake the damaged network is unable to satisfy the minimum pressure requirement
  - After about 21 equivalent days of repair work (with 16 workhours per day) we have a significant improvement



Sharma, N., Tabandeh, A., Gardoni, P., Murphy, C. (2019). "Modeling and evaluating the impact of natural hazards on communities and their recovery," *Structure and Infrastructure Engineering* (under review).

We also predicted the business interruption of a hypothetical shipping company in Shelby Country

- We assume that the shipping company has 9 major locations across Memphis

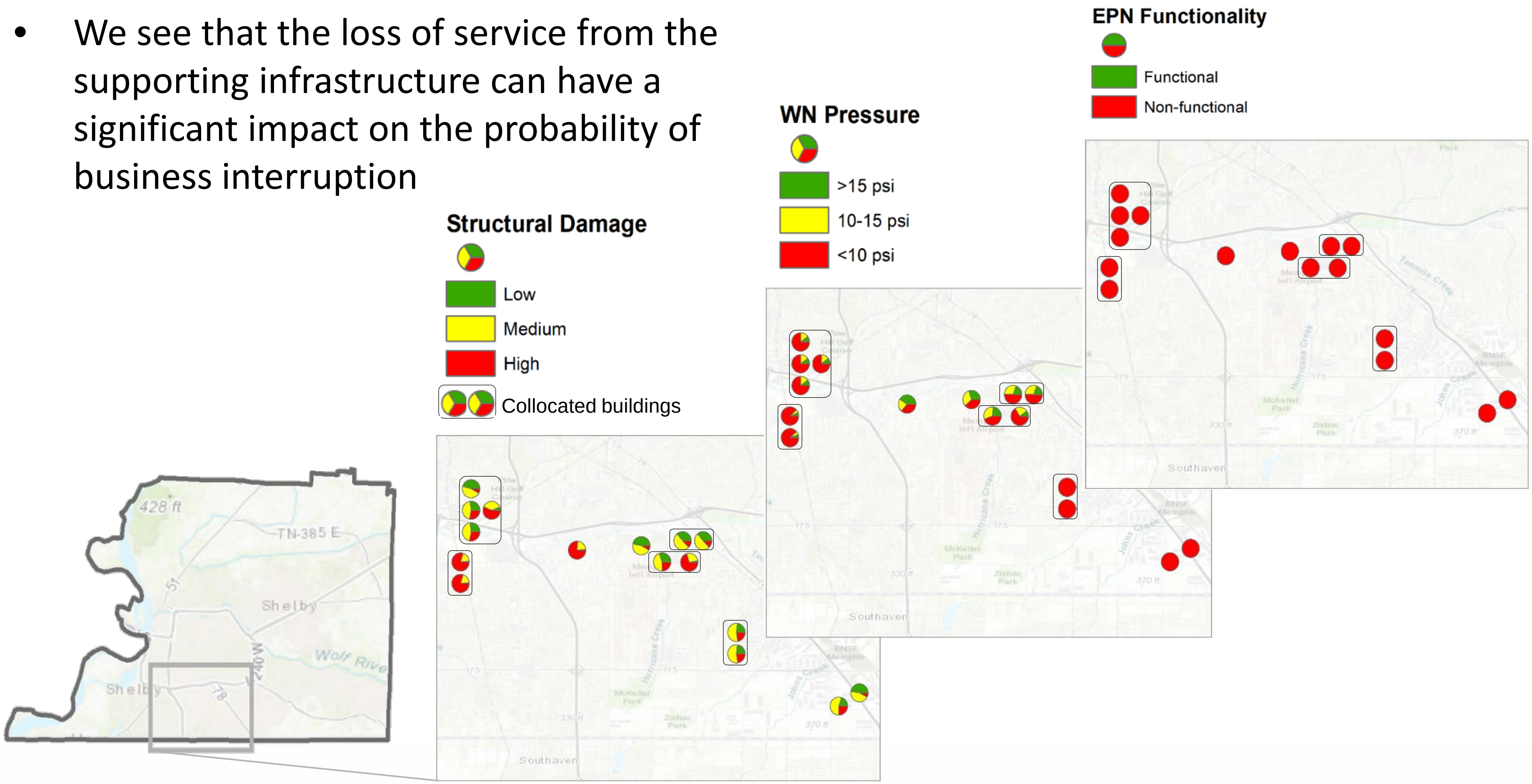


Nocera, F., and Gardoni, P., (2019). "A Ground-up approach to estimate the likelihood of business interruption," *International Journal of Disaster Risk Reduction,* 41, 101314

Sharma, N., Nocera, F., and Gardoni, P. (2019). "Classification and mathematical modeling of infrastructure interdependencies," *Sustainable and Resilience Infrastructure* (under review).

To predict the probability of business interruption we considered structural damage as well as lack of water and power

- We see that the loss of service from the supporting infrastructure can have a significant impact on the probability of business interruption

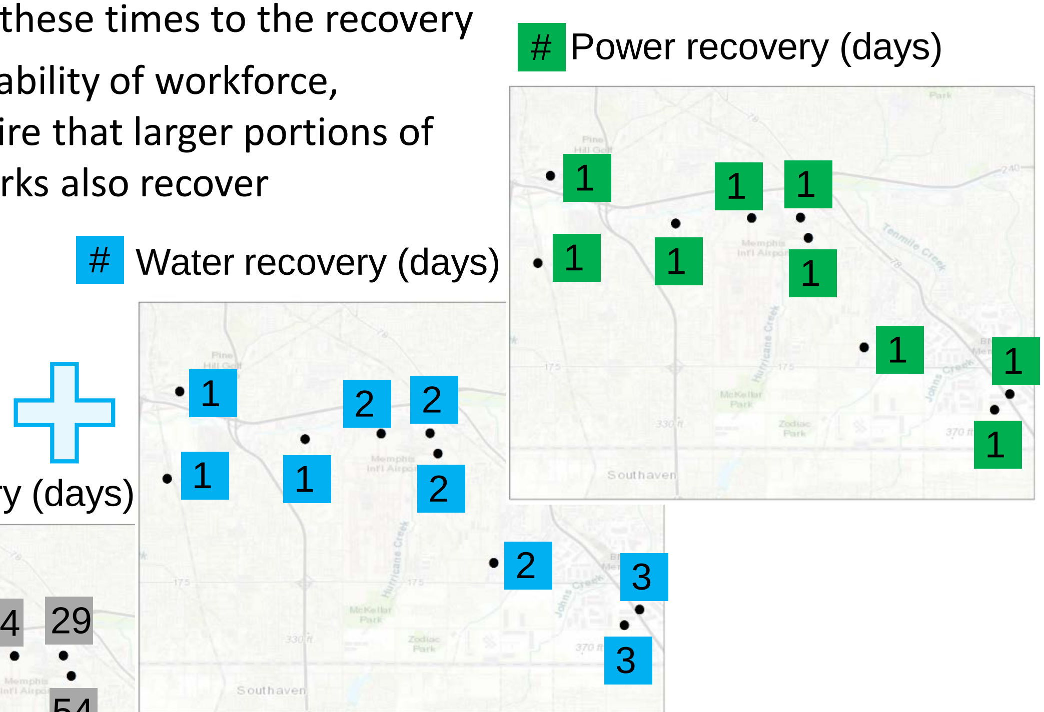


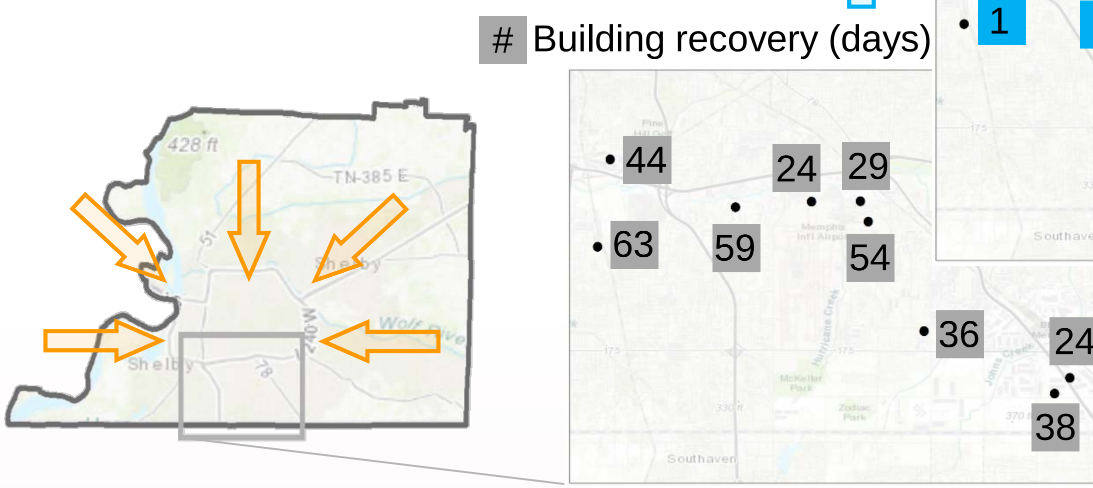
Nocera, F., and Gardoni, P., (2019). “A Ground-up approach to estimate the likelihood of business interruption,” *International Journal of Disaster Risk Reduction,* 41, 101314

Sharma, N., Nocera, F., and Gardoni, P. (2019). “Classification and mathematical modeling of infrastructure interdependencies,” *Sustainable and Resilience Infrastructure* (under review).

Finally, we estimated the time to recover the business operations considering recovery of buildings, water and power

- We see that the building recovery is expected to take the most time
- Since building recovery typically begins only after the recovery of the water and power network, we need to add these times to the recovery
- In addition, building recovery requires availability of workforce, material, and access to the site, which require that larger portions of the water, power and transportation networks also recover
- As a result, the estimated building recovery times shown here are only **lower bounds** of the actual recovery times





- Estimating the actual recovery time requires considering the recovery of the entire servicing area and of all supporting infrastructure

Example: Business interruption

Objectives

- Considering the MMSA testbed as an example, I will talk about the
  - Rationale for selecting a testbed
  - Definition of the hazard and network footprints
  - Definition of the hazard and network resolution/granularity
  - Data requirements and missing data
  - Type of analyses that can be done
  - Some results from preliminary analyses
- A few concluding remarks
- Additional resources

A few concluding remarks

- An accurate catastrophe modeling requires
  - Capturing the spatial variability in the hazard and in the conditions of the structures and infrastructure
  - Selecting the proper model resolution/granularity, since certain population groups may be more impacted than others or recover more slowly, and models that are too coarse would likely underestimate the actual societal impact
  - Dealing with missing/imprecise data using general inference techniques and engineering principles
  - Modeling the dependencies and interdependencies among networks to capture the loss or reduction in functionality of supporting critical infrastructure in addition to the structural damage
  - Modeling the resilience of the structures and infrastructure to estimate the duration of the impact
- A preliminary study of the Memphis Metropolitan Statistical Area has shown that
  - Using traditional attenuation relationships might misrepresent the seismic hazard leading to incorrect estimates of structural damage and loss of functionality
  - It is important to model the interdependencies among networks
    - The loss of functionality of the supporting water and power networks tend to increase
      - the probability that residential, commercial and industrial buildings are not operational in the aftermath of a catastrophic event
      - the duration of the recovery time and business interruptions
  - An accurate prediction of the duration of business interruption requires considering the recovery time not only of the business facilities but also of the supporting infrastructure and the entire servicing area

Objectives

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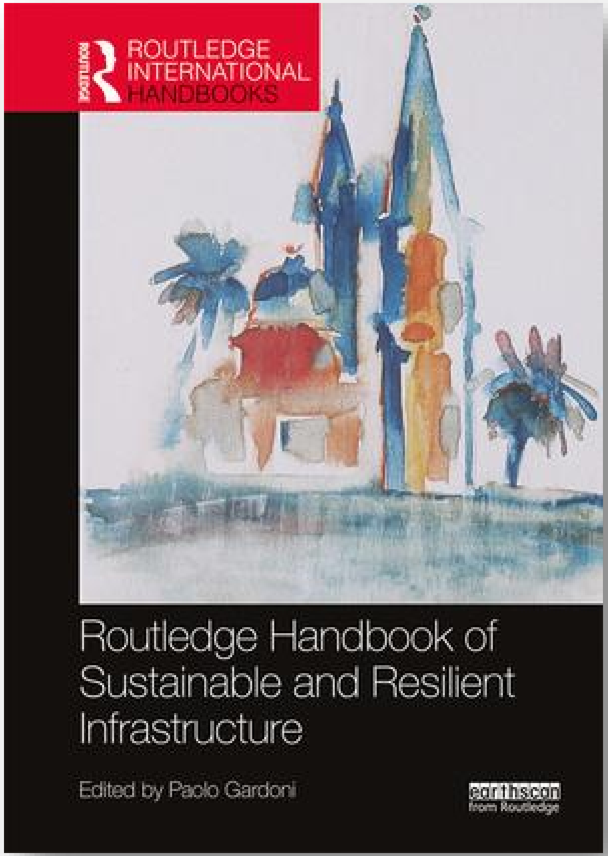
There is handbook on Sustainable and Resilient Infrastructure that includes Center's research



Routledge Handbook of Sustainable and Resilient Infrastructure

"This book collects articles by well-known experts on sustainability and resilience of infrastructure systems in the face of natural hazards, including climate change, and aging. It is a must read for anyone researching or practicing in this field."
— Armen Der Kiureghian, President, American University of Armenia and Taisei Professor of Civil Engineering Emeritus, University of California, USA

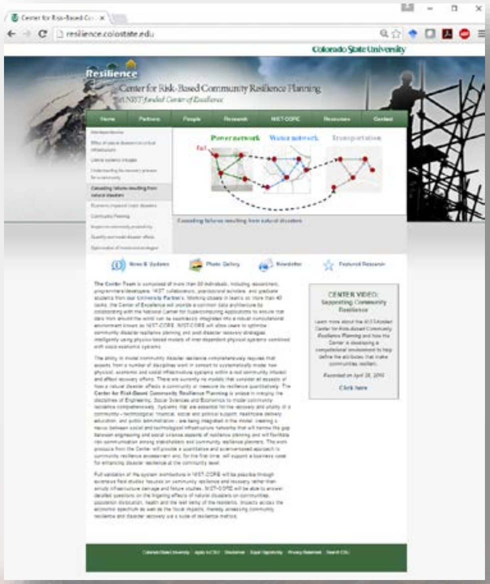
"This truly comprehensive compendium on theories and applications of resilience for the built environment is highly recommended for those seeking a comprehensive understanding of the issues […]."
— Ross B. Corotis, Denver Business Challenge Professor of Engineering, University of Colorado, USA

"Edited by one of the leading scholars in the field, the *Routledge Handbook of Sustainable and Resilient Infrastructure* provides an authoritative and comprehensive overview of the state-of-the-art. Essential reading for both professionals, students, and scholars working on the nexus between sustainability and resilience."
— Neelke Doorn, Professor Ethics of Water Engineering, Delft University of Technology, The Netherlands

Gardoni, P. (Ed.) (2019) *Routledge Handbook of Sustainable and Resilient Infrastructure*, Routledge.

Other resources

The 2018 EMI Objective Resilience Lecture
"Promoting societal well-being by designing sustainable and resilient infrastructure: engineering tools and broader interdisciplinary considerations"
URL: https://www.asce.org/engineering-mechanics/objective-resilience-lecture/



Center of Excellence Website
URL: http://resilience.colostate.edu
Email: resilience@colostate.edu

Thank you!

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Resilience