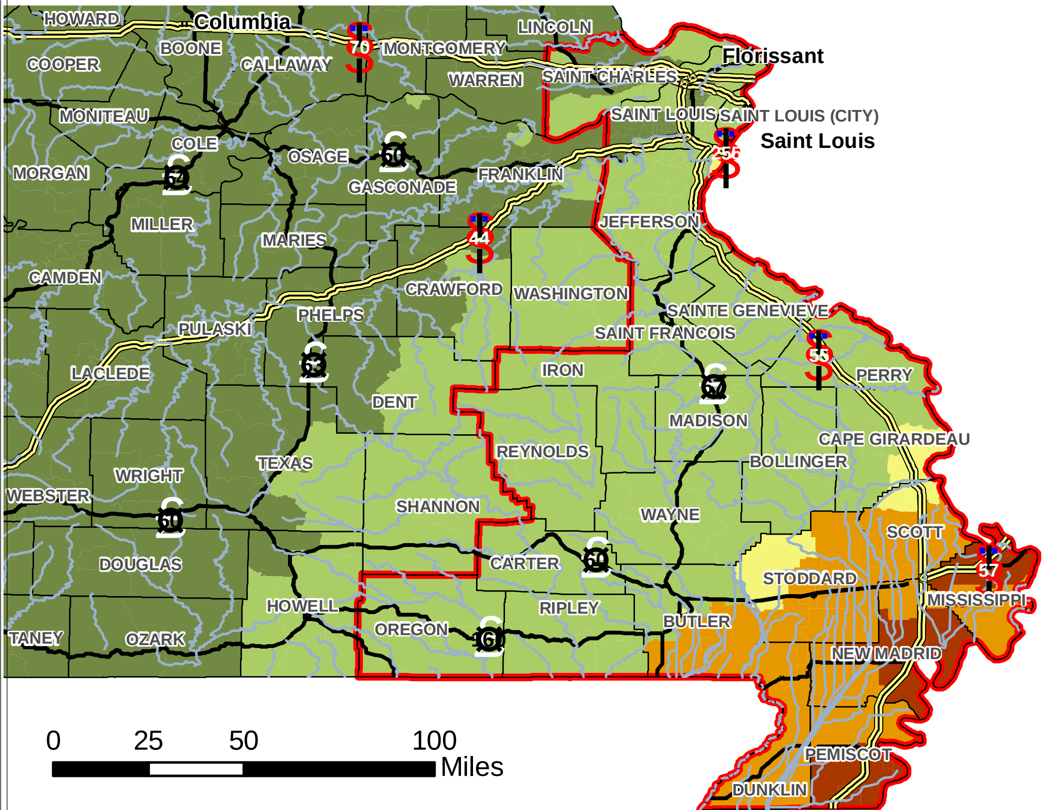
Missouri Modified Mercalli Intensity
New Madrid Seismic Zone: M7.7 Event



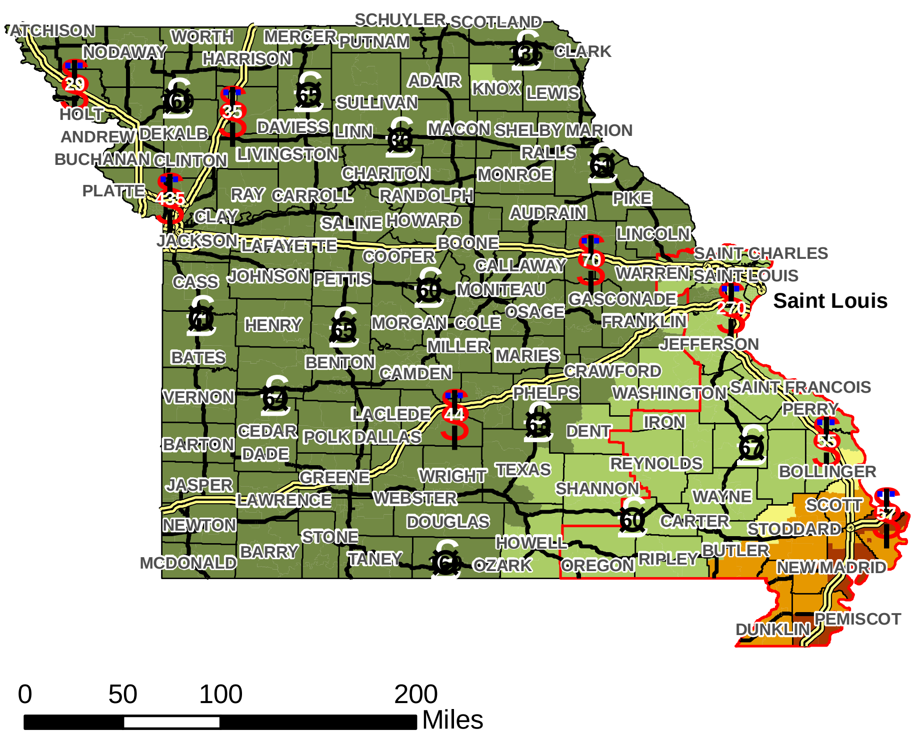
Modified Mercalli Intensity of Critical Area

- VI
- VII
- VIII
- IX
- X+

Impacted Counties Boundary

Modified Mercalli Intensity (State)

- VI
- VII
- VIII
- IX
- X+



Major Cities by Population

- 51,000 - 74,000
- 74,001 - 150,000
- 150,001 - 444,000

Roads

- Interstates
- US Routes

FEMA

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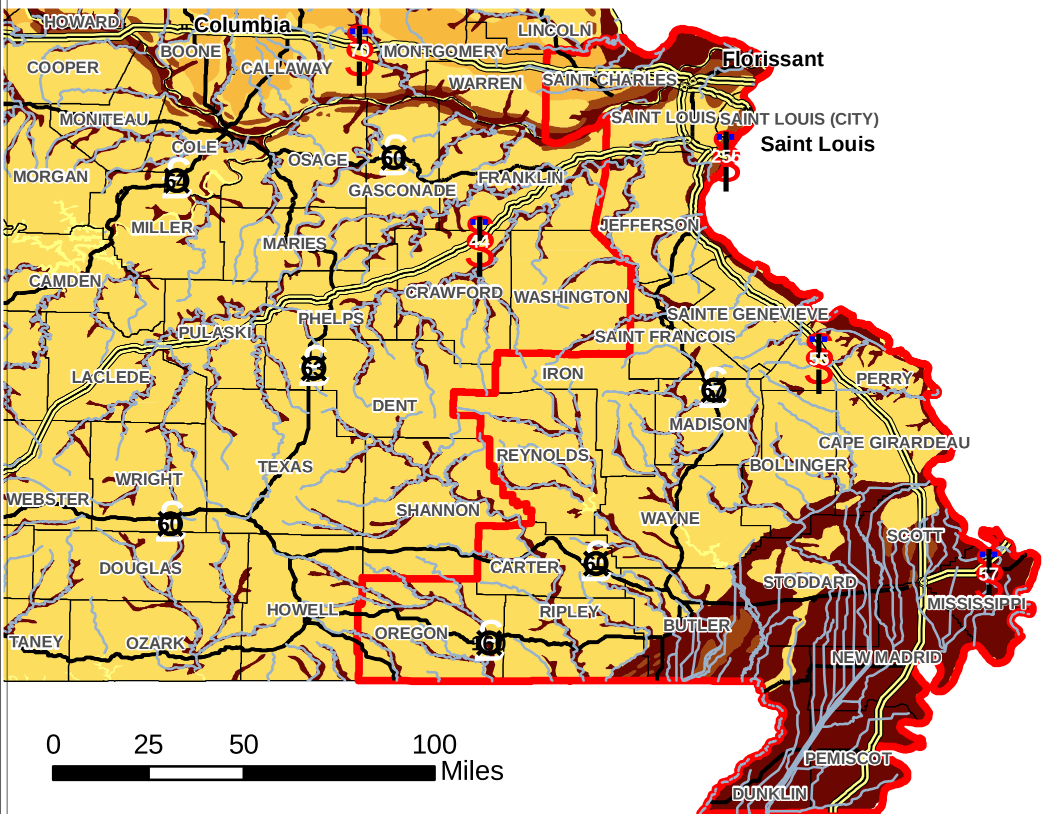
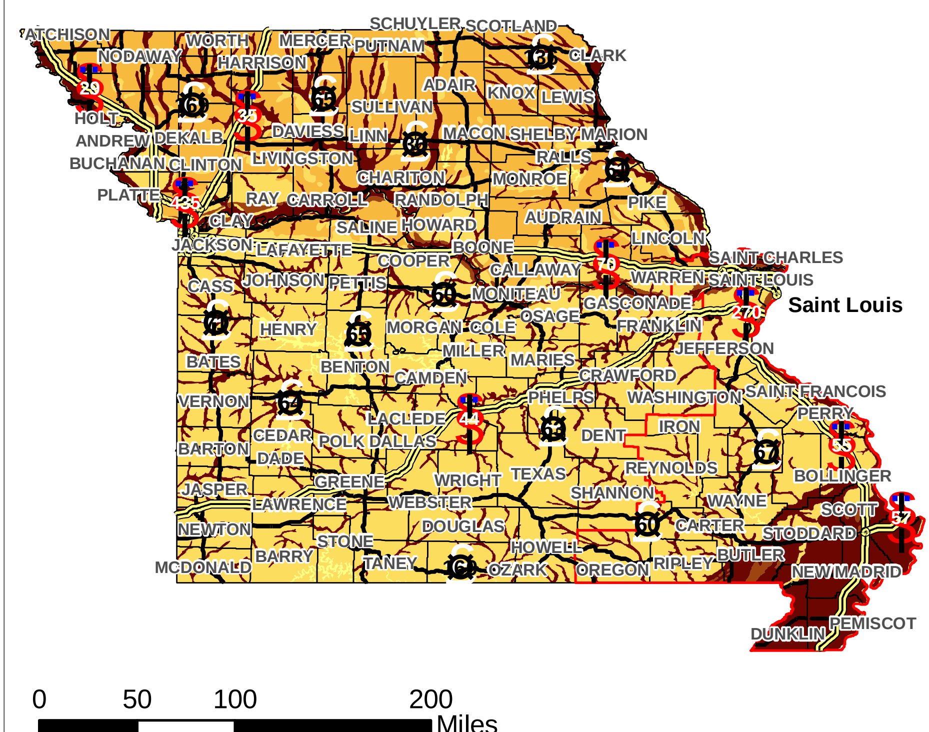
Missouri Liquefaction Susceptibility
New Madrid Seismic Zone: M7.7 Event



Liquefaction Susceptibility in Critical Area

- None
- Very Low
- Low
- Moderate
- High
- Very High



Impacted Counties Boundary

Liquefaction Susceptibility (State)

- None
- Very Low
- Low
- Moderate
- High
- Very High

Major Cities by Population

- 51,000 - 74,000
- 74,001 - 150,000
- 150,001 - 444,000

Roads

- Interstates
- US Routes

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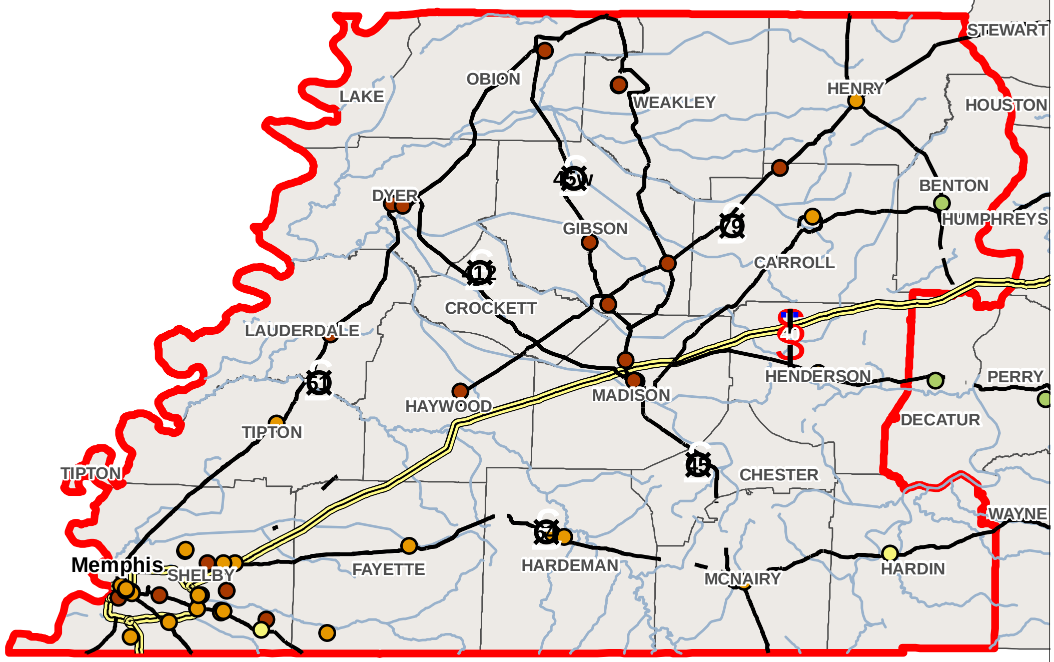
Tennessee Hospitals Damage
New Madrid Seismic Zone: M7.7 Event

Hospitals Damage of Critical Area (Points)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain



0 20 40 80 Miles

0 50 100 200 Miles

Legend

Critical Counties Boundary

Hospitals Damage (Surface)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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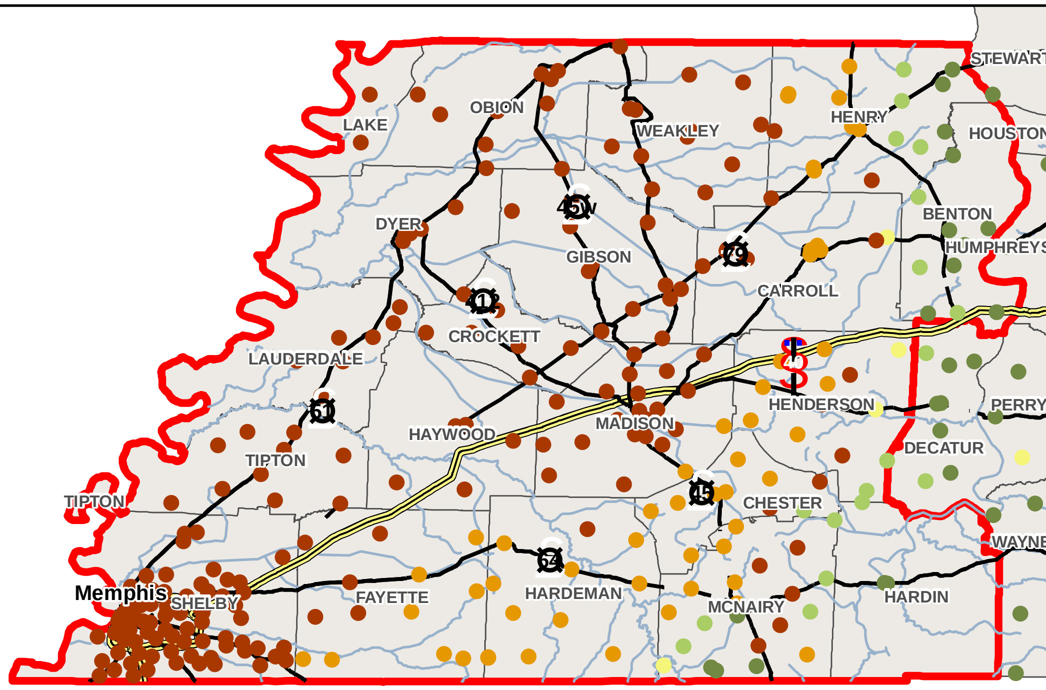
Tennessee Fire Station Damage
New Madrid Seismic Zone: M7.7 Event

Fire Station Damage of Critical Area (Points)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain



0 50 100 200
Miles

Legend

Impacted Counties Boundary

Fire Station Damage (Surface)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain
- No Inventory

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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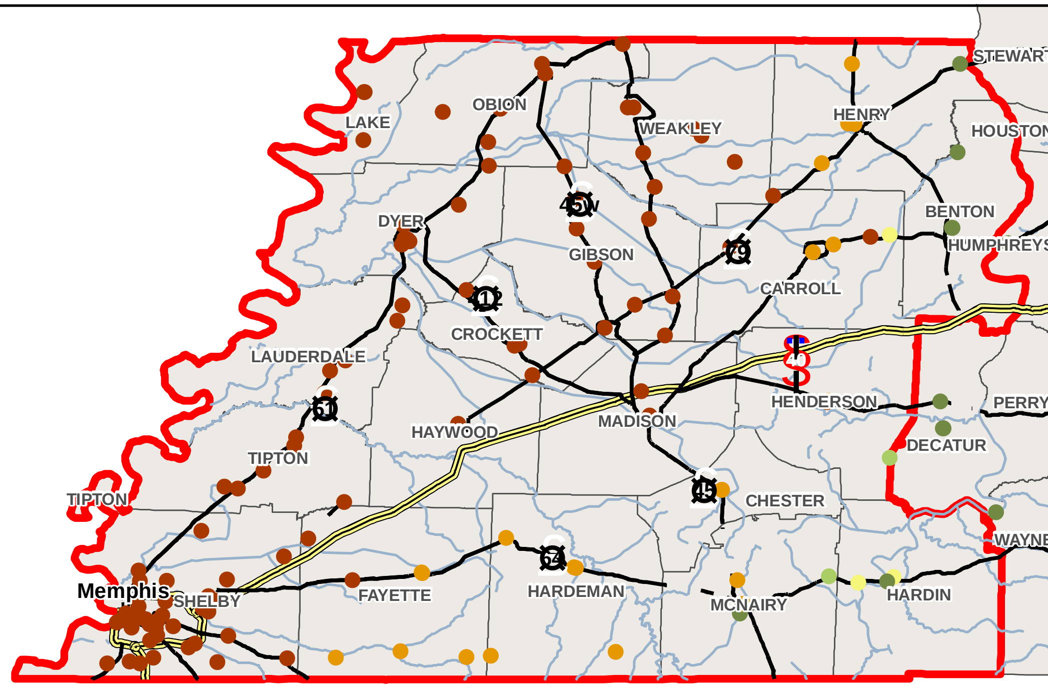
Tennessee Police Station Damage
New Madrid Seismic Zone: M7.7 Event

Police Station Damage of Critical Area (Points)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain



0 20 40 80 Miles

Legend

Impacted Counties Boundary

Police Station Damage (Surface)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain
- No Inventory

0 50 100 200 Miles

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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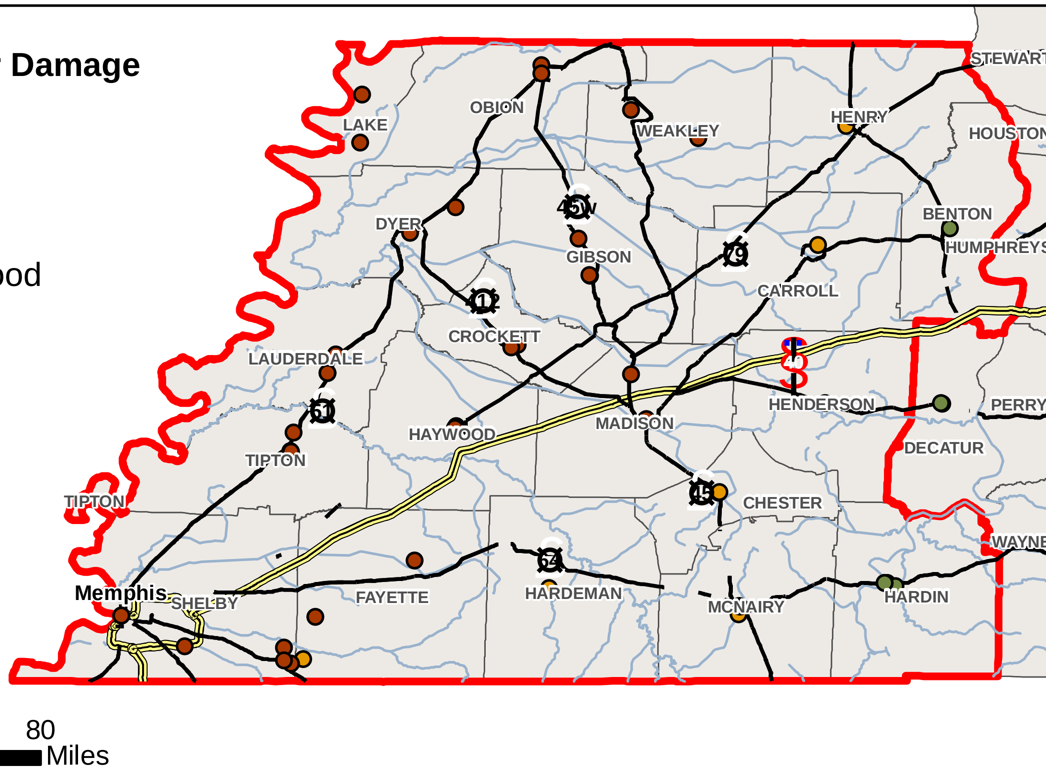
Tennessee Emergency Operation Center Damage
New Madrid Seismic Zone: M7.7 Event

Emergency Operation Center Damage of Critical Area (Points)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain



Legend

Impacted Counties Boundary

Emergency Operation Center Damage (Surface)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain
- No Inventory

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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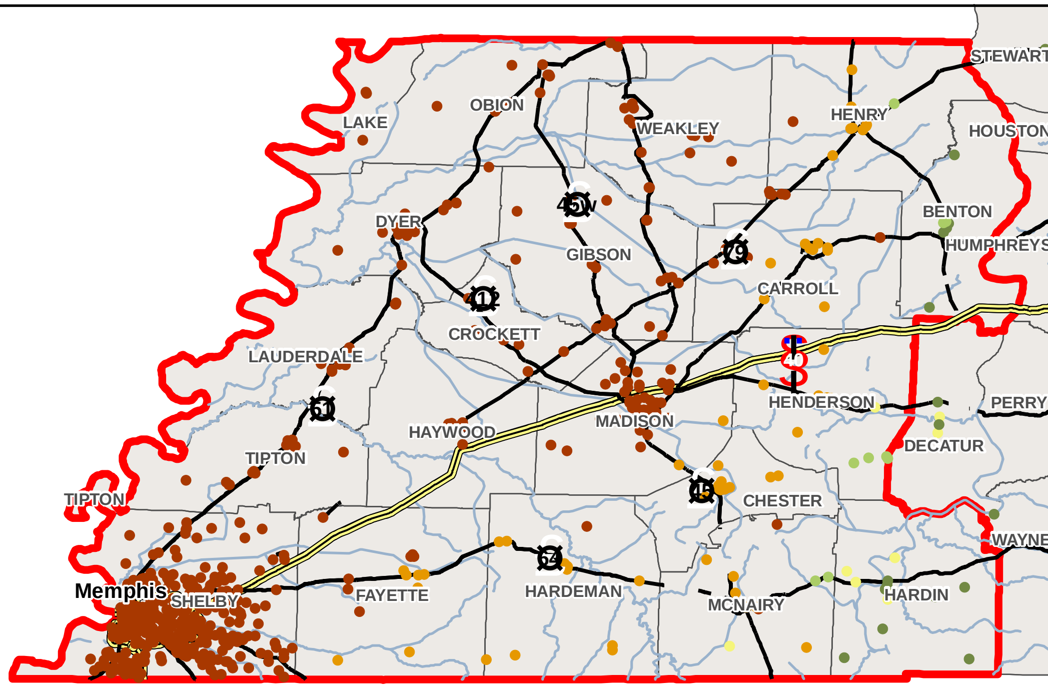
Tennessee Schools Damage
New Madrid Seismic Zone: M7.7 Event

Schools Damage of Critical Area (Points)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain



0 20 40 80
Miles

Legend

Impacted Counties Boundary

Schools Damage (Surface)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain
- No Inventory

0 50 100 200
Miles

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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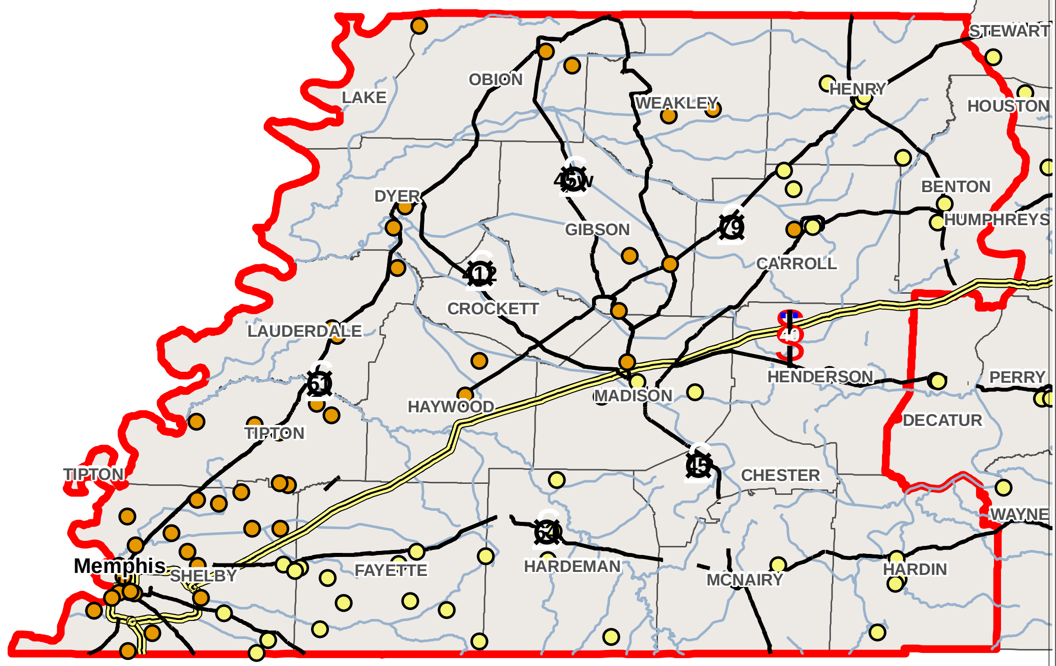
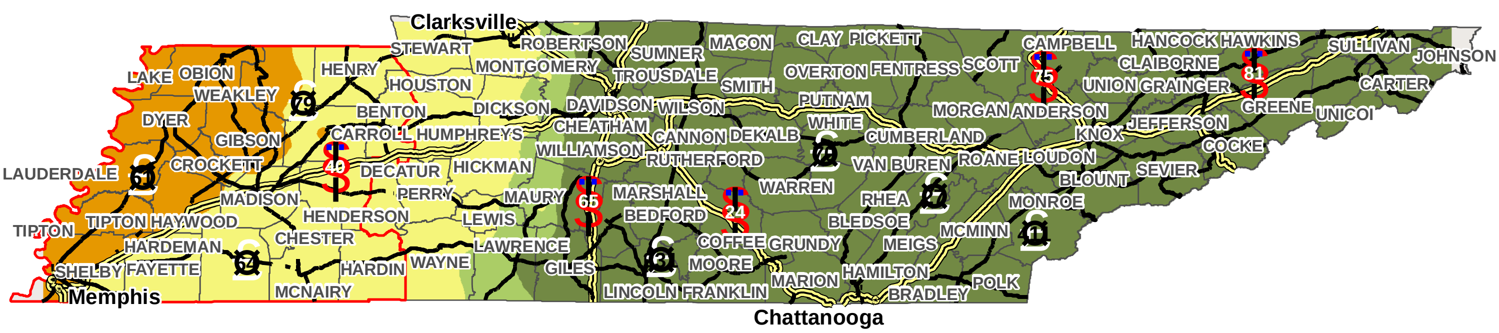
Tennessee Airport Facility Damage
New Madrid Seismic Zone: M7.7 Event

Airport Facility Damage of Critical Area (Points)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain





Legend

Impacted Counties Boundary

Airport Facility Damage (Surface)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain
- No Inventory

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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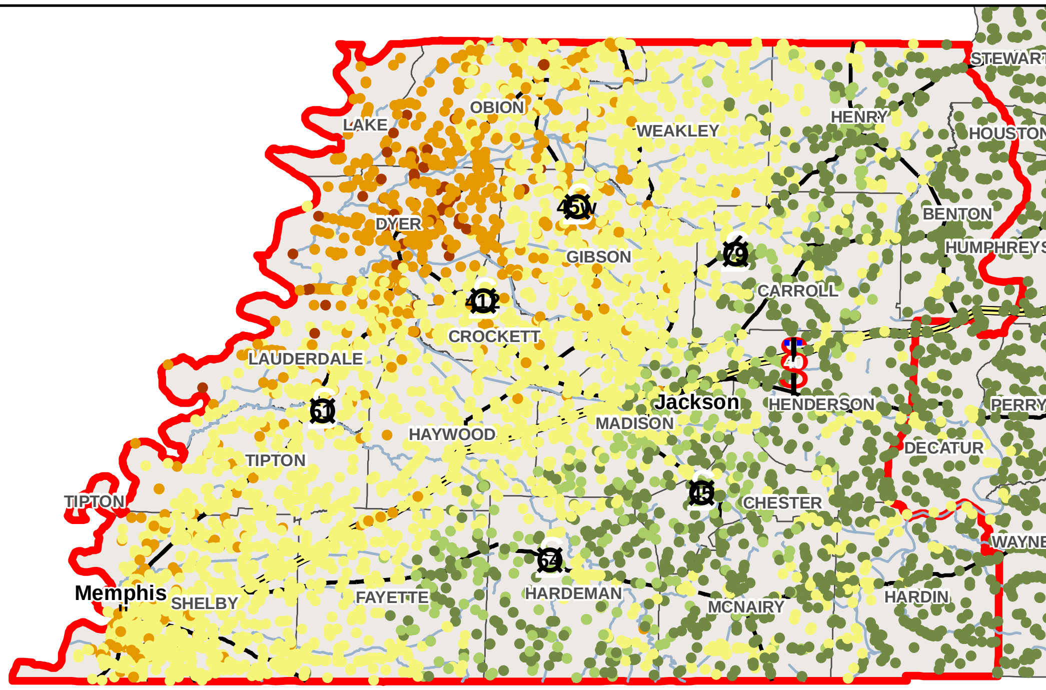
Tennessee Highway Bridge Damage
New Madrid Seismic Zone: M7.7 Event

Highway Bridge Damage of Critical Area (Points)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain



0 20 40 80 Miles

Legend

Impacted Counties Boundary

Highway Bridge Damage (Surface)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain

0 50 100 200 Miles

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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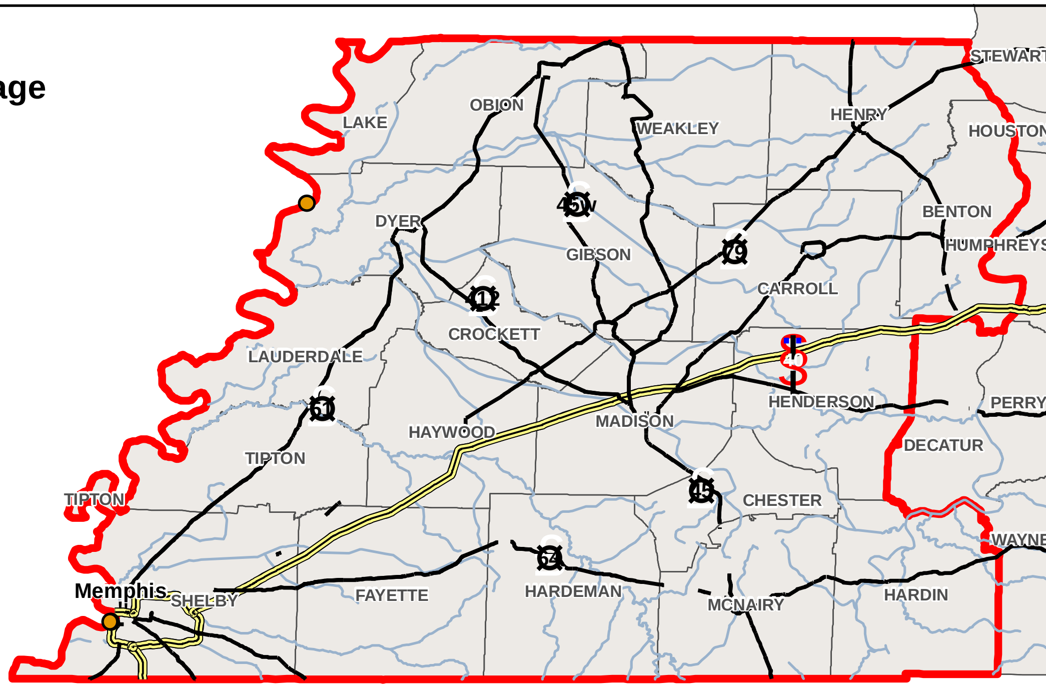
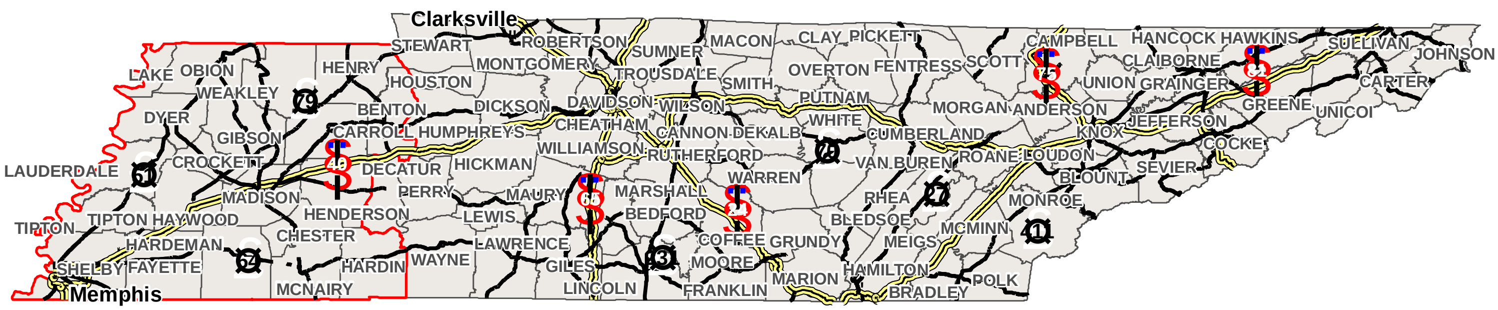
Tennessee Major River Crossings Damage
New Madrid Seismic Zone: M7.7 Event

Major River Crossings Damage in Critical Area (Points)

- Unlikely Damaged
- Likely Damaged





Legend

Impacted Counties Boundary

Major River Crossings Damage (Surface)

- Unlikely Damaged
- Likely Damaged

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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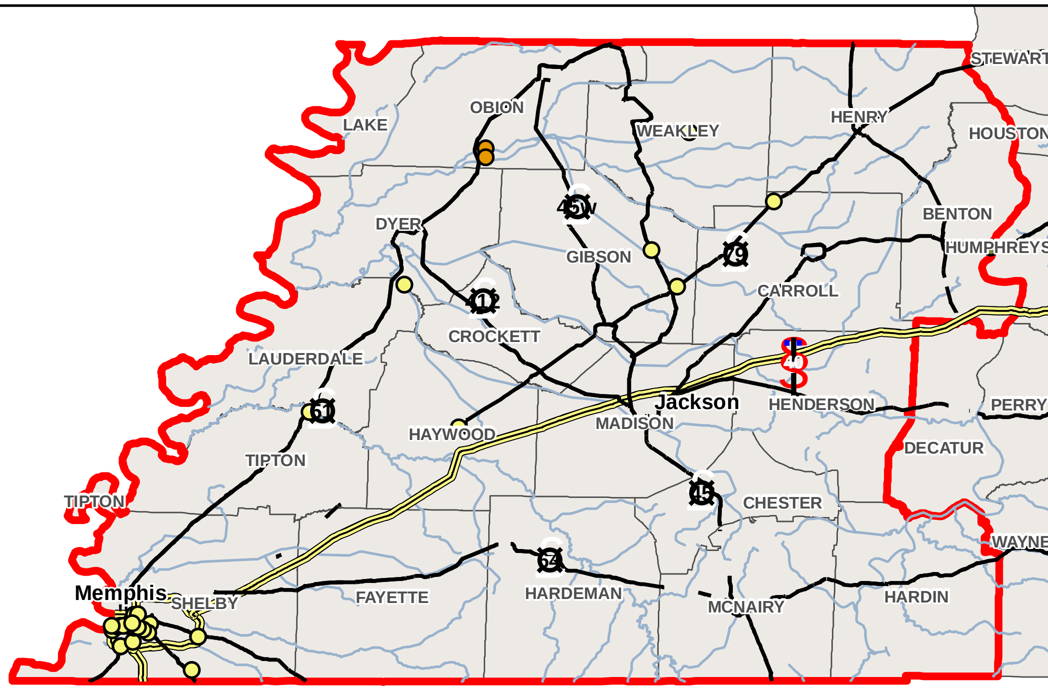
Tennessee Railway Bridge Damage
New Madrid Seismic Zone: M7.7 Event

Railway Bridge Damage of Critical Area (Points)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain



0 20 40 80 Miles

Legend

Impacted Counties Boundary

Railway Bridge Damage (Surface)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain
- No Inventory

0 50 100 200 Miles

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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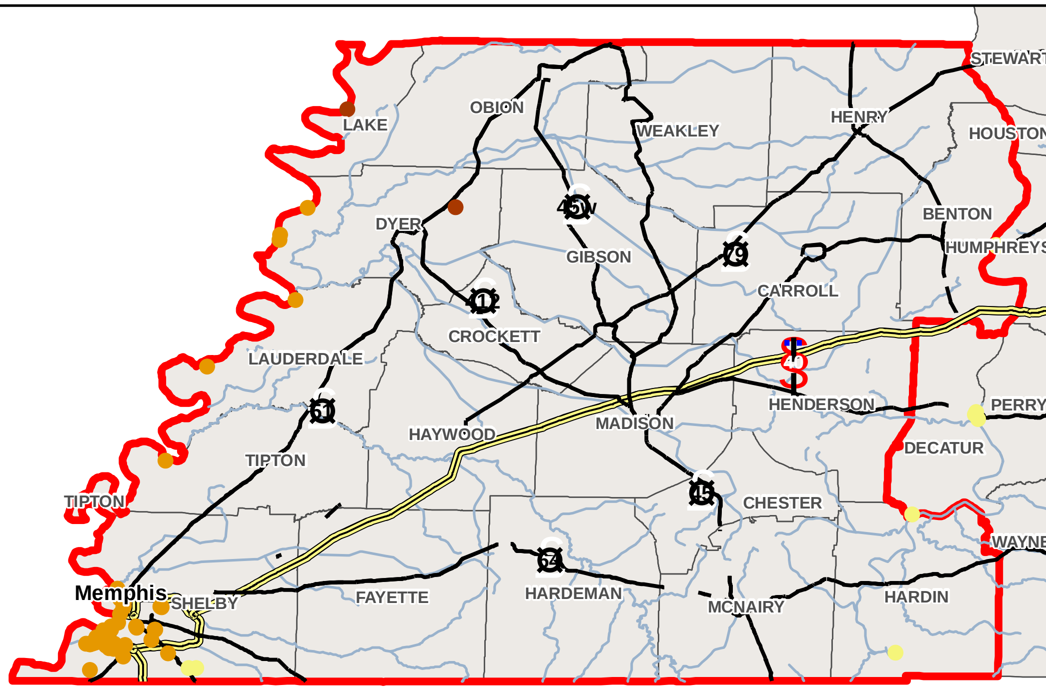
Tennessee Railway Facility Damage
New Madrid Seismic Zone: M7.7 Event

Railway Facility Damage of Critical Area (Points)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain



0 20 40 80 Miles

0 50 100 200 Miles

Legend

Impacted Counties Boundary

Railway Facility Damage (Surface)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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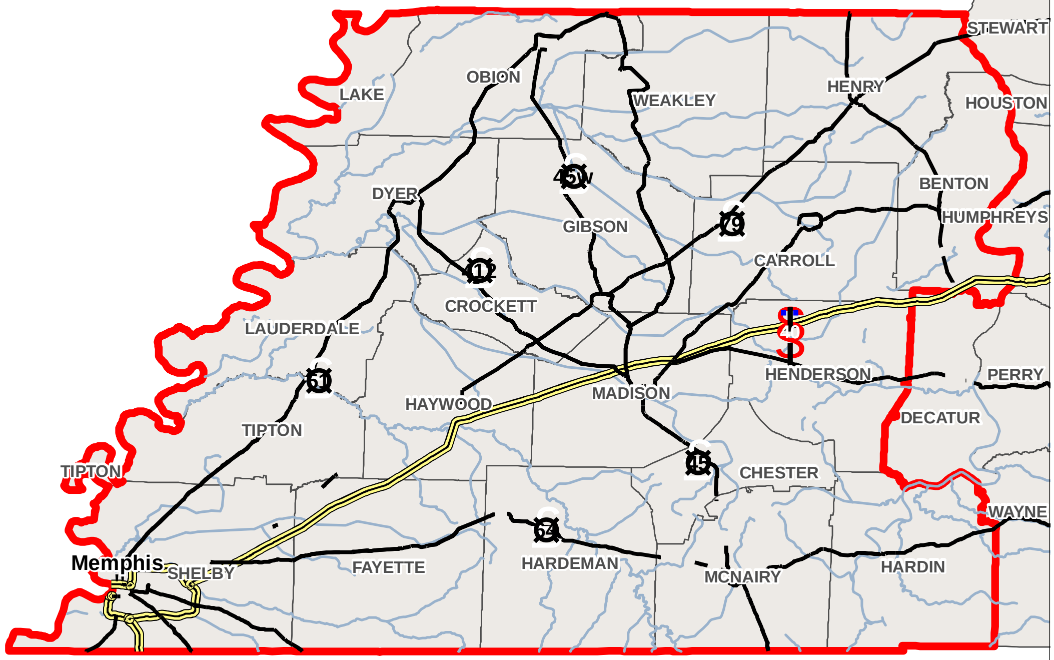
Tennessee Railway Tunnel Damage
New Madrid Seismic Zone: M7.7 Event

Railway Tunnel Damage of Critical Area (Points)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain



0 20 40 80
Miles

Legend

Impacted Counties Boundary

Railway Tunnel Damage (Surface)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain
- No Inventory

0 50 100 200
Miles

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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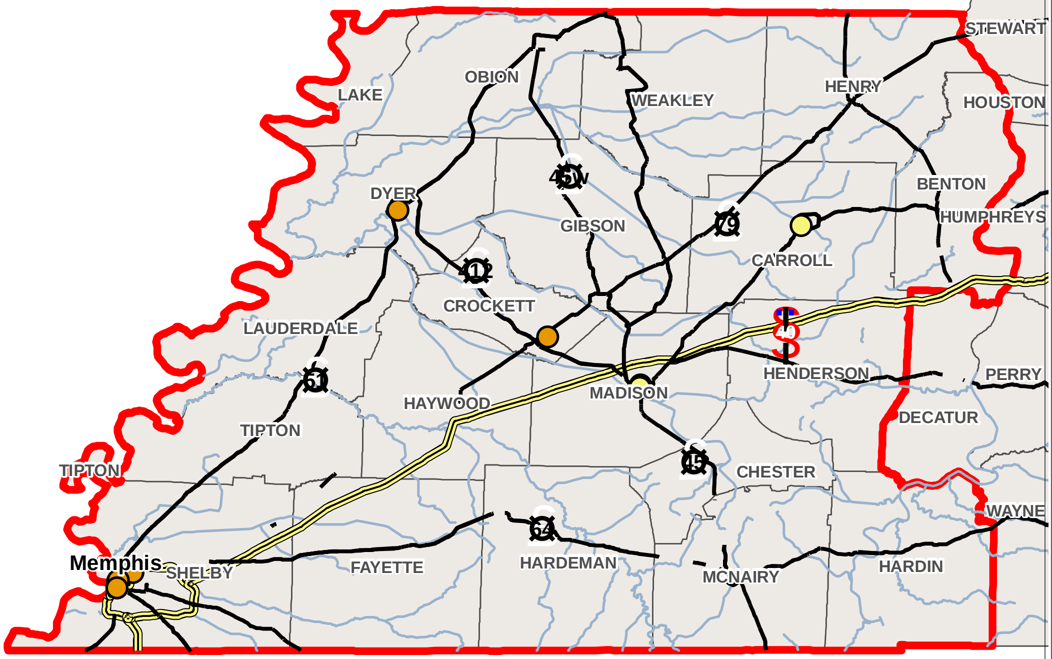
Tennessee Bus Facility Damage
New Madrid Seismic Zone: M7.7 Event

Bus Facility Damage of Critical Area (Points)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain



0 20 40 80
Miles

Legend

Impacted Counties Boundary

Bus Facility Damage (Surface)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain
- No Inventory

0 50 100 200
Miles

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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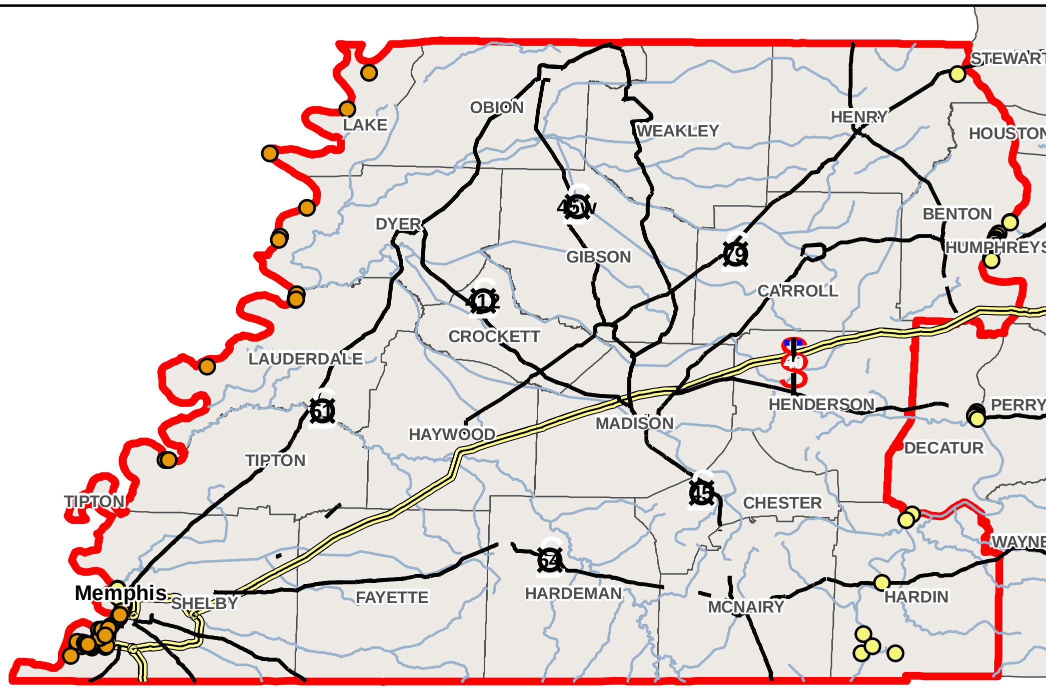
Tennessee Port Facility Damage
New Madrid Seismic Zone: M7.7 Event

Port Facility Damage of Critical Area (Points)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain



Legend

Impacted Counties Boundary

Port Facility Damage (Surface)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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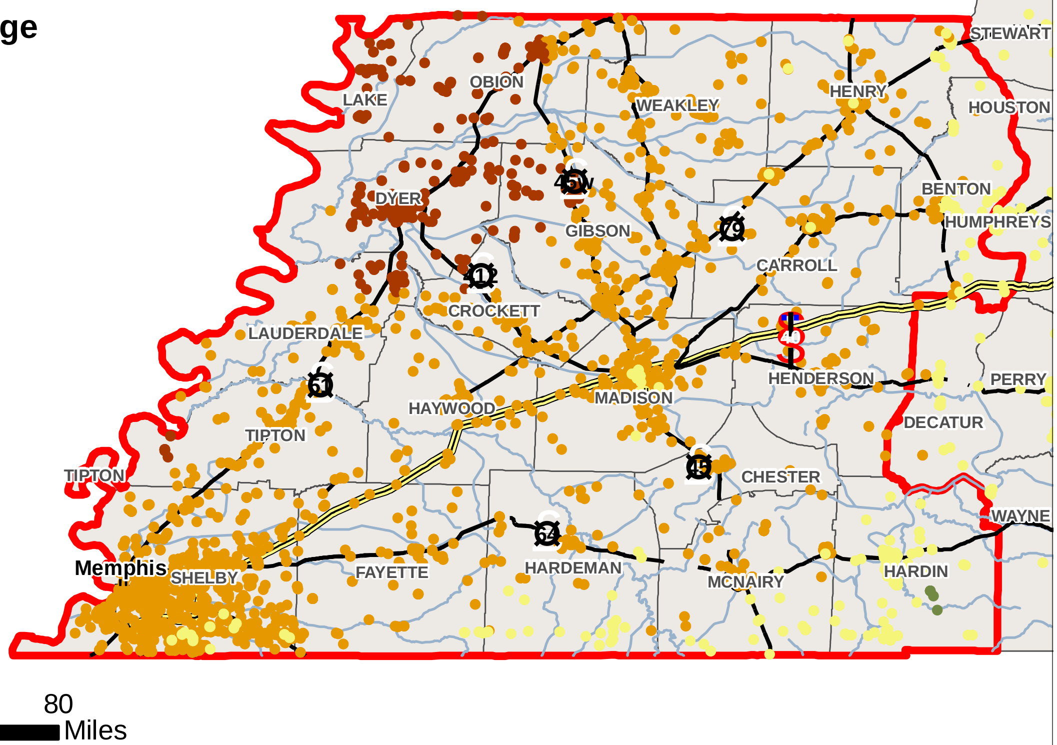
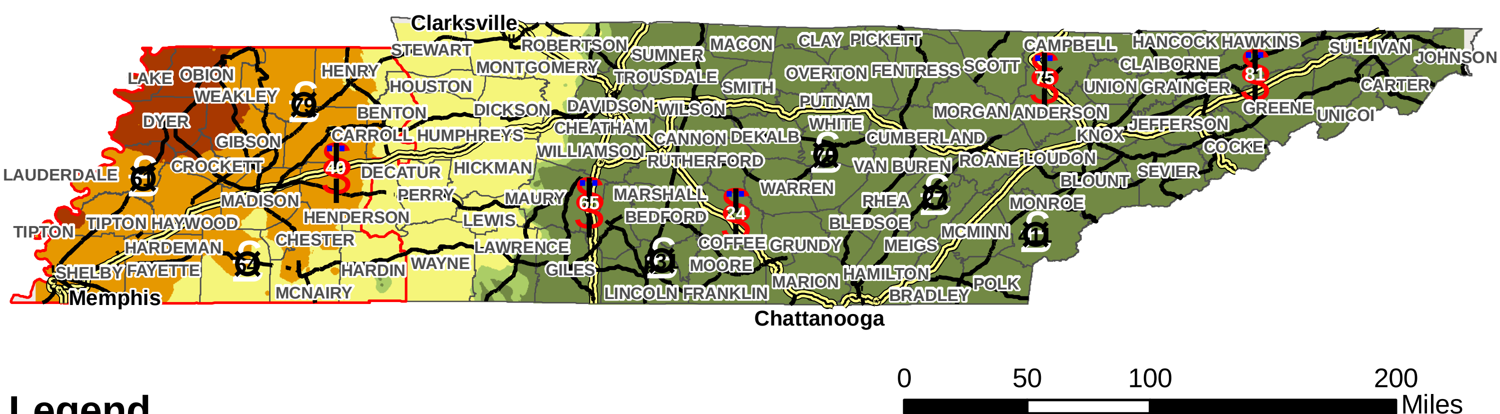
Tennessee Communication Facility Damage
New Madrid Seismic Zone: M7.7 Event

Communication Facility Damage of Critical Area (Points)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain





Legend

Impacted Counties Boundary

Communication Facility Damage (Surface)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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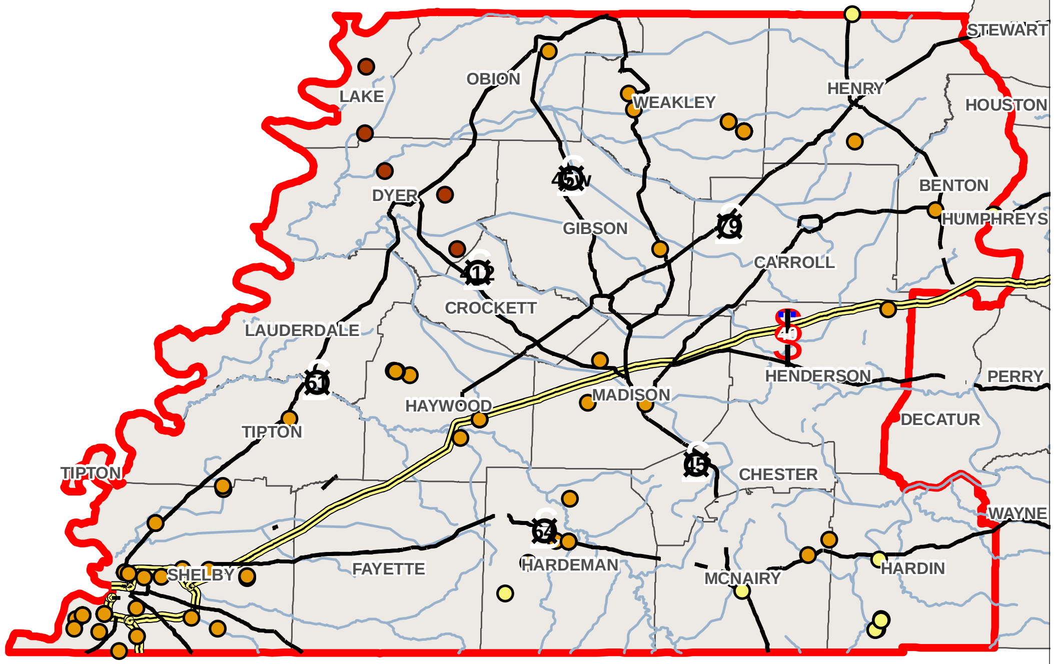
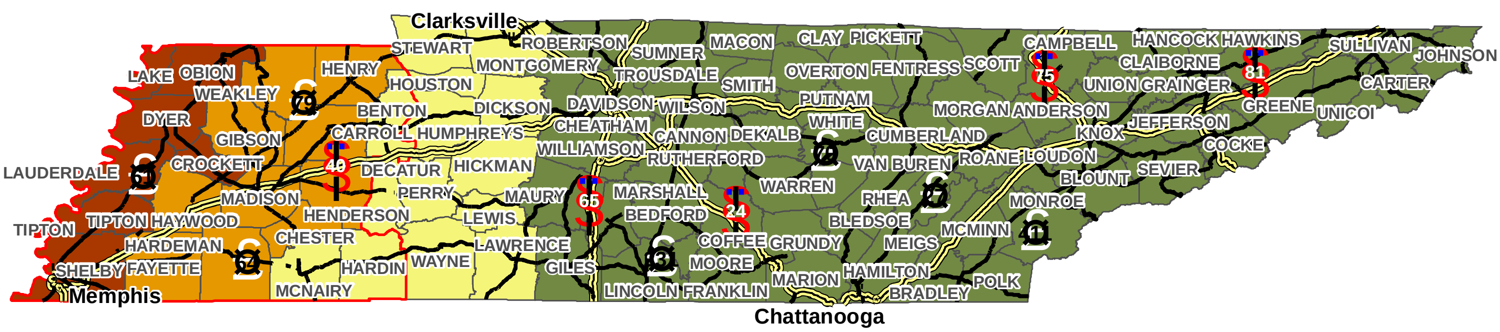
Tennessee Electric Facility Damage
New Madrid Seismic Zone: M7.7 Event

Electric Facility Damage of Critical Area (Points)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain



0 20 40 80 Miles



0 50 100 200 Miles

Legend

Impacted Counties Boundary

Electric Power Outages at Day 1 (% Households w/o Service)

- 0% - 20%
- 21% - 40%
- 41% - 60%
- 61% - 80%
- 81% - 100%

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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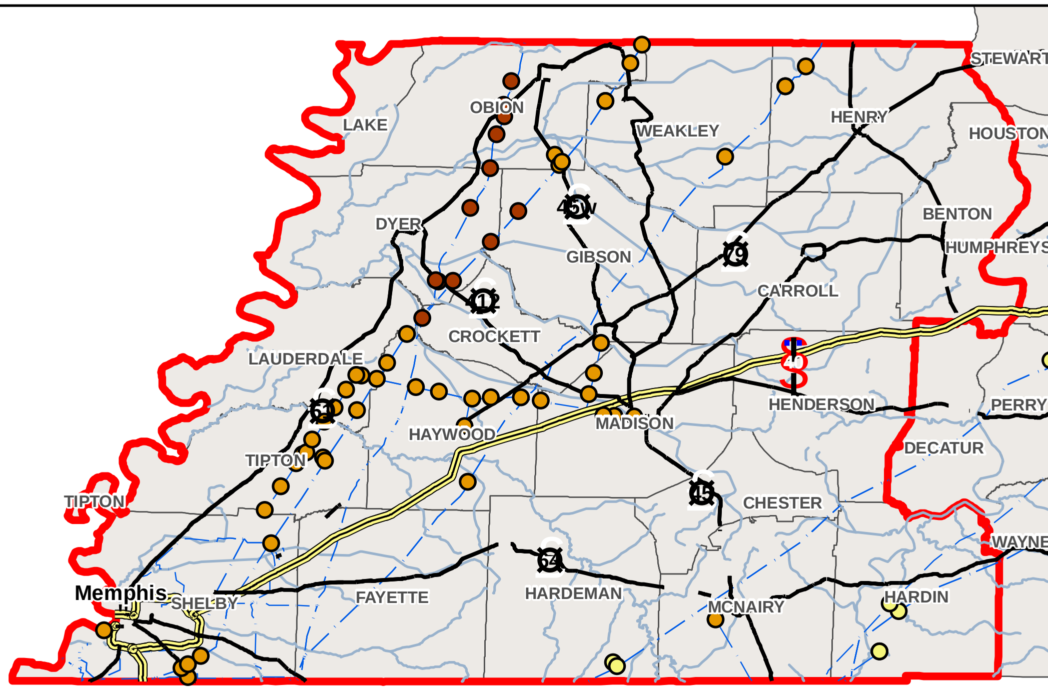
Tennessee Natural Gas Facility Damage
New Madrid Seismic Zone: M7.7 Event

Natural Gas Facility Damage of Critical Area (Points)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain



0 20 40 80 Miles

Legend

Impacted Counties Boundary

Gas Pipelines

Natural Gas Facility Damage (Surface)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain

0 50 100 200 Miles

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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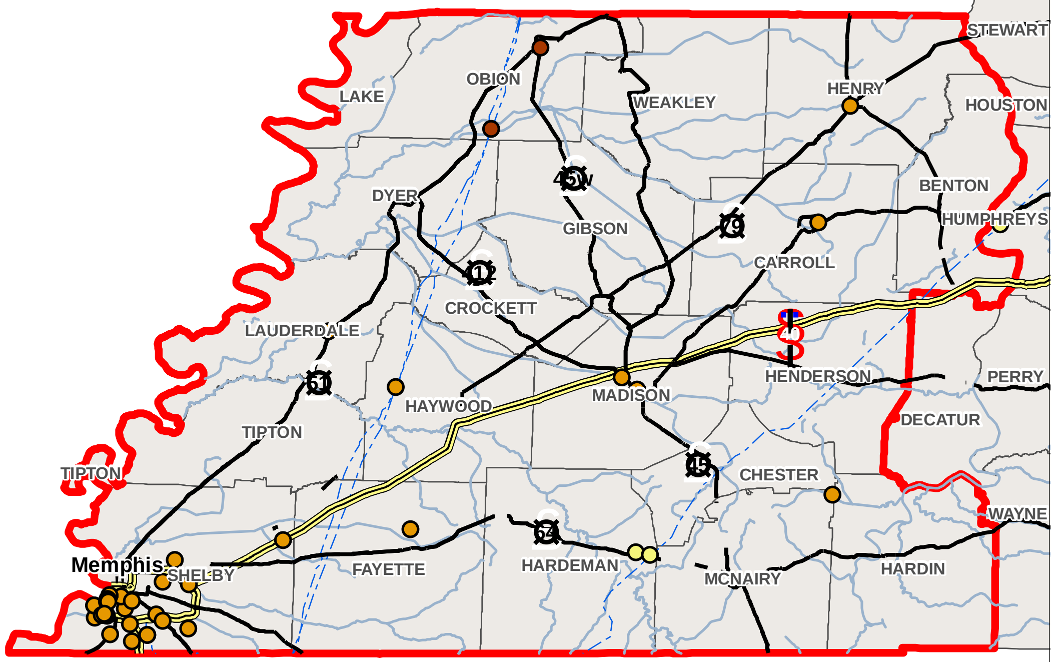
Tennessee Oil Facility Damage
New Madrid Seismic Zone: M7.7 Event

Oil Facility Damage of Critical Area (Points)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain



0 20 40 80 Miles

Legend

Impacted Counties Boundary

Oil Pipelines

Oil Facility Damage (Surface)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain
- No Inventory

0 50 100 200 Miles

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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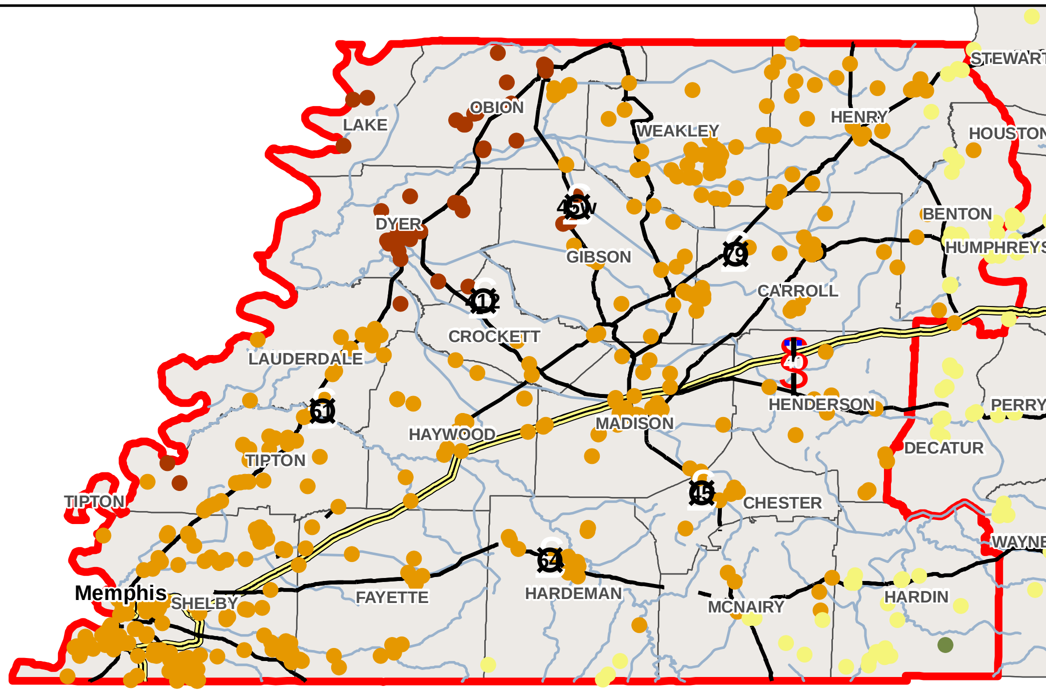
Tennessee Waste Water Facility Damage
New Madrid Seismic Zone: M7.7 Event

Waste Water Facility Damage of Critical Area (Points)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain



Legend

Imacted Counties Boundary

Number of Line Breaks and Leaks

- 0 - 150
- 151 - 650
- 651 - 2,000
- 2,001 - 3,100
- 3,101 - 6,300

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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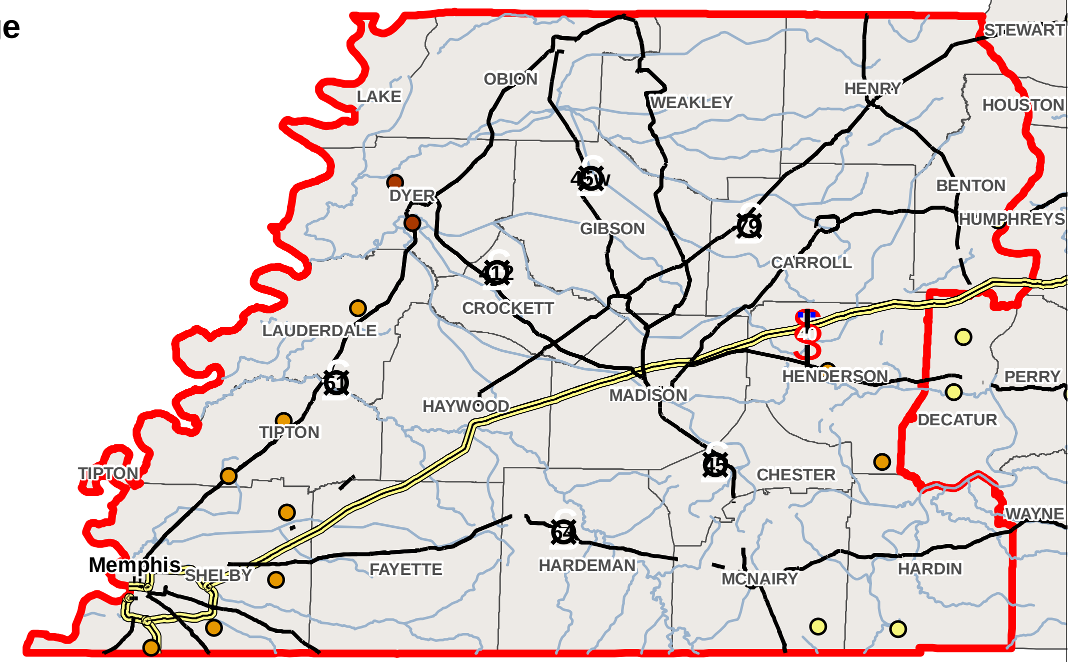
Tennessee Potable Water Facility Damage
New Madrid Seismic Zone: M7.7 Event

Potable Water Facility Damage of Critical Area (Points)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain



0 20 40 80 Miles

0 50 100 200 Miles

Legend

Impacted Counties Boundary

Number of Line Breaks and Leaks

- 1 - 250
- 251 - 1,000
- 1,001 - 2,500
- 2,501 - 4,000
- 4,001 - 8,000

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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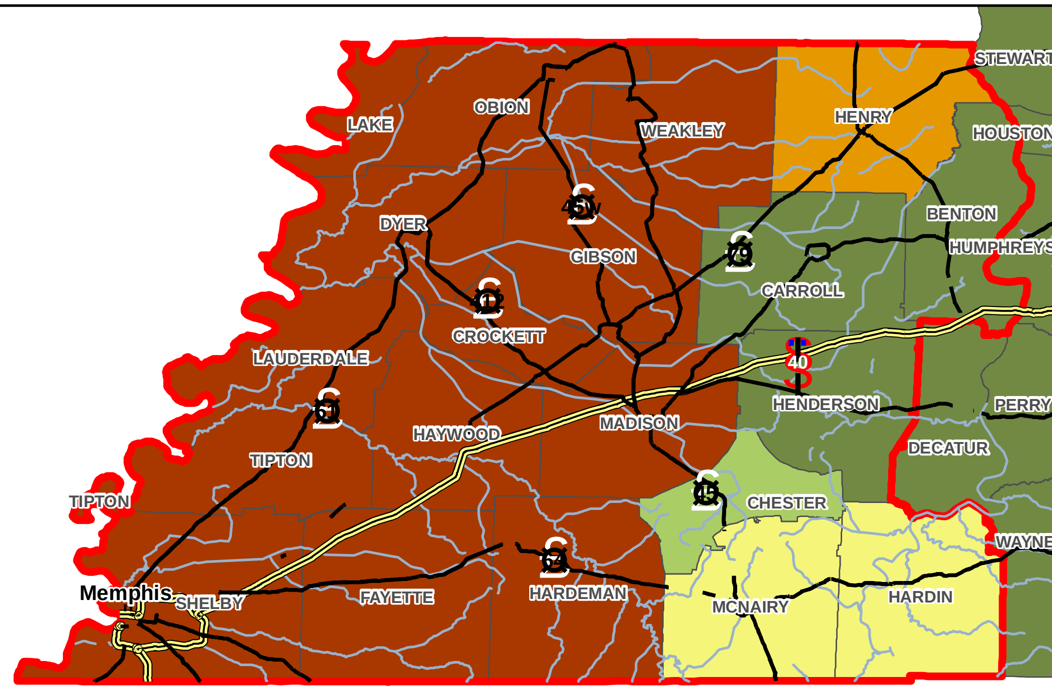
Tennessee Potable Water Outages
New Madrid Seismic Zone: M7.7 Event

Potable Water Outages (Percent) in Critical Counties

- 0% - 20%
- 21% - 40%
- 41% - 60%
- 61% - 80%
- 81% - 100%



0 20 40 80 Miles

0 50 100 200 Miles

Legend

Impacted Counties Boundary

Statewide Potable Water Outages (Percent)

- 0% - 20%
- 21% - 40%
- 41% - 60%
- 61% - 80%
- 81% - 100%

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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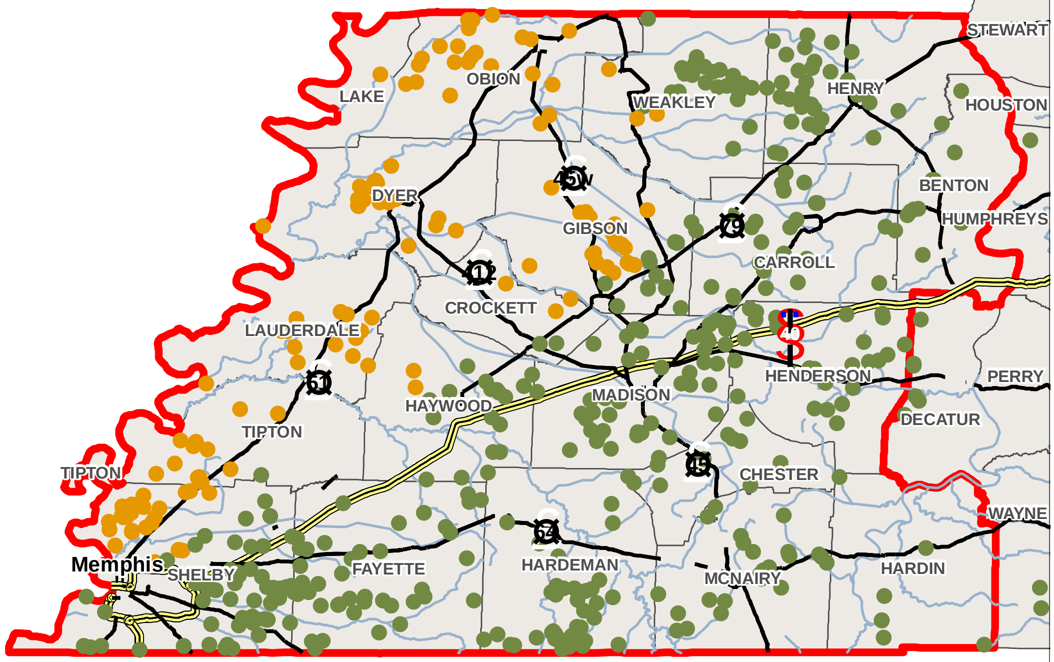
Tennessee Dam Damage
New Madrid Seismic Zone: M7.7 Event

Dam Damage of Critical Area (Points)

- Not Damaged
- Damaged



0 20 40 80 Miles

Legend

Impacted Counties Boundary

Dam Damage (Surface)

- Not Damaged
- Damaged

0 50 100 200 Miles

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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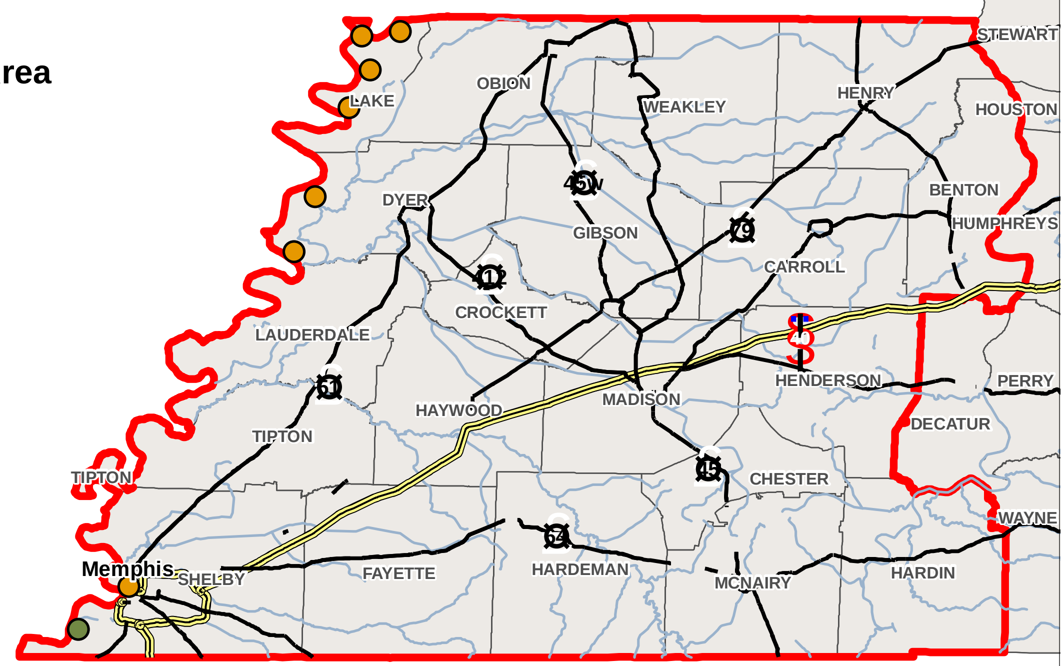
Tennessee Levee Damage
New Madrid Seismic Zone: M7.7 Event

Levee Damage of Critical Area (Points)

- Not Damaged
- Damaged



0 20 40 80 Miles

0 50 100 200 Miles

Legend

Impacted Counties Boundary

Levee Damage (Surface)

- Not Damaged
- Damaged

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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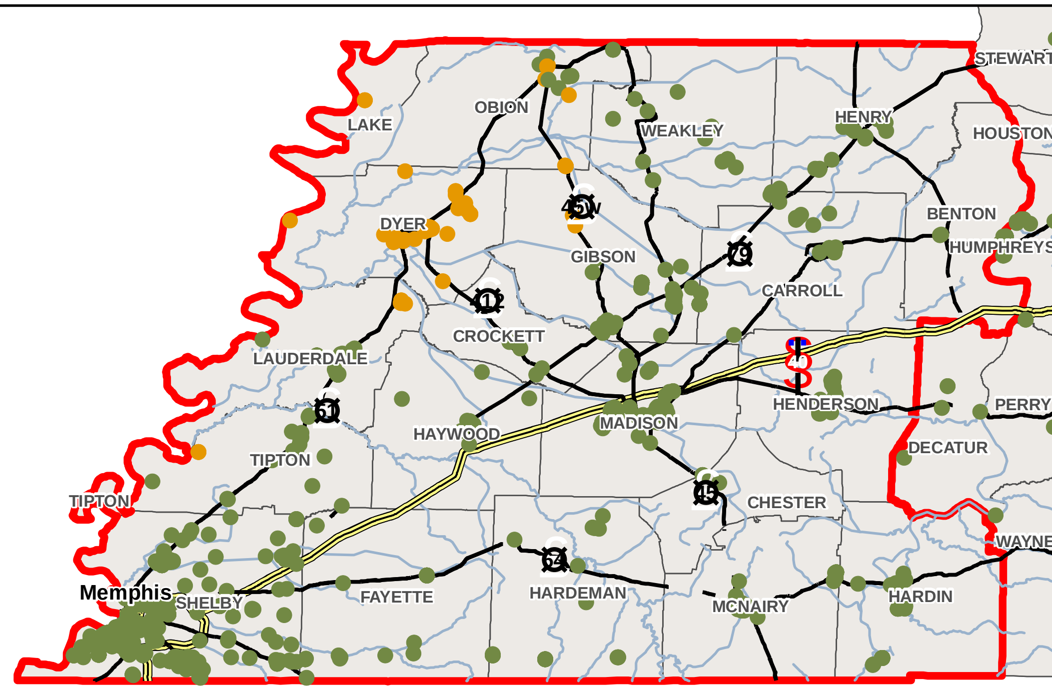
Tennessee Hazmat Facilities Damage
New Madrid Seismic Zone: M7.7 Event

Hazmat Faciities Damage of Critical Area (Points)

- Not Damaged
- Damaged



Legend

Impacted Counties Boundary

Hazmat Facilities Damage (Surface)

- Not Damaged
- Damaged

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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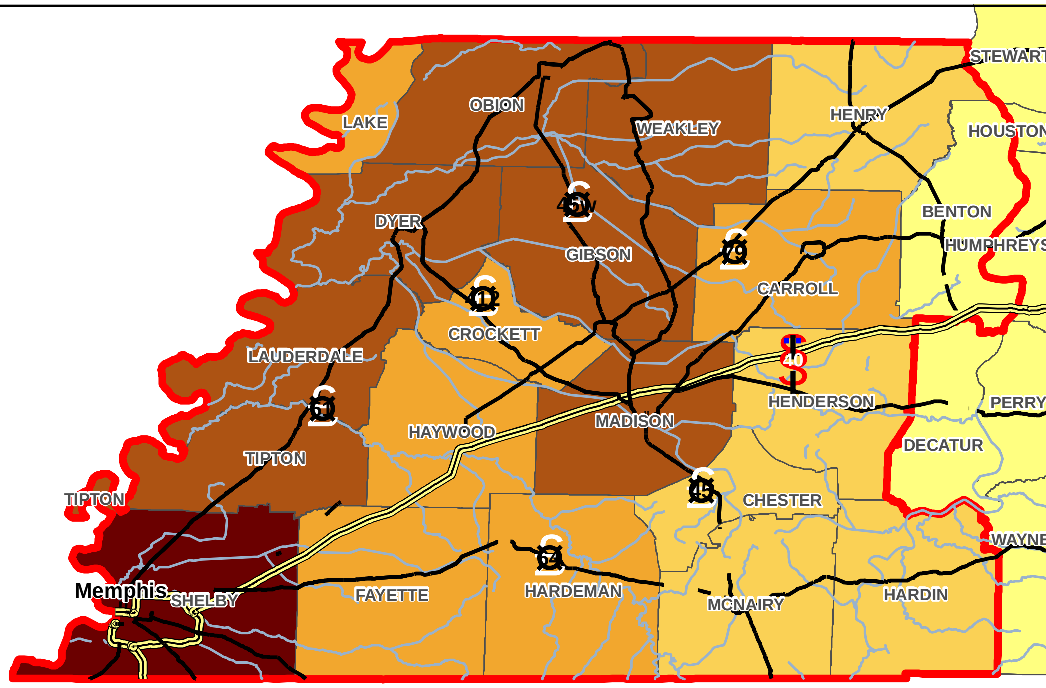
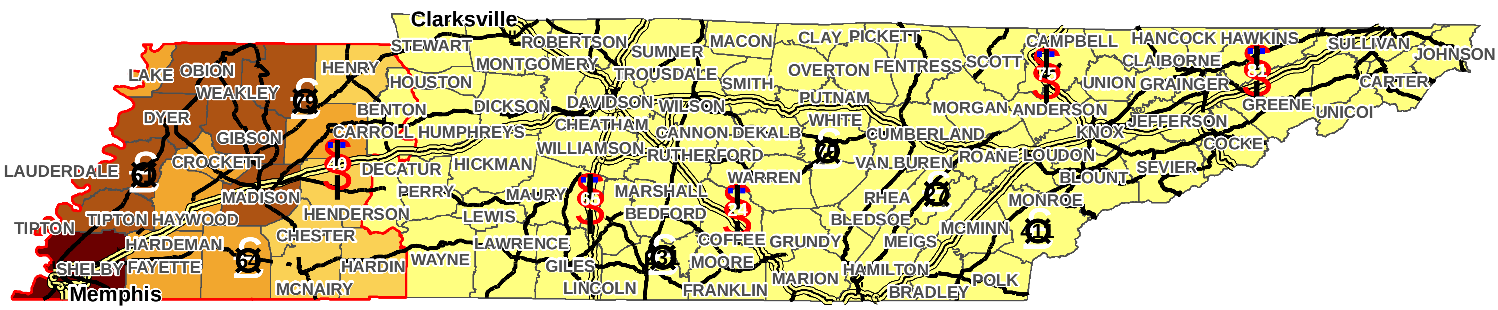
Tennessee Casualties at 2:00 AM
New Madrid Seismic Zone: M7.7 Event

Casualties at 2:00 AM in Critical Area

- 0 - 50
- 51 - 190
- 191 - 510
- 511 - 2,125
- 2,126 - 21,480



0 20 40 80 Miles



Legend

Impacted Counties Boundary

Statewide Casualties at 2:00 AM

- 0 - 50
- 51 - 190
- 191 - 510
- 511 - 2,125
- 2,126 - 21,480

0 50 100 200 Miles

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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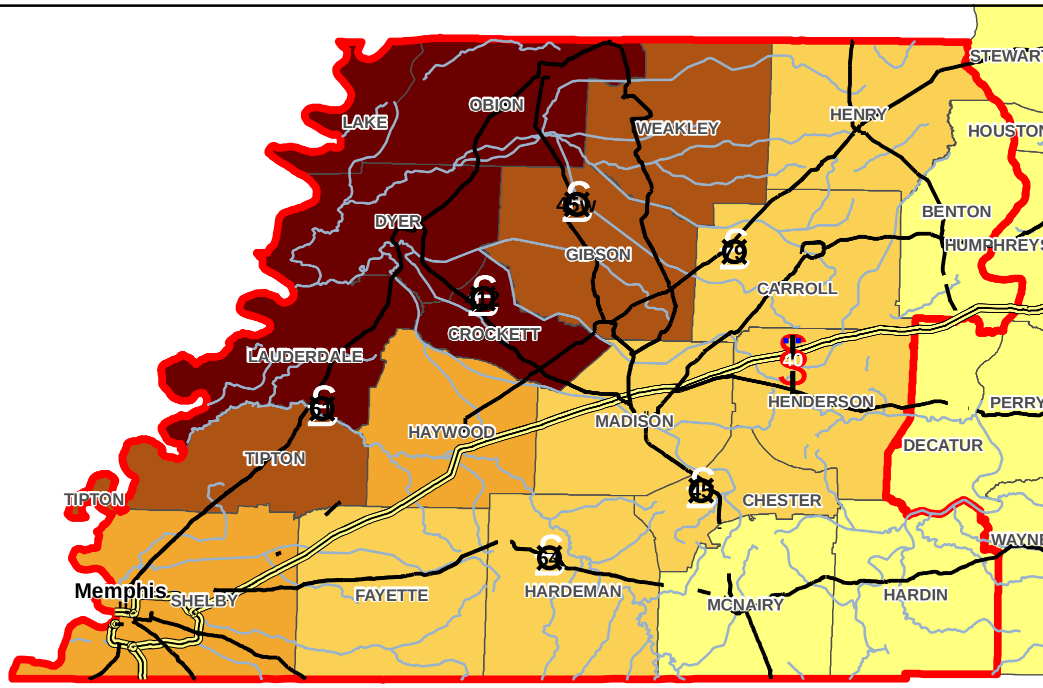
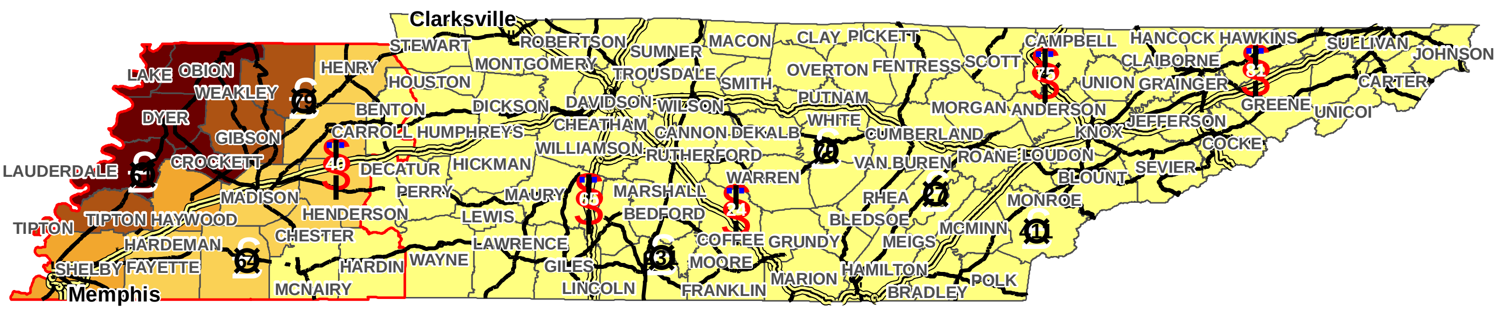
Tennessee Building Damage
New Madrid Seismic Zone: M7.7 Event

Building Damage (Percent) of Critical Area

- 0% - 20%
- 20.1% - 40%
- 40.1% - 60%
- 60.1% - 80%
- 80.1%- 100%



0 20 40 80 Miles



Legend

Impacted Counties Boundary

Statewide Building Damage (Percent)

- 0% - 20%
- 20.1% - 40%
- 40.1% - 60%
- 60.1% - 80%
- 80.1%- 100%

0 50 100 200 Miles

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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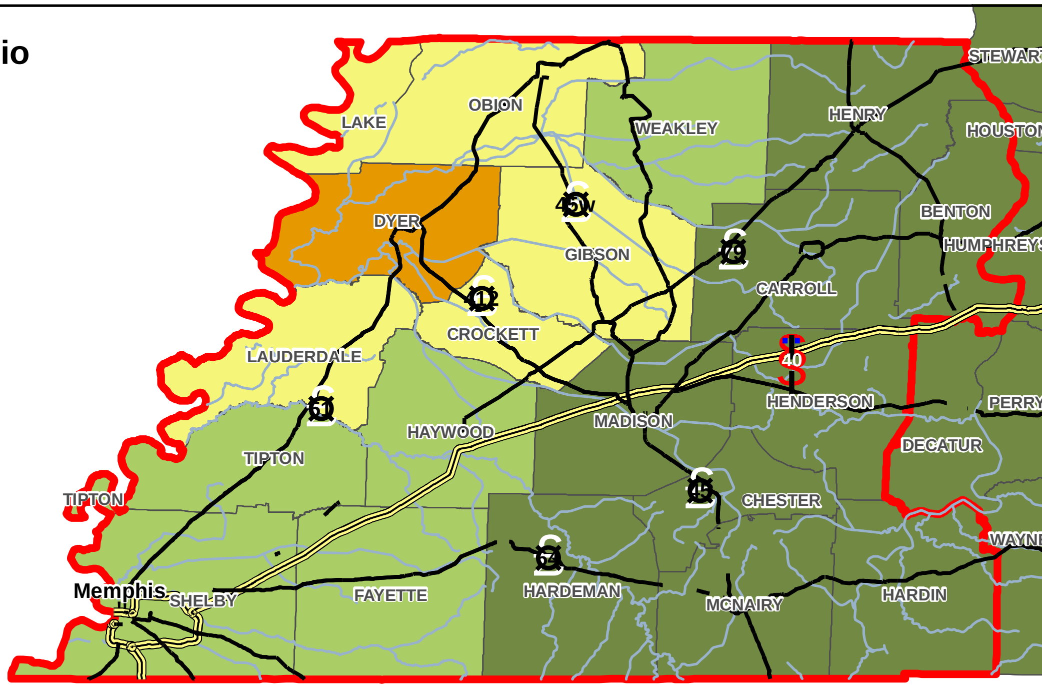
Tennessee Building Asset Value Loss Ratio
New Madrid Seismic Zone: M7.7 Event

Building Asset Value Loss Ratio of Critical Area

- 0%-20%
- 20.1% - 40%
- 40.1% - 60%
- 60.1% - 80%
- 80.1% - 100%



0 20 40 80 Miles

Legend

Impacted Counties Boundary

Building Asset Value Loss Ratio (State)

- 0%-20%
- 20.1% - 40%
- 40.1% - 60%
- 60.1% - 80%
- 80.1% - 100%

0 50 100 200 Miles

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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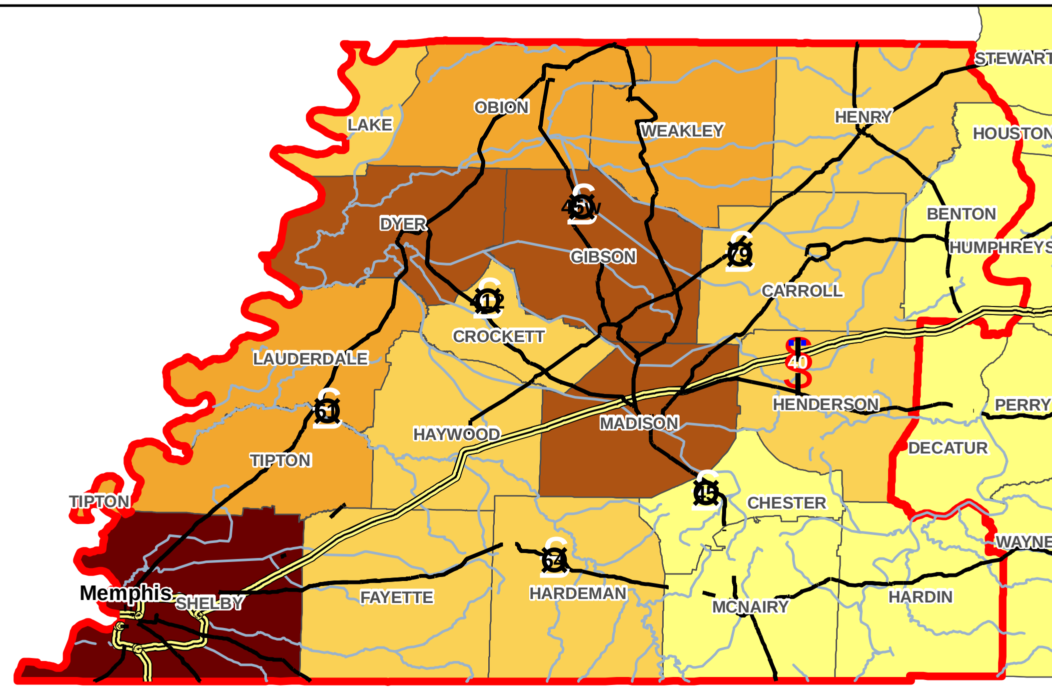
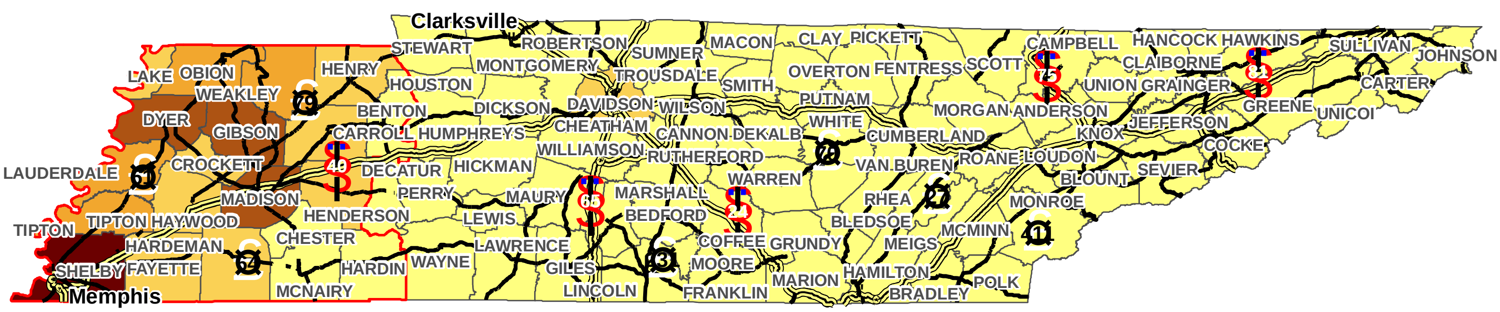
Tennessee Total Debris
New Madrid Seismic Zone: M7.7 Event

Total Debris - thousand tons of Critical Area

- 0 - 100
- 101 - 350
- 351 - 850
- 851 - 1,500
- 1,501 - 13,100



0 20 40 80
Miles



Legend

Impacted Counties Boundary

Total Debris - thousand tons (State)

- 0 - 100
- 101 - 350
- 351 - 850
- 851 - 1,500
- 1,501 - 13,100

0 50 100 200
Miles

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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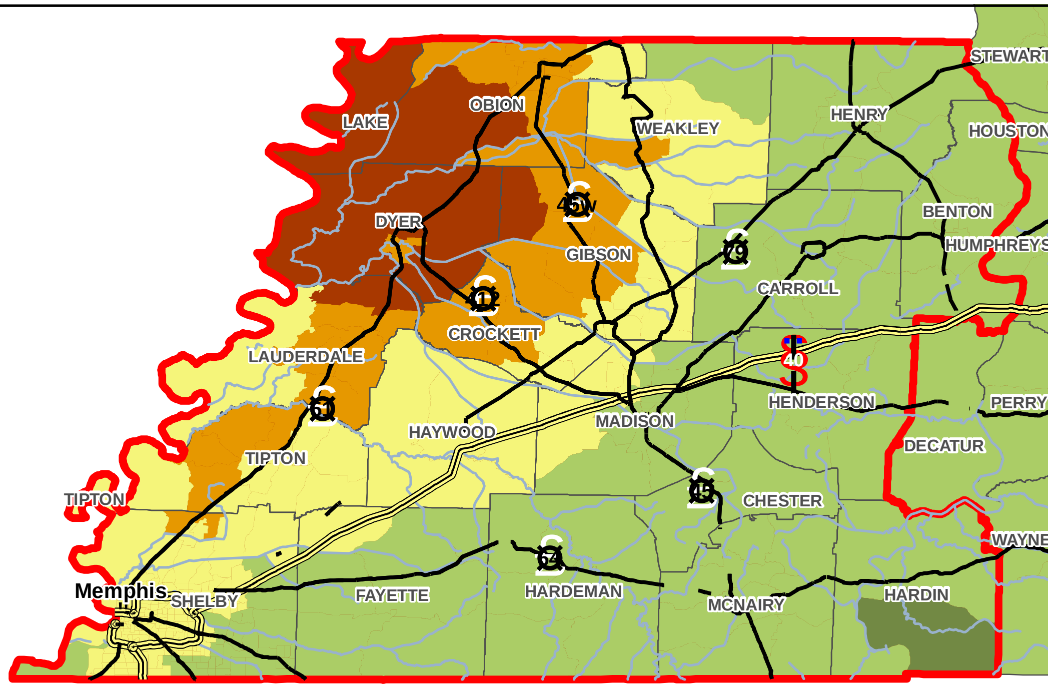
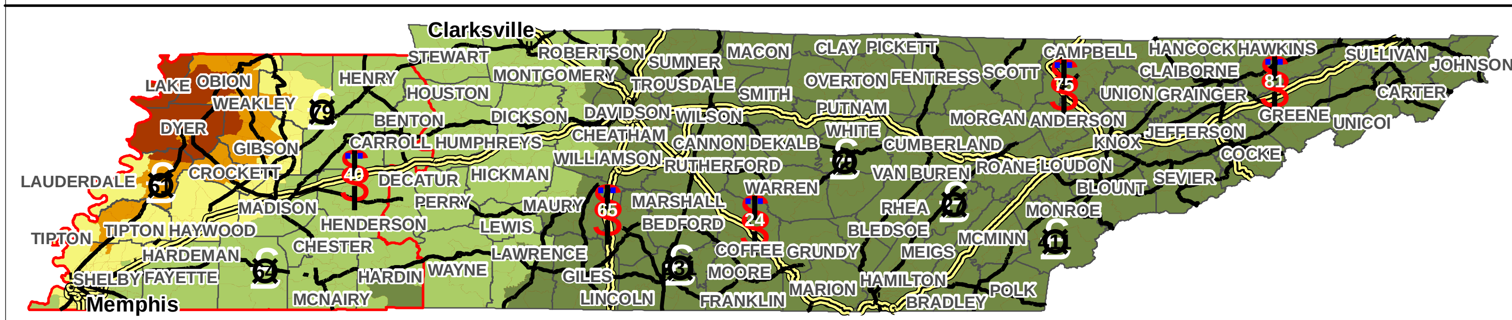
Tennessee Peak Ground Acceleration
New Madrid Seismic Zone: M7.7 Event

Peak Ground Acceleration of Critical Area (g)

- 0 - 0.2
- 0.21 - 0.4
- 0.41 - 0.6
- 0.61 - 0.8
- 0.81 - 1.2



0 20 40 80 Miles



Legend

Impacted Counties Boundary

Peak Ground Acceleration- State (g)

- 0 - 0.2
- 0.21 - 0.4
- 0.41 - 0.6
- 0.61 - 0.8
- 0.81 - 1.2

0 50 100 200 Miles

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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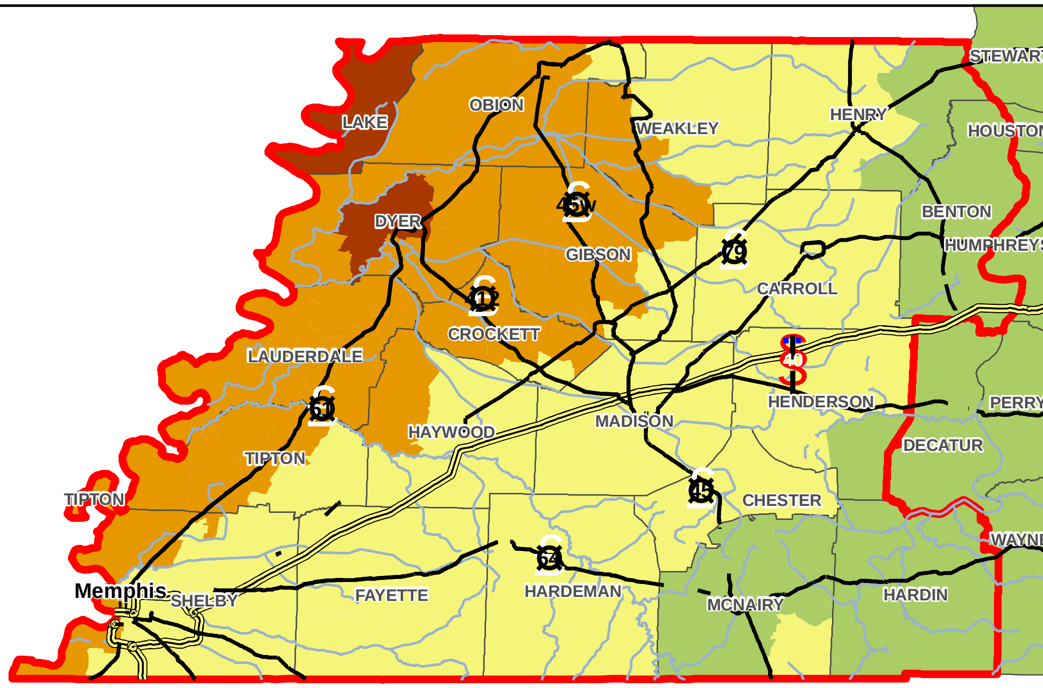
Tennessee Modified Mercalli Intensity
New Madrid Seismic Zone: M7.7 Event

Modified Mercalli Intensity of Critical Area

- VI
- VII
- VIII
- IX
- X+



0 20 40 80 Miles

0 50 100 200 Miles

Legend

Impacted Counties Boundary

Modified Mercalli intensity (State)

- VI
- VII
- VIII
- IX
- X+

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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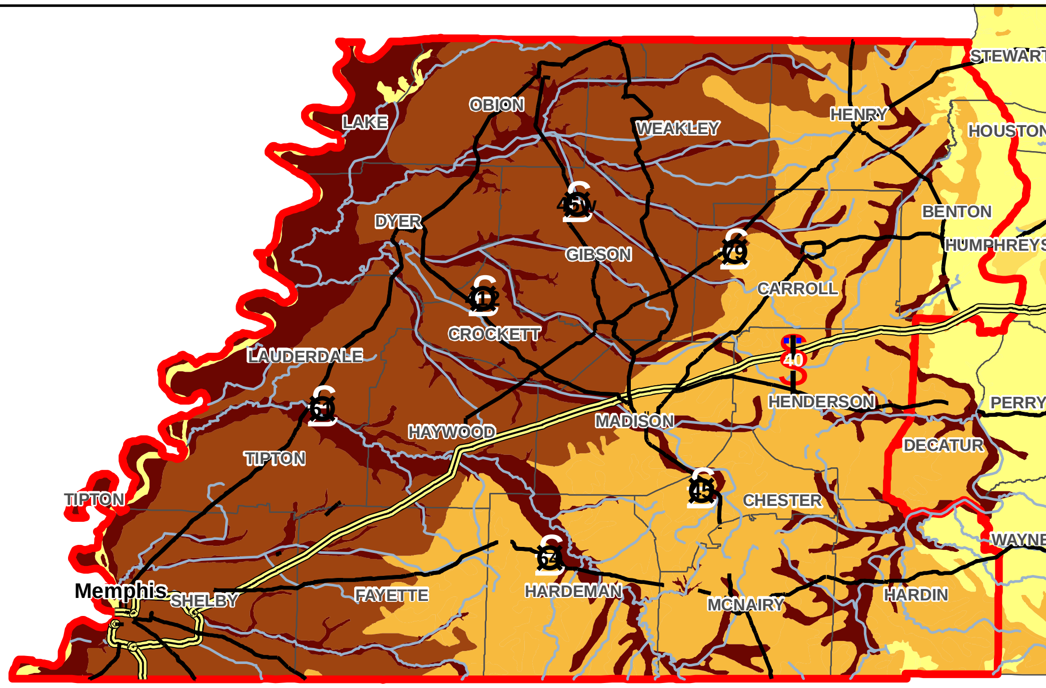
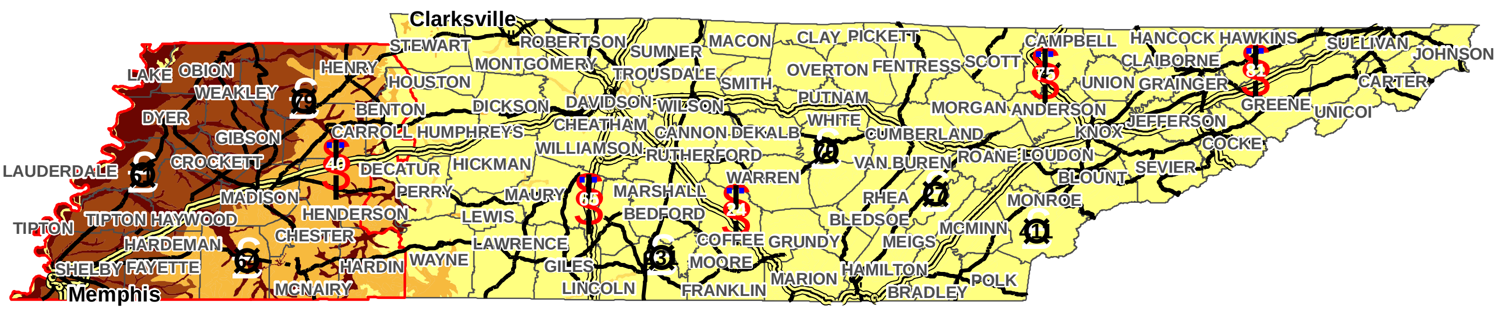
Tennessee Liquefaction Susceptibility
New Madrid Seismic Zone: M7.7 Event

Liquefaction Susceptibility of Critical Area

- None
- Very Low
- Low
- Moderate
- High
- Very High



0 20 40 80 Miles



0 50 100 200 Miles

Legend

Impacted Counties Boundary

Liquefaction Susceptibility (State)

- None
- Very Low
- Low
- Moderate
- High
- Very High

Major Cities by Population

- 51,000 - 60,000
- 60,001 - 170,000
- 170,001 - 615,000

Roads

- US Routes
- Interstates

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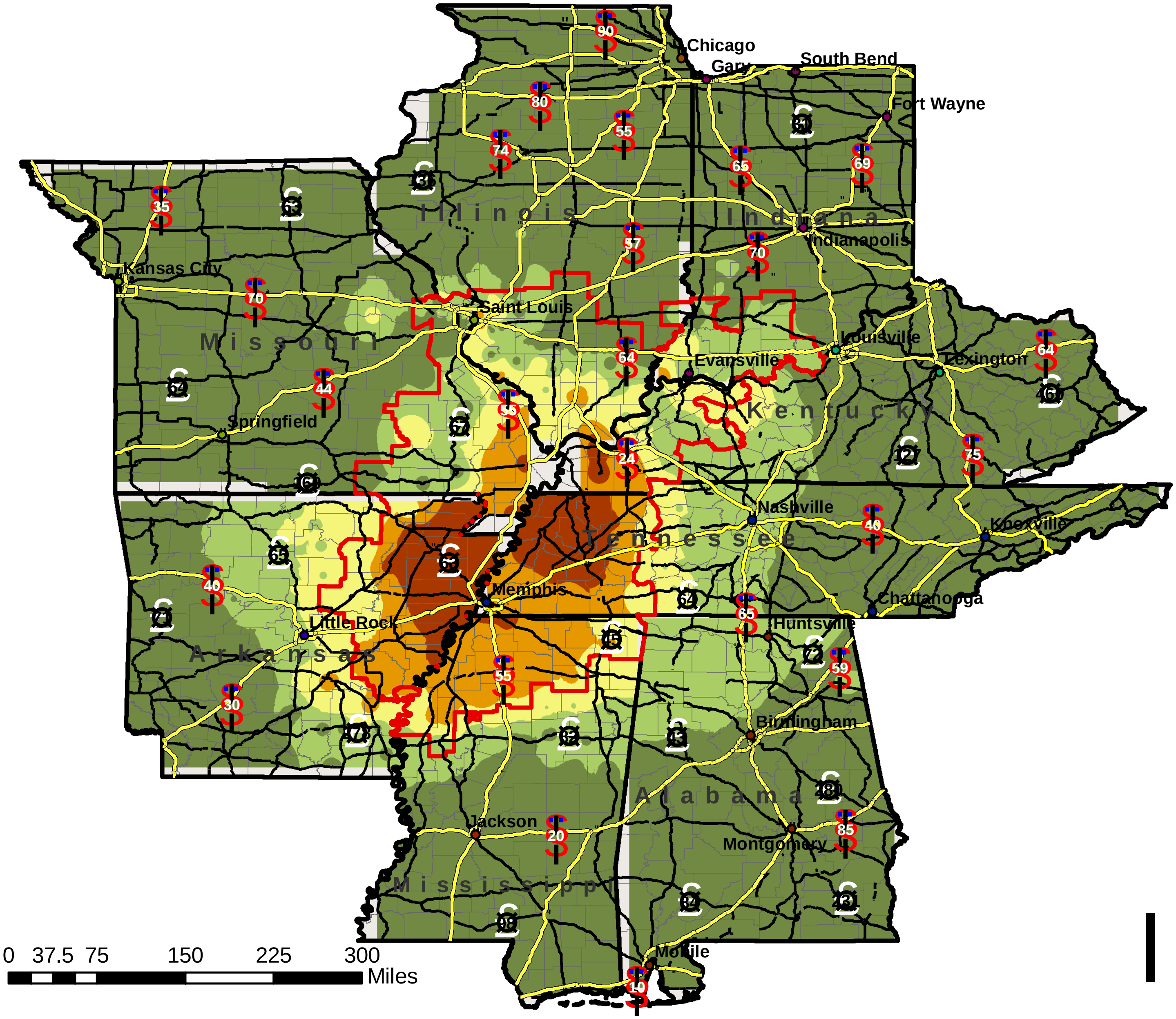
Central US Hospitals Damage
New Madrid Seismic Zone: M7.7 Event



Impacted Counties Boundary

Hospital Facilities Damage (Surface)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain
- No Inventory

Major Cities by Population

- 26,000 - 130,000
- 130,001 - 370,000
- 370,001 - 750,000
- 750,001 - 2,740,000

Roads

- Interstates
- US Routes

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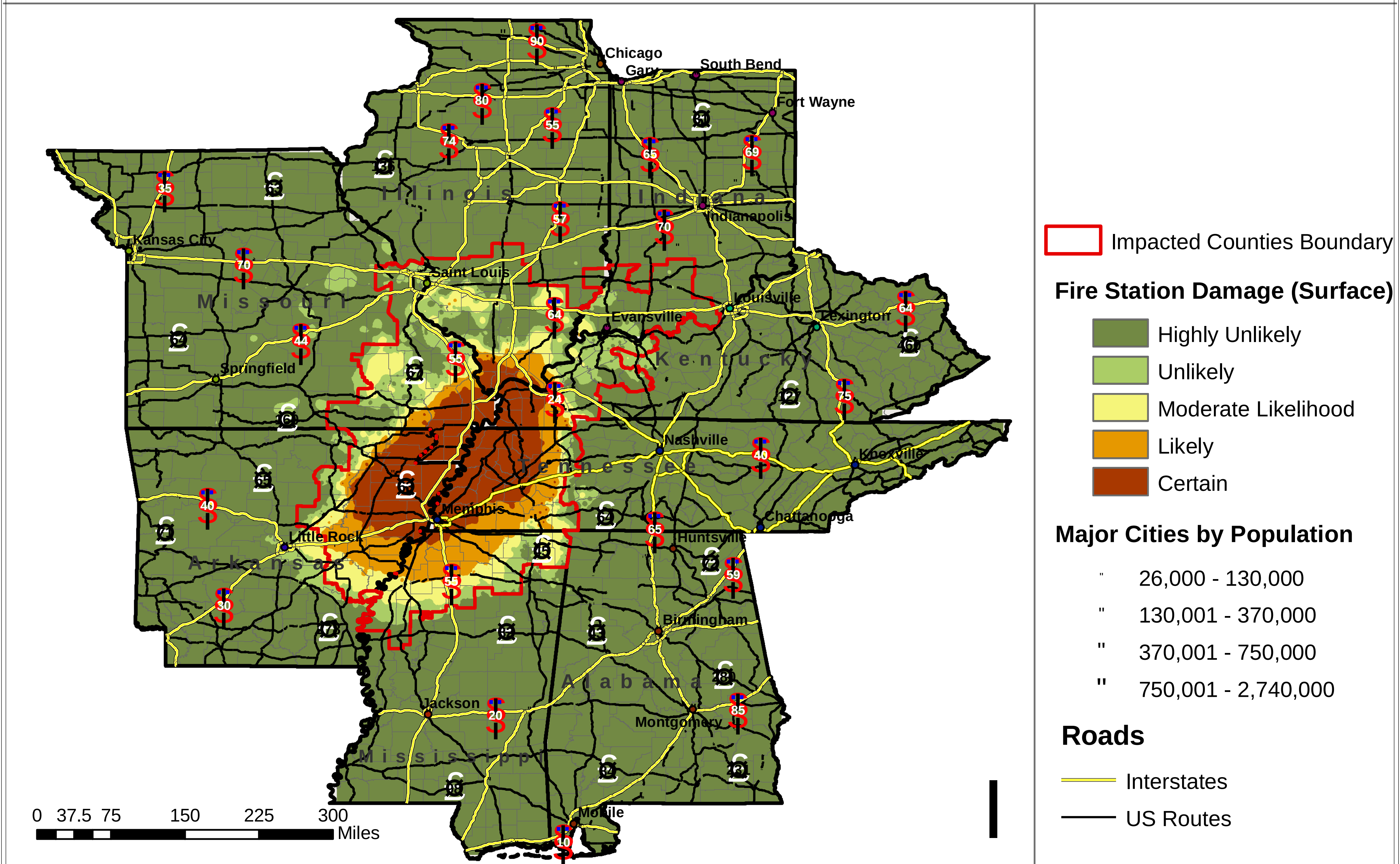
Central US Fire Stations Damage
New Madrid Seismic Zone: M7.7 Event



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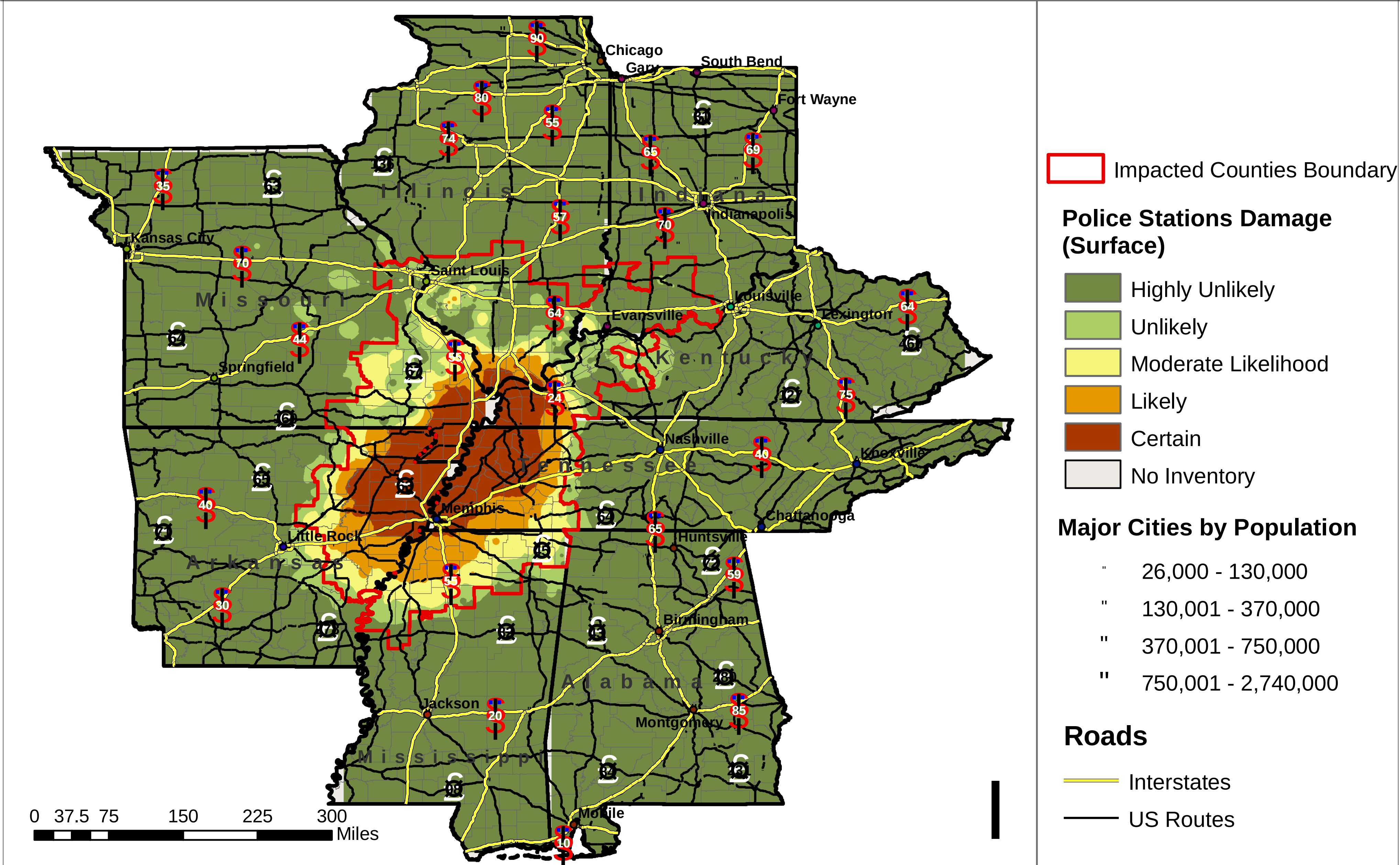
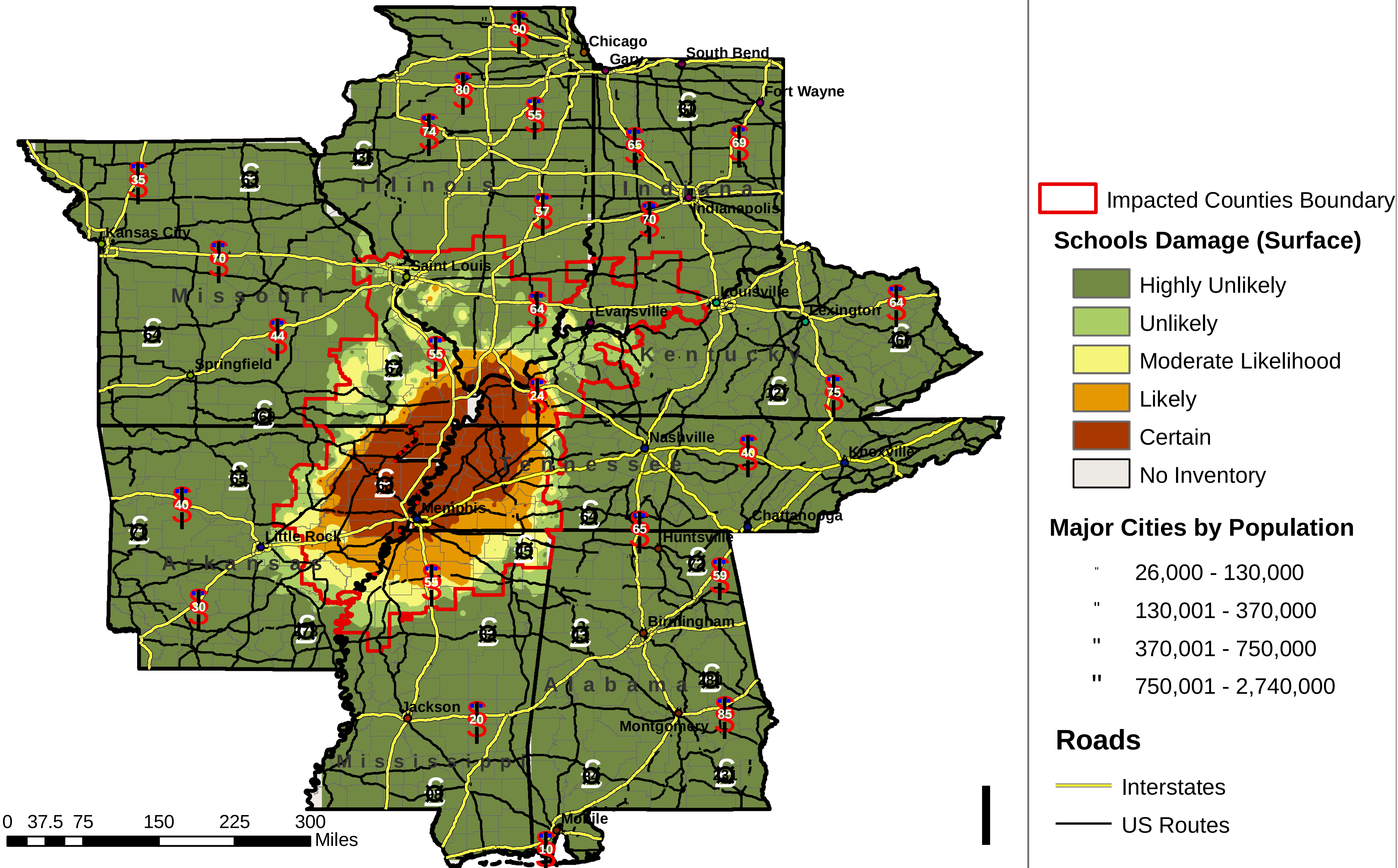
Central US Police Stations Damage
New Madrid Seismic Zone: M7.7 Event



Central US Schools Damage
New Madrid Seismic Zone: M7.7 Event



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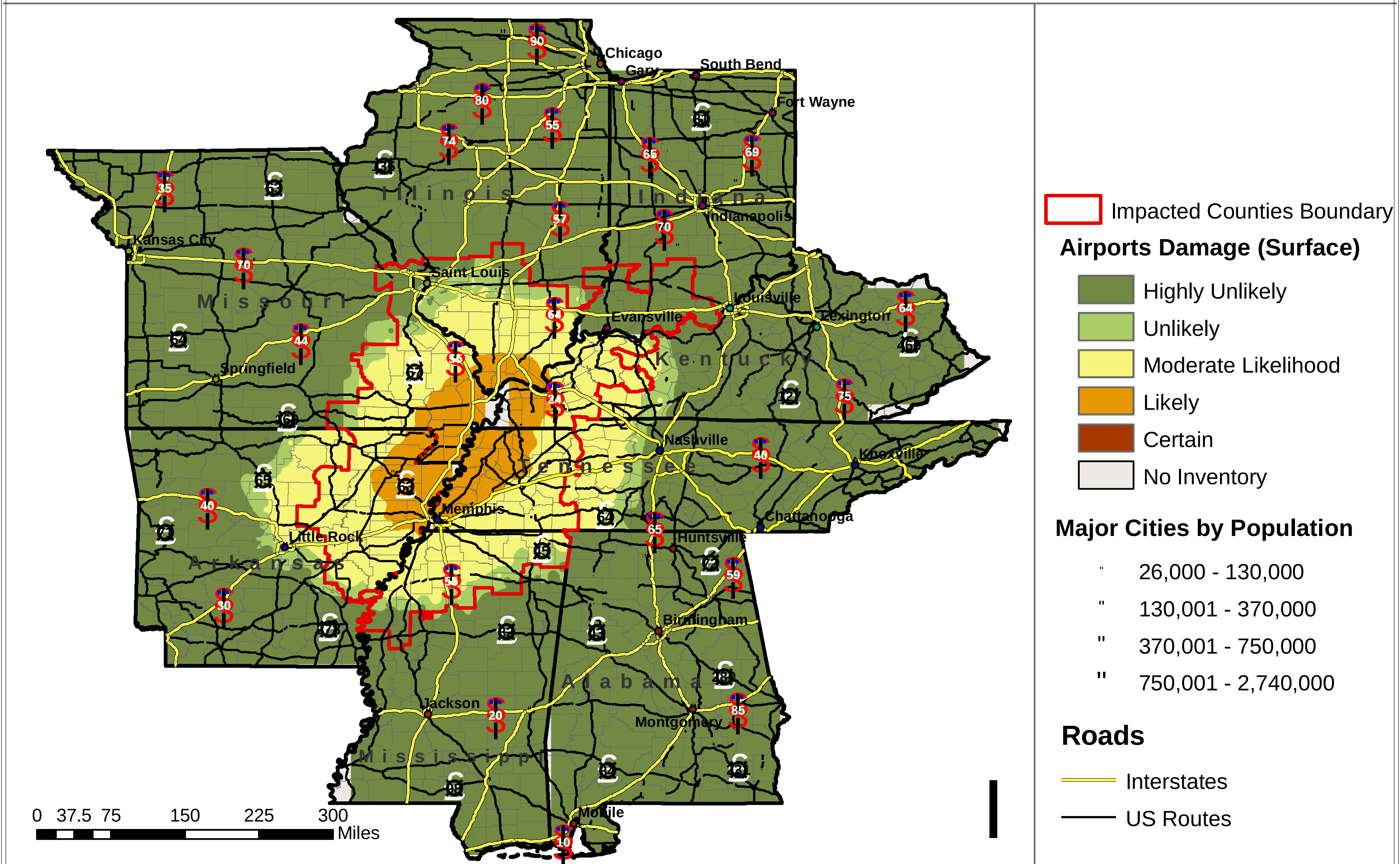
Central US Airports Damage
New Madrid Seismic Zone: M7.7 Event



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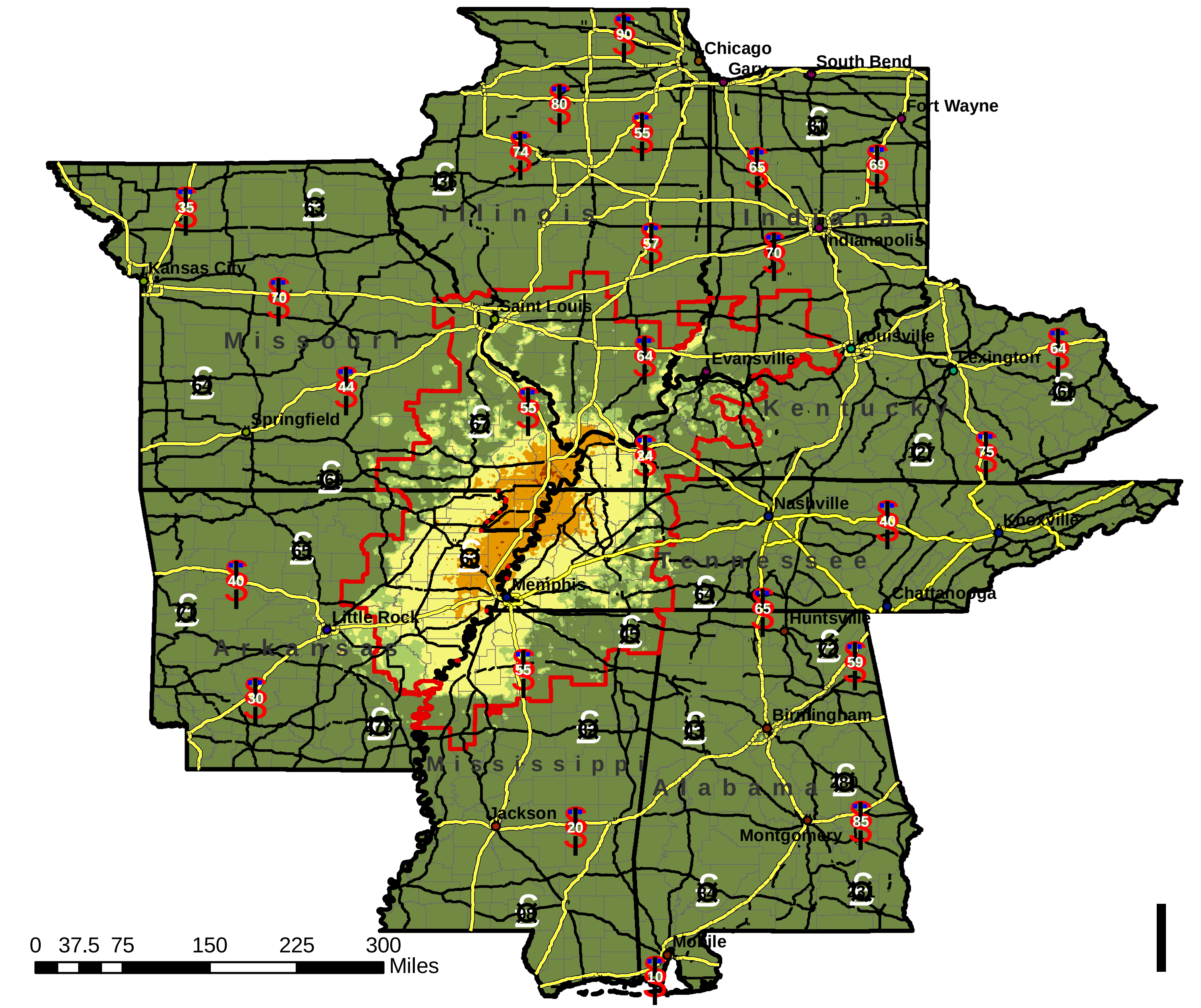
Central US Highway Bridge Damage
New Madrid Seismic Zone: M7.7 Event



Impacted Counties Boundary

Highway Bridge Damage (Surface)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain

Major Cities by Population

- 26,000 - 130,000
- 130,001 - 370,000
- 370,001 - 750,000
- 750,001 - 2,740,000

Roads

- Interstates
- US Routes

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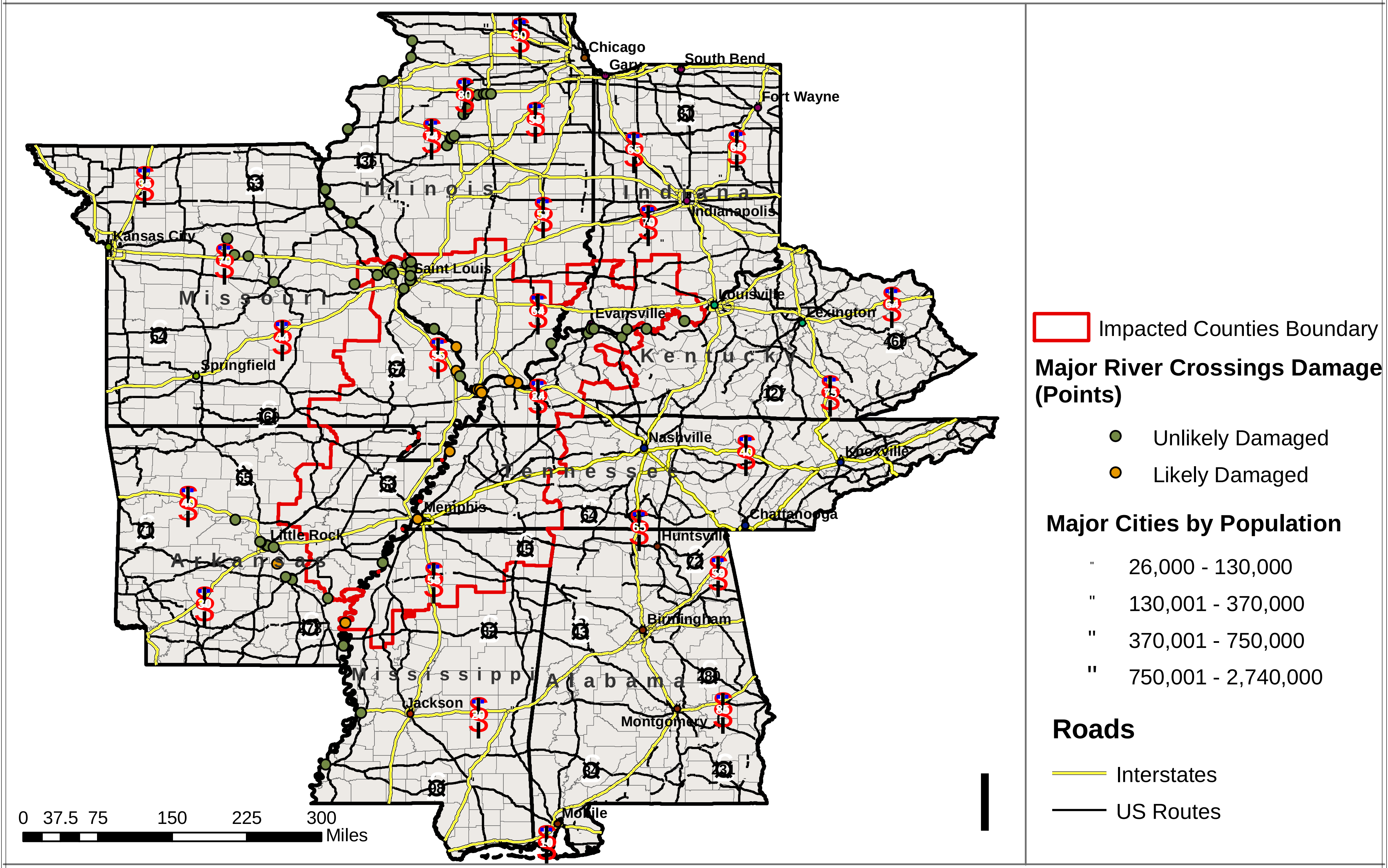
Central US Major River Crossings Damage
New Madrid Seismic Zone: M7.7 Event



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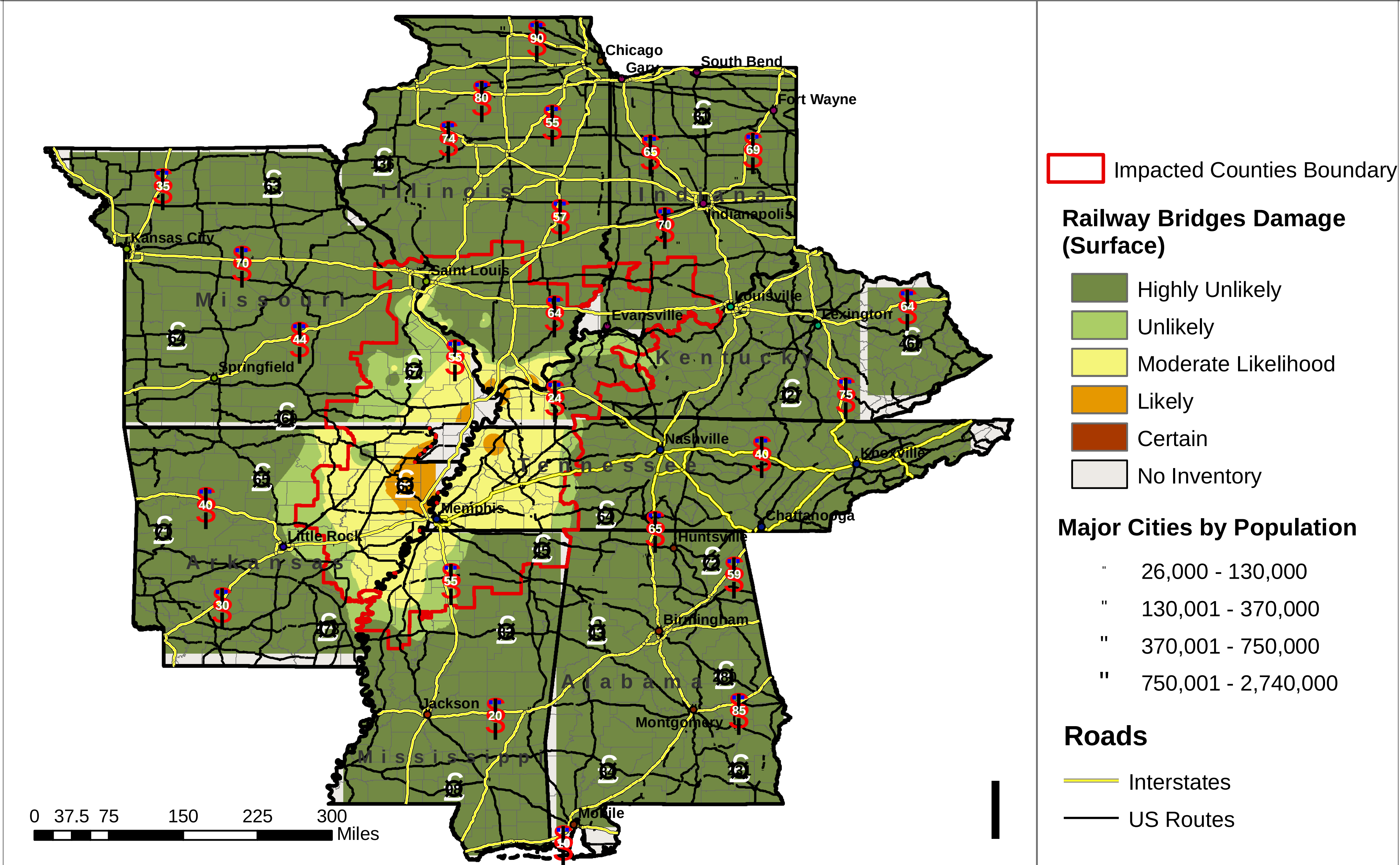
Central US Railway Bridges Damage
New Madrid Seismic Zone: M7.7 Event



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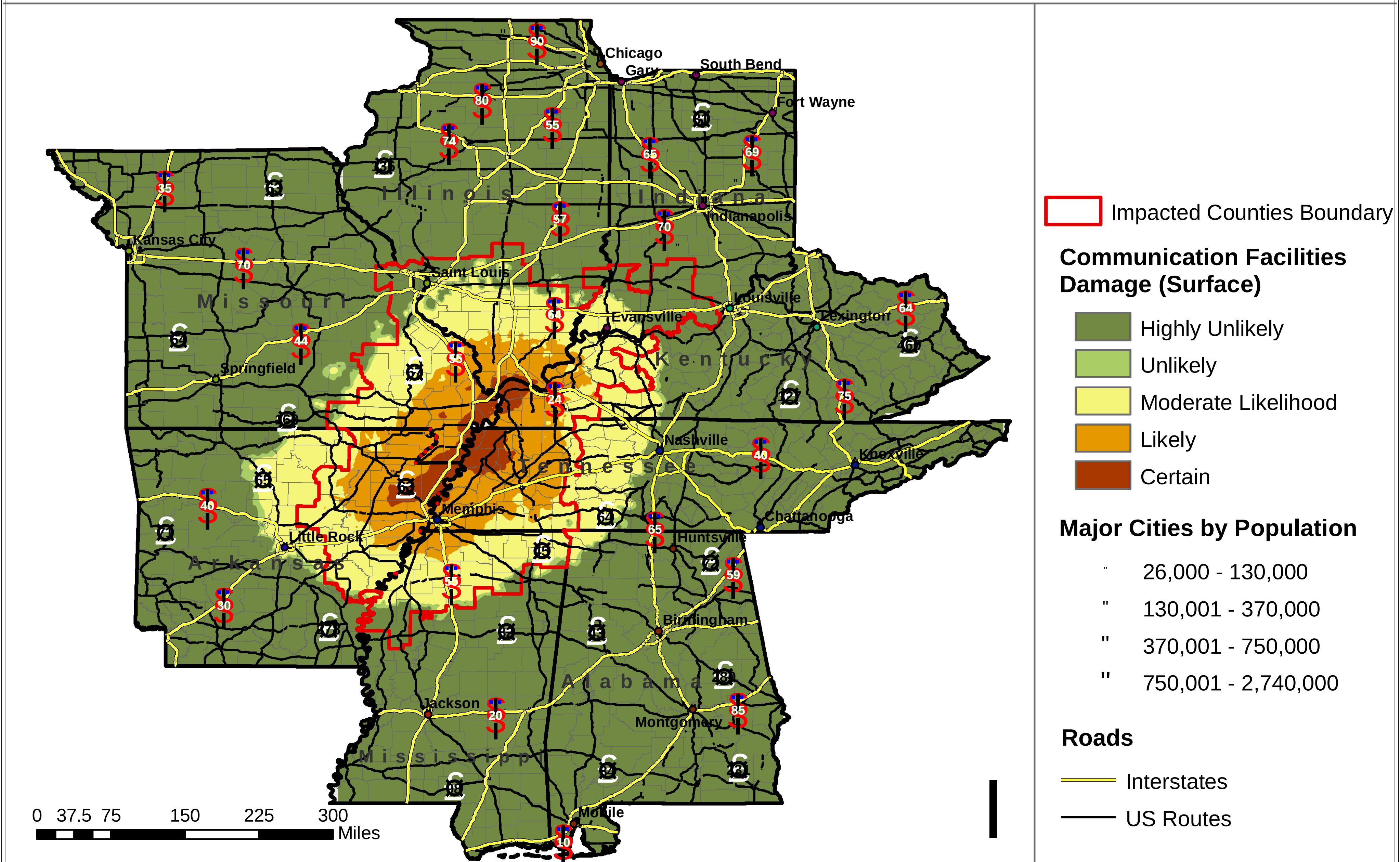
Central US Communication Facilities Damage
New Madrid Seismic Zone: M7.7 Event



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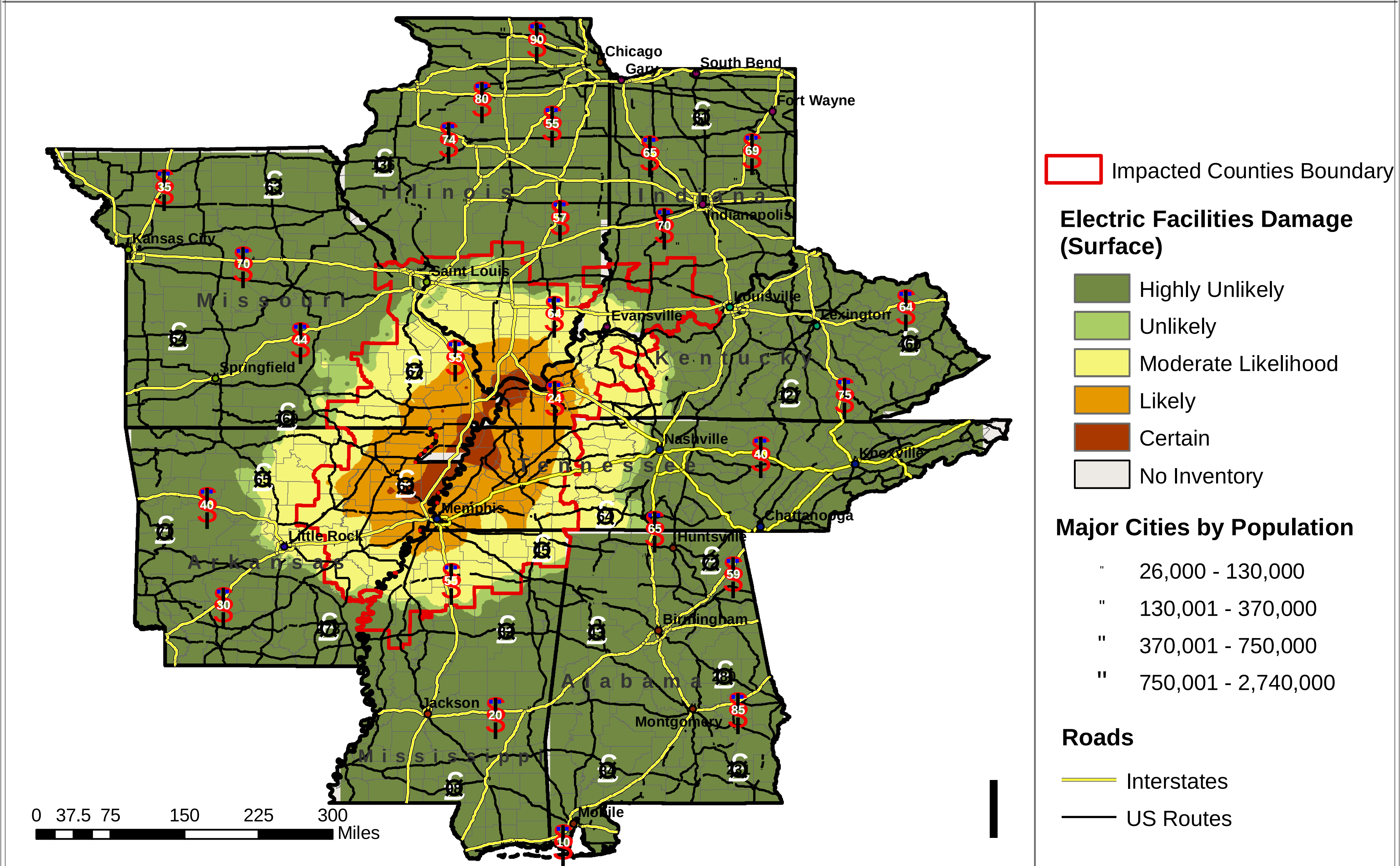
Central US Electric Facilities Damage
New Madrid Seismic Zone: M7.7 Event



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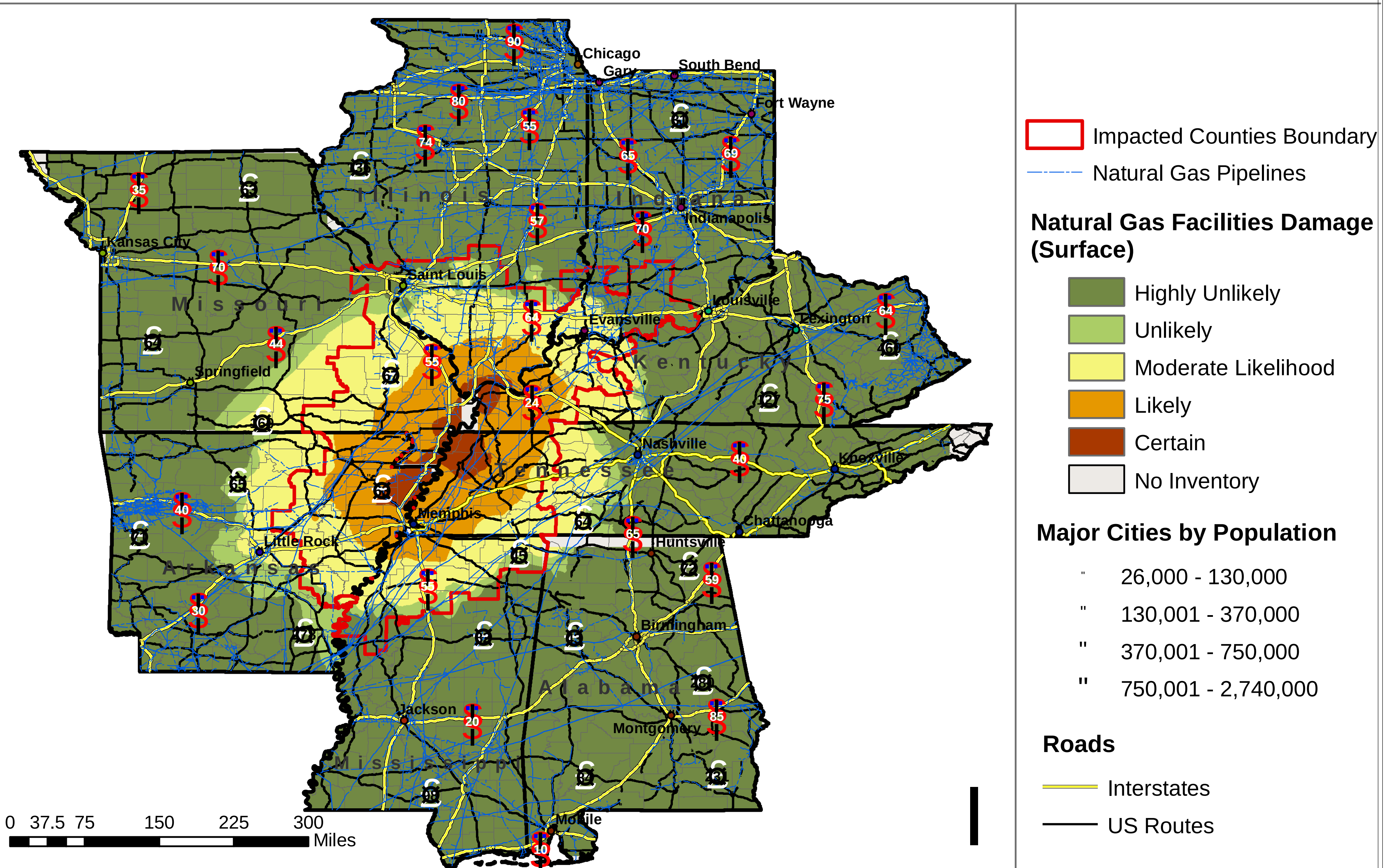
Central US Natural Gas Facilities Damage
New Madrid Seismic Zone: M7.7 Event



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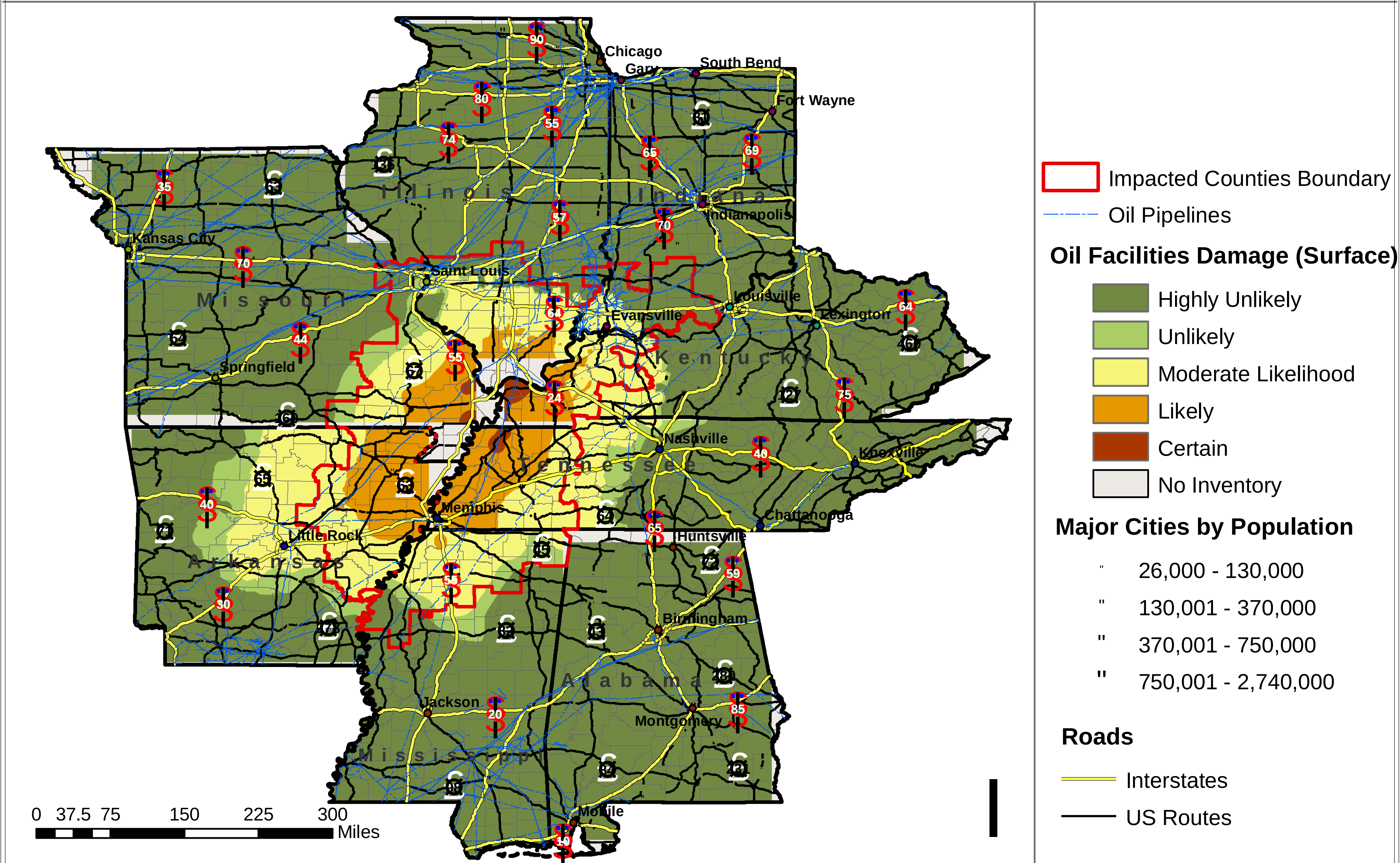
Central US Oil Facilities Damage
New Madrid Seismic Zone: M7.7 Event



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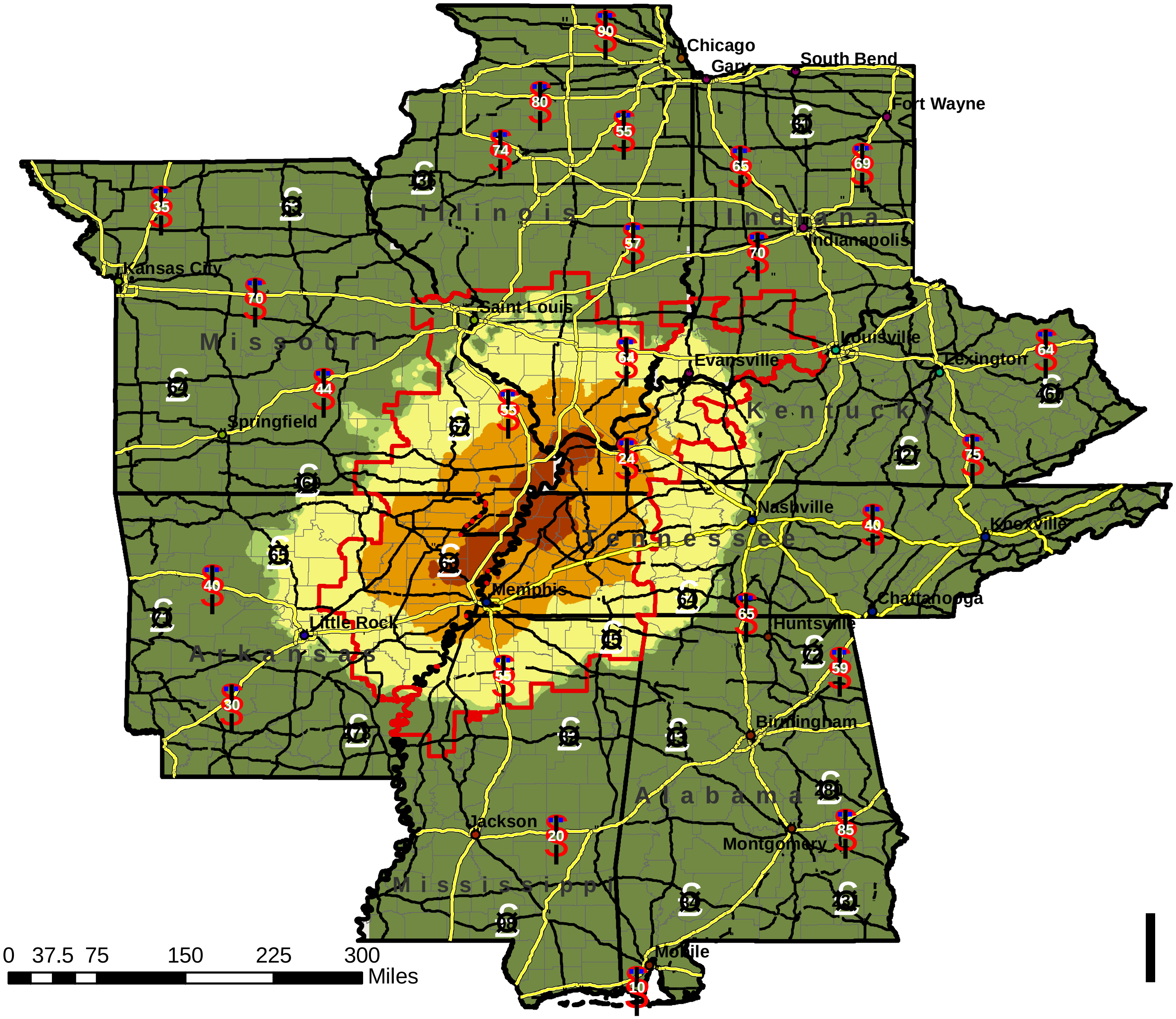
Central US Waste Water Facilities Damage
New Madrid Seismic Zone: M7.7 Event



Impacted Counties Boundary

Waste Water Facilities Damage (Surface)

- Highly Unlikely
- Unlikely
- Moderate Likelihood
- Likely
- Certain
- No Inventory

Major Cities by Population

- 26,000 - 130,000
- 130,001 - 370,000
- 370,001 - 750,000
- 750,001 - 2,740,000

Roads

- Interstates
- US Routes

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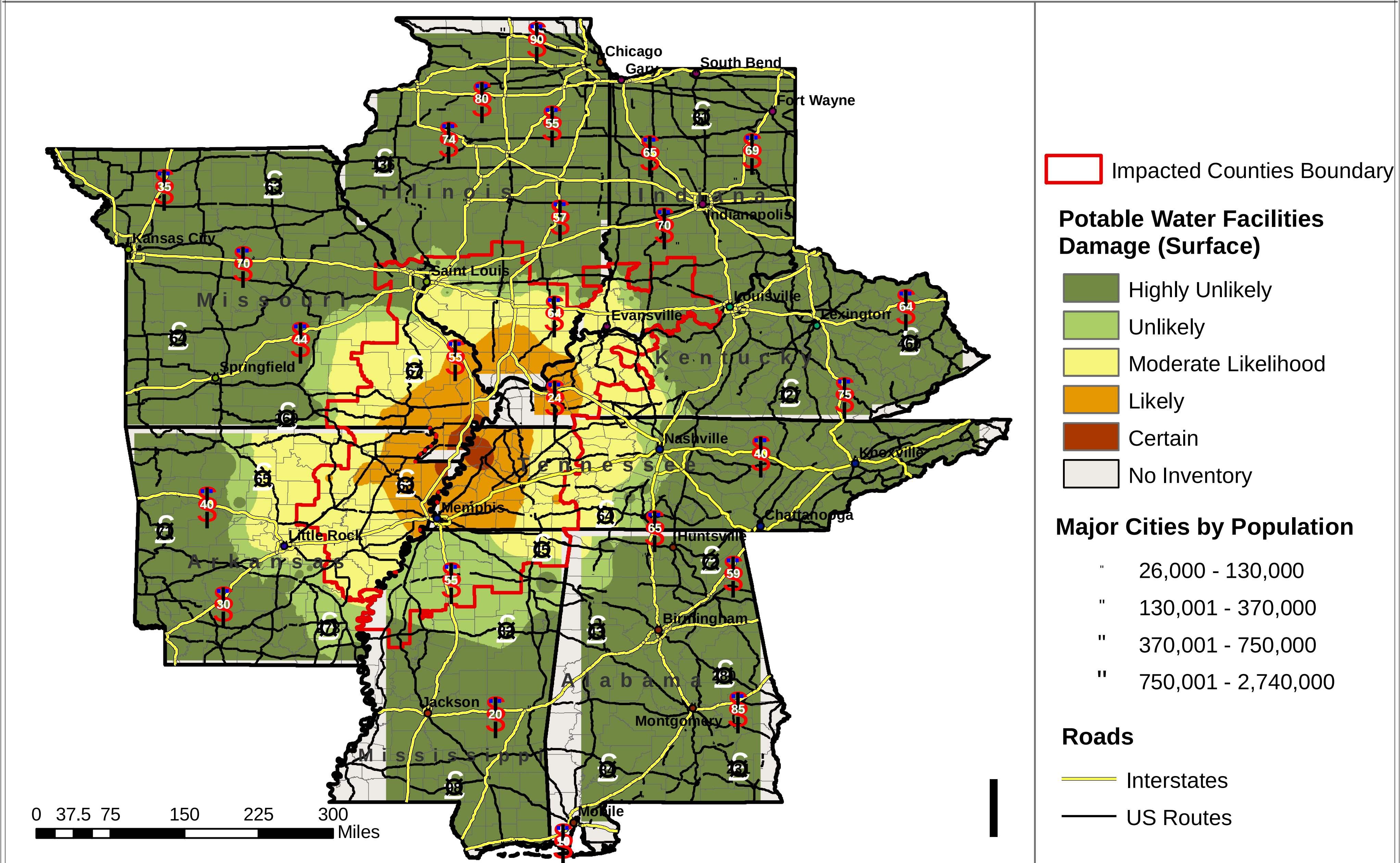
Central US Potable Water Facilities Damage
New Madrid Seismic Zone: M7.7 Event



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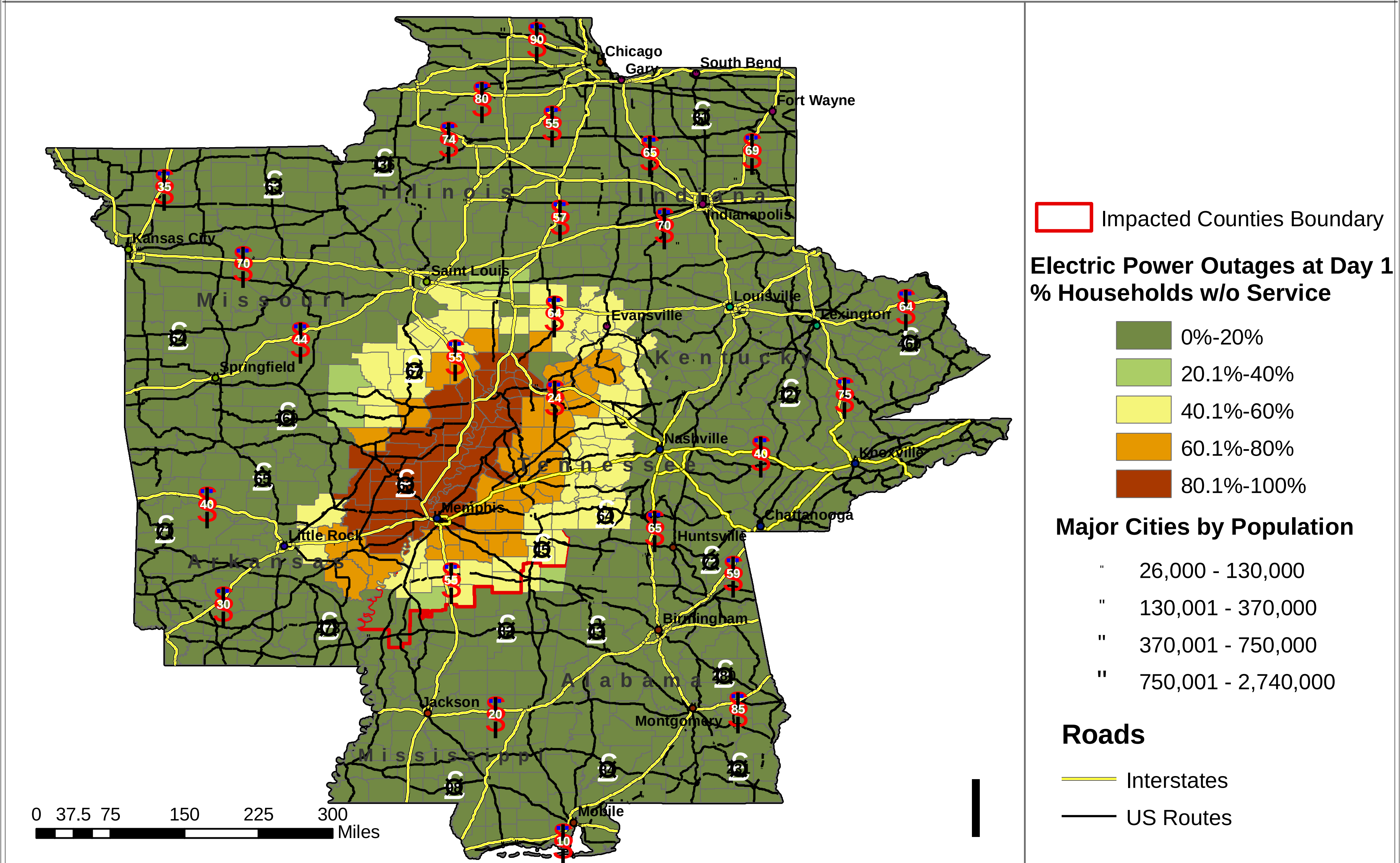
Central US Electric Power Outages
New Madrid Seismic Zone: M7.7 Event



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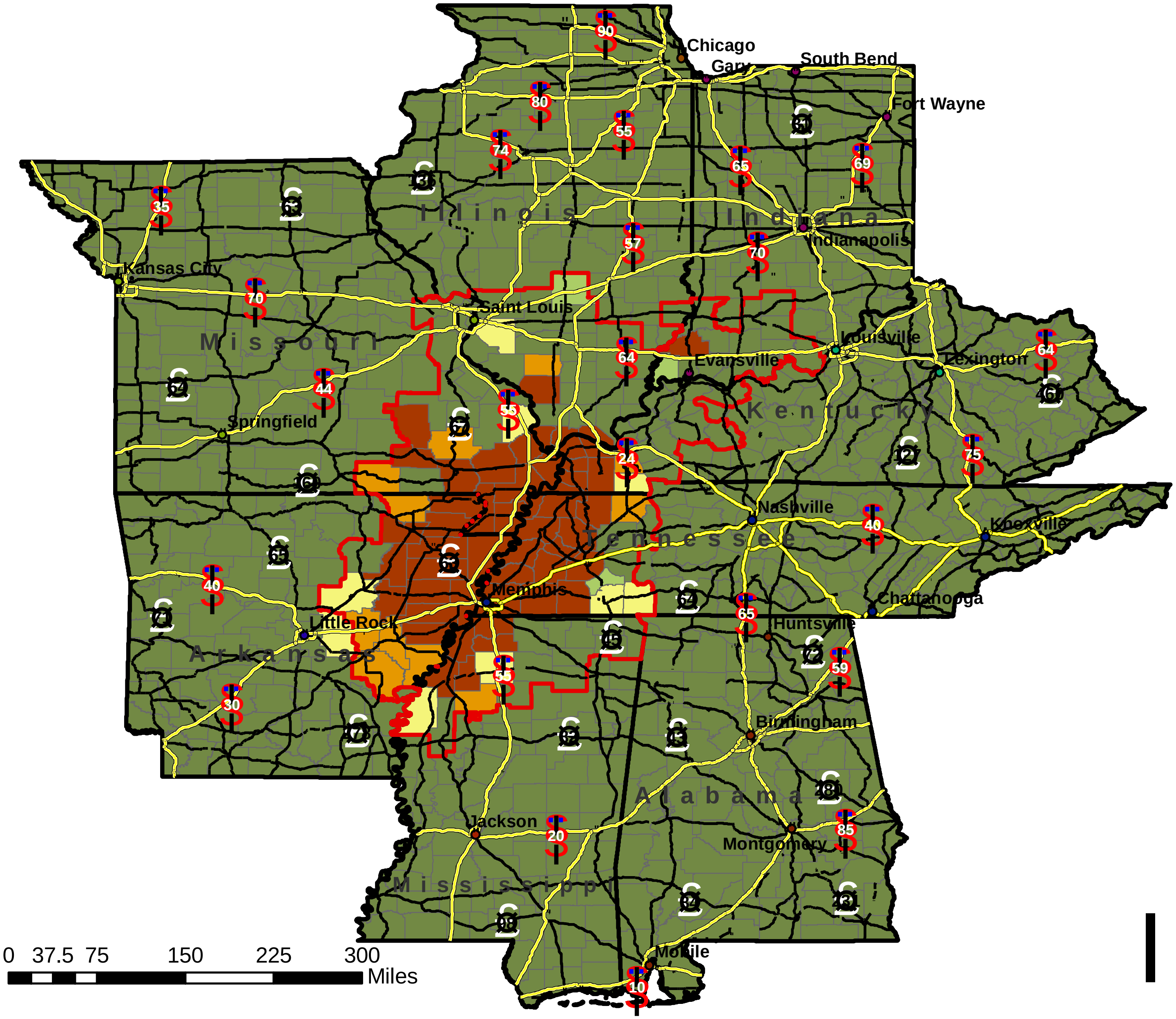
Central US Potable Water Outages
New Madrid Seismic Zone: M7.7 Event



Impacted Counties Boundary

Potable Water Outages
(% of households w/o service at Day 1)

- 0-20%
- 20.1-40%
- 40.1-60%
- 60.1-80%
- 80.1-100%

Major Cities by Population

- 26,000 - 130,000
- 130,001 - 370,000
- 370,001 - 750,000
- 750,001 - 2,740,000

Roads

- Interstates
- US Routes

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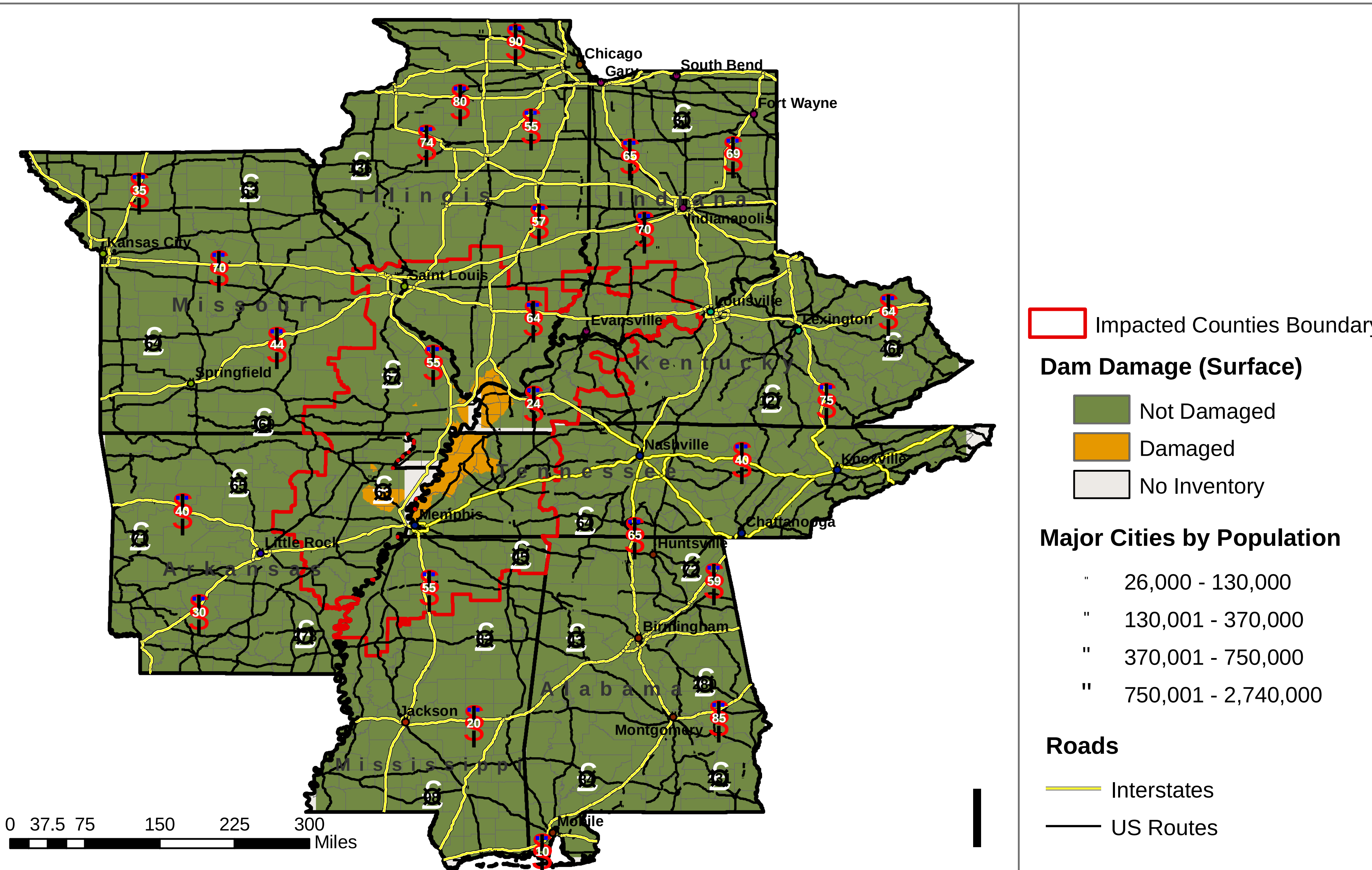
Central US Dams Damage
New Madrid Seismic Zone: M7.7 Event



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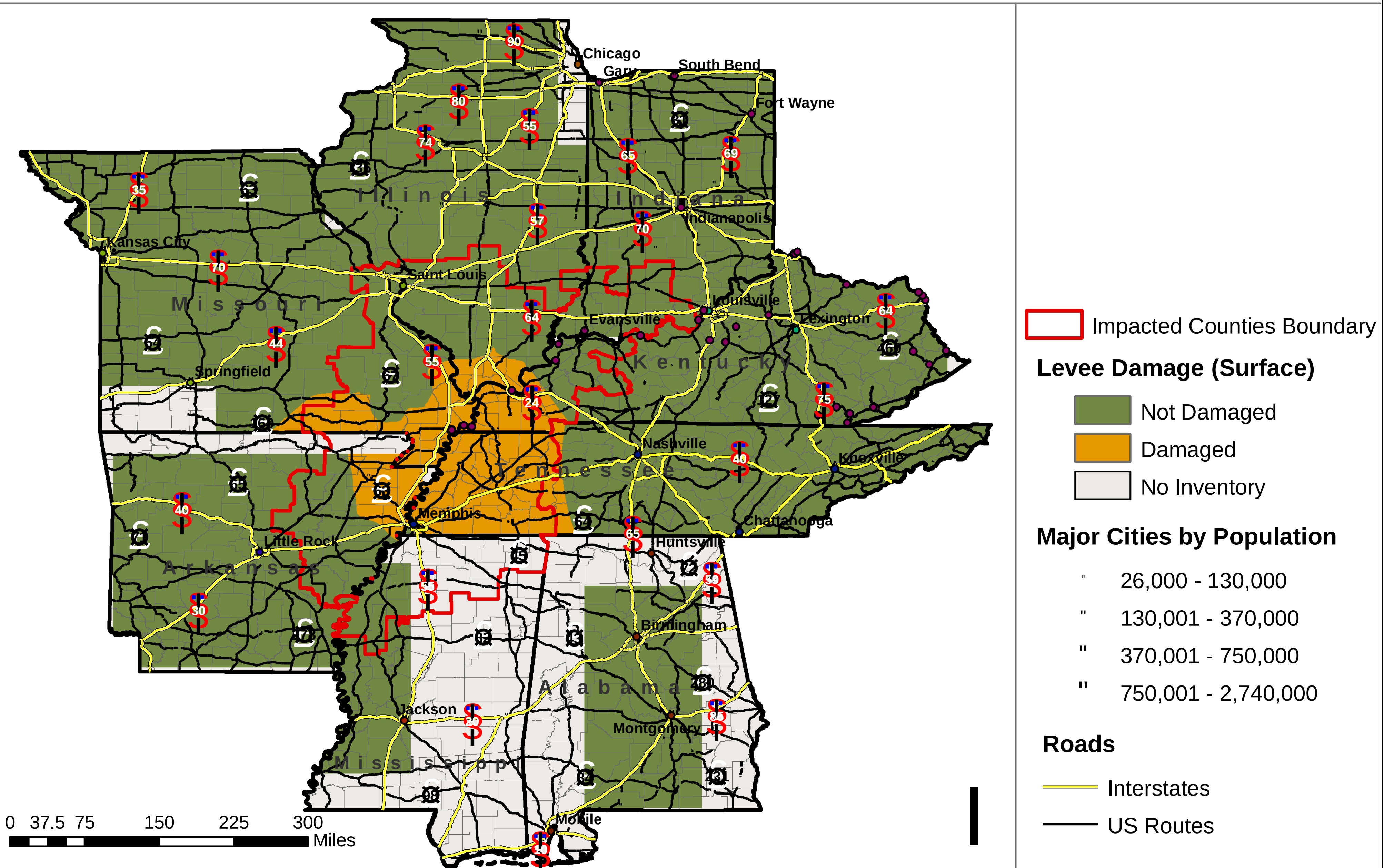
Central US Levee Damage
New Madrid Seismic Zone: M7.7 Event



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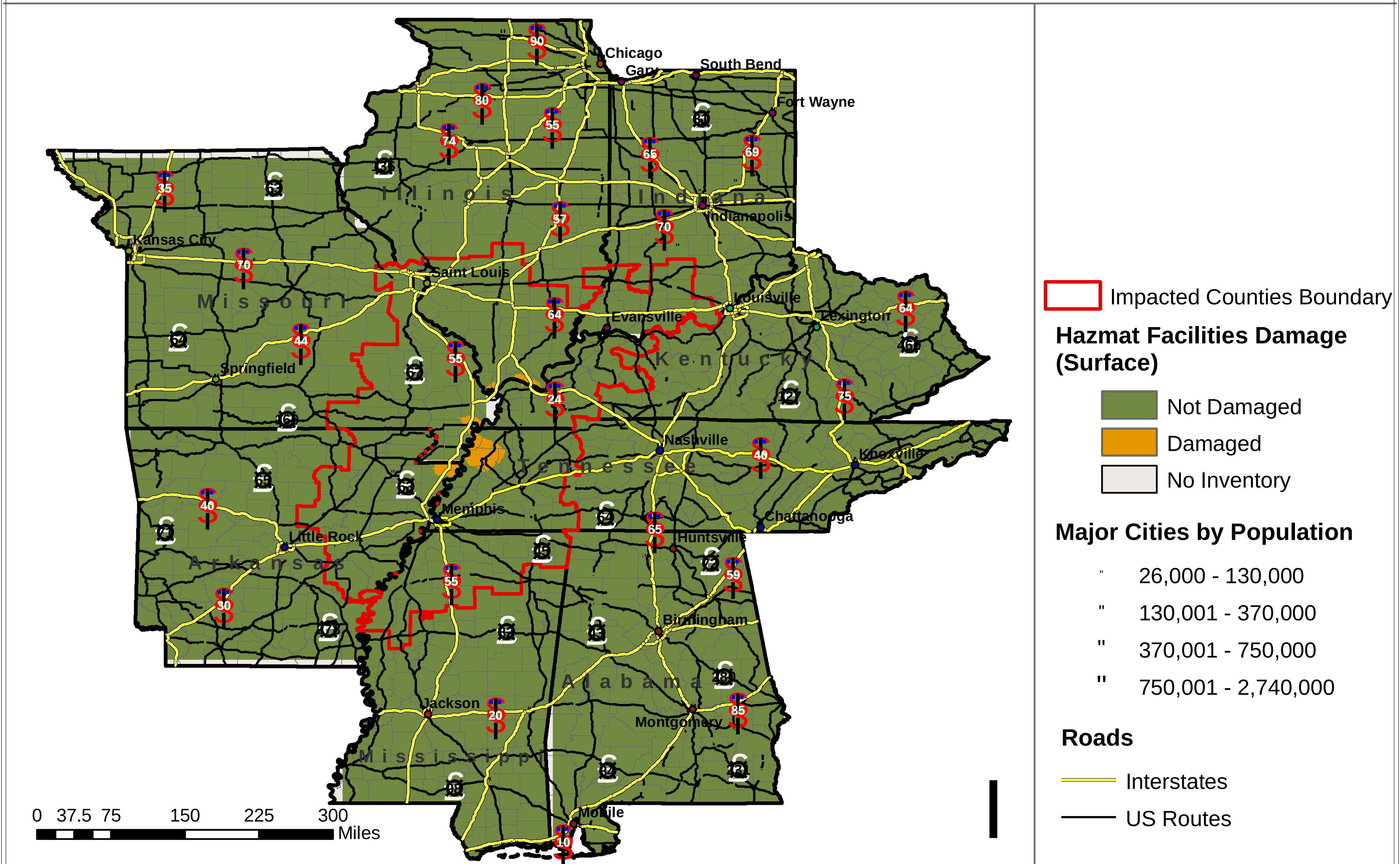
Central US Hazmat Facilities Damage
New Madrid Seismic Zone: M7.7 Event



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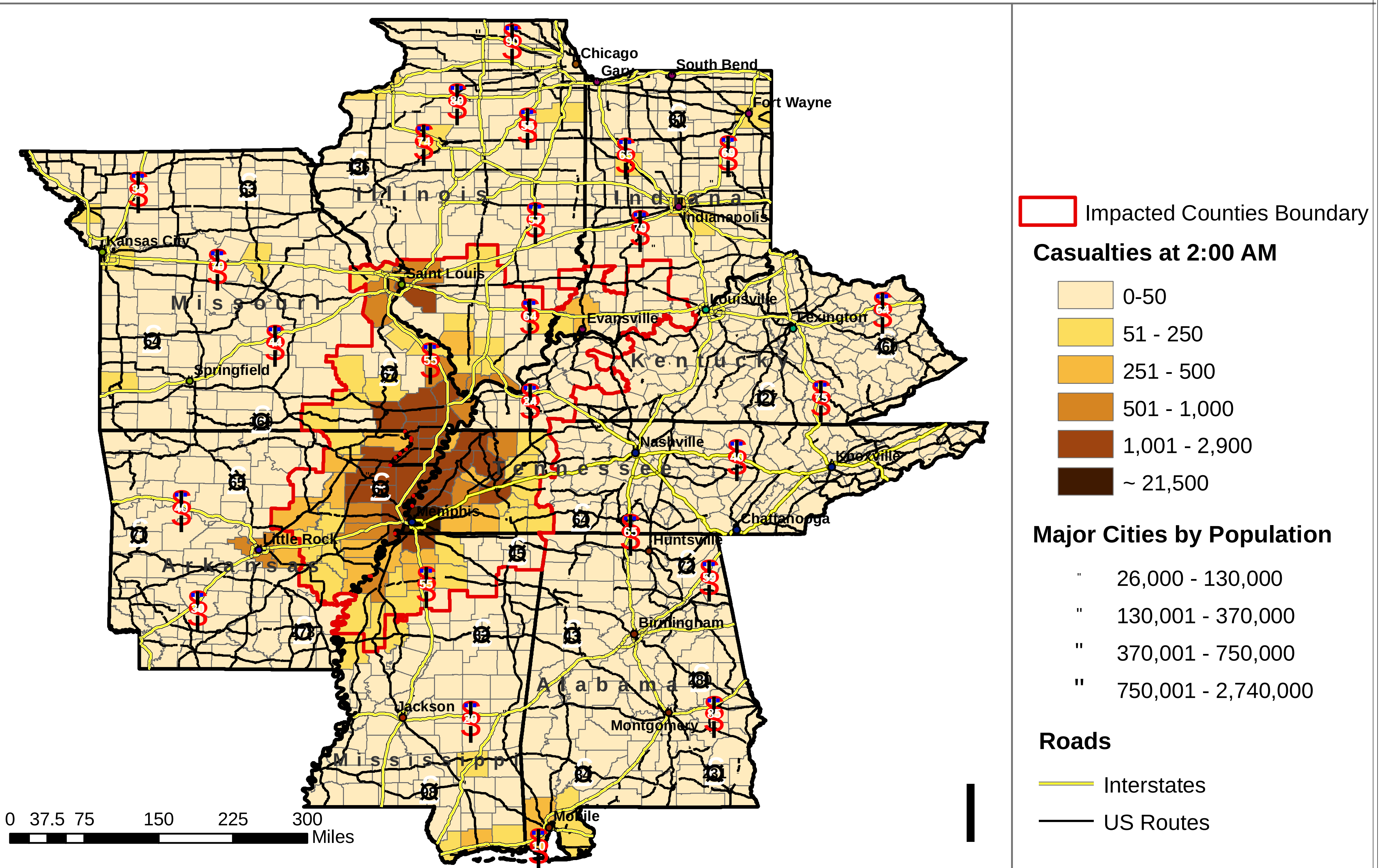
Central US Casualties at 2:00 AM
New Madrid Seismic Zone: M7.7 Event



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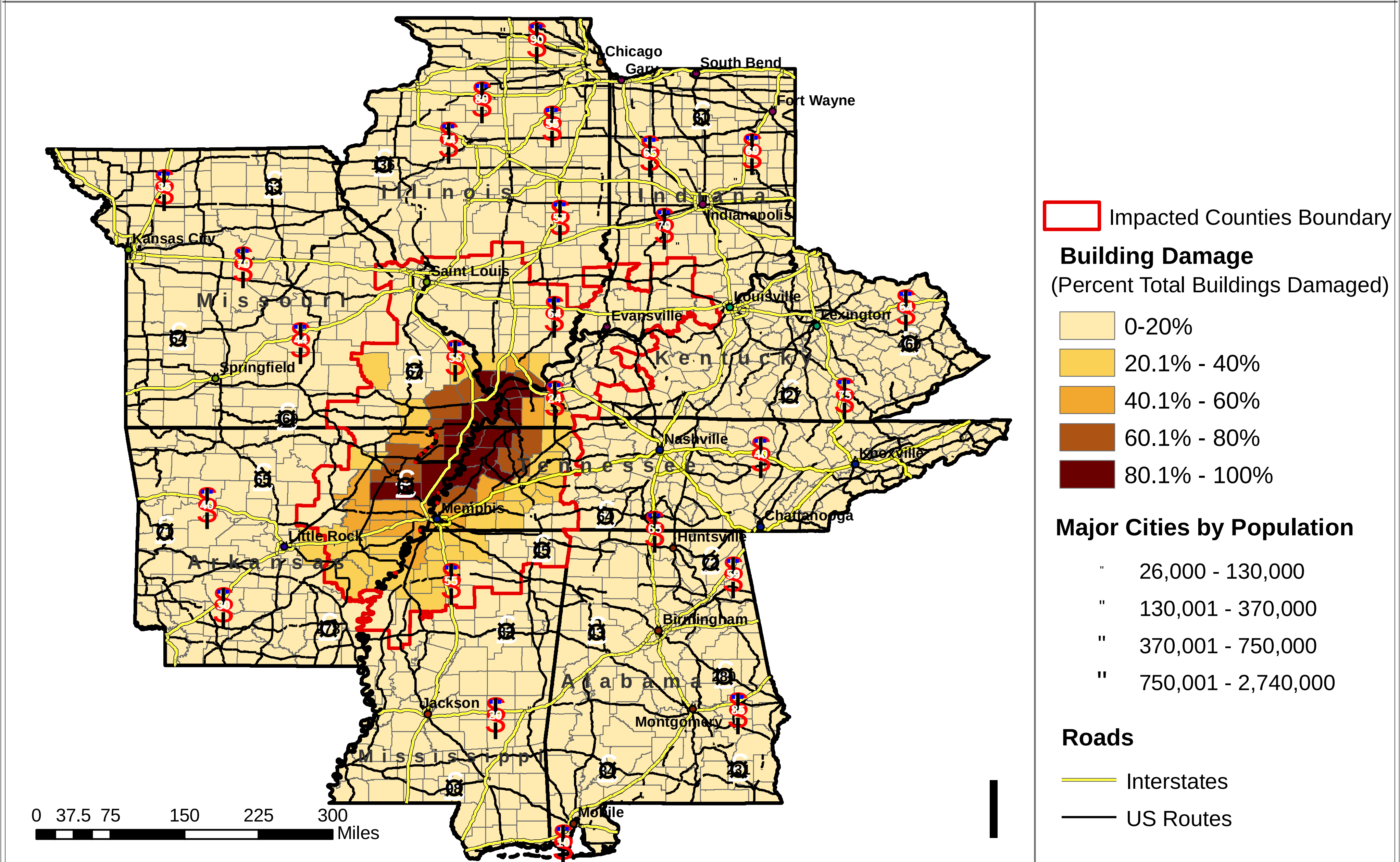
Central US Building Damage
New Madrid Seismic Zone: M7.7 Event



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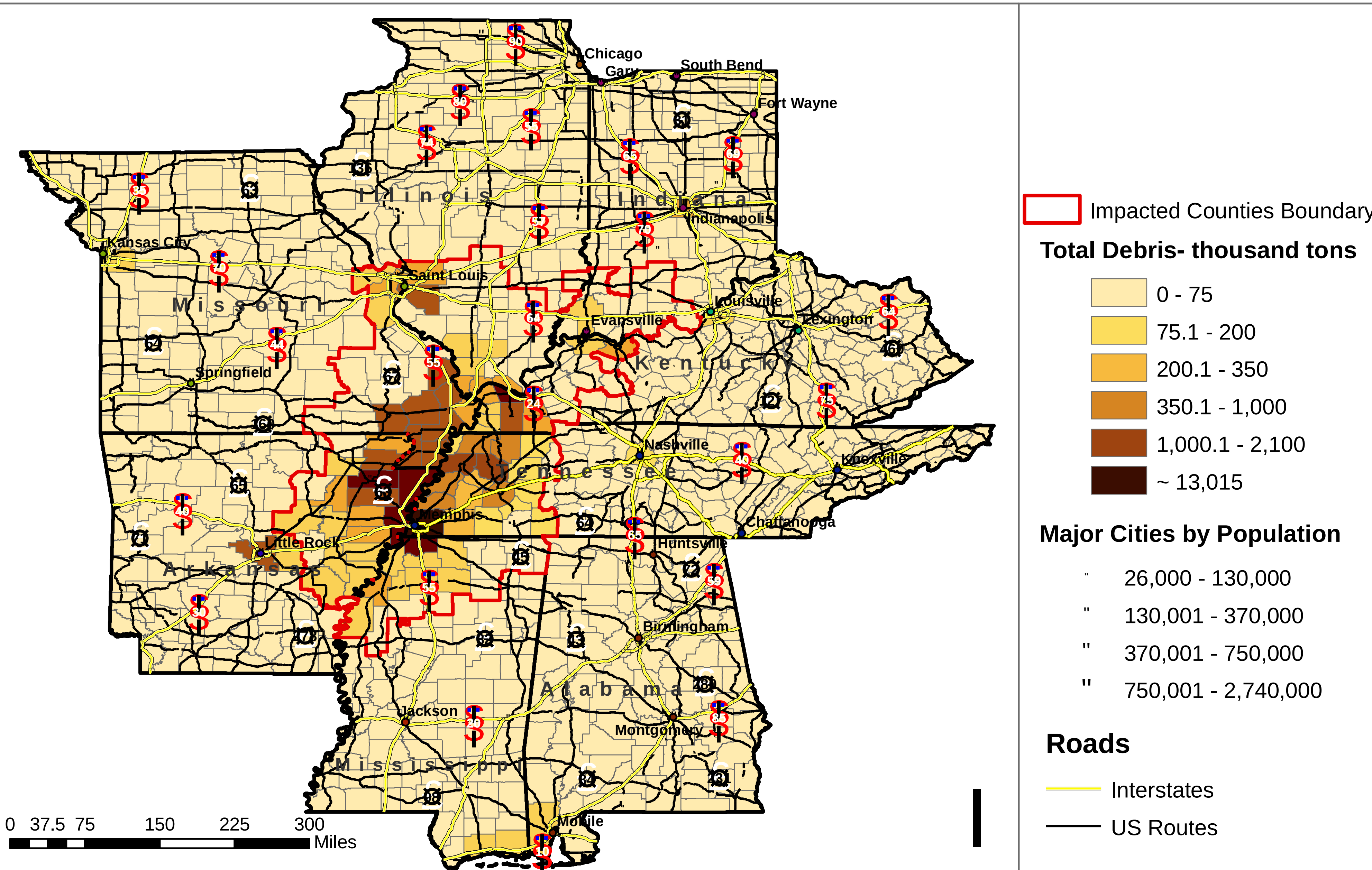
Central US Total Debris
New Madrid Seismic Zone: M7.7 Event



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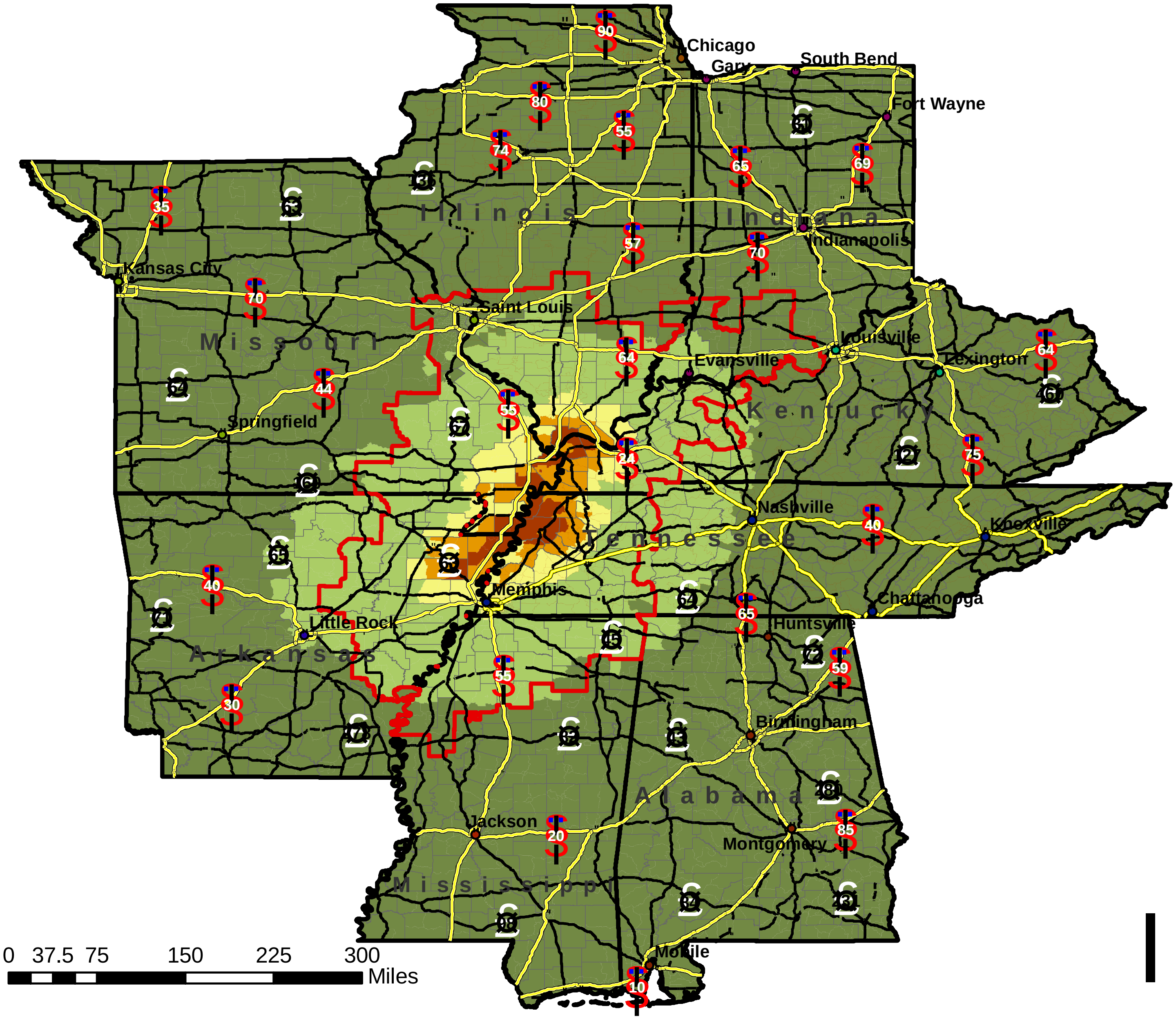
Central US Peak Ground Acceleration
New Madrid Seismic Zone: M7.7 Event



Impacted Counties Boundary

Peak Ground Acceleration (g)

- 0 - 0.2
- 0.21 - 0.4
- 0.41 - 0.6
- 0.61 - 0.8
- 0.81 - 1.2

Major Cities by Population

- 26,000 - 130,000
- 130,001 - 370,000
- 370,001 - 750,000
- 750,001 - 2,740,000

Roads

- Interstates
- US Routes

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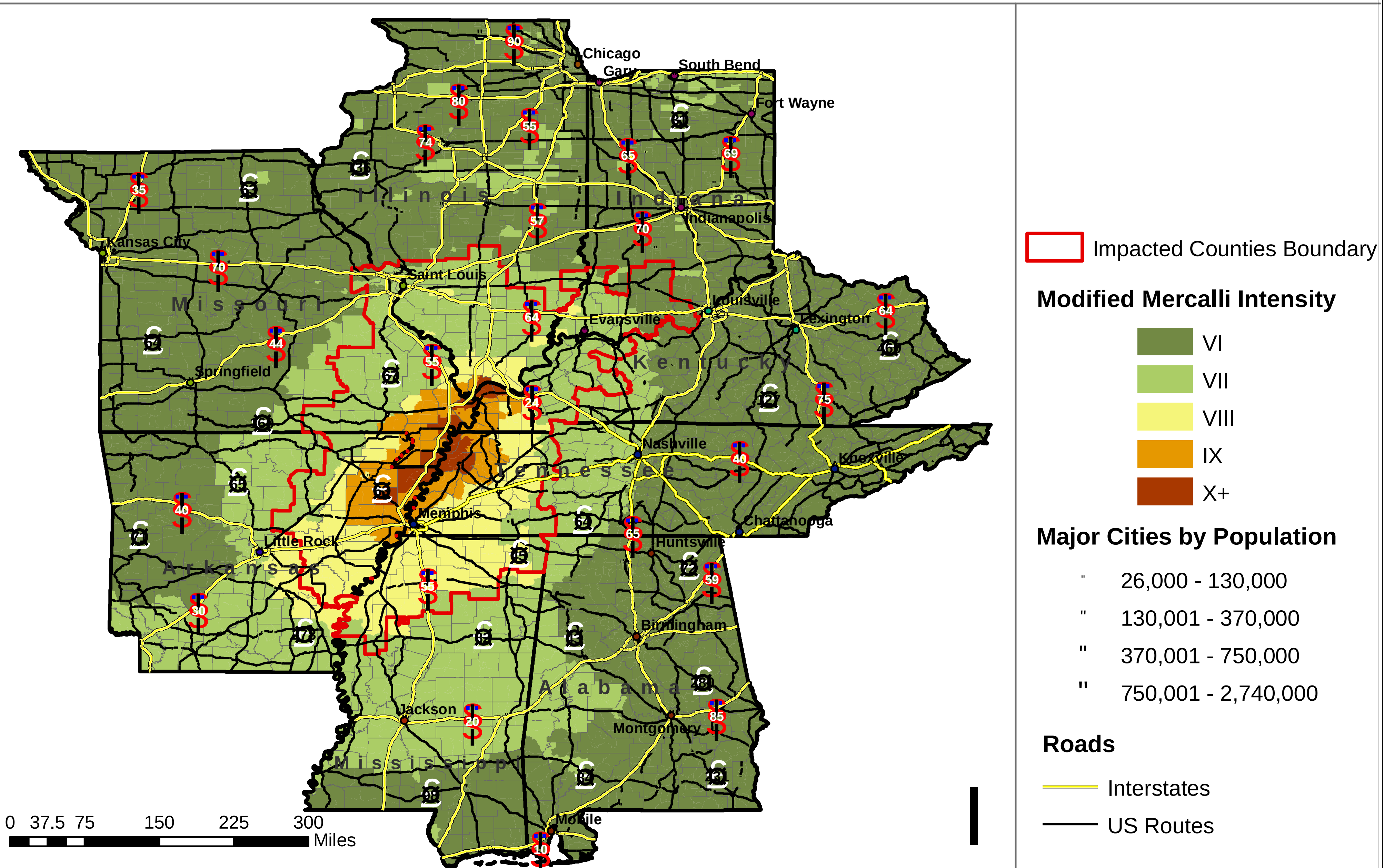
Central US Modified Mercalli Intensity
New Madrid Seismic Zone: M7.7 Event



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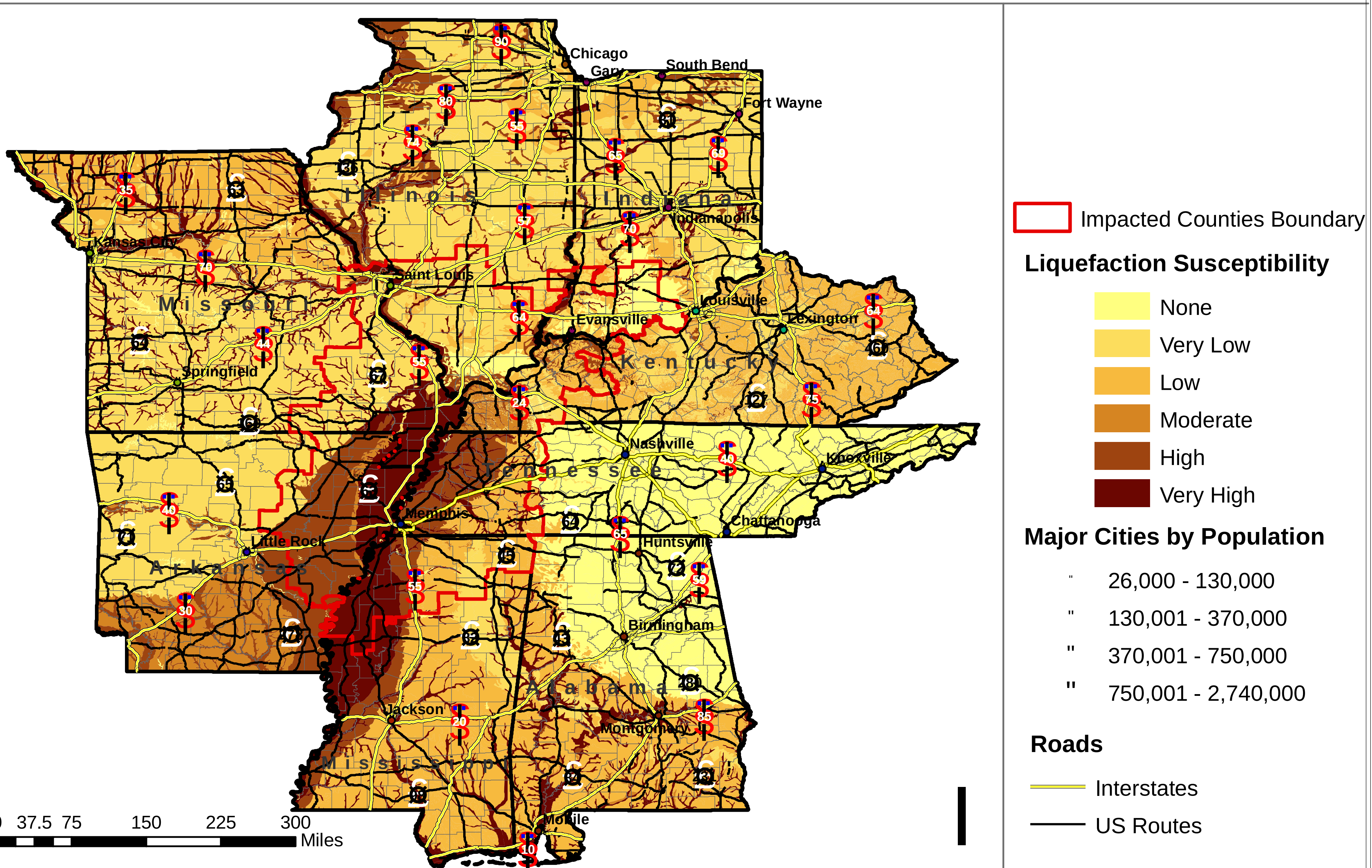
Central US Liquefaction Susceptibility
New Madrid Seismic Zone: M7.7 Event



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Appendix 8 - Flood Risk Modeling

General Model Description

The flood risk model utilizes the previously discussed threshold methodology to determine dam damage. The two categories are defined as “damaged” or “not damaged” and the threshold limit is based on the assumption that any dam expected to release water after an earthquake must incur at least a moderate level of damage which generates significant cracks for water seepage or substantial displacement of the structure.

Once the dams are classified into the two aforementioned categories, the selected flood risk methodology is applied to determine areas at risk. According to the selected model, parameters such as dam height, elevation, and maximum storage capacity can be used to determine the danger zones by determining a danger reach length (relevant distance that water travels after dam fails) and width of the overflowing water. By combining the two, an area or surface is created to define potential flood risk zone. Respective elevations are then assigned to each potential flood risk zone created for each damaged dam, based on dam elevation information. The elevation at the bottom of the dam is assigned as the elevation of the respective potential flood risk zone.

After the potential flood risk zones are drawn and respective elevations are assigned, the flood surfaces are intersected with a 3D elevation map of the study region, and a cut-fill analysis is performed to determine which areas are at risk. Based on the analysis results, areas from the elevation map that lie below the potential flood risk zone elevations are considered to be ‘at risk’. Once the areas that exhibit flood risk potential are identified, the infrastructure in these areas is identified.

Procedure and Methodology

Prior to determinations of flood risk, damaged infrastructure is identified via pass/fail criteria. Potential flood risk zones are estimated near damaged dams based on potential flood reach length and water overflow width. Potential flood reach length is a key parameter, since it determines how far downstream the flood analysis should continue, thus defining the extent of flood risk. In A minimum of two parameters are required to complete this analysis, namely the height and maximum storage capacity of the dam. The peak discharge is determined by applying the following equation:

$$Q_{max} = 3.2\ H_w^{2.5}$$

where, Q_{max} is the peak discharge (cfs) and H_w is the water depth at failure (ft).

The flood risk methodology implemented in this study was adapted from information contained in the Soil Conservation Service TSC Engineering-UD-16, 1969 (Johnson, 1998). According to the methodology, a dam is assumed to fail at maximum capacity, that is, when the water height is at the top of the dam. The water height, which is equal to dam height in this case, as well as the maximum storage capacity and 100-year flood plain valley width are utilized to approximate the potential flood reach length (in feet) from a pre-defined graph. The example below illustrates how the potential flood reach is determined.

Required parameters:

- Height of dam, H = 10 feet
- Volume of storage = 8 acre feet
- Average valley width (usually at the 100-year flood plain) = 400 feet

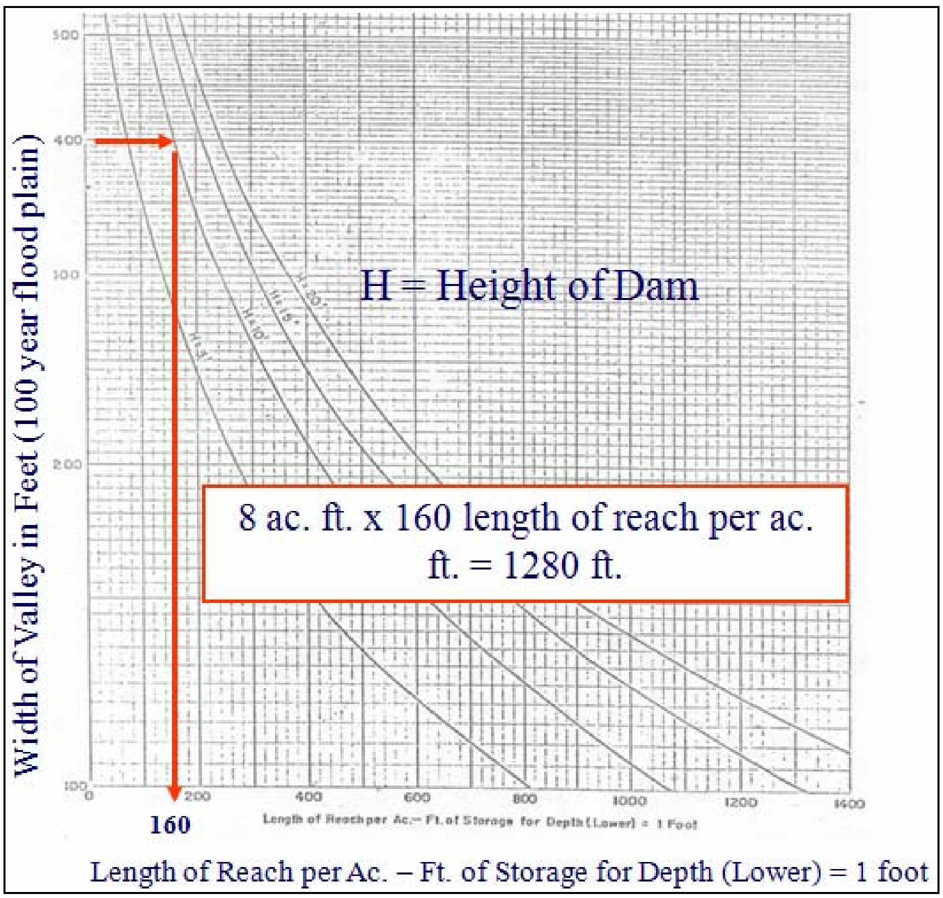


Figure 1: Example of Danger Reach Length Estimation

The second essential parameter in determining potential flood risk zones is the water width. Initially a breach width is determined, which is approximated as the valley width for simplistic assessments in river valleys. For areas outside valleys and relatively small dams, two different slopes are considered, depending on the local population. A 1:2 slope is used for a residential or heavily populated area and a 1:4 slope is applied to open areas such as roadways (Johnson, 1998). Ultimately, the average of the two slopes is used in this study, where sloping lines defining the flood risk zone are extended until they meet the potential flood risk length requirement discussed previously.

The identification of the potential flood reach length and the breach width are sufficient to determine potential flood risk areas. These two parameters are utilized to define polygons signifying the potential flood risk areas on an elevation map in GIS software. Adequate elevation information is added to each polygon, corresponding to the elevation of the respective dam bottom, since it is assumed that damaged dams fail completely. Once elevation data is added to the polygon information, the polygons are converted to triangulated surfaces, or “tin”-s, and a GIS cut-fill analysis is conducted to identify potentially flooded areas.

Once potentially flooded areas are separated from the general landscape, critical infrastructure located in the flood zone is identified. Various key inventory groups are considered including numerous types of essential facilities, transportation lifelines and utility lifelines. Any facilities potentially at risk from flooding are likely inoperable due to secondary flooding if the facility is not already structurally damaged by the earthquake event.

Though the implemented methodology is simplistic and includes significant uncertainty, it is a necessary first step in the more involved process of developing a comprehensive flood risk model. Uncertainty is attributed to the pass/fail criteria utilized to determine dam damage and the method employed to determine the potential flood risk zone. Future improvements to both damage and flood risk procedures are recommended, though the basic estimates provided by this methodology are extremely useful when addressing secondary hazard in the emergency planning and response process.

Flood Risk Modeling Results

The flood risk modeling methodology used in this study determines potential flood zones and identifies infrastructure in those regions that are at risk. Inventory that is located inside a flooded region boundary, either partially or completely, is classified as potentially flooded. Analysis results indicate that portions of five out of the eight study region states are at risk flood from potential flooding. The affected states include Arkansas, Illinois, Kentucky, Missouri, and Tennessee. Overall, the most impacted facilities include communication facilities, fire stations, waste water facilities, and highway bridges. Tennessee incurs the most serious damage by a large margin when compared to the four other states. Table 1 presents a regional summary, while the regional flood potential is illustrated in Figure 2.

At-risk infrastructure is highlighted by state following the regional overview statistics and map. All at risk facilities are catalogued in tables for each state and are represented on various maps of potentially flooded areas in each state.

Table 1: Flood Risk Results – Regional Summary

Inventory Category	Facility Type	Number of Potentially Flooded Facilities					Total by Facility Type
		AR	IL	KY	MO	TN	
Essential Facilities	EOC	0	0	0	0	2	**2**
	Fire Stations	2	1	1	0	7	**11**
	Hospitals	0	0	0	0	1	**1**
	Police Stations	0	0	0	0	7	**7**
	Schools	0	1	0	1	8	**10**
Transportation	Airports	0	0	0	0	2	**2**
	Bus Facilities	0	0	0	0	1	**1**
	Highway Bridges	25	2	23	2	132	**184**
	Ports	0	0	0	0	0	**0**
	Railway Bridges	0	0	0	0	0	**0**
	Railway Facilities	0	0	0	0	0	**0**
Utilities	Communication Facilities	0	0	4	1	59	**64**
	Electric Power Facilities	0	0	0	0	1	**1**
	Natural Gas Facilities	0	0	0	2	1	**3**
	Oil Facilities	0	0	0	0	1	**1**
	Potable Water Facilities	0	0	0	0	2	**2**
	Waste Water Facilities	0	2	3	0	15	**20**
Total Facilities by State		**27**	**6**	**31**	**6**	**239**	**309**

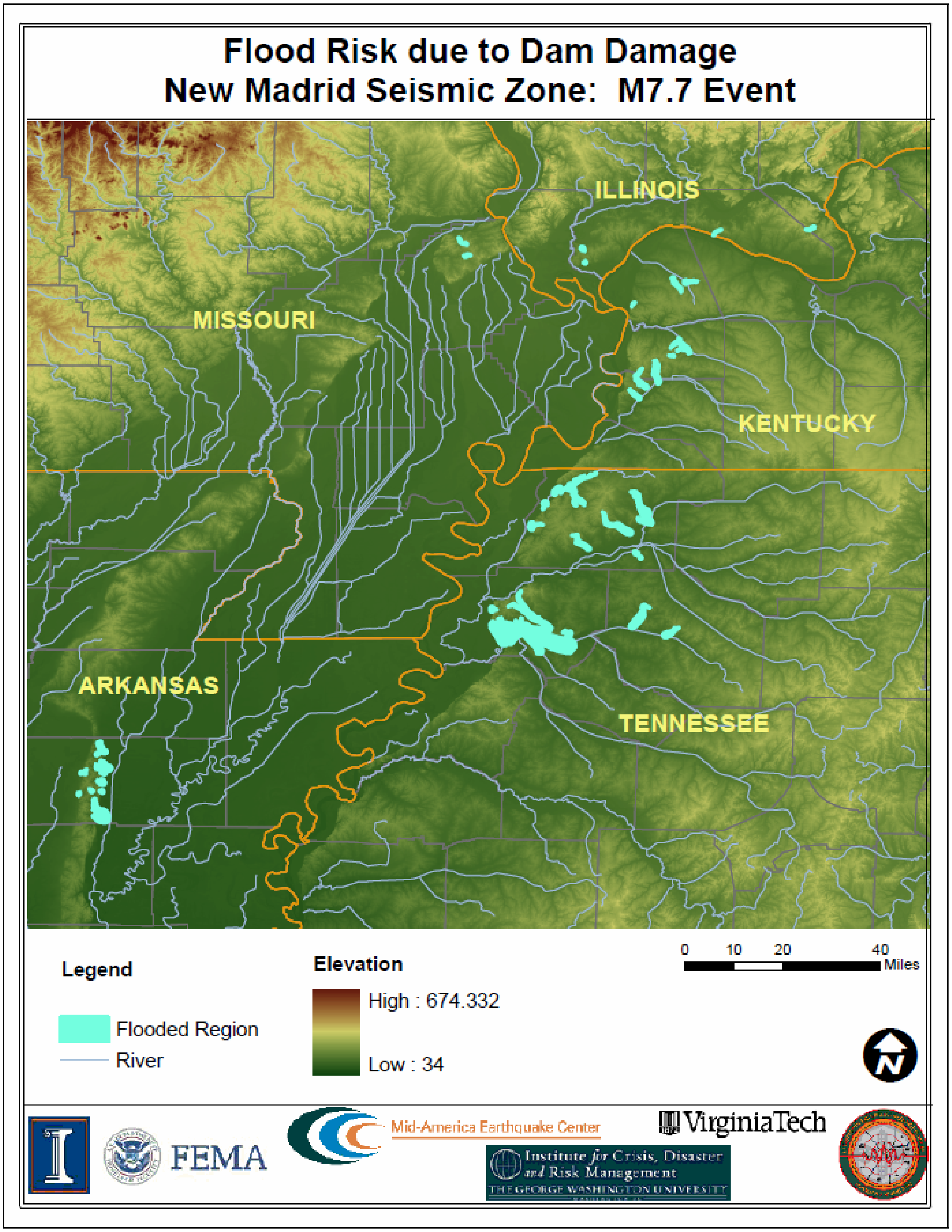


Figure 2: Regional Flood Risk

Arkansas

Arkansas has infrastructure moderately affected by secondary flooding. Poinsett County is the only county that exhibits flood potential. Table 2 summarizes results based on facility types, while Figure 3 thru Figure 5 represent flood risk to essential facilities, transportation, and utility systems, respectively. Highway bridges are the most critical infrastructure for this state with 25 bridges at risk. Fire stations are the only essential facilities that are potentially flooded, while utilities likely see no damage due to dam breaches.

Table 2: Arkansas Flood Risk Assessment Results

Inventory Category	Facility	Number of Potentially Flooded Facilities
Essential Facilities	EOC	0
	Fire Stations	2
	Hospitals	0
	Police Stations	0
	Schools	0
Transportation	Airports	0
	Bus Facilities	0
	Highway Bridges	25
	Ports	0
	Railway Bridges	0
	Railway Facilities	0
Utilities	Communication Facilities	0
	Electric Power Facilities	0
	Natural Gas Facilities	0
	Oil Facilities	0
	Potable Water Facilities	0
	Waste Water Facilities	0
Total Facilities at Risk		**27**

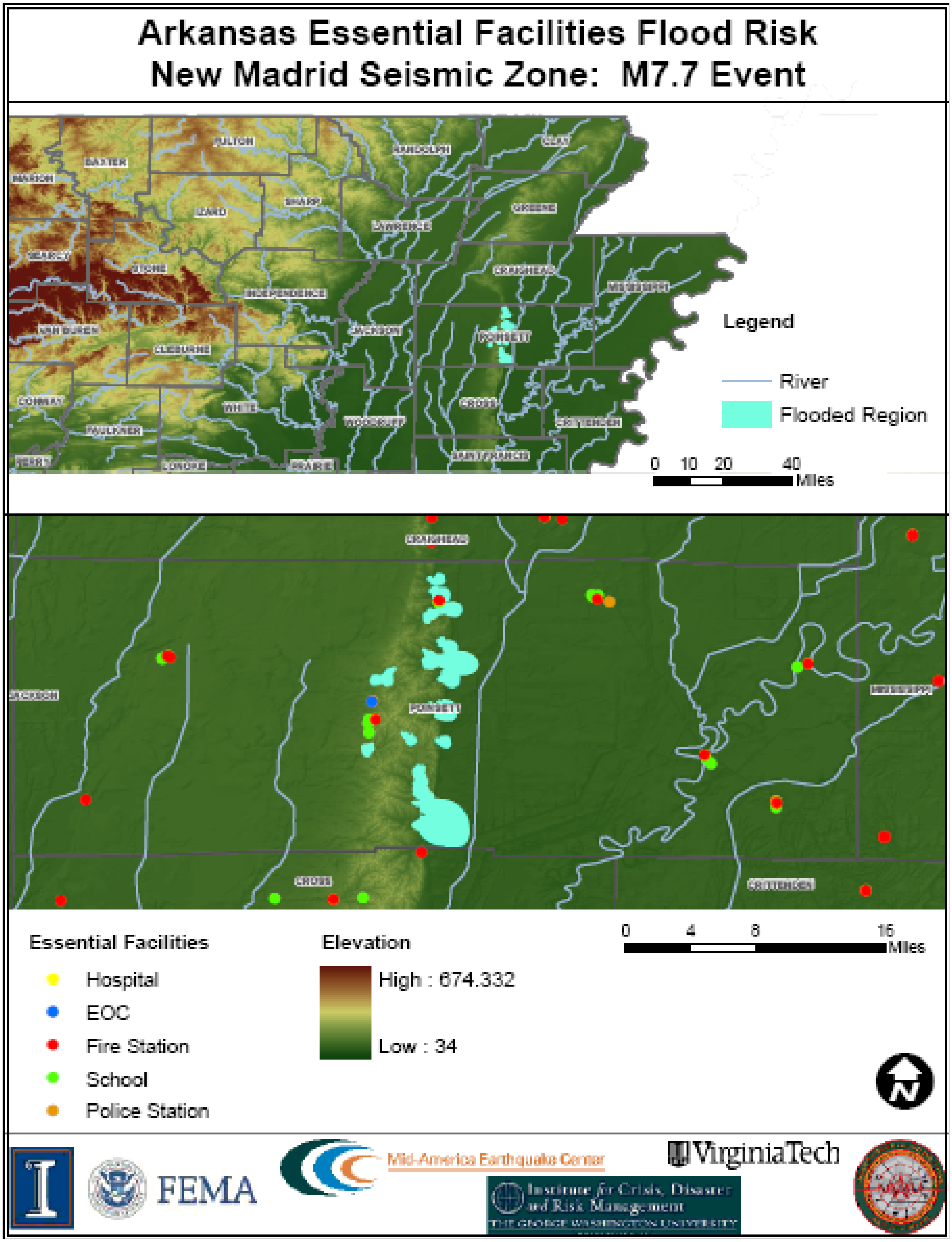


Figure 3: Arkansas Flood Risk of Essential Facilities

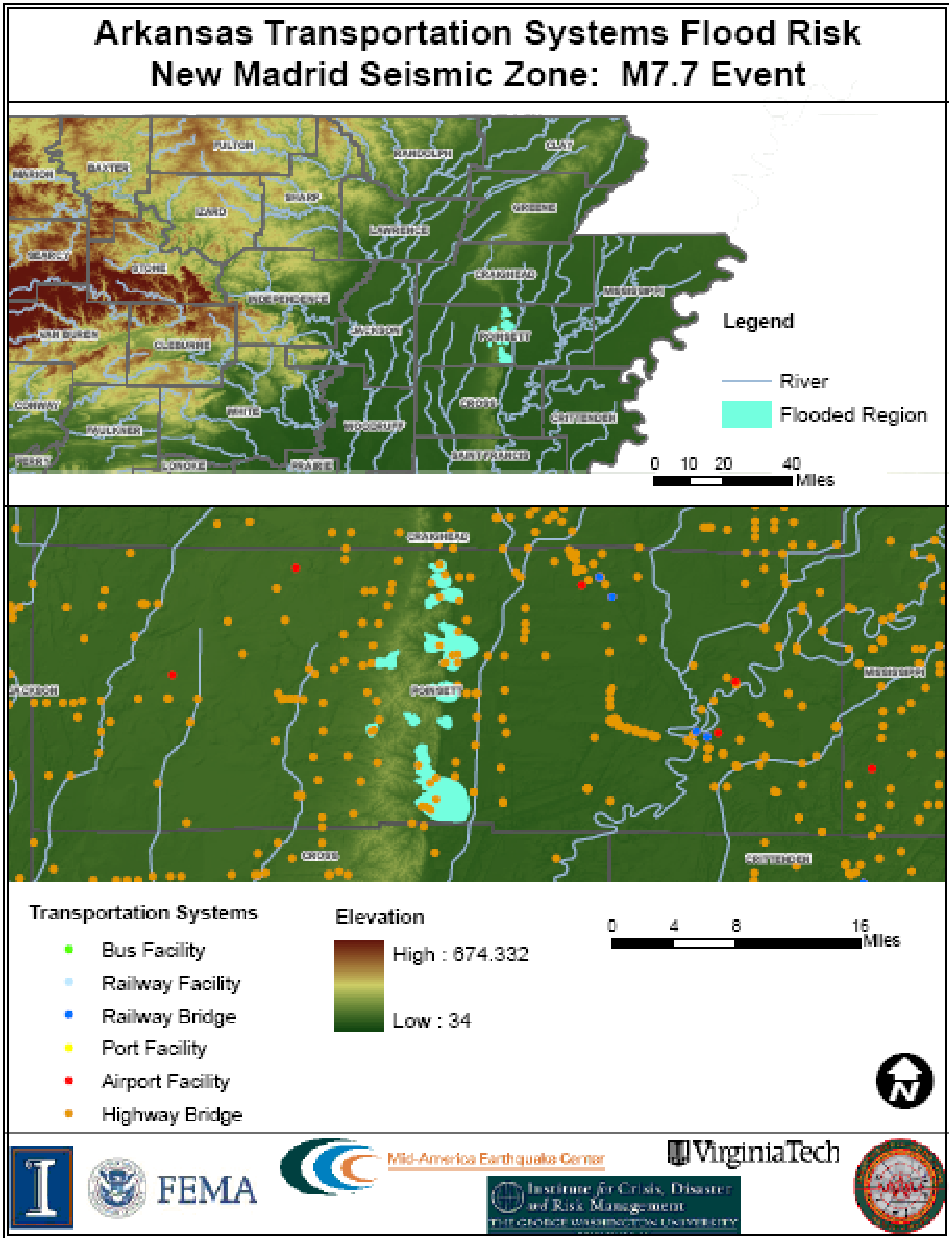


Figure 4: Arkansas Flood Risk of Transportation Systems

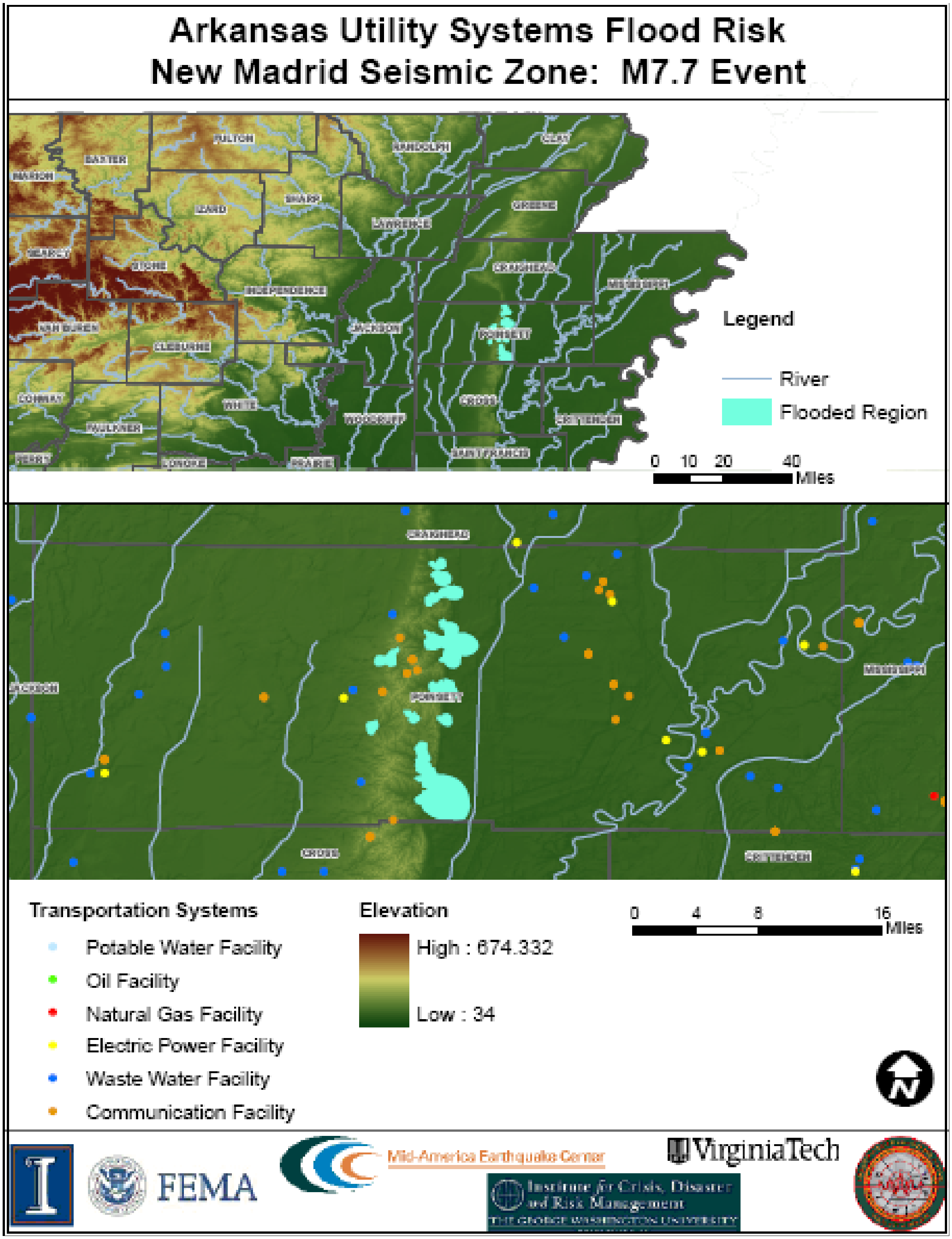


Figure 5: Arkansas Flood Risk of Utility Systems

Illinois

Illinois is one of the least impacted states in terms of secondary flooding. The three affected counties in Illinois include:

- Massac
- Pope
- Pulaski

A total of six facilities are at risk from flooding in these three counties, as shown in Table 3. Fire stations, schools, highway bridges, and waste water facilities are among the affected facilities. Additionally, Figure 6 thru Figure 8 illustrate the locations of potentially flooded areas in relation to critical infrastructure in Illinois.

Table 3: Illinois Flood Risk Assessment Results

Inventory Category	**Facility**	**Number of Potentially Flooded Facilities**
Essential Facilities	EOC	0
	Fire Stations	1
	Hospitals	0
	Police Stations	0
	Schools	1
Transportation	Airports	0
	Bus Facilities	0
	Highway Bridges	2
	Ports	0
	Railway Bridges	0
	Railway Facilities	0
Utilities	Communication Facilities	0
	Electric Power Facilities	0
	Natural Gas Facilities	0
	Oil Facilities	0
	Potable Water Facilities	0
	Waste Water Facilities	2
Total Facilities at Risk		**6**

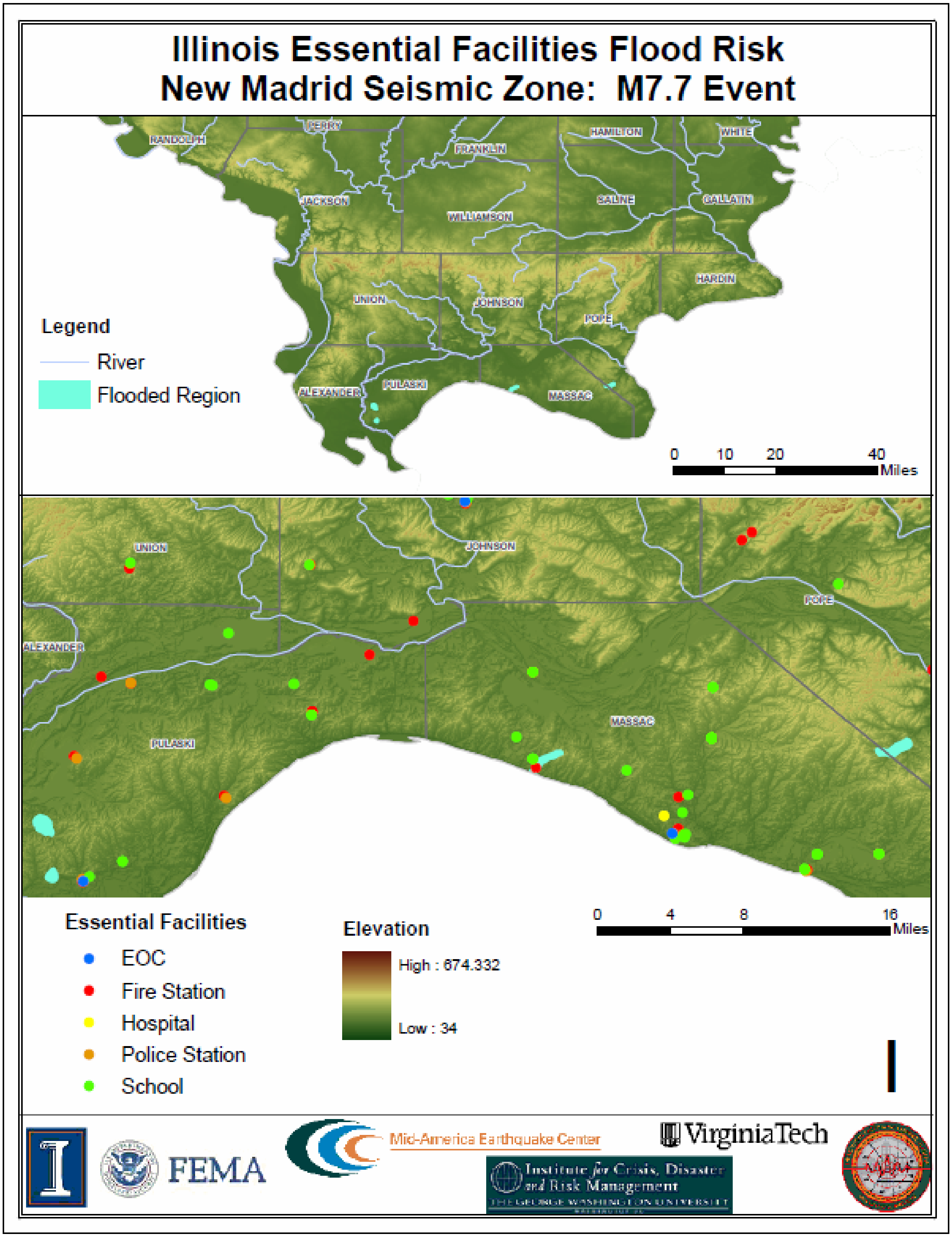


Figure 6: Illinois Flood Risk of Essential Facilities

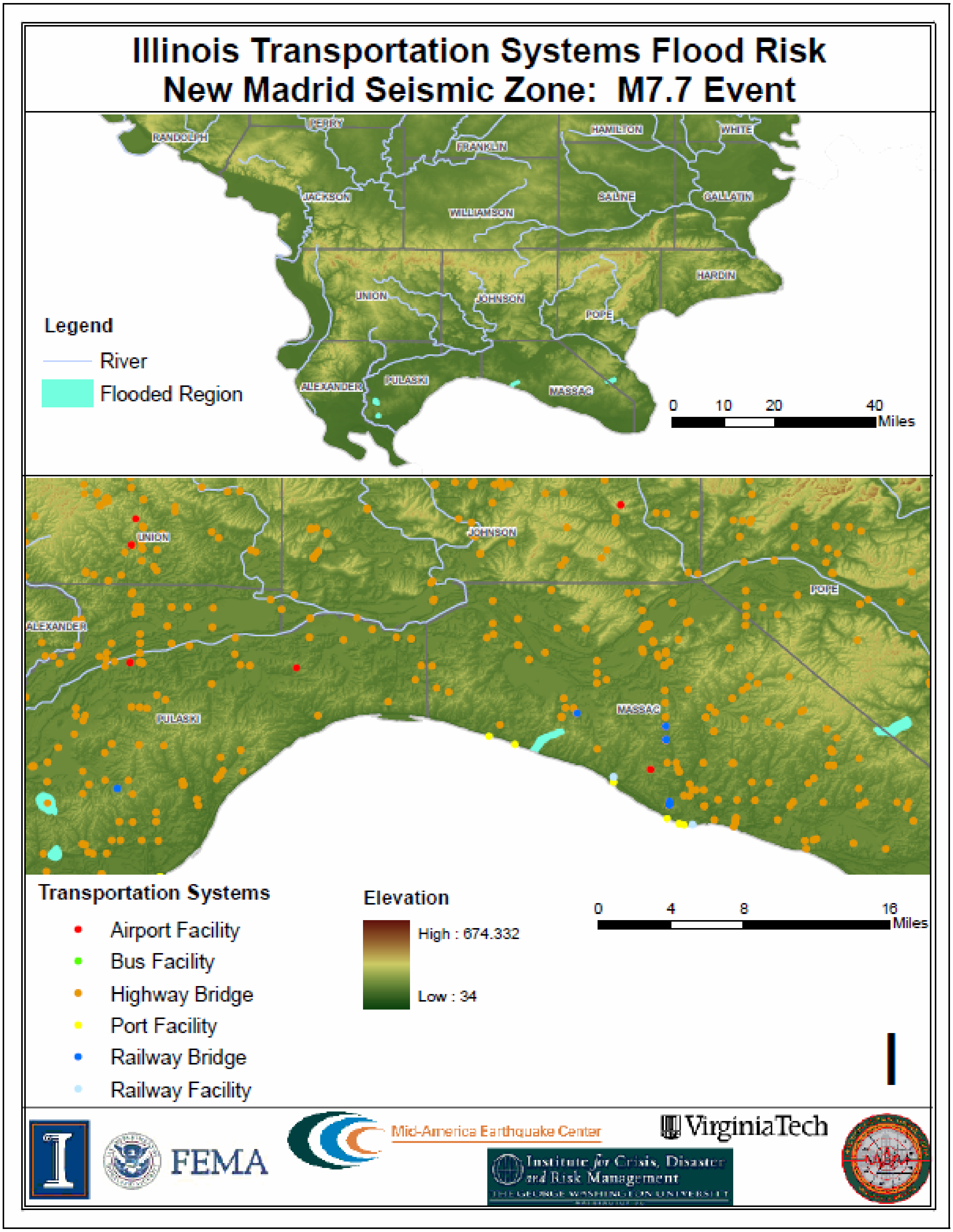


Figure 7: Illinois Flood Risk to Transportation Systems

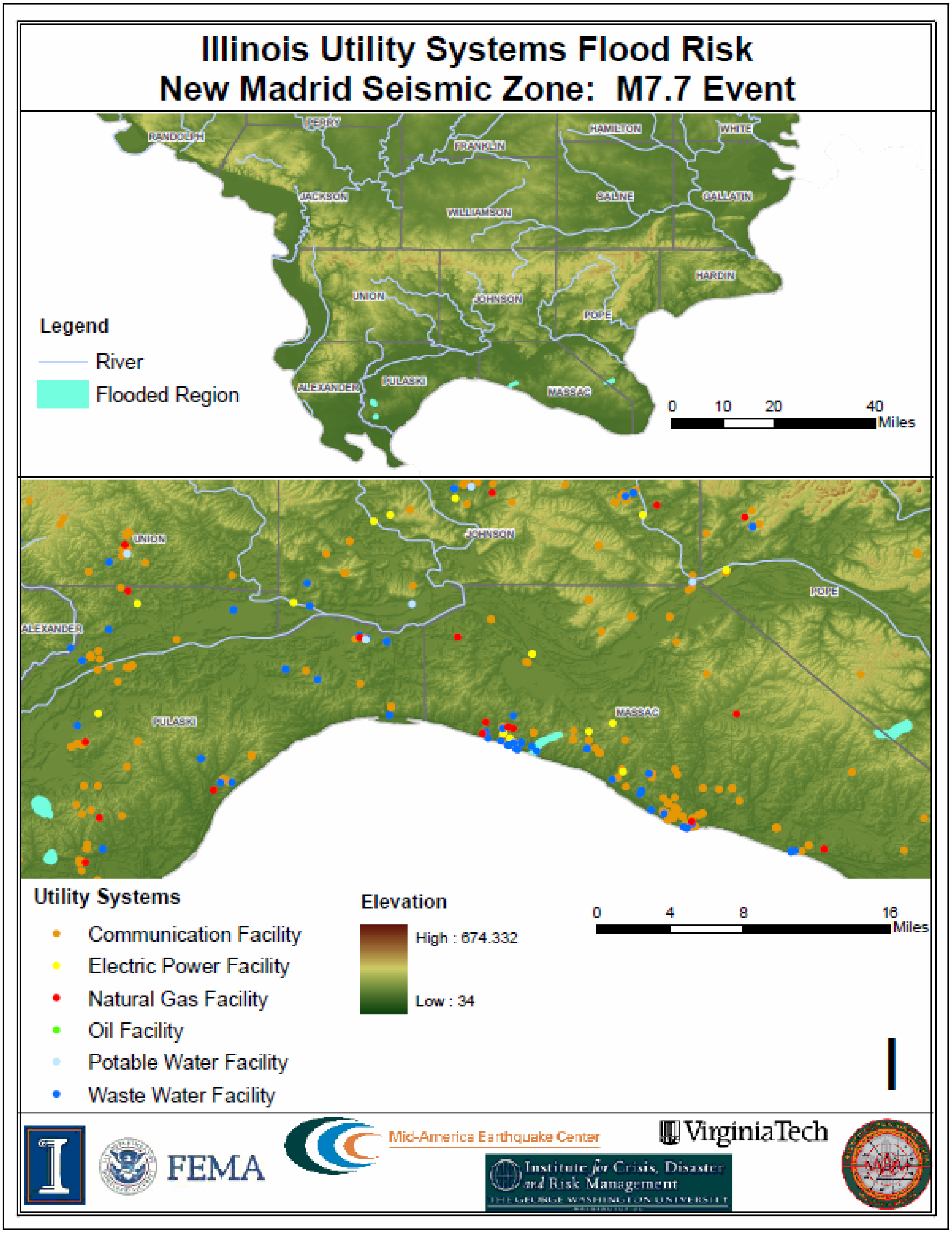


Figure 8: Illinois Flood Risk to Utility Systems

Kentucky

Kentucky shows moderate flood risk in the three following affected counties:

- Ballard
- Carlisle
- Hickman

Similar to the other four at risk states, highway bridges are the most common structure type at risk. Slight impact is observed for fire stations, communication facilities, and waste water facilities as shown in Table 4. Additionally, Figure 9 thru Figure 11 illustrate the locations of potentially flooded areas in relation to critical infrastructure in Kentucky.

Table 4: Kentucky Flood Risk Assessment Results

Inventory Category	Facility	Number of Potentially Flooded Facilities
Essential Facilities	EOC	0
	Fire Stations	1
	Hospitals	0
	Police Stations	0
	Schools	0
Transportation	Airports	0
	Bus Facilities	0
	Highway Bridges	23
	Ports	0
	Railway Bridges	0
	Railway Facilities	0
Utilities	Communication Facilities	4
	Electric Power Facilities	0
	Natural Gas Facilities	0
	Oil Facilities	0
	Potable Water Facilities	0
	Waste Water Facilities	3
Total Facilities at Risk		**31**

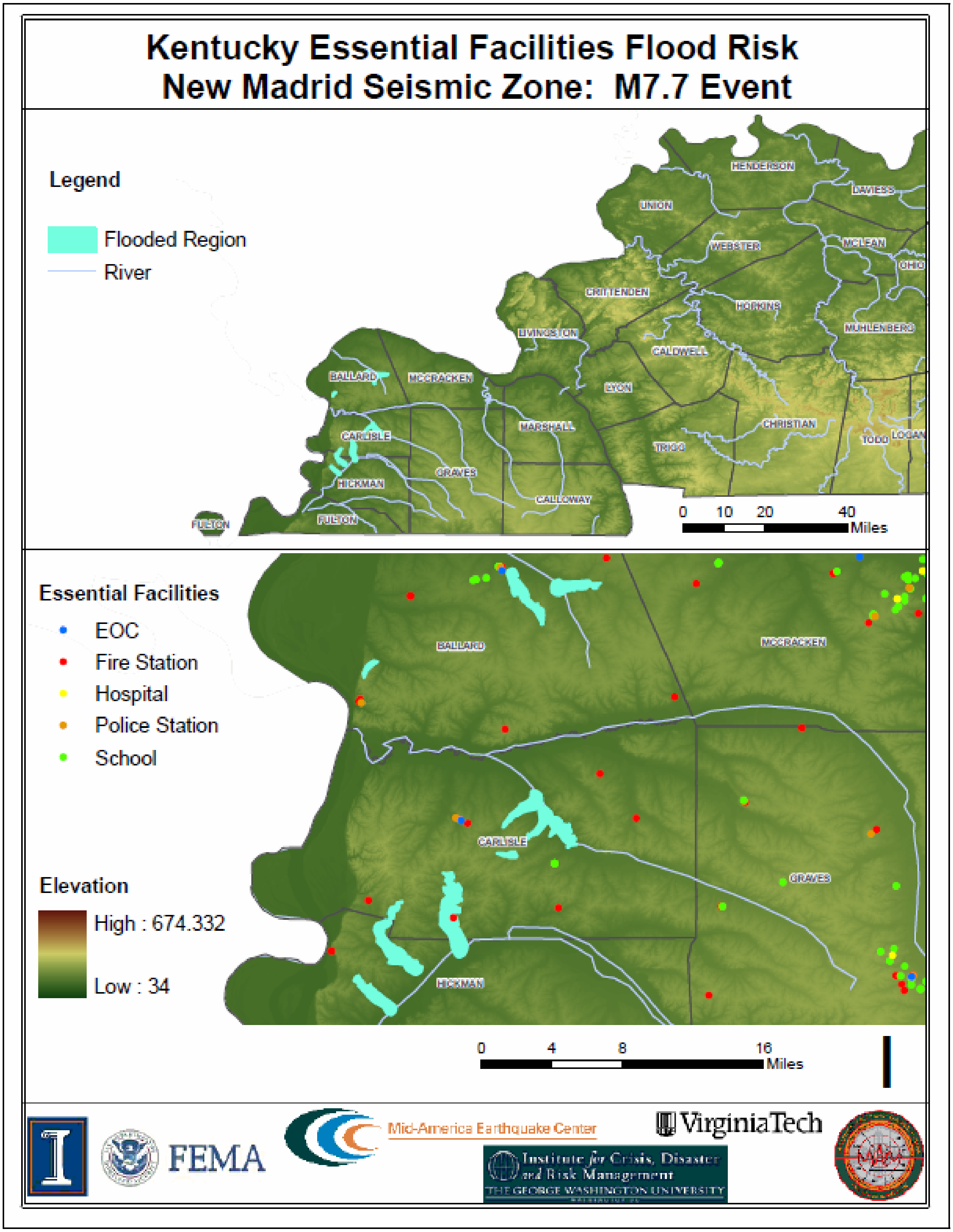


Figure 9: Kentucky Flood Risk to Essential Facilities

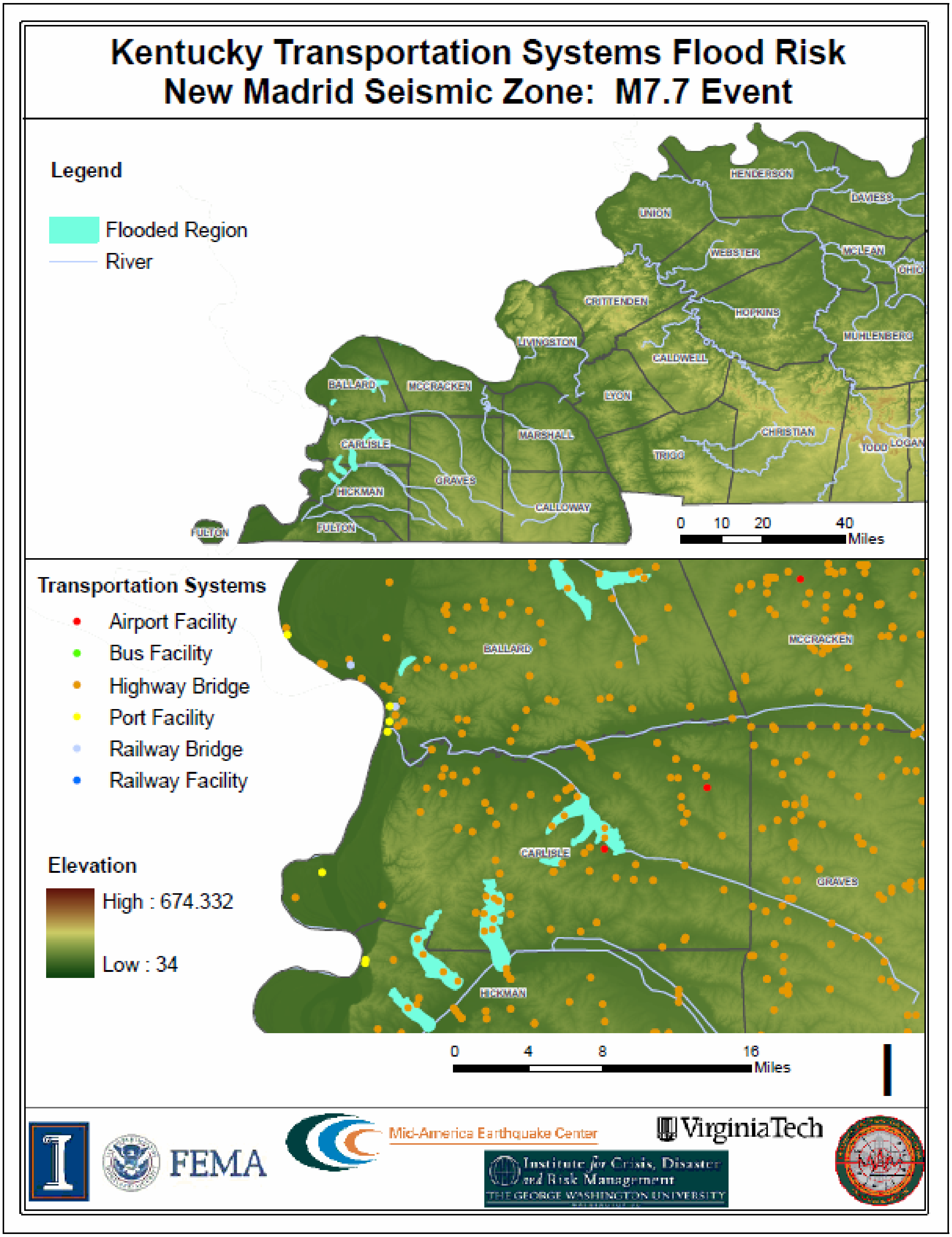


Figure 10: Kentucky Flood Risk to Transportation Systems

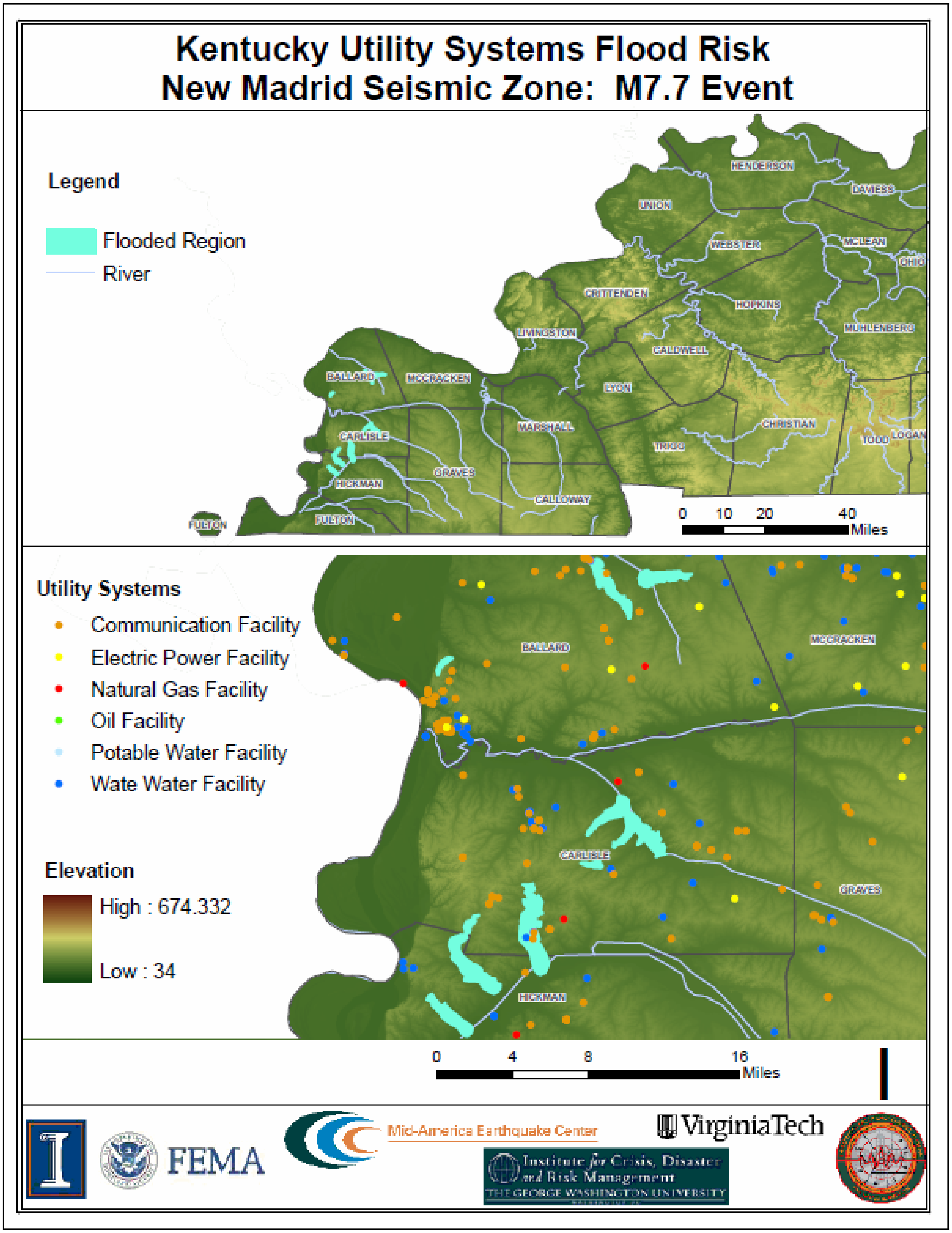


Figure 11: Kentucky Flood Risk to Utility Systems

Missouri

Expected flooding is limited in the State of Missouri. The only affected county is:

- Scott

A total of six facilities are affected including schools, highway bridges, communication facilities, and natural gas facilities. Table 5 details flood risk statistics for Missouri infrastructure. Additionally, Figure 12 thru Figure 14 illustrate the locations of potentially flooded areas in relation to critical infrastructure in Missouri.

Table 5: Missouri Flood Risk Assessment Results

Inventory Category	Facility	Number of Potentially Flooded Facilities
Essential Facilities	EOC	0
	Fire Stations	0
	Hospitals	0
	Police Stations	0
	Schools	1
Transportation	Airports	0
	Bus Facilities	0
	Highway Bridges	2
	Ports	0
	Railway Bridges	0
	Railway Facilities	0
Utilities	Communication Facilities	1
	Electric Power Facilities	0
	Natural Gas Facilities	2
	Oil Facilities	0
	Potable Water Facilities	0
	Waste Water Facilities	0
Total Facilities at Risk		**6**

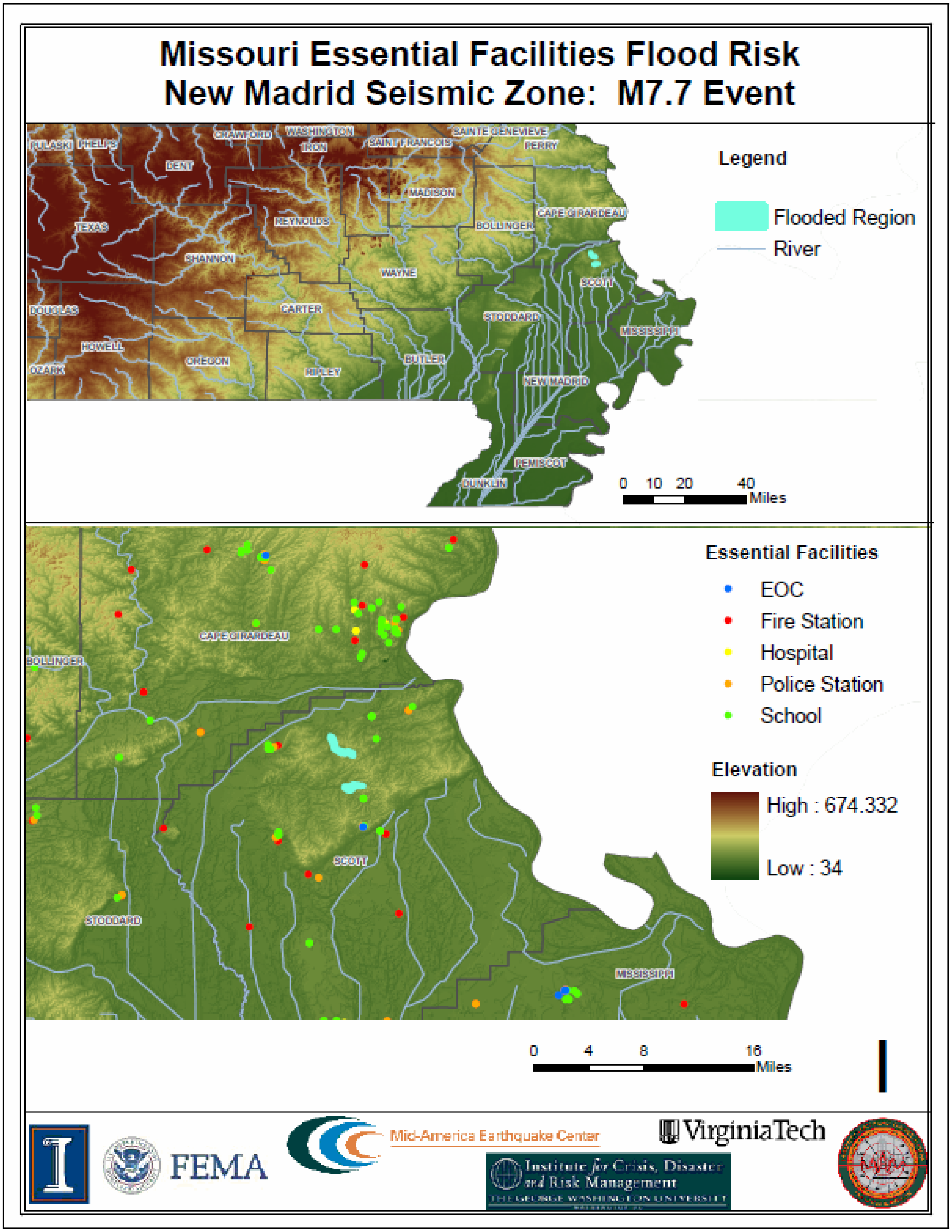


Figure 12: Missouri Flood Risk of Essential Facilities

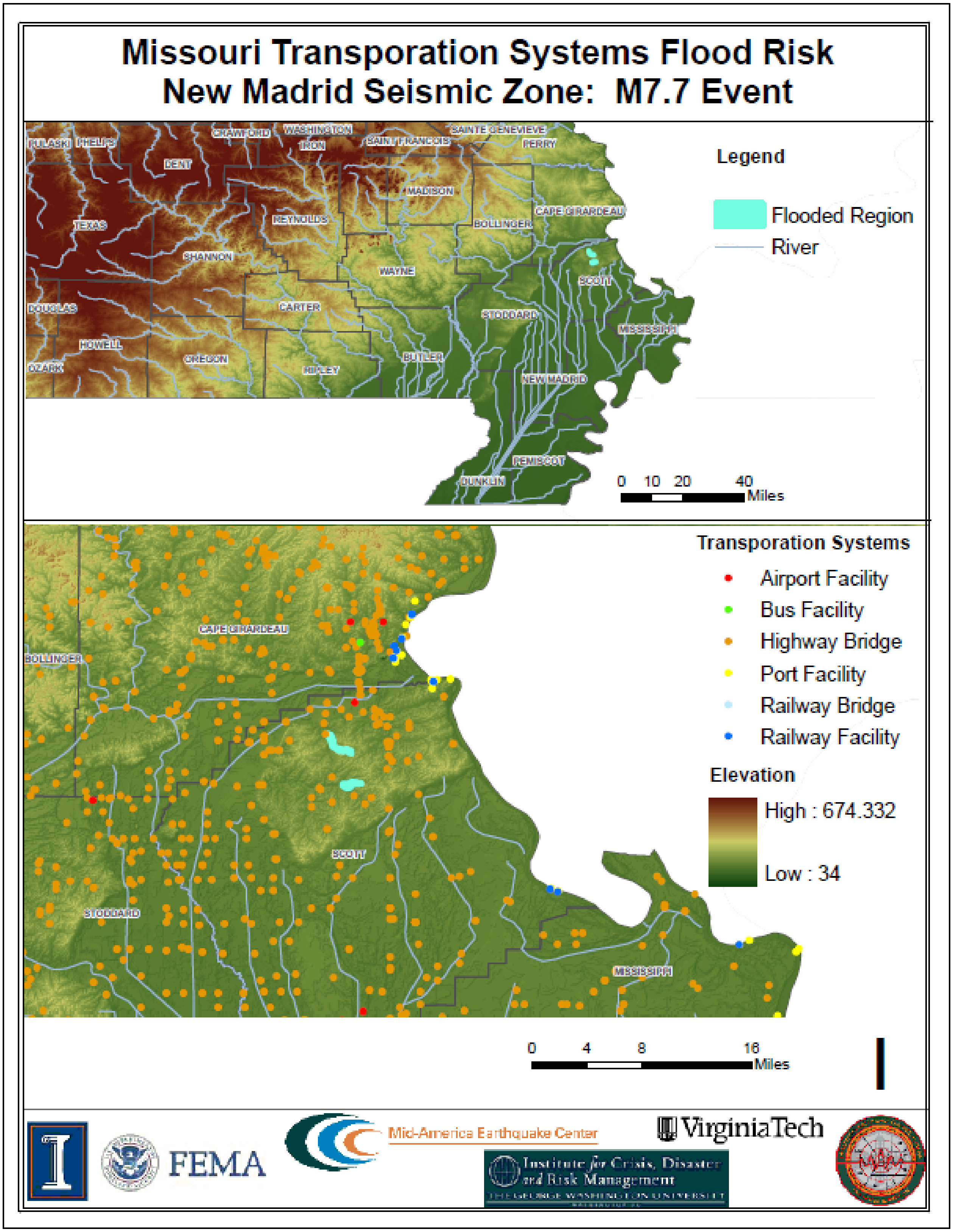


Figure 13: Missouri Flood Risk of Transportation Systems

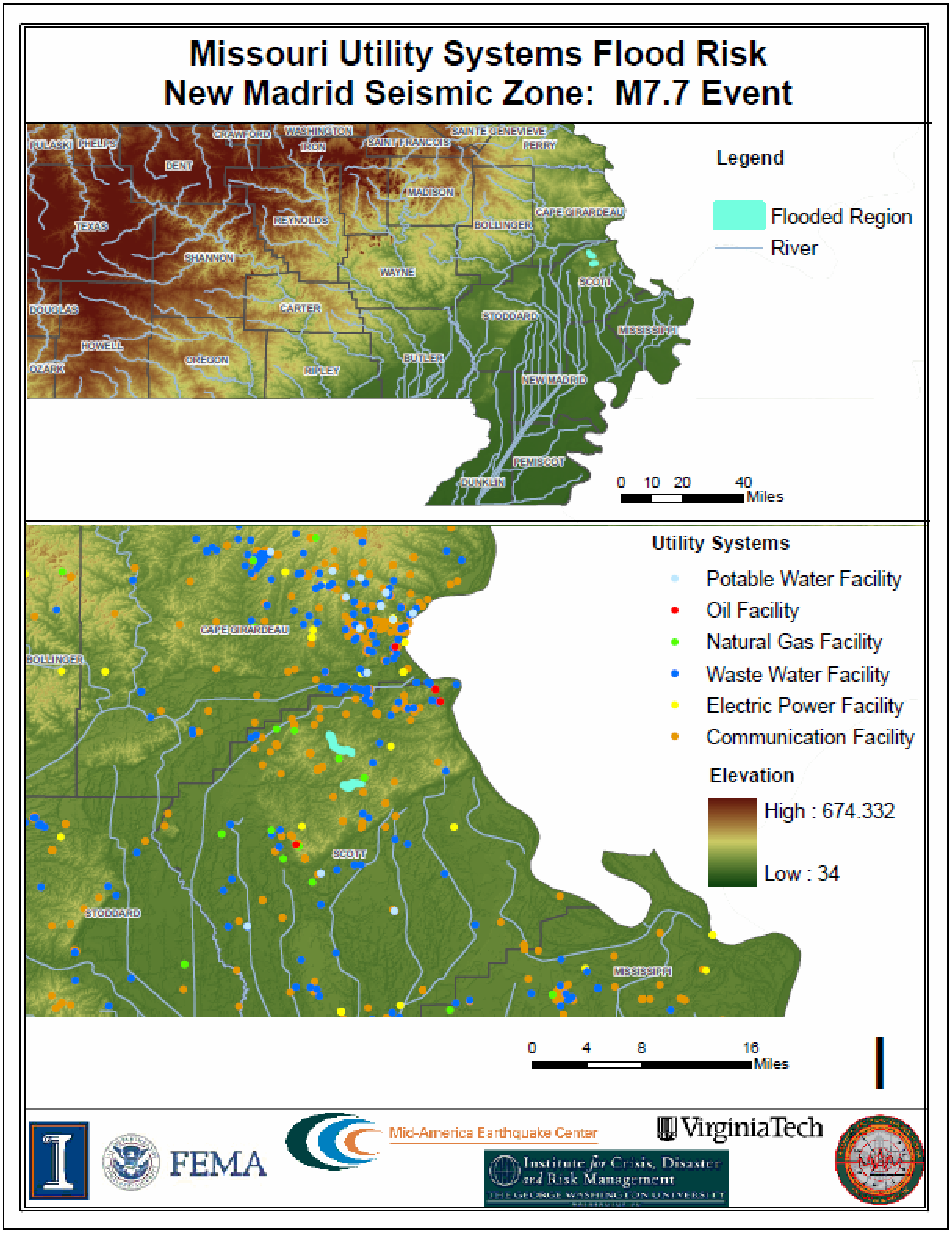


Figure 14: Missouri Flood Risk of Utility Systems

Tennessee

Tennessee is the most heavily affected state in terms of flood risk. The potential flood damage includes numerous types of inventory with the exception of ports, railway bridges, and railway facilities. The three at risk counties are:

- Dyer
- Gibson
- Obion

Numerous highway bridges, communication facilities, and waste water facilities are at risk from secondary flooding in Tennessee (Table 6). Approximately 240 facilities are impacted in the three aforementioned counties. Additionally, Figure 15 thru Figure 17 illustrate the locations of potentially flooded areas in relation to critical infrastructure in Tennessee.

Table 6: Tennessee Flood Risk Assessment Results

Inventory Category	Facility	Number of Potentially Flooded Facilities
Essential Facilities	EOC	2
	Fire Stations	7
	Hospitals	1
	Police Stations	7
	Schools	8
Transportation	Airports	2
	Bus Facilities	1
	Highway Bridges	132
	Ports	0
	Railway Bridges	0
	Railway Facilities	0
Utilities	Communication Facilities	59
	Electric Power Facilities	1
	Natural Gas Facilities	1
	Oil Facilities	1
	Potable Water Facilities	2
	Waste Water Facilities	15
Total Facilities at Risk		**239**

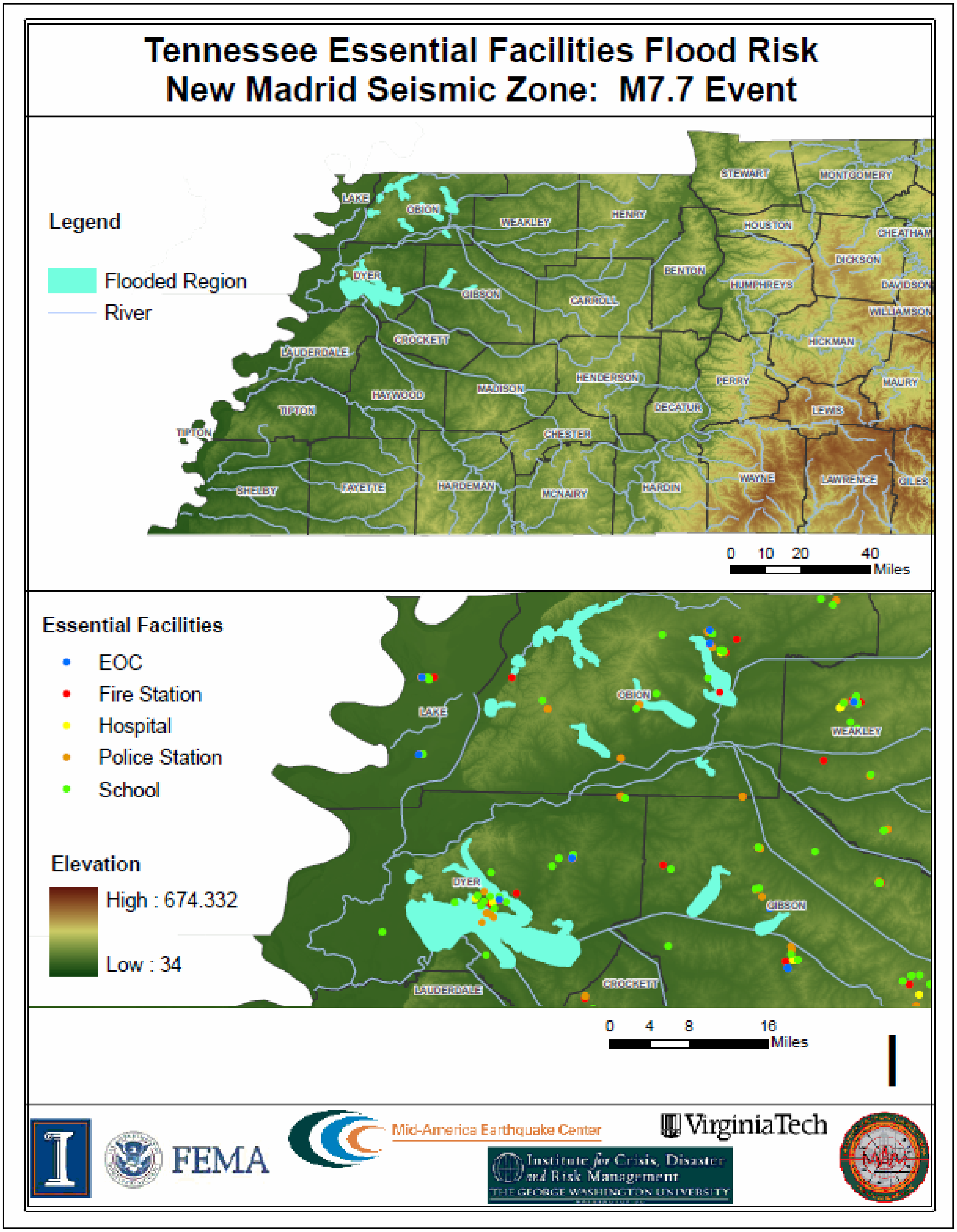


Figure 15: Tennessee Flood Risk of Essential Facilities

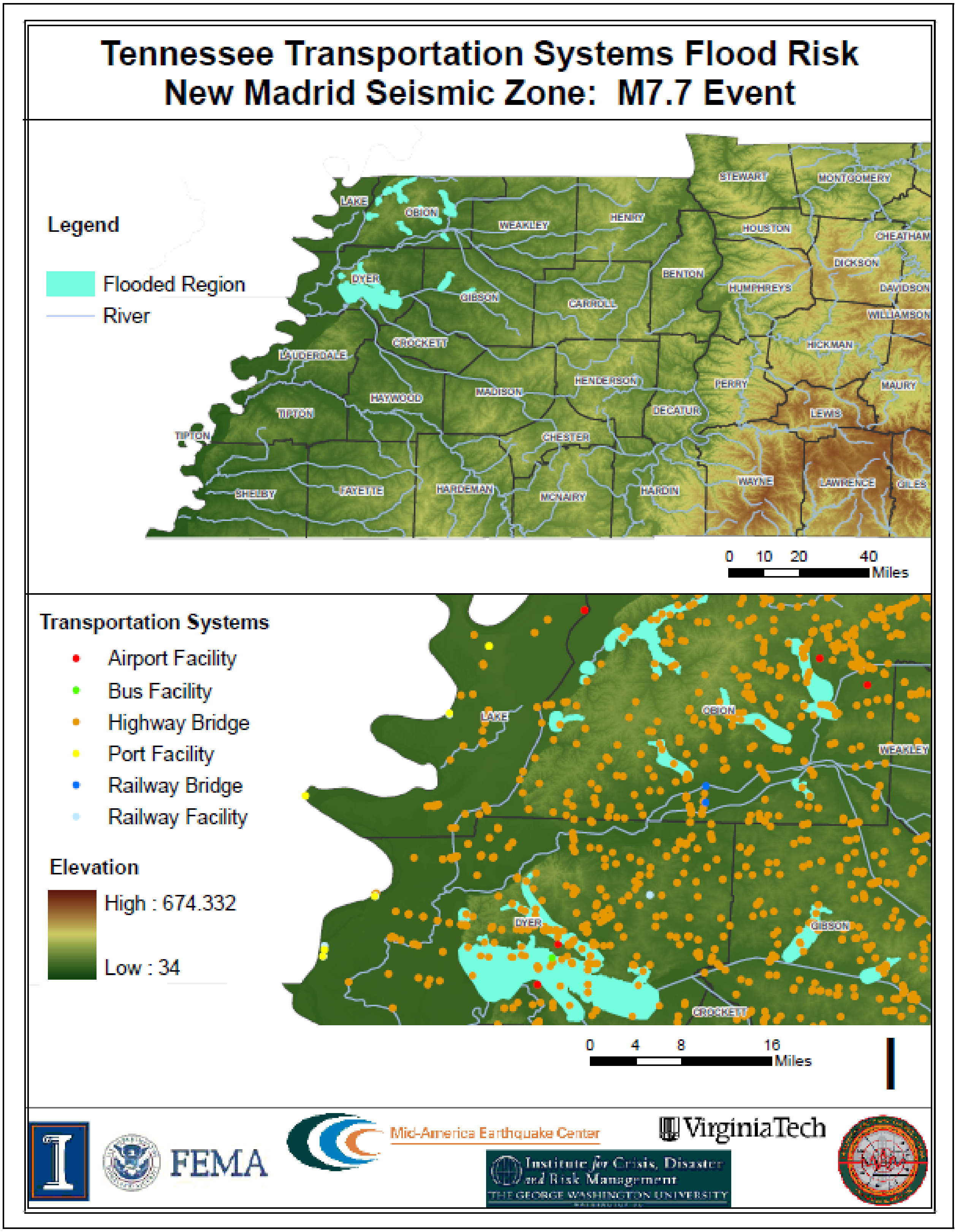


Figure 16: Tennessee Flood Risk of Transportation Systems

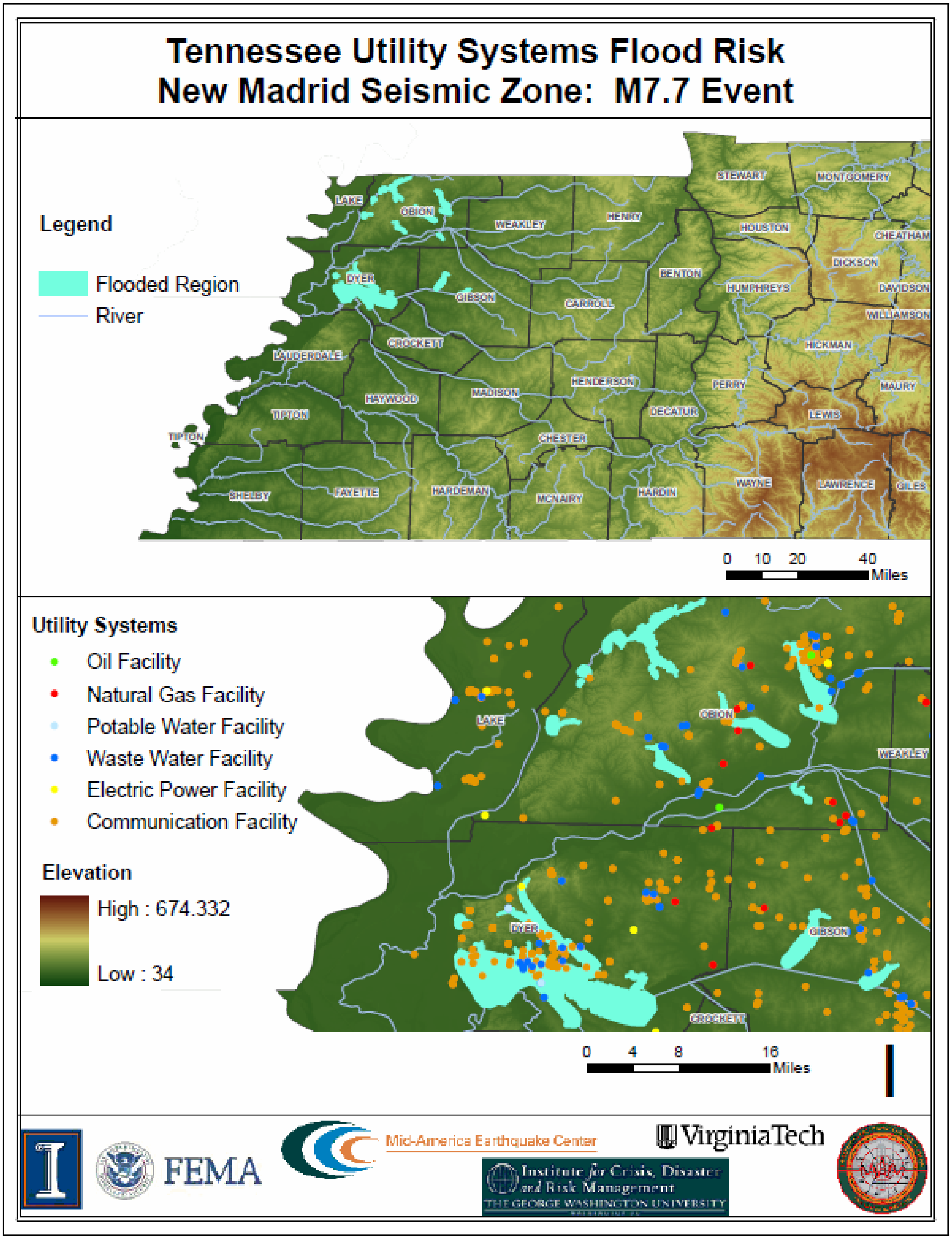


Figure 17: Tennessee Flood Risk of Utility Systems

Appendix 9 – Transportation Network Modeling

Introduction

Transportation systems are major civil infrastructure systems which are prominent components of modern societies (Duke, 1981). These infrastructure systems are susceptible to natural and man-made hazards, as evidenced by recent extreme events such as the 2008 catastrophic Wenchuan Earthquake in China and the 2007 tragic rush-hour collapse of the Minneapolis, Minnesota, I-35W highway bridge in the United States.

Transportation systems also serve as escape routes for survivors of disasters and provide emergency transport networks for rescue workers, construction repair teams, and disaster relief (EERI, 1986). The physical damage and functionality loss to the transportation infrastructure not only hinders residential and commercial activities, but also impairs post-disaster response and recovery, resulting substantial socio-economic losses (Chang & Nojima, 1998; Basoz and Kiremidjian, 1996; Nojima, 1998). Understanding the disastrous impact on these infrastructure systems and evaluating their performance are vital for stakeholders, emergency managers, and government agencies to mitigate, prepare for, response to, and recovery from catastrophic impact.

Transportation networks with collapsed bridges could result in system functionality loss and hinder post-disaster emergency response. For example, emergency rescuers are not able to gain access to impacted areas when transportation infrastructure collapses due to direct earthquake impact or secondary landslides. Thus, it is essential to ensure that when bridges sustain seismic impact, they also retain traffic carrying capacities so that emergency relief resources can be dispatched to an impacted area in a timely manner.

Governmental agencies (e.g., the state Deportments of Transportation) are usually responsible for the operation, inspection, and maintenance of transportation infrastructure. These agencies must work with emergency managers to identify and evaluate the emergency routes to be used for ingress and egress, and make emergency response plans for extreme events such as earthquakes. However, it is not easy to evaluate the transportation system's performance under extreme events, because transportation networks are often large-scale systems with thousands of components and a complex topology. Furthermore, stochastic damages and capacities of bridges result in the uncertainties of network configuration, making the problem more difficult.

This report describes the components and procedures of transportation system performance modeling under earthquake impacts through the use of the Network Loss Analysis (NLA) module in MAEViz - the comprehensive risk assessment software package developed by the Mid-America Earthquake (MAE) Center. The road networks in the metropolitan areas of St. Louis, Missouri, and Memphis, Tennessee, are used as case studies to illustrate the application of the NLA module. The results of this study could be useful to evaluate systems performance under extreme events and make preparedness plans for emergency responses.

Target Region and Data Sources

The Central United States is an important "hub" of the national transportation system. According to the 2002 Commodity Flow Survey by the Bureau of Transportation Statistics (BTS), more than 968 billion ton-miles, or about 31% all US commodities originate, pass through, or arrive in the Central United States region (BTS, 2005).

The greater metropolitan areas of Memphis and St. Louis are particularly of significance. With regard to freight, the Federal Express Corporation (FedEx) worldwide headquarters and world hub are located in Memphis. The third largest U.S. cargo facility of the United Parcel Service, Inc. (UPS), and also the only UPS facility capable of processing both air and ground cargo, is located in Memphis (Hanson, 2007). The Memphis International Airport has been the world's busiest airport in terms of cargo traffic volume. St. Louis is also the home of the nation's second-largest inland port by trip ton-miles and the nation's third-largest rail center (St. Louis RCGA, n.d.).With regard to general travel, the Central United States is home to millions of people, including two major population centers in the St. Louis and Memphis metropolitan areas. In order to determine impacts to the transportation network in these major urban centers the aforementioned M_W7.7 scenario earthquake is used to estimate the damage of bridges and subsequent impact on the road network.

Unfortunately, the Central United States is one of the most vulnerable regions to seismic hazards in the U.S. This is mainly due to its proximity to the New Madrid Seismic Zone (NMSZ), which is roughly located between St. Louis, Missouri and Memphis, Tennessee. The NMSZ was responsible for several devastating earthquakes in 1811-1812 which are the largest earthquakes ever recorded in the conterminous United States. Additionally, major earthquakes in the central or eastern United States generally have longer return periods and affect much larger areas than those of similar magnitude in the western United States (Schweig et al., 1995). Moreover, most structures in the NMSZ were not seismically designed during original construction nor retrofitted to improve performance during seismic activity.

The likelihood of a moderate earthquake occurring in the NMSZ in the near future is also high and the estimated earthquake-related losses are substantial. According to a previous study completed by the MAE Center, a M_W7.7 earthquake in the NMSZ could cause $200 billion direct economic loss, tens of thousands of causalities, and leave hundreds of thousands displaced throughout eight states in the Central US (Elnashai et al., 2008).

The study discussed herein employs a deterministic M_W7.7 scenario earthquake on all the three segments simultaneously, which is advised by the USGS as the most appropriate scenario for the purpose of NMSZ catastrophic earthquake planning. Four ground shaking maps are required, including peak ground acceleration (PGA) (see Figure 1), peak ground velocity (PGV), and spectral acceleration (S_a) at 0.3 seconds and 1.0 seconds. For more information on regional seismicity and the hazard employed in this study, please refer to Appendix 1.

NMSZ Hazard Map

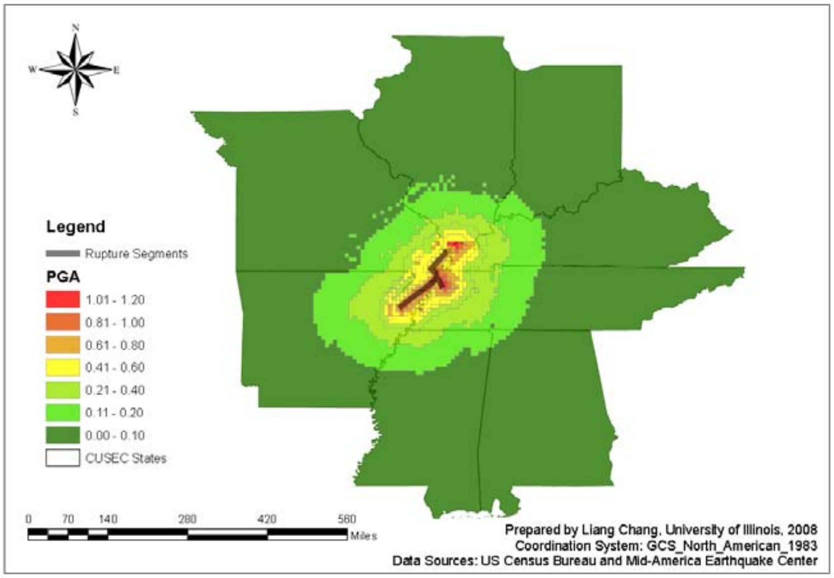


Figure 1: PGA Map of a M7.7 Earthquake on All Three New Madrid Fault Segments (g)

The road network data for the two metropolitan areas, including locations of nodes and links, road characteristics, and travel demand are collected from the local metropolitan planning organizations (MPOs) (i.e., the East-West Gateway Council of Governments [EWGCOG] in St. Louis, Missouri, and the Memphis Urban Area MPO in Memphis, Tennessee). The road network databases contain over 100 fields with descriptive characteristics for each link that are used to estimate capacity and speed setting for traffic modeling.

The transportation network data and travel demand information for the St. Louis area is collected from the EWGCOG. The EWGCOG consists of Franklin, Jefferson, St. Charles, and St. Louis Counties and the City of St. Louis in Missouri, as well as Madison, Monroe and St. Clair Counties in Illinois. The road network databases are extracted form the 2002 loaded highway network product from the EWGCOG's TransEval transportation model. Figure 2 shows the transportation network in the metropolitan area of St. Louis, Missouri. The 2002 St. Louis MPO network contains 17,352 nodes, 40,432 links, and 7,263,025 origin-destination (OD) pairs.

The transportation data for the Memphis area is collected from the Memphis Urban Area MPO. The Memphis Urban Area MPO includes Shelby County and parts of Fayette and Tipton Counties in Tennessee, as well as Desoto and Marshall Counties in Mississippi. Figure 3 shows the Memphis MPO transportation network. The road network database and travel demand information are both extracted from the 2004 highway network model obtained from the Memphis MPO. The Memphis network consists of 12,399 nodes and 29,308 links, and travel demand of the network is represented by 1,605,289 OD pairs.

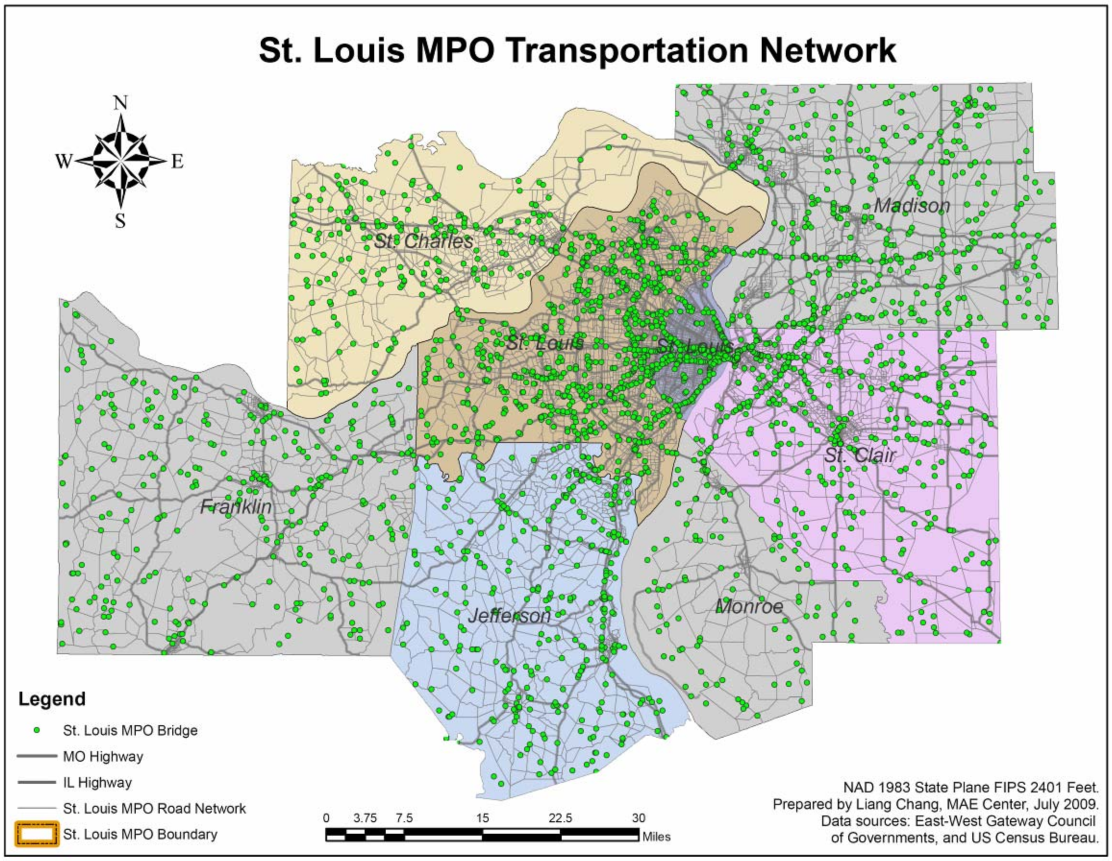


Figure 2: Transportation Network in St. Louis Area

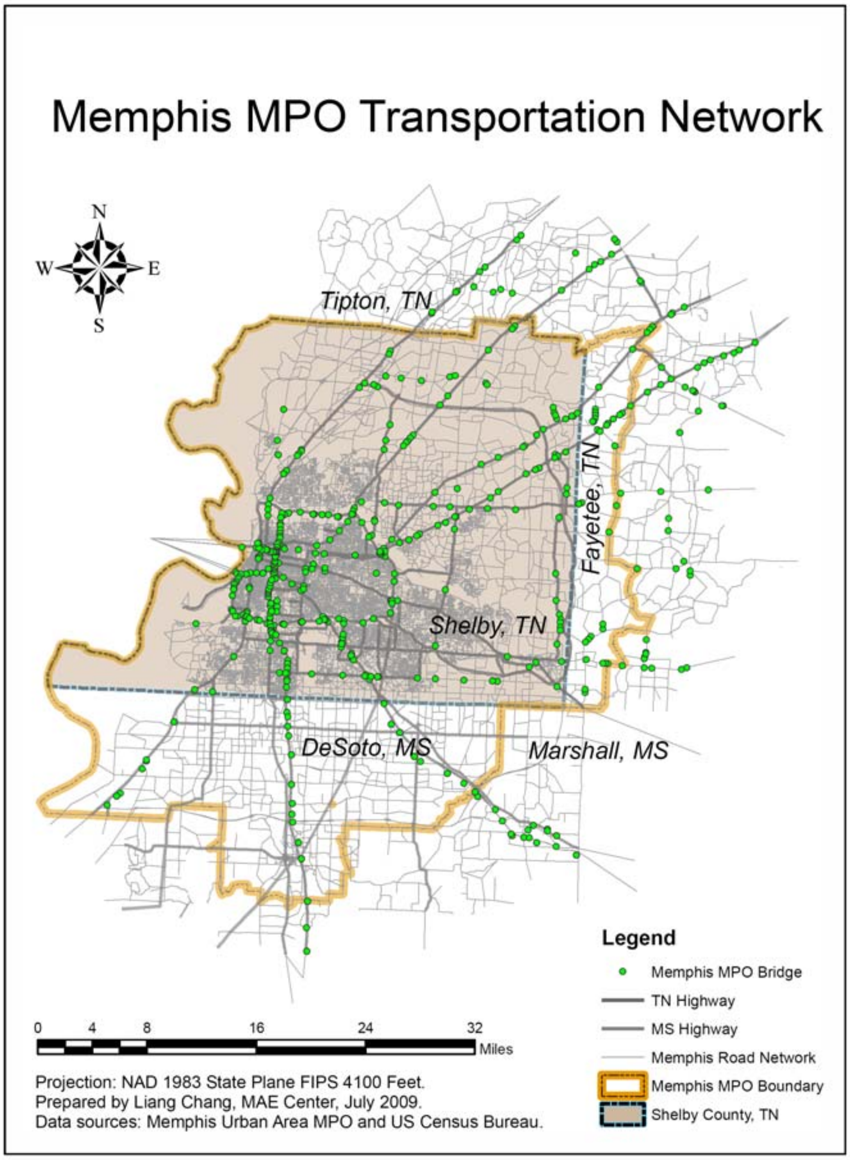


Figure 3: Memphis MPO Transportation Network

Bridge information is extracted from the 2002 National Bridge Inventory (NBI) database from the Federal Highway Administration (FHWA). The NBI is a collection of information which includes around 600,000 bridges on public roads in the U.S. Specific bridge metadata includes location, year built, geometry, material, construction, and conditions (FHWA, 1995). The 2002 version of the NBI database is chosen because it is compatible with the road network information provided by the local MPOs. From the database, a total number of 3,095 and 615 bridges within the MPO boundaries are filtered in GIS for St. Louis and Memphis MPO, respectively.

Methodology and Implementation

This section presents the implementation of the MAEViz Network Loss Analysis (NLA) module for transportation network performance assessment and its application to the St. Louis road network. Figure 4 summarizes the major components of the overall methodological framework, including input data, major analysis procedures, and outputs.

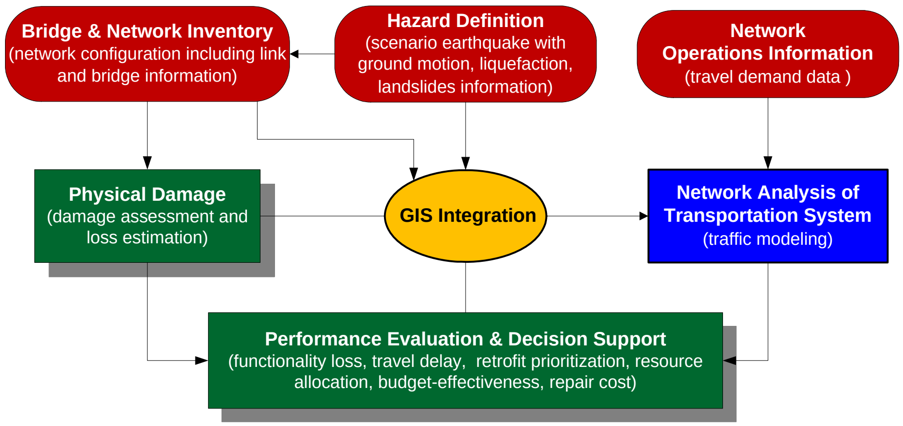


Figure 4: Methodological Framework

The baseline analyses define the seismic hazard and estimate the pre-event system performance as a reference point. Then, the probable damage states are determined with the structural vulnerabilities (or fragility curves) for bridges and input hazard information. Next, the post-event network states are determined by evaluating bridge functionalities under the given scenario earthquake with the damage-functionality relationship. The damage-functionality relationship, or traffic state, defines the residual traffic capacity of a component that is in a particular damage state. In other words, the damage-functionality relationship maps the structural damage states to the reduced traffic flow through capacities due to bridge collapse, lane or road closure, and detour, etc. Once the functionalities of components in the network are obtained, the time-dependent system functionality that corresponds to the level of serviceability or traffic carrying capacity is determined. Figure 5 illustrates bridge functionality at various damage states. With the bridge fragility curves and the damage-functionality relationship, the performance of bridges is linked to earthquake intensity. The residual capacities of bridges are then used to determine the capacities of corresponding links in the network. The post-event system performance with damaged bridges is assessed with traffic assignment models and recommendations are made based on the system functionality losses.

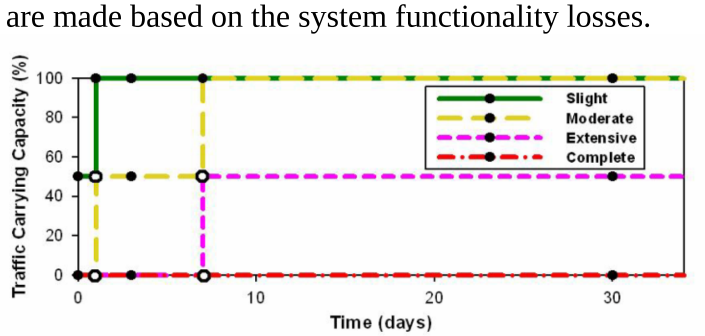
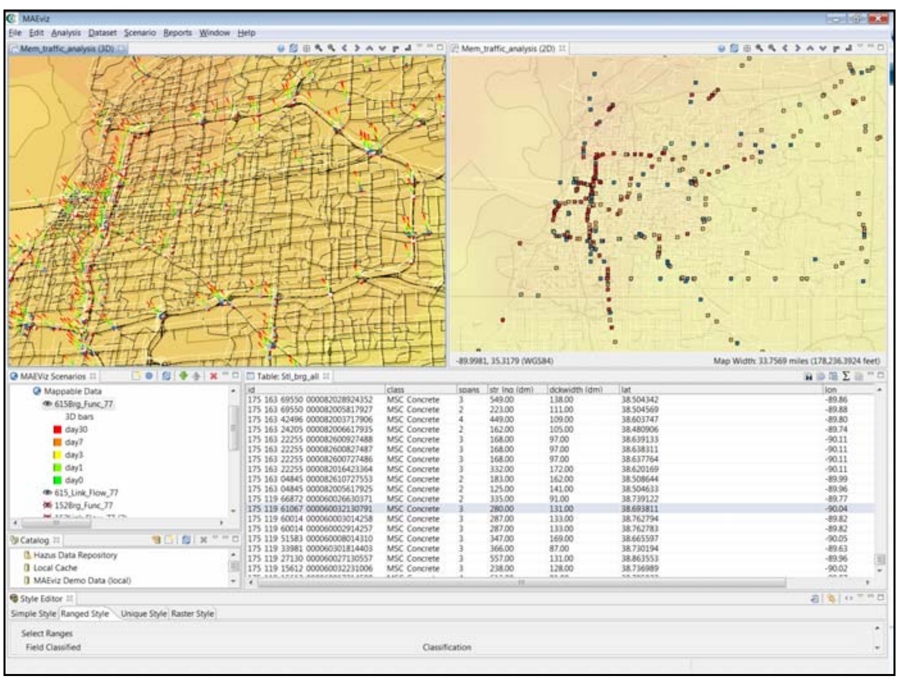


Figure 5: Bridge Damage-Functionality Relationship (Padgett & DesRoches, 2007)

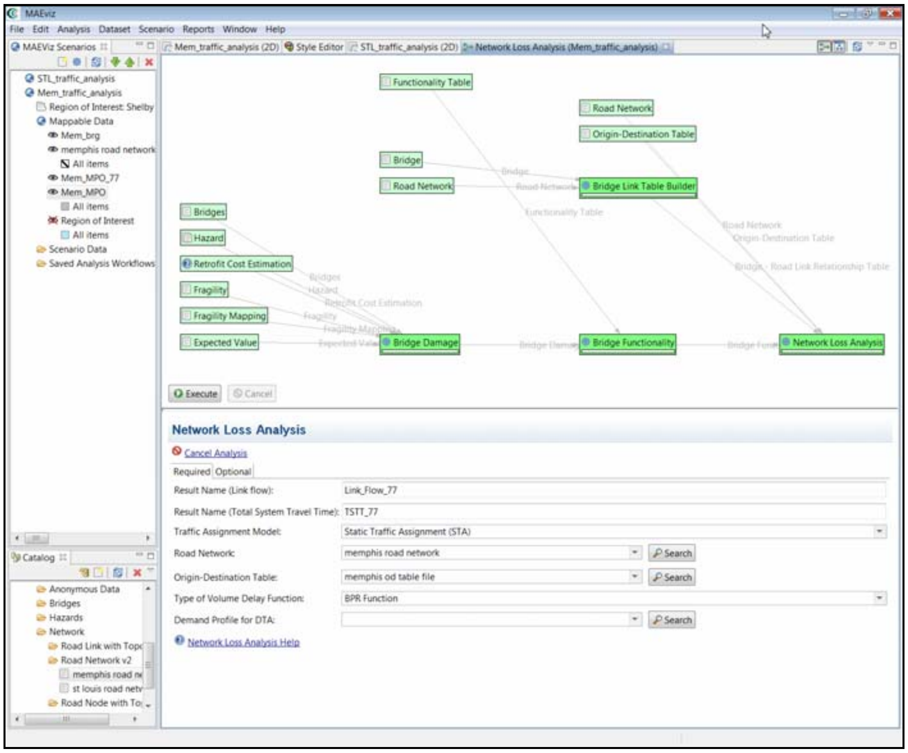
Traffic modeling provides essential information on traffic flow changes and travel delays that result from particular route closures due to excessive damage to key infrastructure elements, or from the reduced traffic carrying capacity because of less severe damage (e.g., lane closure for repair or imposed lower speed limit). The system delay (i.e. total system travel time) obtained via the traffic assignment model is used to measure the performance of transportation system.

Static traffic assignment models are employed in this report because of the substantial amount of work required, their legitimacy in emergency planning, and the wide acceptance among transportation practitioners. A static traffic assignment model assumes the model parameters (e.g. traffic demand and travel cost) do not vary in time, that is, the model parameters are static. The static model gives steady state traffic flow in user (traveler) equilibrium (UE), in which no traveler in the network can unilaterally change routes and improve his/her travel time thereby (Wardrop, 1952). The Deterministic User Equilibrium (DUE) model assumes the driver always choose the shortest path, while the driver' route choice is stochastically determined in the Stochastic User Equilibrium (SUE) model. The DUE model's assumption on drivers' choice is reasonable in urban road networks since the driver tends to minimize his/her individual travel time. Therefore it has been widely used to study the driving behavior in urban area (Sheffi, 1985).

The MAEViz interface and the procedural framework of NLA are given in Figure 6. The NLA module described previously is implemented in the latest version of MAEViz and demonstrated with the transportation networks in the St. Louis and Memphis metropolitan areas. For demonstration purposes, this section only gives the results of the traffic analysis of the St. Louis network before and after earthquake (day 0). Performance at other time frames such as days 3, 7, and 30, can be obtained by using the time-dependent functionality restoration relationship (Padgett and DesRoches, 2007).



(a). MAEViz Interface



(b). Network Loss Analysis Module

Figure 6: MAEViz Traffic Modeling Module

St. Louis MPO Results

The M_w7.7 NMSZ scenario earthquake is used as the hazard input for the transportation modeling in the St. Louis region. Simulation results from the scenario earthquake are given in the following discussion, including post-earthquake bridge functionality, the traffic condition of road sections (level of service), and changes of travel time.

Figure 7 gives the functionalities of bridges after the M_w7.7 NMSZ scenario earthquake (day 0). Most bridges with severe damage are located in the City of St. Louis, and Madison, St. Clair, and Monroe Counties in Illinois. Figure 8 gives the post-earthquake travel flow characteristics, i.e. the level of service (LOS), which is used to describe the vehicular congestion on the roadway. Most major arterials in St. Louis County and the City of St. Louis are estimated to experience severe congestion. Major arterials connecting St. Louis and the surrounding counties also experience high-density traffic or severe congestion. The changes in travel time (pre- vs. post- earthquake) are shown in Figure 9. Travel delays on segments of interstates I-44, I-55, I-170, I-64, I-70, I-255, and I-270 in the City of St. Louis are estimated to increase significantly after the earthquake, while travel delays in other regions increase moderately or slightly. Table 1 gives the system performance of the road network and its performance recovers to its pre-quake level over time.

Table 1: Post-Earthquake Road Network Performance (St. Louis MPO)

Time Frame	Total System Travel Time (mins)	Performance (percentage of pre-earthquake)
Pre-EQ	1,632,578,789.08	100%
Day 0	1,639,766,034.61	99.56%
Day 1	1,632,919,529,22	99.98%
Day 7	1,632,670,511,82	99.99%

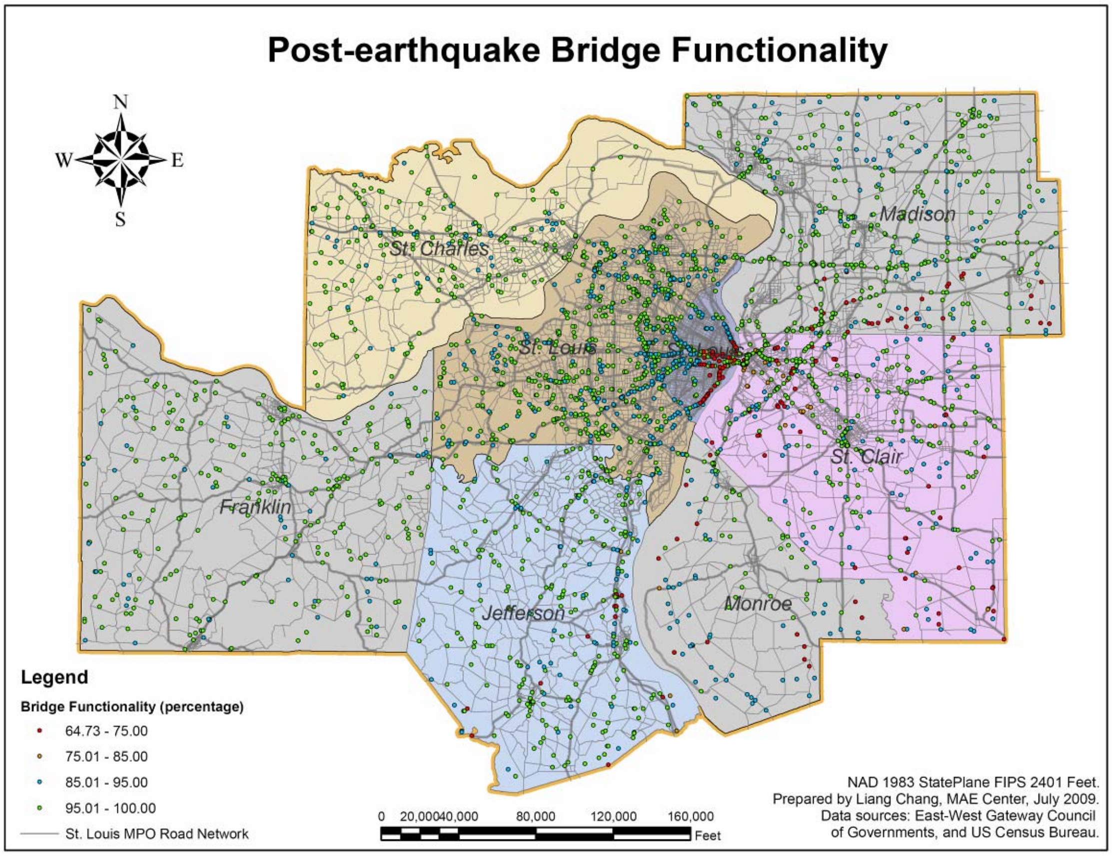


Figure 7: Post-Earthquake Bridge Functionality (St. Louis MPO)

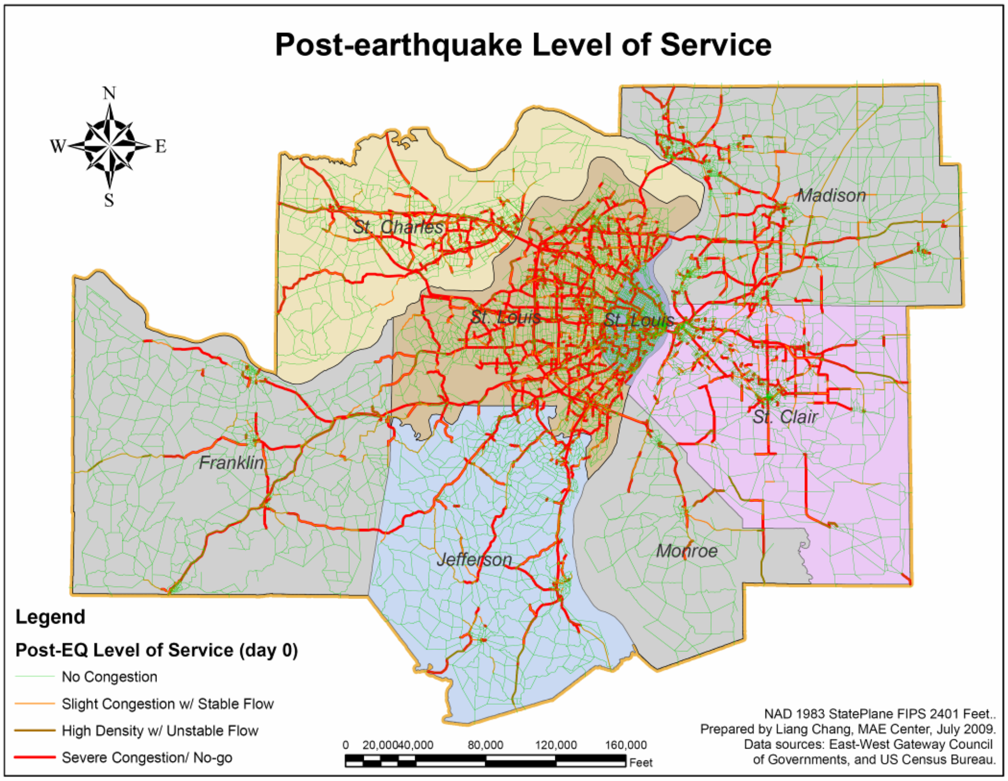


Figure 8: Post-Earthquake Congestion of St. Louis Road Network

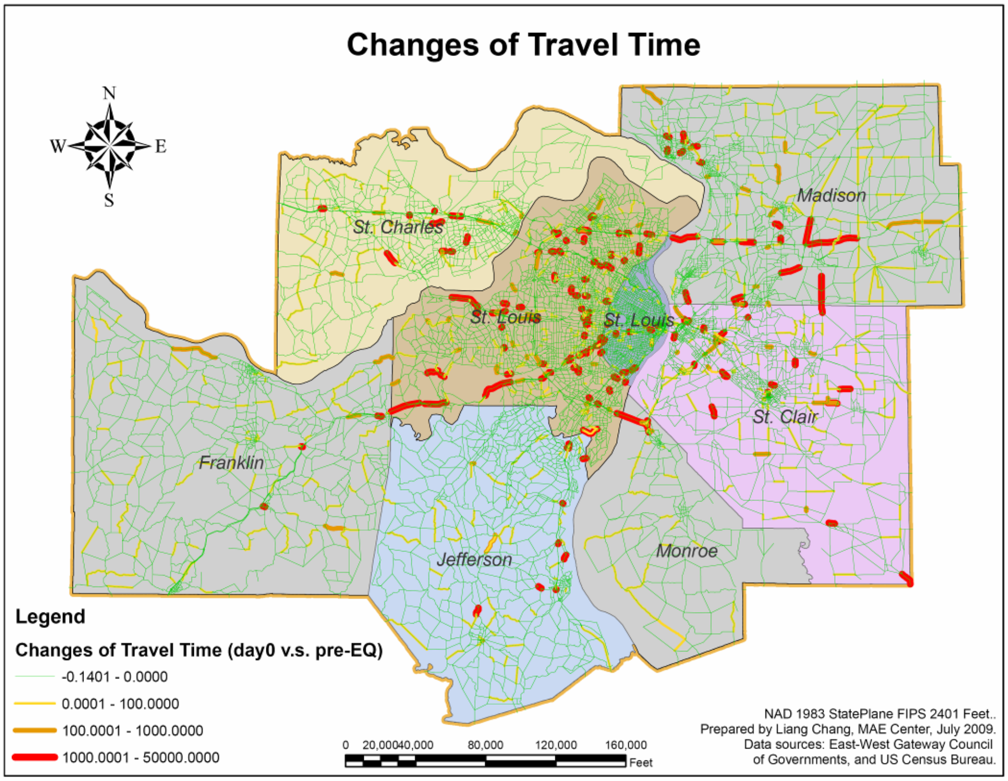


Figure 9: Post-Earthquake Changes of Travel Delay (Day 0) (St. Louis MPO)

Memphis MPO Results

This section presents the simulation results of the Memphis region for the M_w7.7 NMSZ scenario earthquake, including post-earthquake bridge functionality, traffic condition of road sections (LOS), and changes of travel time. Figure 10 gives the functionalities of the bridges after the M_w7.7 NMSZ scenario earthquake (day 0). Most bridges with severe damage are located in Shelby County, Tennessee. Figure 11 gives the post-earthquake level of service of the road segments. Note that most major arterials in the Memphis MPO are estimated to experience minimal congestion. Only segments of I-240 and I-40 in the City of Memphis experience high-density traffic or severe congestion. The changes in travel times (pre- vs. post- earthquake) are shown in Figure 12. Travel delays on the segments of interstates I-40 and I-240, and several major and minor arterials in the City of Memphis and Shelby County are estimated to increase significantly after the earthquake, while travel delays in other regions increase moderately or slightly. Table 2 gives the system performance of the road network and its performance recovers to its pre-quake level over time.

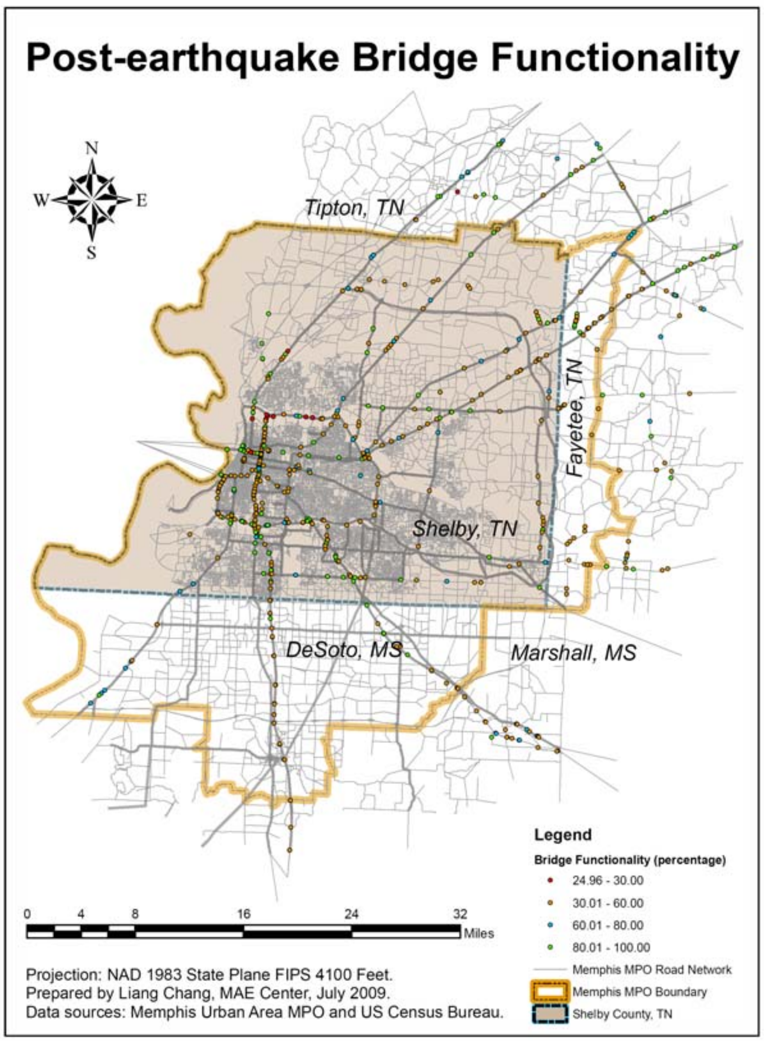


Figure 10: Post-Earthquake Bridge Functionality (Memphis MPO)

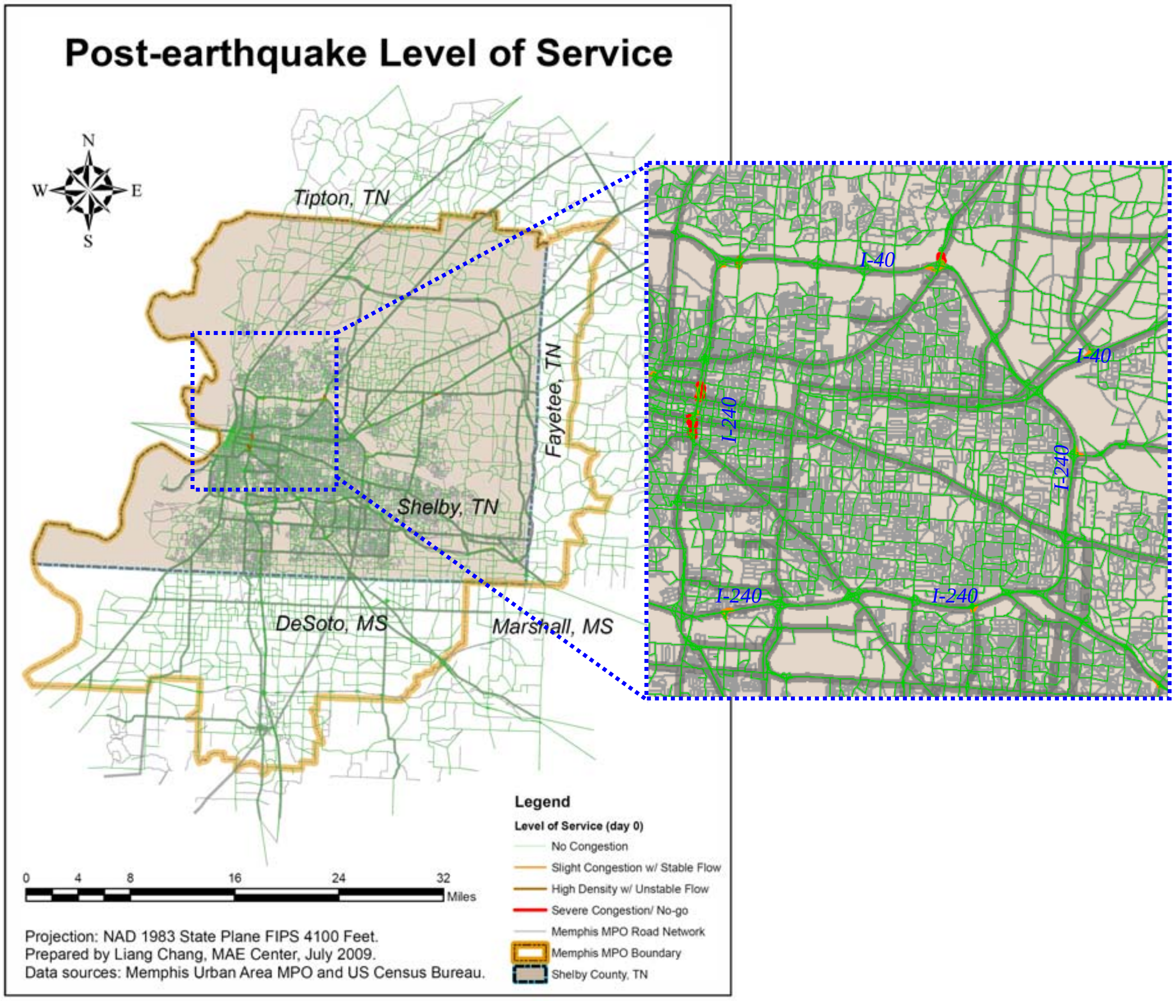


Figure 11: Post-Earthquake Congestion of Memphis Road Network

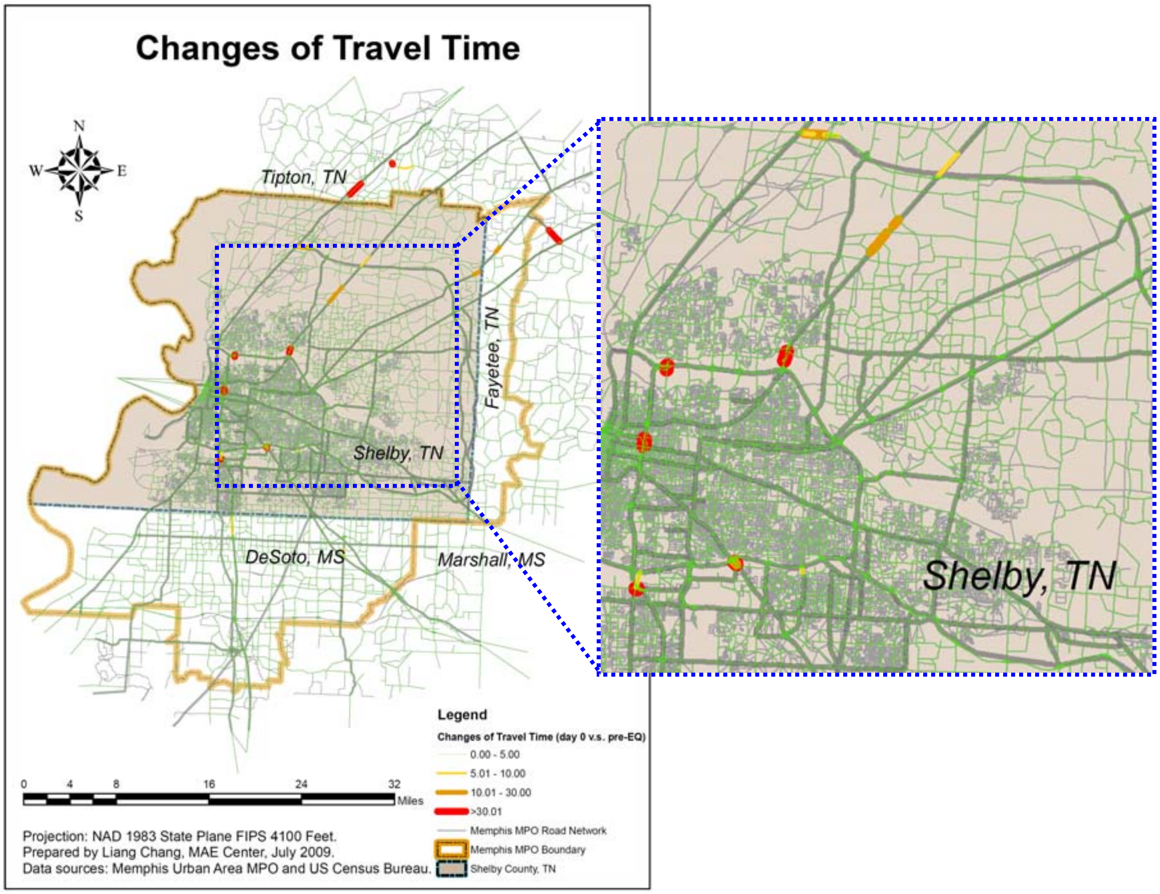


Figure 12: Post-Earthquake Change of Travel Time (Memphis MPO)

Table 2: Post-Earthquake Road Network Performance (Memphis MPO)

Time Frame	Total System Travel Time (mins)	Performance (percentage of pre-earthquake)
Pre-earthquake	8,797,742.68	100%
Day 0	8,808,428.31	99.88%
Day 1	8,799,506.30	99.98%
Day 7	8,798,329.33	99.99%

Conclusions and Future Research

Transportation systems are major civil infrastructure systems which are prominent components of modern societies. In the aftermath of disasters, such as earthquakes, significantly heavier traffic flows occur throughout the network. Thus, it is critical to secure the ingress and egress transportation routes of emergency response vehicles in addition to avoiding excessive queues and delays.

This report presents the recent developments of the MAEViz Network Loss Analysis module for transportation system performance modeling at the MAE Center. Current state-of-the-art hazard information in the NMSZ, structural fragility curves, and damage-functionality relationships are utilized to evaluate the damages and capacities of network components. Traffic assignment models are used to evaluate the performance of transportation systems. The NLA module is demonstrated with real-world road network data in the St. Louis and Memphis metropolitan areas which are both located in seismically vulnerable portions of the Central US.

Future research is needed to evaluate the post-disaster emergency traffic and performance of complex transportation infrastructure with more realistic dynamic traffic simulation models. Dynamic traffic assignment (DTA) models provide an alternative way to address the unrealistic issues with the static assignment models that have been utilized in current study. Instead of assuming static traffic demand, the DTA models take into account the fluctuation of road traffic by introducing time-dependent traffic flow and route choices. The state-of-the-art dynamic models (i.e., Visual Interactive System for Transport Algorithms, VISTA), which incorporate the enhanced cell transmission model (CTM), and supports variable-sized cells and signalized intersections, will be employed to simulate the dynamic traffic flow over the network. In addition, emergency scenarios representing various post-event traffic demands will be designed to evaluate emergency response plans. The performance and congestion of emergency routes will be evaluated to ensure post-earthquake ingress and egress to the impacted area (e.g., disaster relief dispatch and evacuation).

The NLA module in MAEViz is useful to evaluate system performance of transportation networks in the context of emergency management. The travel flow pattern and delays estimated by traffic modeling provides useful information for emergency managers and relevant government agencies to make emergency response plans for ingress and egress of impacted areas (e.g. disaster relief dispatch and evacuation), and to indentify emergency routes and evaluate their performance under extreme events.

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Appendix 10 – Utility Network Modeling

Methodology

Inventory

Certain inventory information must be provided in order to carry out the analysis of interdependent utility network systems. Those attributes are required by MAEViz either to match each individual object to a fragility curve, or to build topology for the interdependent performance analysis. All inventory items must be defined in GIS format with power lines and buried pipelines in polyline features; power, water, and natural gas network facilities in point data format. No structural analysis is performed for power lines though they are defined with the necessary information for topological modeling (Table 1). Buried pipelines for water and natural gas networks (Table 2), and facilities in all networks (Table 3) must include all necessary attributes for both structural and topological modeling.

Table 1: Necessary Attributes for Electric Power Lines

Necessary Attributes	Explanation
Power Lines	
Link ID	Distinct ID for each segment
Start Node	Facility ID of the starting point
End Node	Facility ID of the end point
Flow Capacity	Maximum carriage capacity of the segment
Flow Directivity	Bidirectional/Unidirectional Flow

Table 2: Necessary Attributes for Buried Pipelines

Necessary Attributes	Explanation
Buried Pipelines	
Link ID	Distinct ID for each segment
Pipe Material	Steel, Cast Iron, Concrete, PVC, Polyethylene, etc.
Joint Type	Welded, Screwed, etc.
Pipe Diameter	
Soil Corrosivity	Corrosivity effect of the soil surrounding the segment
Start Node	Facility ID of the starting point
End Node	Facility ID of the end point
Flow Capacity	Maximum carriage capacity of the segment
Flow Directivity	Bidirectional/Unidirectional Flow

Table 3: Necessary Attributes for Natural Gas Networks

Necessary Attributes	Explanation
Power Facilities	
Facility ID	Distinct ID for each node
Node Type	Generation, Distribution, or Intermediate
Facility Type	Power Plant, Substation, Transformer, etc.
Flow Capacity	Amount of production or demand
Water Facilities	
Facility ID	Distinct ID for each node
Node Type	Generation, Distribution, or Intermediate
Facility Type	Well, Pumping Plant, Tank, etc.
Flow Capacity	Amount of production or demand
Availability of Backup Power	
Natural Gas Facilities	
Facility ID	Distinct ID for each node
Node Type	Generation, Distribution, or Intermediate
Facility Type	Gate Station, Regulator Station, etc.
Flow Capacity	Amount of production or demand
Availability of Backup Power	

Fragilities

Buried Pipelines

Fragilities, or damage functions, for buried pipelines are utilized to estimate the number of repairs on a unit length of one segment. Results are presented in numbers of repairs per kilometer (O'Rourke and Ayala, 1993; O'Rourke and Jeon, 1999) or numbers of repairs per 1,000 feet (Eidinger, 2001). The number of repairs includes those caused by both leaks in the pipe or complete ruptures. Damage to pipelines is induced by ground shaking and/or ground failure due to liquefaction, landslides, fault rupture, or settlement. Ground shaking indicates transient deformations of soil due to seismic wave propagation and is defined in terms of peak ground velocity. Ground failure accounts for the permanent displacement of the soil profiles. These displacements occur due to settlement at transition zones where soil properties change, at fault rupture areas, or at liquefaction areas. Displacements are defined in terms of permanent ground deformation (Eidinger, 2001).

In MAEviz, each pipe segment is matched with a fragility curve from the fragility set during the analysis. Table 4 shows the pipeline damage functions for ground shaking in MAEviz. Each equation represents expected damage to certain pipe segments according to the pipeline inventory data from which they are derived. Fragility assignments are made according to pipe material, joint type, pipe diameter, and soil corrosivity, if specified. Coefficients of Eidinger (2001) functions for different pipe properties are given in Table 5.

Table 4: MAEViz PGV-Induced Damage Functions for Buried Pipelines (Steelman et al., 2007)

Material	Researcher	Backbone Fragility Curve	Non - dimensional Coefficient (K)	Source Earthquake	Required Mapping Data	NOTES
Cast-Iron Pipe	O'Rourke, T and Jeon (1999)	$RR = 0.050(PGV / D^{1.138})^{0.865}$	N/A	Northridge Earthquake (1994)	Pipe material, diameter	RR : Repairs / Km
Ductile Iron Pipe		$RR = 0.004(PGV / D^{0.468})^{1.378}$			Pipe material, diameter	PGV : cm/sec
Asbestos Cement Pipe		$Log(RR) = -4.59 Log(D) + 8.96$			Pipe material, diameter	D: cm
Asbestos Cement Pipe		$Log(RR) = 2.26 Log(PGV) - 11.01$			Pipe material	PGV : cm / sec
Buried Pipeline	O'Rourke, M and Ayala (1993)	$RR = K \cdot 0.00003(PGV)^{2.65}$	1.0 - Cast – Iron, Asbestos, Cement, Concrete 0.3 - Steel, Ductile Iron, PVC	11 data points from 4 U.S. and 2 Mexican Earthquakes	Pipe material Pipe material	RR Repairs / Km PGV: cm / sec
Buried Pipeline	Eidinger (2001)	$RR = K \cdot 0.0187 \cdot PGV$	Depends on Composition Joint Type, Soil Condition and Diameter	81 data points from 18 Earthquakes	Pipe material, diameter, joint type, soils (see Table 2)	PGV: in / sec RR : Repairs / 1000 ft

Table 5: Coefficient K for Eidinger (2001) Relation

Pipe Material	Joint Type	Soils	Diameter	K
Cast Iron	Cement	All	Small	1.0
Cast Iron	Cement	Corrosive	Small	1.4
Cast Iron	Cement	Non-corrosive	Small	0.7
Cast Iron	Rubber Gasket	All	Small	0.8
Welded Steel	Lap – Arc Welded	All	Small	0.6
Welded Steel	Lap – Arc Welded	Corrosive	Small	0.9
Welded Steel	Lap – Arc Welded	Non-corrosive	Small	0.3
Welded Steel	Lap – Arc Welded	All	Large	0.2
Welded Steel	Rubber Gasket	All	Small	0.7
Welded Steel	Screwed	All	Small	1.3
Welded Steel	Riveted	All	Small	1.3
Asbestos Cement	Rubber Gasket	All	Small	0.5
Asbestos Cement	Cement	All	Small	1.0
Concrete w/Steel Cylinder	Lap – Arc Welded	All	Large	0.7
Concrete w/Steel Cylinder	Rubber Gasket	All	Large	1.0
Concrete w/Steel Cylinder	Rubber Gasket	All	Large	0.8
PVC	Rubber Gasket	All	Small	0.5
Ductile Iron	Rubber Gasket	All	Small	0.5

Liquefaction-induced PGD, especially lateral spreading, is one of the most common causes of lifeline damage from seismic activity (O’Rourke et. al., 2001). The damage algorithm for pipelines due to ground failure uses damage functions based on the study by Honegger and Eguchi (1992) as implemented in the HAZUS methodology (FEMA, 2008). The damage function is formulated as:

$$RR(repairs/km) = K \times P(liquefaction) \times PGD^{0.56} \qquad (1)$$

Where K is the coefficient used in the O'Rourke and Ayala (1993) equation. K is equal to 1 for brittle pipe materials such as cast iron, and 0.3 for ductile pipe materials such as steel or PVC. *P*(*liquefaction*) is the probability of liquefaction where the pipe segment is located, and PGD is expressed in inches.

Damage functions for pipelines give pipeline damage in the number of repairs per kilometer of pipe segment. Estimated repairs consist of the combined numbers of pipe leaks and breaks. For damage caused by ground shaking (PGV-induced damage), 80% of the repairs are assumed to be leaks, whereas 20% are assumed to be pipe breaks. In the case of liquefaction damage (PGD-induced), amount of breaks are assumed to be 80%, and leaks to be 20% (FEMA, 2008). MAEViz generates fields for total leak, break, and repair rates for each segment in the data table and calculates the values. Number of repairs for each segment is obtained by multiplication of pipe lengths and repair rates for each segment. Total number of repairs for the network is obtained by the summation of these values.

In order to model the pipeline failure with the interdependent network analysis tool, a probabilistic approach is followed assuming that the breaks constitute a Poisson process. The model proposed by Duenas-Osorio et al. (2005), and implemented by Kim et al. (2007) suggests that at least one break on a pipe segment is assumed to impair the segment, and the probability of at least one break occurring on a segment is calculated as:

$$P(B_r > 0) = 1 - P(B_r = 0) = 1 - e^{-BreakRate \times length} \qquad (2)$$

Where B_r is the number of breaks.

Network Structures

Damage estimations are given in terms of the probability of a structure being in a particular damage state through the implementation of fragility curves. Fragility information for electric power, water, and natural gas network structures is taken from the HAZUS methodology (FEMA, 2008). Four limit states are utilized to describe the degree of damage to structures: slight (S), moderate (M), extensive (E), and complete (C). The fragilities are defined by a lognormal distribution with median and dispersion (β) parameters for the calculation of limit states:

$$P\left[LSi \middle| PGA = a\right] = \Phi\left(\frac{\ln(a) - \ln(median)}{\beta}\right) \qquad (3)$$

Where a is the demand peak ground acceleration taken from hazard maps at the location of each facility, Φ represents the standard normal cumulative distribution function, and $P[LS_i|PGA=a]$ is the conditional probability of exceeding the i^{th} limit state given the hazard PGA=a. The range and severity of damage to network structures is defined by five damage states: None, slight, moderate, extensive, and complete.

$$P(DS = C) = P(LS > C) \tag{4}$$

$$P(DS = E) = P(LS > E) - P(LS > C) \tag{5}$$

$$P(DS = M) = P(LS > M) - P(LS > E) \tag{6}$$

$$P(DS = S) = P(LS > S) - P(LS > M) \tag{7}$$

$$P(DS = N) = 1 - P(DS > S) \tag{8}$$

Liquefaction damage (PGD-induced) estimations for buildings, which also utilize the lognormal cumulative distribution function, are used to calculate the probability of exceeding limit states for ground failure with a median value of *ln(60)* for permanent ground displacement. The dispersion, β, is taken as 1.2. The probability of ground failure caused by liquefaction is calculated as:

$$P_{GF}(LSi) = \alpha \times \Phi\left(\frac{\ln(PGD) - \ln(60)}{1.2}\right) \times P[liquefaction] \tag{9}$$

Combined limit state probabilities resulting from ground shaking and ground failure are calculated by the following equations:

$$P_{COMB}(LS > C) = P(LS > C) + P_{GF}(LS4) - P_{GF}(LS4) \times P(LS > C) \tag{10}$$

$$P_{COMB}(LS > E) = P(LS > E) + P_{GF}(LS3) - P_{GF}(LS3) \times P(LS > E) \tag{11}$$

$$P_{COMB}(LS > M) = P(LS > M) + P_{GF}(LS2) - P_{GF}(LS2) \times P(LS > M) \tag{12}$$

$$P_{COMB}(LS > S) = P(LS > S) + P_{GF}(LS1) - P_{GF}(LS1) \times P(LS > S) \tag{13}$$

Damage probabilities for combined ground shaking and ground failure are calculated by combining the limit state probabilities as shown in equations 4 through 8 instead of limit state probabilities due to ground shaking (Steelman et al., 2007). Thus, probabilities of occurrence of each damage state due to combined ground shaking and ground failure become:

$$P(DS = C) = P_{COMB}(LS > C) \tag{14}$$

$$P(DS = E) = P_{COMB}(LS > E) - P_{COMB}(LS > C) \tag{15}$$

$$P(DS = M) = P_{COMB}(LS > M) - P_{COMB}(LS > E) \tag{16}$$

$$P(DS = S) = P_{COMB}(LS > S) - P_{COMB}(LS > M) \tag{17}$$

$$P(DS = N) = 1 - P_{COMB}(DS > S) \tag{18}$$

As failure criteria in the interdependent network analysis tool, network components are expected to have at least extensive damage for losses of functionality (Kim et al., 2007). The probability of a structure to experiencing at least extensive damage is calculated in Equation 3, using the values from the fragility curves for the appropriate structural type given for the extensive damage limit state. Fragility curves assigned for various network components are given in Table 6.

Table 6: Fragility Relations for Network Components

Network Facility	Slight	Moderate	Extensive	Complete
	Median / Dispersion (PGA)			
Power Network				
Small Power Plants (< 100 MW) (without Backup Power)	0.15 / 0.60	0.30 / 0.60	0.60 / 0.60	1.25 / 0.65
Small Power Plants (< 100 MW) (with Backup Power)	0.25 / 0.60	0.40 / 0.60	0.70 / 0.60	1.35 / 0.65
Medium Power Plants (100 - 500 MW) (without Backup Power)	0.15 / 0.60	0.30 / 0.60	0.60 / 0.60	1.25 / 0.65
Medium Power Plants (100 - 500 MW) (with Backup Power)	0.25 / 0.60	0.40 / 0.60	0.70 / 0.60	1.35 / 0.65
Large Power Plants (> 500 MW) (without Backup Power)	0.15 / 0.60	0.30 / 0.60	0.60 / 0.60	1.25 / 0.65
Large Power Plants (> 500 MW) (with Backup Power)	0.25 / 0.60	0.40 / 0.60	0.70 / 0.60	1.35 / 0.65
Low Voltage (115 KV) Substation (without Backup Power)	0.15 / 0.60	0.30 / 0.60	0.60 / 0.60	1.25 / 0.65
Low Voltage (115 KV) Substation (with Backup Power)	0.35 / 0.60	0.50 / 0.60	0.80 / 0.60	1.45 / 0.65
Medium Voltage (230 KV) Substation (without Backup Power)	0.15 / 0.60	0.30 / 0.60	0.60 / 0.60	1.25 / 0.65
Medium Voltage (230 KV) Substation (with Backup Power)	0.25 / 0.60	0.40 / 0.60	0.70 / 0.60	1.35 / 0.65
High Voltage (500 KV) Substation (without Backup Power)	0.15 / 0.60	0.30 / 0.60	0.60 / 0.60	1.25 / 0.65
High Voltage (500 KV) Substation (with Backup Power)	0.25 / 0.60	0.40 / 0.60	0.70 / 0.60	1.35 / 0.65
Transformer - Anchored - 100V	0.75 / 0.70	0.75 / 0.70	0.75 / 0.70	0.75 / 0.70
Transformer - Unanchored - 100V	0.50 / 0.70	0.50 / 0.70	0.50 / 0.70	0.50 / 0.70
Transformer - Anchored - 165V	0.60 / 0.70	0.60 / 0.70	0.60 / 0.70	0.60 / 0.70
Transformer - Unanchored - 165V	0.30 / 0.70	0.30 / 0.70	0.30 / 0.70	0.30 / 0.70
Transformer - Unanchored - 500V	0.25 / 0.70	0.25 / 0.70	0.25 / 0.70	0.25 / 0.70
Transformer - Anchored - 500V	0.40 / 0.70	0.40 / 0.70	0.40 / 0.70	0.40 / 0.70
Default Facility	0.25 / 0.60	0.40 / 0.60	0.70 / 0.60	1.35 / 0.65
Water Network				
Wells (without Backup Power)	0.15 / 0.60	0.30 / 0.60	0.60 / 0.60	1.25 / 0.65
Wells (with Backup Power)	0.25 / 0.60	0.40 / 0.60	0.70 / 0.60	1.35 / 0.65
Small Water Treatment Plant (< 50 MGD) (without Backup Power)	0.15 / 0.60	0.30 / 0.60	0.60 / 0.60	1.25 / 0.65
Small Water Treatment Plant (< 50 MGD) (with Backup Power)	0.25 / 0.60	0.40 / 0.60	0.70 / 0.60	1.35 / 0.65
Medium Water Treatment Plant (50-200 MGD) (without Backup Power)	0.15 / 0.60	0.30 / 0.60	0.60 / 0.60	1.25 / 0.65
Medium Water Treatment Plant (50-200 MGD) (with Backup Power)	0.25 / 0.60	0.40 / 0.60	0.70 / 0.60	1.35 / 0.65
Large Water Treatment Plant (> 200 MGD) (without Backup Power)	0.15 / 0.60	0.30 / 0.60	0.60 / 0.60	1.25 / 0.65
Large Water Treatment Plant (> 200 MGD) (with Backup Power)	0.25 / 0.60	0.40 / 0.60	0.70 / 0.60	1.35 / 0.65

Small Pumping Plant (< 10 MGD) (without Backup Power)	0.15 / 0.60	0.30 / 0.60	0.60 / 0.60	1.25 / 0.65
Small Pumping Plant (< 10 MGD) (with Backup Power)	0.25 / 0.60	0.40 / 0.60	0.70 / 0.60	1.35 / 0.65
Medium Pumping Plant (10 to 50 MGD) (without Backup Power)	0.15 / 0.60	0.30 / 0.60	0.60 / 0.60	1.25 / 0.65
Medium Pumping Plant (10 to 50 MGD) (with Backup Power)	0.25 / 0.60	0.40 / 0.60	0.70 / 0.60	1.35 / 0.65
Large Pumping Plant (> 50 MGD) (without Backup Power)	0.15 / 0.60	0.30 / 0.60	0.60 / 0.60	1.25 / 0.65
Large Pumping Plant (> 50 MGD) (with Backup Power)	0.25 / 0.60	0.40 / 0.60	0.70 / 0.60	1.35 / 0.65
Buried Concrete Tank (without Backup Power)	0.15 / 0.60	0.30 / 0.60	0.60 / 0.60	1.25 / 0.65
Buried Concrete Tank (with Backup Power)	0.25 / 0.60	0.40 / 0.60	0.70 / 0.60	1.35 / 0.65
On Ground Wood Tank (without Backup Power)	0.15 / 0.60	0.30 / 0.60	0.60 / 0.60	1.25 / 0.65
On Ground Wood Tank (with Backup Power)	0.25 / 0.60	0.40 / 0.60	0.70 / 0.60	1.35 / 0.65
On Ground Concrete Tank (without Backup Power)	0.15 / 0.60	0.30 / 0.60	0.60 / 0.60	1.25 / 0.65
On Ground Concrete Tank (with Backup Power)	0.25 / 0.60	0.40 / 0.60	0.70 / 0.60	1.35 / 0.65
On Ground Steel Tank (without Backup Power)	0.15 / 0.60	0.30 / 0.60	0.60 / 0.60	1.25 / 0.65
On Ground Steel Tank (with Backup Power)	0.25 / 0.60	0.40 / 0.60	0.70 / 0.60	1.35 / 0.65
Above Ground Steel Tank (without Backup Power)	0.15 / 0.60	0.30 / 0.60	0.60 / 0.60	1.25 / 0.65
Above Ground Steel Tank (with Backup Power)	0.25 / 0.60	0.40 / 0.60	0.70 / 0.60	1.35 / 0.65
Default Facility	0.25 / 0.60	0.40 / 0.60	0.70 / 0.60	1.35 / 0.65
Natural Gas Network				
Facilities With Unanchored Components	0.12 / 0.60	0.24 / 0.60	0.77 / 0.65	1.50 / 0.80
Facilities With Anchored Components	0.15 / 0.75	0.34 / 0.65	0.77 / 0.65	1.50 / 0.80

In estimating the liquefaction damage, the same fragility curves used for buildings are assigned to network components. The four limit states for ground shaking damage (slight, moderate, extensive, and complete) are simplified for ground failure to account for the combined extensive and complete damage states. A single fragility curve is utilized for all network components with a median of 60 inches and a standard deviation of 1.2. The HAZUS methodology suggests that structures either remain undamaged or experience extensive damage due to ground failure; and slight or moderate damage are considered less likely and relatively small compared to ground shaking damage (FEMA, 2008).

Interdependent Network Analysis

The MAEViz Interdependent Network Analysis (INA) Tool is developed to model the frequently connected lifeline utility networks via a variety of mechanisms. To account for interdependency, a relationship must be defined to simulate how the failure of a component in a network is affected by the failures in another network. Kim (2007) gives an example of two interdependent networks to describe interdependent failure mechanisms (Figure 1). In the given example of systems, water generation node 1 (WG1) is dependent on power distribution nodes 1 (PD1) and 2 (PD2); and water generation node 2 (WG2) is dependent on power distribution node 2 (PD2). The α values in the tool account for the degree of dependency of each node in the water network to the nodes in the power network.

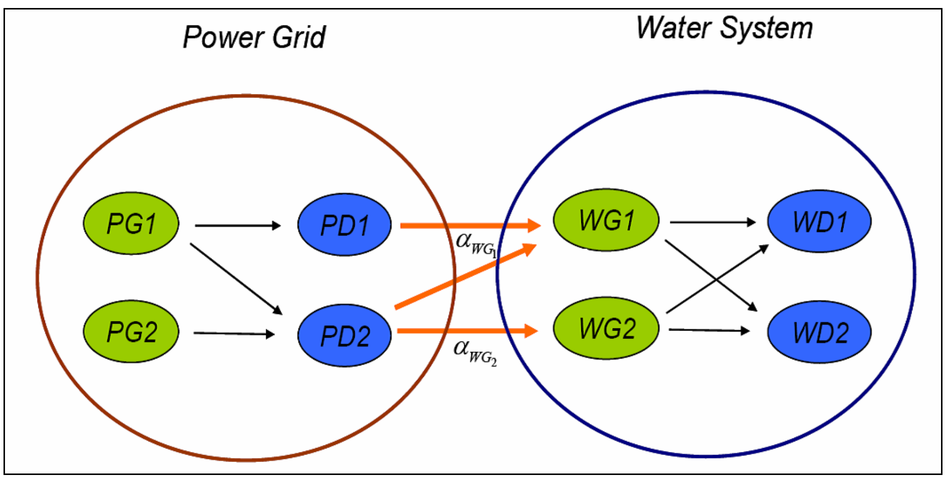

Figure 1: Interdependent Networks (Kim, 2007)

All dependencies in the analyzed networks have to be provided in a network interdependency table in the software along with their degrees of dependency. Since the analysis tool currently supports dependencies of water and natural gas networks to electric power systems, only those dependencies are considered in the analysis. A dependency checklist for various water and natural gas network components was prepared and sent to utility supply professionals in order to determine the dependent components along with their dependencies to electric power. Table 7 gives the dependencies of water and natural gas network components to electric power mainly according to professional opinions from Memphis Light, Gas and Water Co. (MLGW, Memphis, TN, personal communication, 2009a). It is shown that dependencies of natural gas network components on electric power are lower than the dependencies of water network components on electric power. In determining the dependency levels (α), a value between 0 and 1 is given for each defined dependency with 0 representing total independence and 1 representing total dependence. For example, a water well without a backup power generator is assigned with a dependency level of 1 since electric power is crucial for operation; whereas a water well with a backup power generator will have a dependency level of 0.5.

Table 7: Network Dependency Checklist for Water and Natural Gas Networks

Natural Gas Network Facility	Does it use electric power?	Is electric power crucial for operation?	Backup power availibility
Gate Stations / Plants	X	X	X UPS
Regulator Stations	X Not all		
Valves			
Station Valving			
Automatic Valves	X	X	X UPS at Gates
Natural Gas Network Facility	**Does it use electric power?**	**Is electric power crucial for operation?**	**Backup power availibility**
Processing Plants	X	X	X some
Wells	X	X	X some
Pumping Stations	X	X	X some
Booster Stations	X	X	X some
Automatic Valves	X	X	

Kim (2007) attributed the failure of a component after an earthquake to two main reasons: failure due to earthquake damage, and nonfunctionality of a network component due to power outage. Power outage can be caused by earthquake damage to the distribution facility, or failure of the nodes and links in the power network feeding electric power to the distribution node. Furthermore, although being functional and not affected by interdependency, a network node can still fail by losing its connectivity to the network. This happens when a generation node has no surviving outgoing links, or when a distribution node has no surviving incoming links, thus being isolated from the network.

In order to measure the functional loss of a system when some of the components are likely dysfunctional, two performance measures are defined to quantify those losses: connectivity loss (C_L), and service flow reduction (S_{FR}). These measures assess the network performance with metrics depending on the topological settings of the network, or with more detailed metrics depending on supply, demand, and flow patterns additional to the topological settings.

Connectivity loss (C_L) measures the ability of every distribution node to receive flow from generation nodes (Kim, 2007). It is calculated as:

$$C_L = 1 - \frac{1}{N}\sum_{i=1}^{N}\frac{nG^i_{post}}{nG^i_{pre}} \tag{19}$$

Where N is the number of distribution nodes, nG^i_{pre} is the number of generation nodes able to feed flow to the i^{th} distribution node in undisturbed state, and nG^i_{post} is the number of generation nodes able to supply power to the i^{th} distribution node under seismic conditions. C_L only requires the topological settings of the network before and after an earthquake.

Service flow reduction (S_{FR}) determines the amount of flow that the system can provide compared to the demand before the disturbance (Kim, 2007). It is calculated as:

$$S_{FR} = 1 - \frac{1}{N}\sum_{i=1}^{N}\frac{S^i}{D^i} \qquad (20)$$

Where N is the number of distribution nodes, S^i is the actual flow at the i^{th} distribution node under seismic conditions, and D^i is the demand at the i^{th} distribution node. Kim (2007) states that SFR provides a better estimate of the effects of a seismic event on lifeline utility networks since supply/demand, and flow patterns are considered in addition to the topological settings.

Network Inventory

The St. Louis utility network inventory analyzed in this study contains the natural gas pipelines and the electric power transmission network in the City of St. Louis, as well as St. Louis, St. Charles, and Jefferson Counties; and the water network for the City of St. Louis. Natural gas pipelines consist of approximately 250,000 segments and are a total of 8,622 miles in length. Water network information is provided by City of St. Louis Water Division (Figure 2). The water pipelines are 1,485 miles in total length and consist of 56,102 segments. There are two water treatment plants, two water reservoirs, six power plants, and 43 substations serving St. Louis networks.

The information on electric power networks is obtained from Homeland Security Infrastructure Program's (HSIP) 2008 datasets. The facilities and power transmission lines in the City of St. Louis, as well as St. Louis, St. Charles, and Jefferson Counties are extracted from the datasets for use in the INA tool (Figure 3). The power transmission network covering these counties consists of 6 power plants, 42 substations, and 3 electric taps.

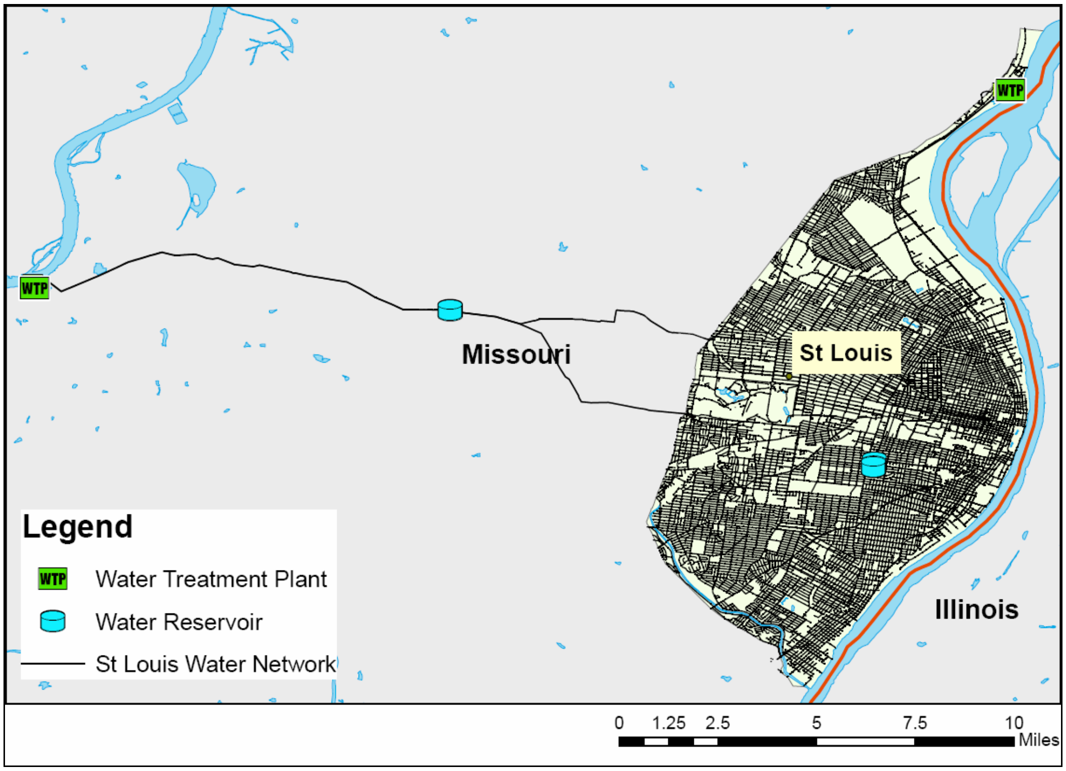

Figure 2: St. Louis Water Network (Courtesy of St. Louis Water Division)

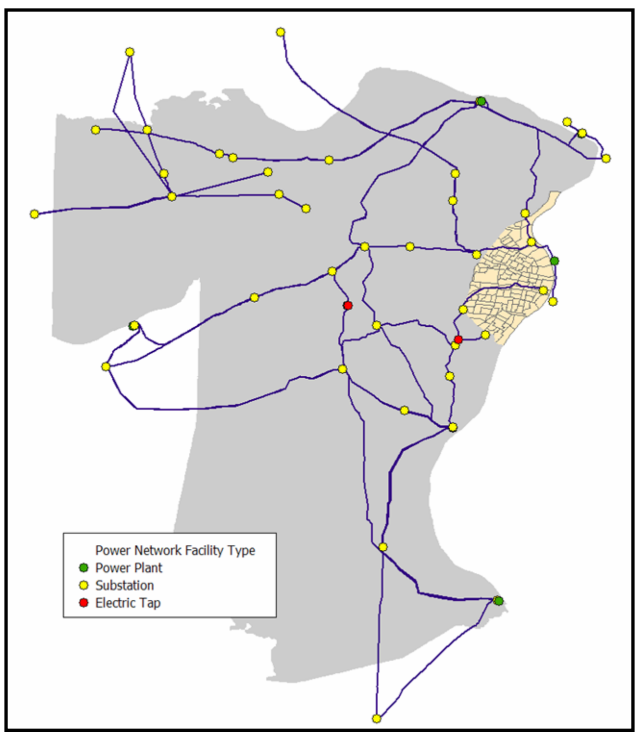

Figure 3: St. Louis Electric Power Network

The water network for the INA tool is built by the water mains having diameters equal to or larger than 12 inches (Figure 4). The two water treatment plants in the network are modeled as generation nodes, while the distribution nodes are determined according to 5 pressure zones specified by St. Louis Water Division. The demands are obtained from the 2008 water usage statistics for these pressure zones.

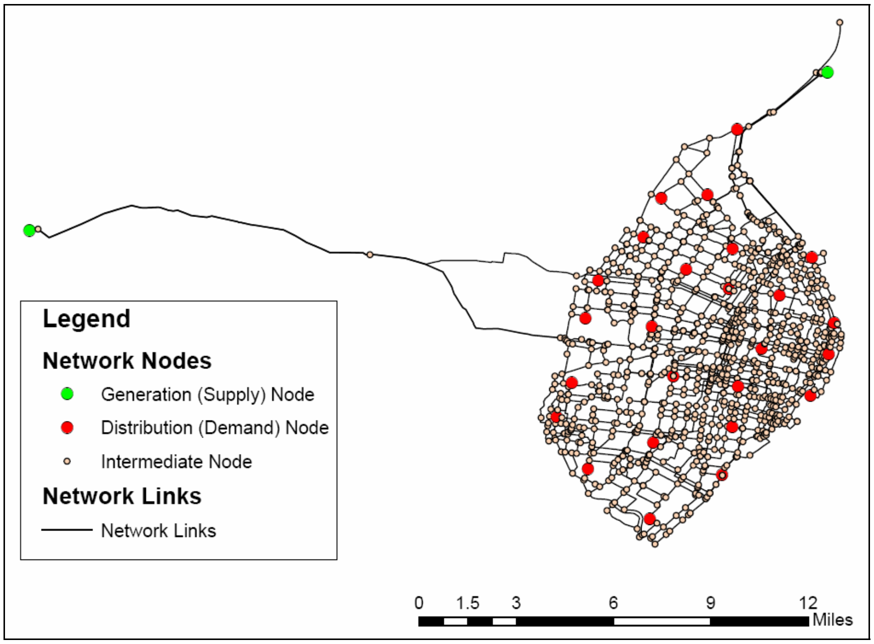

Figure 4: St. Louis Water Network, Topologically Modeled for the INA Tool

The analysis inventory consists of the entire electric power, natural gas, and water systems of Shelby County, Tennessee, where the City of Memphis is located. The electric power network in Shelby County has 28 substations distributing electric power to the county through 3,666 transformer stations (Figure 5).

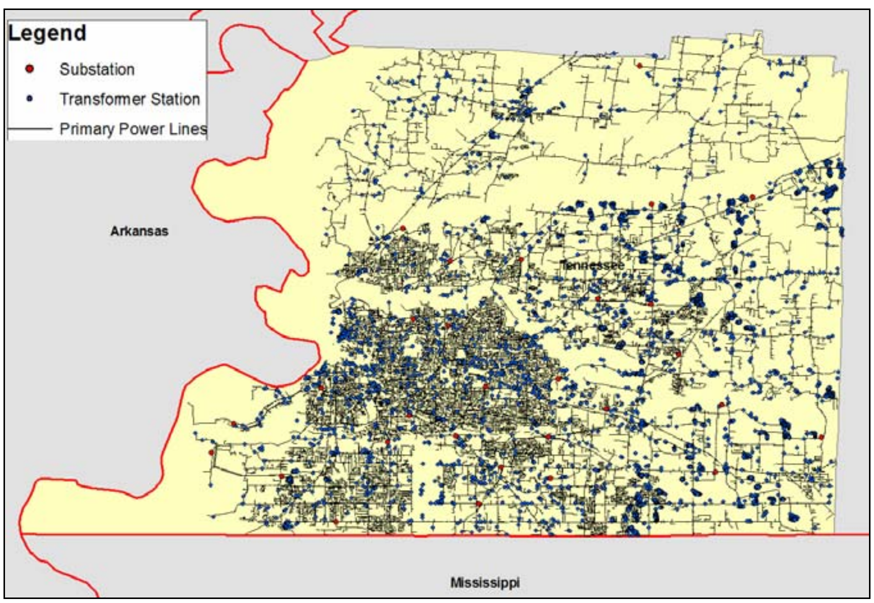

Figure 5: Shelby County Power Network

Shelby County has 192 water wells, 17 water tanks, 39 water pumps, and 27 booster stations in the potable water network (Figure 6). The potable water pipelines are a total 4,350 miles long, consisting of 202,294 pipe segments. Water pipelines are predominantly cast iron; while other pipe materials in the network include ductile iron, asbestos cement, PVC, and steel.

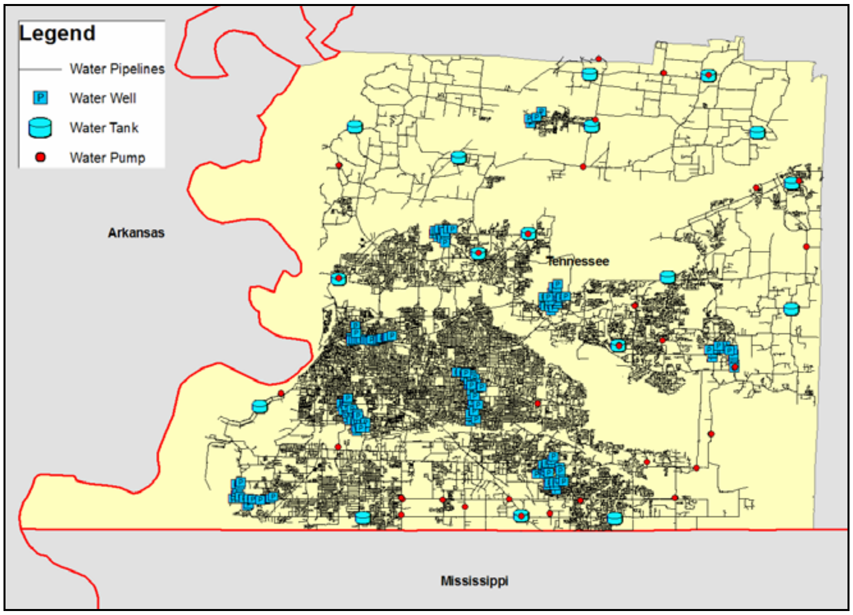

Figure 6: Shelby County Water Network

The natural gas network contains 3 gate stations, 120 pressure regulator stations, and 6,773 miles of main and service pipelines (Figure 7). The natural gas mains consist of 200,794 segments. The service lines, which are also analyzed, consist of 123,115 pipe segments.

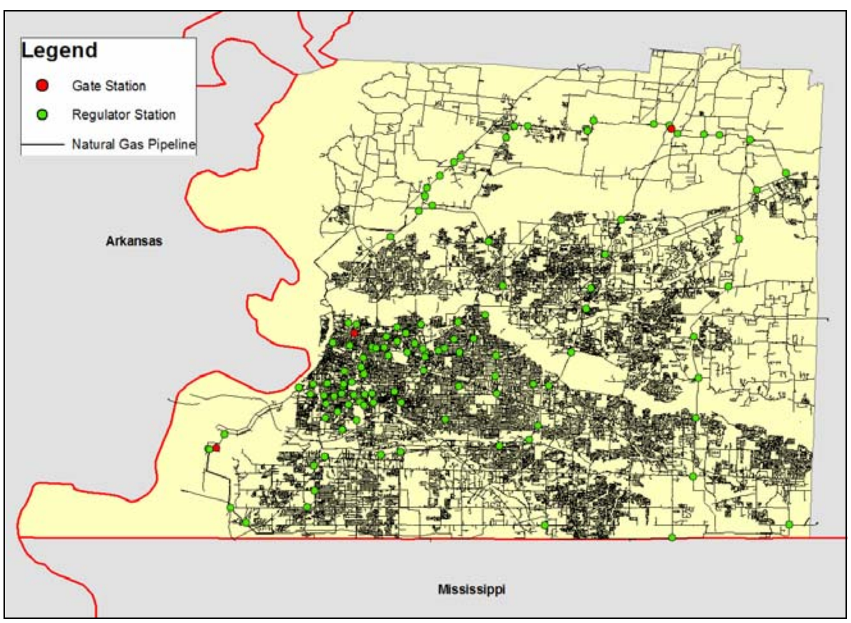

Figure 7: Shelby County Natural Gas Network

Electric power, water, and natural gas networks in Shelby County were also modeled topologically with the INA tool. The power distribution network was built by assigning substations as generation nodes and transformers as distribution nodes (Figure 8). Transformers clustered together were represented by a single distribution node with a total capacity obtained by summing the capacities of all transformers within the cluster.

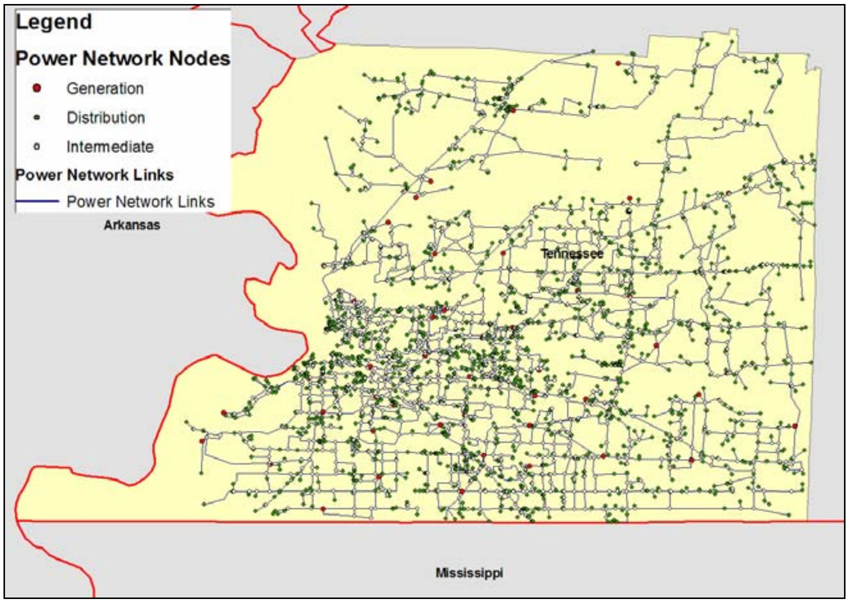

Figure 8: Shelby County Power Network, Topologically Modeled for the INA Tool

The water network was built using pipe segments with diameters of 12 inches or larger (Figure 9). Water wells are modeled as generation nodes; pumping plants and water tanks are modeled as distribution nodes for the water network.

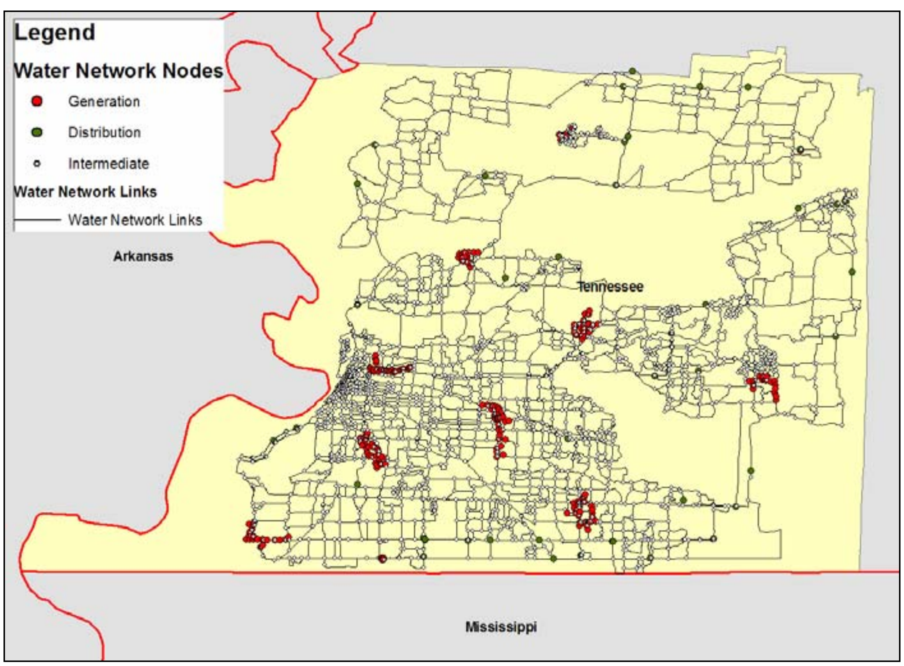

Figure 9: Shelby County Water Network, Topologically Modeled for the INA Tool

The natural gas network was built using pipe segments with diameters of 6 inches or larger (Figure 10). Gate stations were modeled as generation nodes, and pressure regulator stations were modeled as distribution nodes.

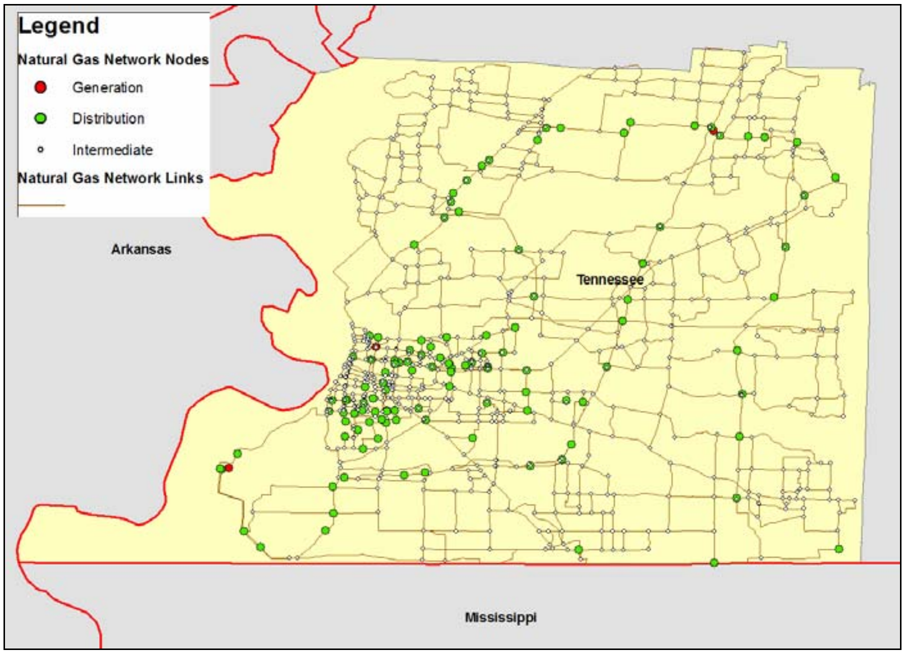

Figure 10: Shelby County Natural Gas Network, Topologically Modeled for the INA Tool

The supply and demand values for both water and natural gas networks were obtained from the web site of the company where general information about the company networks is given (MLGW, 2009b).

Analysis Results

The expected damage caused by the New Madrid Seismic Zone scenario is estimated at 165 repairs on the water network (Figure 11), and approximately 310 repairs on the natural gas network. In total, about 175 of these repairs are expected to be caused by pipe leaks, 305 by pipe breaks. Damage estimates for both water and natural gas pipelines are shown in Table 8. Expected damage due to the New Madrid Seismic Zone earthquake scenario is relatively low for the water facilities (Figure 12). All water facilities are expected to experience approximately 10% probability of at least moderate damage in St. Louis.

Table 8: St. Louis, Missouri Pipeline Damage

St. Louis Inventory	Total pipe length (miles)	Ground Shaking Induced Pipeline Repairs	Liquefaction Induced Pipeline Repairs	Total Leaks	Total Breaks
New Madrid Seismic Zone Scenario (Mw=7.7)					
Water Pipelines	1485	27	138	49	116
Natural Gas Pipelines	8622	102	211	124	189

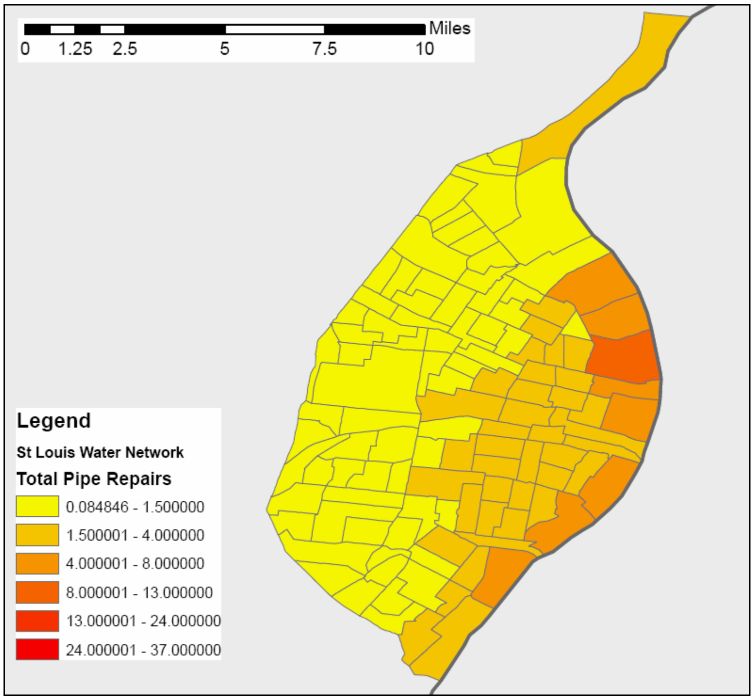

Figure 11: NMSZ Scenario Damage to St. Louis Water Network

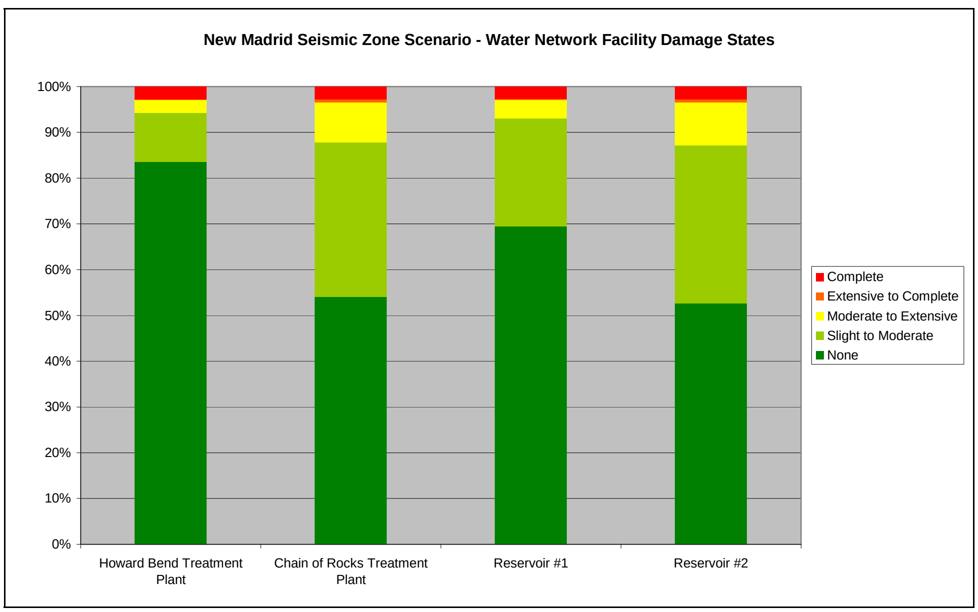

Figure 12: NMSZ Scenario Damage to St. Louis Water Network Facilities

Power facilities of St. Louis are expected to experience relatively little damage from the New Madrid Seismic Zone earthquake scenario. Damage due to scenario event is higher in facilities in the City of St. Louis or south, along Mississippi River (Figure 13). The NMSZ scenario gives results for the power network with C_L 2.5% and S_{FR} less than 1%; C_L for the water network is expected to be 7.7%, and S_{FR} to be 39.2% for the scenario.

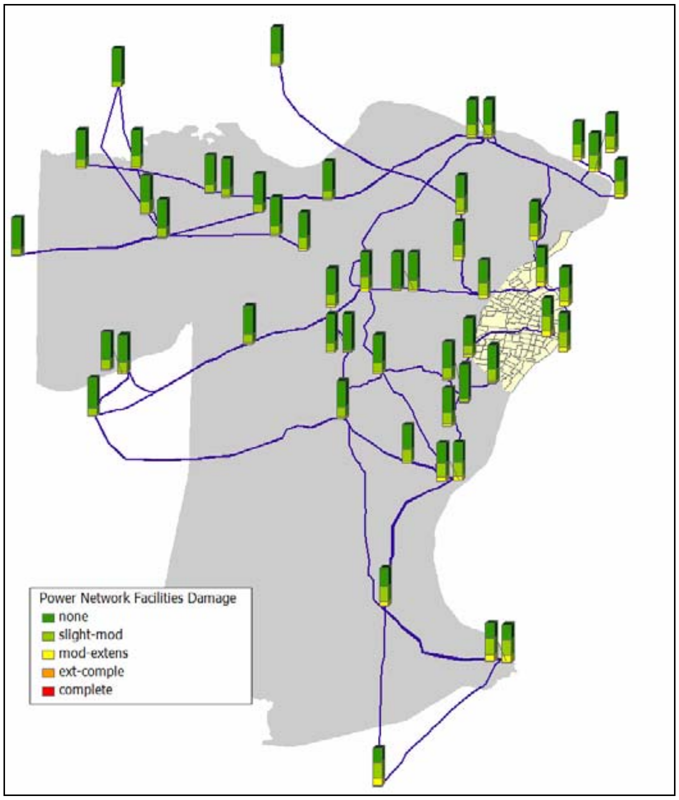

Figure 13: NMSZ Scenario Damage to St. Louis Power Network Facilities

Shelby County lifeline utility systems inventory was analyzed for the New Madrid Seismic Zone scenario. The damage from the scenario earthquake is expected to require 13,500 repairs in the water pipeline system (Figure 14), and a total of 9,000 repairs in the natural gas pipelines (Figure 15). Approximately 17,500 of the total repairs in the water and natural gas systems are due to liquefaction effects, whereas approximately 5,000 repairs are pipe leaks (Table 9).

Network facilities are expected to experience severe damage from the New Madrid Seismic Zone earthquake as well. All facilities in the power (Figure 16), natural gas (Figure 17), and water (Figure 18) networks are expected to have at least 50% probability of moderate damage or more because of the NMSZ scenario earthquake. Shelby County lifeline utility networks are expected to suffer severe damage and disruptions. Reduction in the natural gas network performance is quantified with C_L of 9.2% and S_{FR} of 75.8%. C_L for the water network is expected to be 99%; S_{FR} to be 96%.

Table 9: Memphis, Tennessee Pipeline Damage

Memphis Inventory	Total pipe length (miles)	Ground Shaking Induced Pipeline Repairs	Liquefaction Induced Pipeline Repairs	Total Leaks	Total Breaks
New Madrid Seismic Zone Scenario (Mw=7.7)					
Water Pipelines	4350	452	13097	2981	10568
Natural Gas Pipelines	6773	435	8606	2069	6972

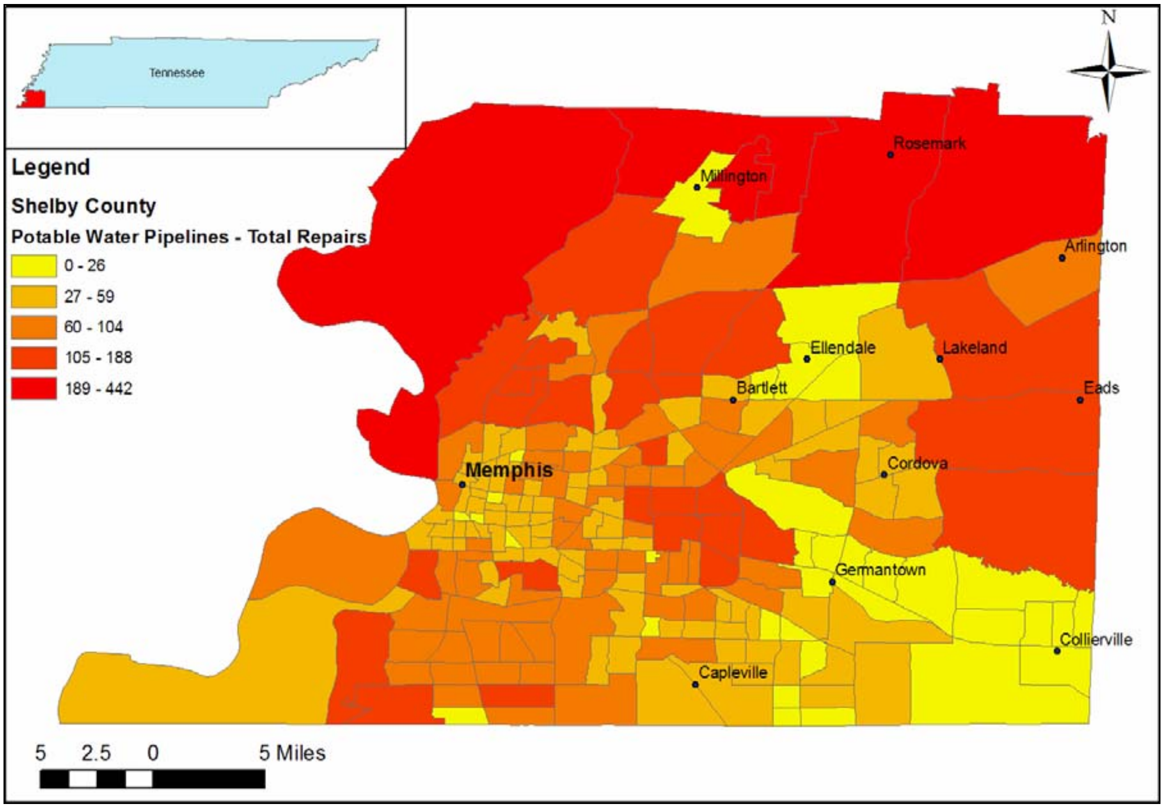

Figure 14: NMSZ Scenario Damage to Shelby County Water Pipelines

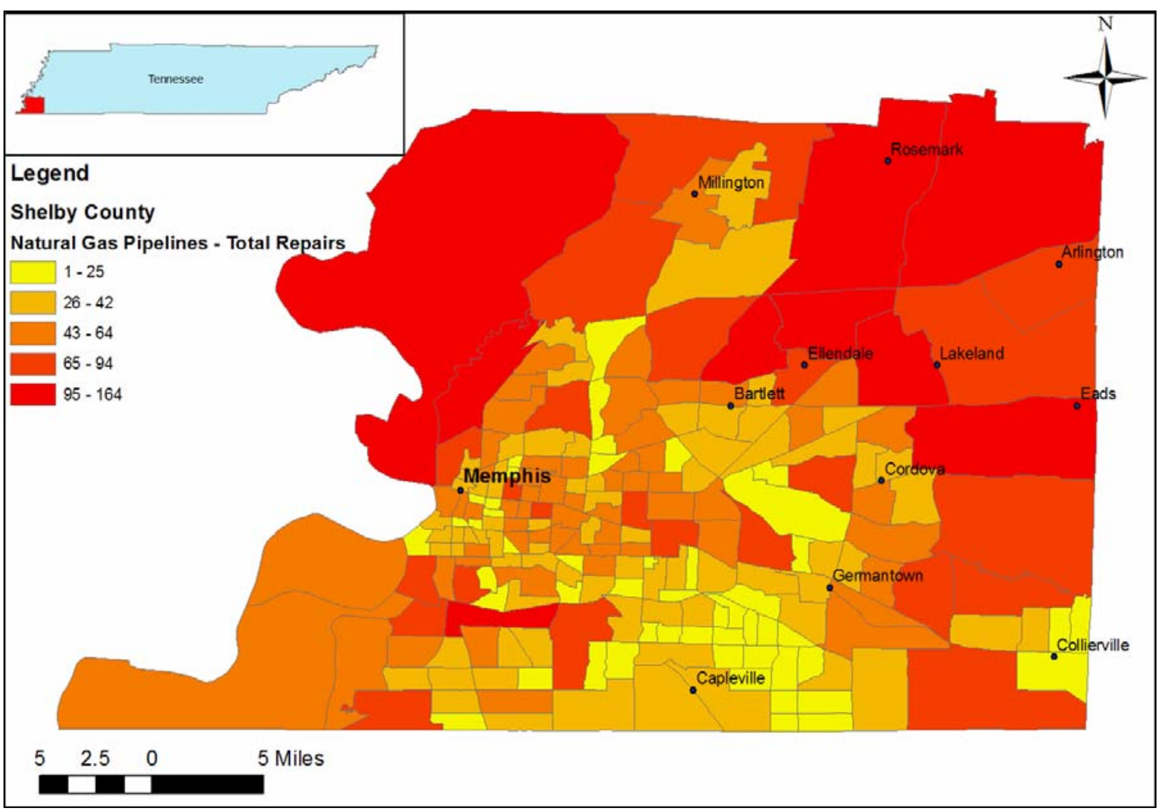

Figure 15: NMSZ Scenario Damage to Shelby County Natural Gas Pipelines

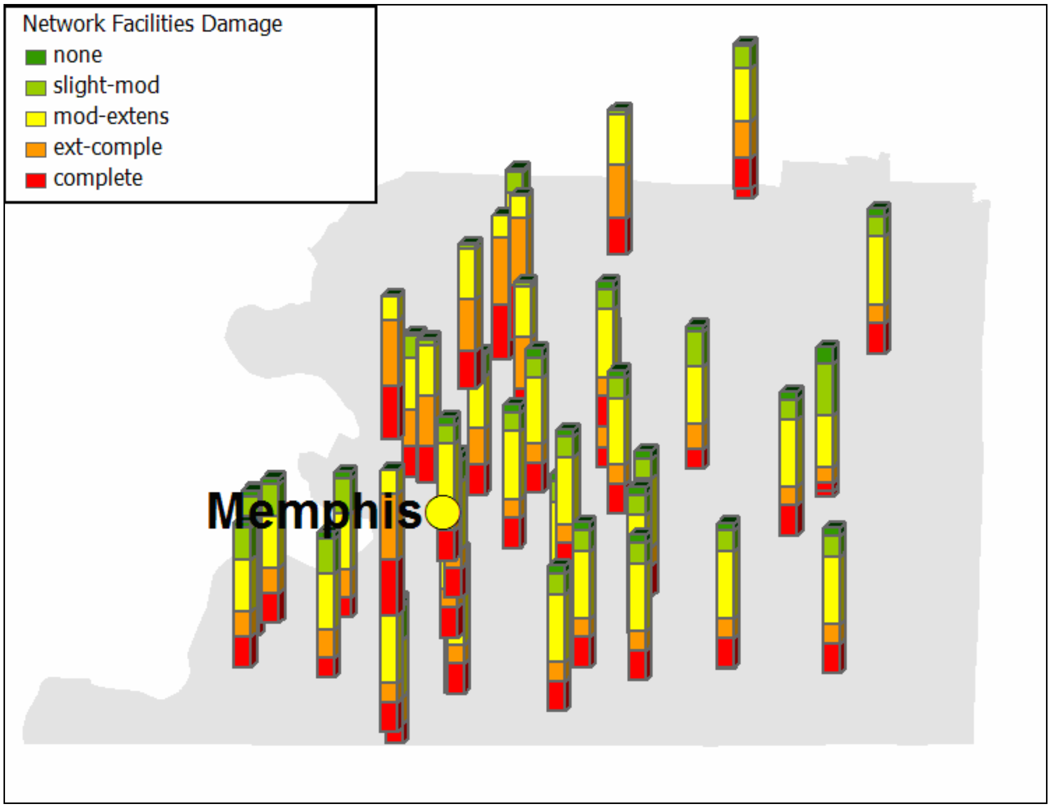

Figure 16: NMSZ Scenario Damage to Shelby County Electric Power Facilities

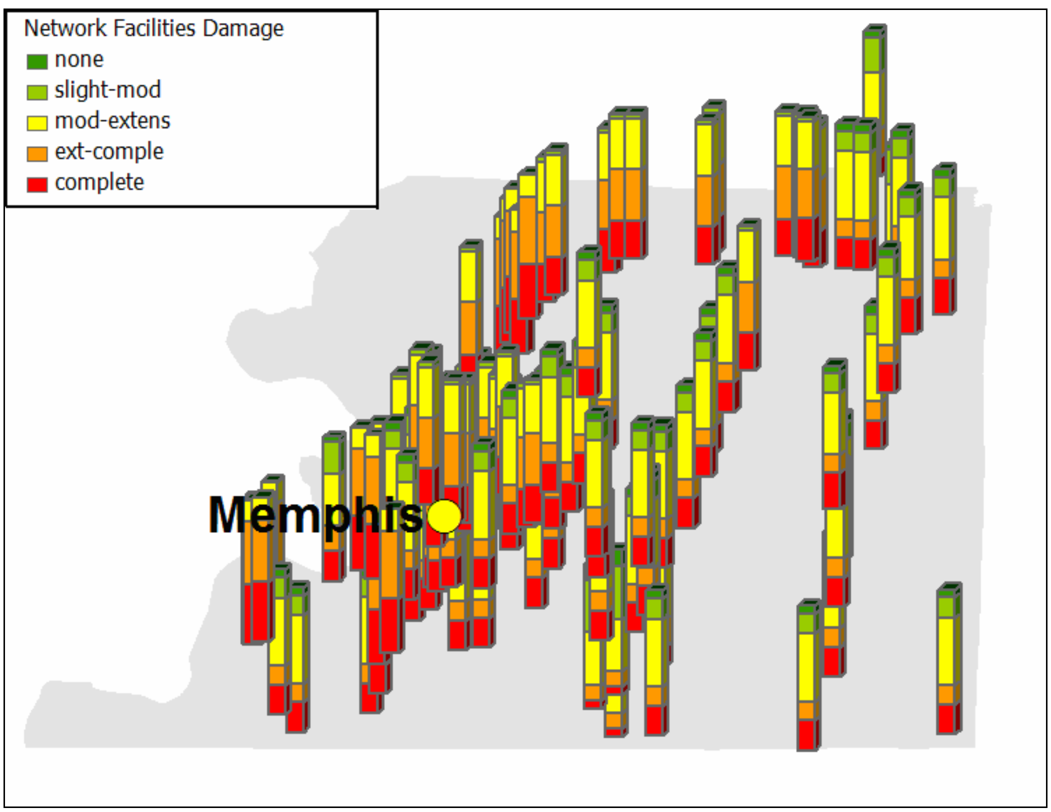

Figure 17: NMSZ Scenario Damage to Shelby County Natural Gas Facilities

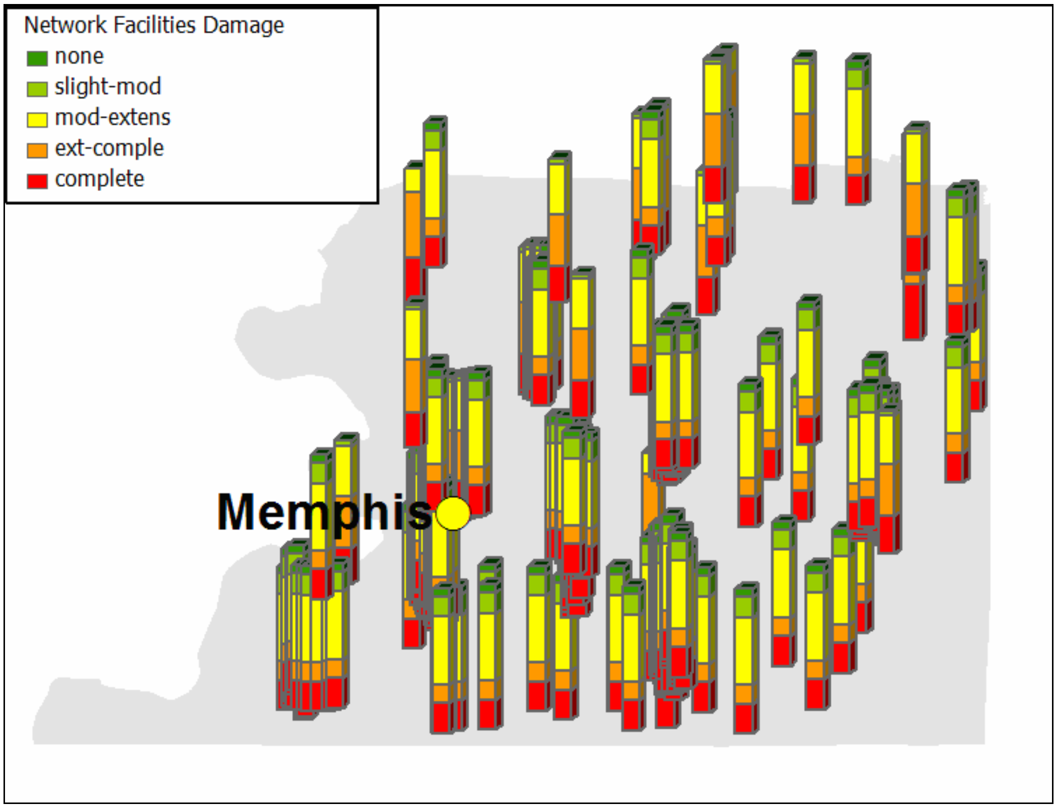

Figure 18: NMSZ Scenario Damage to Shelby County Water Facilities

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Appendix 11 – Uncertainty Characterization Method 1

Introduction

Due to the random nature of seismic hazards and the lack of complete knowledge or data, various types of uncertainties are inherent in regional seismic loss estimation, such as:

- Intrinsic randomness in seismic intensity (SI) measures such as spectral acceleration (S_a), peak ground acceleration (PGA), peak ground velocity (PGV), and permanent ground displacement (PGD), which is also referred to hazard characterization.
- Uncertainty in predicting the seismic performance of structures (e.g. exceedance of prescribed limit-states) and the number of damaged items (ND)
- Variations of damage-related measures (DM) such as damage factors, repair cost ratios, and reduced traffic capacities
- Statistical uncertainties of parameters that appear in socio-economic loss models
- Erroneous or outdated data in inventory databases
- Existence of multiple competing models

Therefore, deterministic regional seismic loss assessment may lead emergency managers to make decisions based on under- or overestimated loss due to unquantified risk. Currently, regional seismic loss assessment is often performed by use of computer software such as HAZUS and MAEviz, which consist of various computational modules connected by complex data flows. Therefore, in order to quantify the uncertainties in the estimated regional seismic losses, it is necessary to have a probabilistic framework that can propagate various uncertainties in inputs and models through such computational modules and data flows. As a preliminary effort toward the development and implementation of such a probabilistic regional loss assessment method, efficient computational procedures have been developed to propagate selected types of uncertainties. This document presents the computational procedures and the computer code developed for quantifying the uncertainties in HAZUS in an efficient manner. The results of this method's applications to eight states in the Central US are also presented.

Scope of Work

The goals of this study are to develop computational procedures that enable efficient uncertainty quantification within HAZUS, and to test the feasibility of the approach. For the sake of demonstration, this study deals with three types of uncertainties only: (1) the randomness in the seismic intensity (SI), (2) the uncertainty in the number of damaged items (ND), and (3) the variations of damage measures (DM). Table 1 shows HAZUS regional seismic loss measures that are affected by the three types of uncertainties. Due to the lack of information, the application examples in this study rely on assumed statistical parameters when real data are not readily available. Therefore, the quantified uncertainties of the final loss estimates shown in the examples may not necessarily represent the actual level of uncertainties.

Table 1: Regional Seismic Loss Measures and Uncertainties Considered in This Study

Regional Seismic Loss Measures	*Uncertainty Type*		
	Seismic Intensity (SI)	*Number of Damaged Items* (ND)	*Damage Measures* (DM)
Physical Loss			
• Number of damaged building	X	X	
Direct Economic Loss			
• Structural	X	X	X
• Non-structural	X	X	X
• Contents	X	X	X
• Inventory	X	X	X
Social Loss			
• Displaced households	X	X	X

There have been previous research efforts to quantify the uncertainties in regional seismic loss assessment. For example, Grossi (2000) proposed a logic tree method to quantify the uncertainties and to assess the sensitivity of HAZUS. This approach considers the bounds on uncertain parameters to estimate the propagated uncertainties in impacts. Although the approach helps identify the effects of individual uncertainties through parameter sensitivity analysis, it is generally time-consuming due to numerous runs of HAZUS. An alternative approach to consider is Monte Carlo simulations using randomly generated samples. The implementation of this approach is straightforward, but it may also require a large number of HAZUS simulations for reliable estimates. For efficient uncertainty quantification, this study attempts to develop an analytical approach that does not require repeated HAZUS simulations.

Methodology

Uncertainty Representation

In general, the variability of an uncertain quantity is represented by variance, standard deviation, or coefficient of variation (c.o.v.). For intuitive interpretation of the result, in this study, the uncertainty in the estimated losses is presented by a confidence interval, which is the interval around the expectation value (mean) for a given level of confidence. In this report, the seismic losses are assumed to follow log-normal distributions. Therefore, the interval with 'confidence level' $(1-\alpha)\times 100\%$ is determined as:

$$\begin{aligned} &\text{Confidence Interval} = \left[\exp(\lambda - k_{\alpha/2}\cdot\beta),\ \exp(\lambda + k_{\alpha/2}\cdot\beta)\right] \\ &\lambda = \ln\mu - 0.5\beta^2 \\ &\beta = \sqrt{\ln[1+(\sigma/\mu)^2]} \end{aligned} \tag{1}$$

where λ and β denote the logarithmic mean and logarithmic standard deviation of the loss, respectively; $k_{\alpha/2}$ is the standard normal variate with the cumulative probability level, $1-\alpha/2$, calculated by $k_{\alpha/2}=\Phi^{-1}(1-\alpha/2)$ in which $\Phi(\cdot)$ denotes the cumulative distribution function (CDF) of the standard normal distribution; and μ and σ denote the mean and the standard deviation of the loss, respectively.

Uncertainty Quantification

This subsection describes the methods used for propagating the three types of the uncertainties considered in this study. As a result, the means and standard deviations of the loss measures will be computed and then substituted into Equation (1) for the confidence intervals.

Uncertainty in Seismic Intensity (SI)

For a given earthquake scenario characterized by epicenter location and earthquake magnitude, HAZUS utilizes the spatial distribution of the corresponding seismic intensity measures (e.g. PGA, PGV, PGD, S_a) using attenuation models. These attenuated seismic intensity measures are subjected to both intrinsic randomness of physical parameters and uncertain errors in the mathematical models of ground motion attenuation relationships. According to Adachi and Ellingwood (2009), the c.o.v. of the variability caused by seismic attenuation models is typically 0.60 or more. In this study, the c.o.v.'s of the attenuated seismic intensity measures are assumed to be 0.60 for the numerical examples.

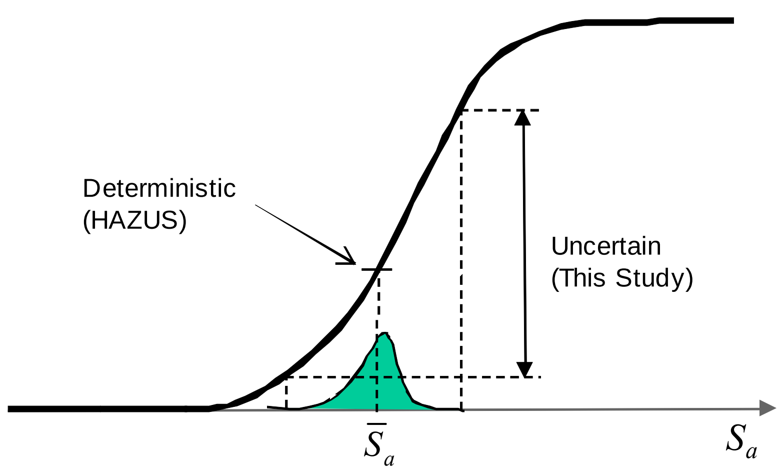

Figure 1: Uncertainty in Seismic Intensity and Fragility Evaluation

HAZUS does not consider uncertainty related to the fragility of a structure, i.e. the probability of limit state exceedance, is evaluated at the median value of the seismic intensity (shown as S_a) only, as illustrated in Figure 1: Uncertainty in Seismic Intensity and Fragility Evaluation. However, the uncertainty in the seismic intensity affects the actual exceedance probabilities as shown in the figure. This effect is considered in this study as follows.

According to the HAZUS Technical Manual (FEMA 2008a), the fragility is defined as the conditional probability of being in or exceeding a particular damage state, ds, given that a seismic intensity measure such as spectral acceleration, S_a, takes its median value, $\bar{S}_a$, i.e.:

$$P(\text{exceeds } ds \mid S_a = \bar{S}_a) = \Phi\left[\frac{1}{\beta_{ds}} \ln\left(\frac{\bar{S}_a}{\bar{S}_{a,ds}}\right)\right] \tag{2}$$

where, $\bar{S}_{a,ds}$ is the median value of spectral acceleration at which the building reaches the threshold of the damage state, ds; and β_{ds} is the logarithmic standard deviation of the spectral acceleration of the damage state. Herein, $\bar{S}_{a,ds}$ and β_{ds} are the parameters of a given fragility model. The uncertainty in the seismic intensity is incorporated by the total probability theorem (Ang and Tang 2006), that is:

$$P(\text{exceeds } ds) = \int_{-\infty}^{+\infty} P(\text{exceeds } ds \mid S_a) f_{S_a}(s_a) ds_a \tag{3}$$

in which $f_{S_a}(s_a)$ is the probability density function (PDF) of the spectral acceleration. If the seismic intensity measure is assumed to follow a lognormal distribution, the numerical integration in Equation (3) can be avoided by using a closed-form expression:

$$P(\text{exceeds } ds) = \Phi\left[\frac{1}{\sqrt{\beta_{ds}^2 + \beta_{Sa}^2}} \ln\left(\frac{\bar{S}_a}{\bar{S}_{a,ds}}\right)\right] \tag{4}$$

where β_{Sa} is the logarithmic standard deviation of S_a; and $\bar{S}_a$ is the median of S_a that can be obtained in terms of the logarithmic mean of S_a, i.e. $\bar{S}_a = \exp(\lambda_{S_a})$.

In this study, the HAZUS fragility calculations in Equation (2) are replaced with those in Equation (4) to account for the uncertainty in the seismic intensity. In order to illustrate the impact of this change, consider a fragility model with $\bar{S}_{a,ds} = 0.5$ and β_{ds} = 0.4. Suppose the spectral acceleration follows a lognormal distribution with β_{Sa} = 0.555 (c.o.v. 0.6). Figure 2 shows the fragilities in Equations (2) and (4) for a range of $\bar{S}_a$. If the uncertainty is not considered, the exceedance probability is overestimated when $\bar{S}_a > \bar{S}_{a,ds}$ and underestimated otherwise. This noticeable impact needs to be considered during the seismic loss estimation. In this study, the confidence intervals are obtained with and without consideration of the uncertainty in seismic intensity to investigate the effects.

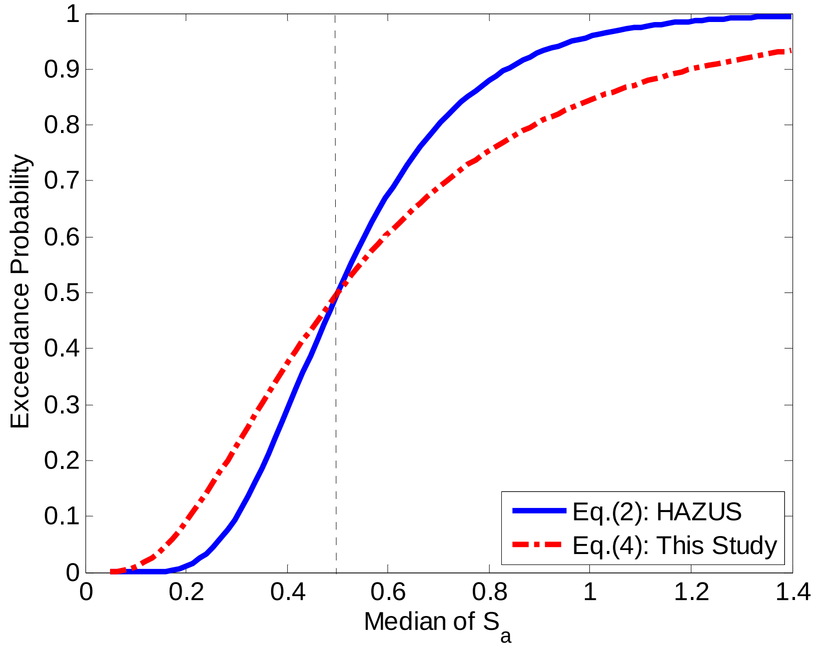

Figure 2: Effects of Uncertain Seismic Intensity on Fragility Evaluations

Uncertainty in Number of Damaged Buildings (ND)

The number of damaged buildings in a region is uncertain because of the uncertainty in damage states definition of the 36 building types. HAZUS computes the average number of the damaged buildings based on the fragility evaluations, and then substitutes them into various seismic loss models (see Table 1 for example loss measures) to provide deterministic loss estimates. In this study, the standard deviation of the number of damaged buildings is also computed to obtain the confidence intervals of the losses.

Using the exceedance probabilities in Equations (2) or (4), one can obtain the probability that a building is in one of the prescribed damage states, *ds*, i.e. no damage (N), slight (S), moderate (M), extensive (E), and complete (C) damage states. These damage state probabilities are computed by use of the fragilities as follows:

$$\begin{aligned} P(\mathrm{N}) &= 1 - P(\text{exceeds S}) \\ P(\mathrm{S}) &= P(\text{exceeds S}) - P(\text{exceeds M}) \\ P(\mathrm{M}) &= P(\text{exceeds M}) - P(\text{exceeds E}) \\ P(\mathrm{E}) &= P(\text{exceeds E}) - P(\text{exceeds C}) \\ P(\mathrm{C}) &= P(\text{exceeds C}) \end{aligned} \qquad (5)$$

First, consider the same type of buildings located in a given census tract. HAZUS assumes that the buildings in a census tract are located at the same coordinate. Therefore, these buildings have the same damage state probabilities. Although the spatial correlation of the seismic intensity causes the damage of the buildings to be statistically dependent, this study assumes statistical independence due to the lack of information about spatial correlation and the census-tract based aggregation by HAZUS. Because of the assumed independence and the equal probabilities of the damage states, the number of the buildings in a specified damaged state follows a binomial distribution (Ang and Tang 2006). Thus, the mean and variance of the number of damaged buildings are computed by:

$$\mu_{NDB_{ds,i,j}} = NB_{i,j} \times P(ds)_{i,j}$$
$$\sigma^2_{NDB_{ds,i,j}} = NB_{i,j} \times P(ds)_{i,j} \times \left[1 - P(ds)_{i,j}\right] \quad (6)$$

Where $NDB_{ds,i,j}$ denotes the number of the *i*-th type of buildings in the *j*-th census tract that are in the damage state *ds* (i.e., one of N, S, M, E and C); and $NB_{i,j}$ and $P(ds)_{i,j}$ denote the total number of the buildings and the probability of damage state *ds* for the *i*-th type of the buildings in the *j*-th census tract, respectively.

Next, assuming that the numbers of damaged buildings between different types, census tracts and damage states are also statistically independent, the mean and variance of the number of the damaged buildings over all the census tracts in a given region and all the types of buildings are computed as:

$$\mu_{NDB_{ds}} = \sum_i \sum_j \mu_{NDB_{ds,i,j}}$$
$$\sigma^2_{NDB_{ds}} = \sum_i \sum_j \sigma^2_{NDB_{ds,i,j}} \quad (7)$$

Uncertainty in Damage Measures (DM)

For a given damage state, damage related measures such as damage factor and repair cost ratio have a certain level of variability. As shown in Figure 3(a), however, HAZUS assigns a single repair cost ratio value to each of the prescribed damage states, i.e. None, Slight, Moderate, Extensive, and Complete to calculate the seismic losses, which neglects the variability in the repair cost. In an effort to account for this uncertainty in the seismic loss estimations by Mid-America Earthquake Center, Bai et al. (2009) proposed to assume that the repair cost ratio follows the beta distribution with its mean at the midpoint of the range and the standard deviation of one-fifth of the length of the range.

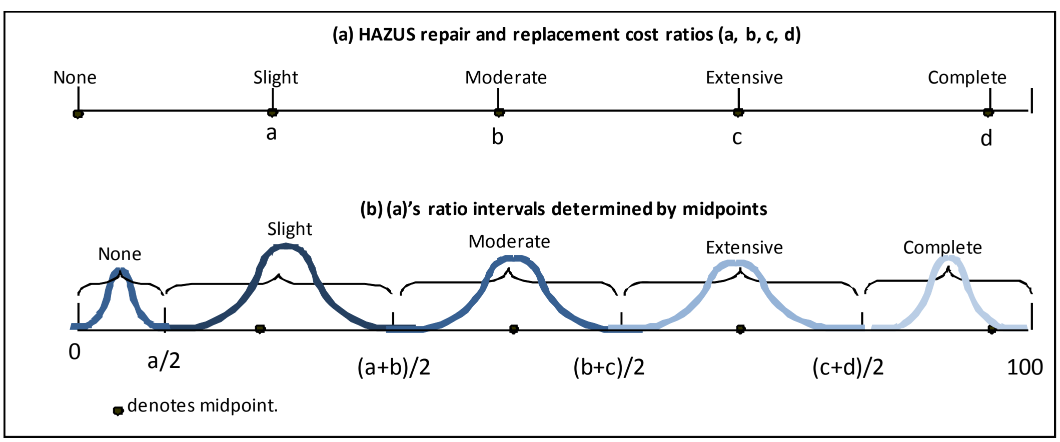

Figure 3: Probabilistic Model for HAZUS Repair and Replacement Cost Rations

Following this approach, this study assigns the beta distribution to each of the five damage states as shown in Figure 3(b). The standard deviations of various loss estimates using damage related measures are computed to obtain the confidence intervals. For example, the mean and variance of the direct economic loss in the structural components of the *i*-th type of the buildings, denoted by SEL_i, are calculated as:

$$\begin{aligned} \mu_{SEL_i} &= BRC_i \times \sum_{ds} \left[P(ds)_i \times \mu_{RCR_i|ds} \right] \\ \sigma^2_{SEL_i} &= BRC_i^2 \times \sum_{ds} \left[P(ds)_i \cdot \mu_{RCR_i^2|ds} \right] - \mu^2_{SEL_i} \\ &= BRC_i^2 \times \sum_{ds} \left\{ P(ds)_i \cdot \left[\sigma^2_{RCR_i|ds} + \mu^2_{RCR_i|ds} \right] \right\} - \mu^2_{SEL_i} \end{aligned} \quad (8)$$

Where BRC_i and $\mu_{RCRi|ds}$ denote the building replacement cost and the mean repair cost ratio for the damage state, *ds*, for the *i*-th type of the buildings, respectively; and $\sigma^2_{RCRi|ds}$ is the variance of the repair cost ratio for the damage state, *ds*. Assuming statistical independence between the economical losses of the damaged buildings again, the mean and variance of the total economical losses in the region are computed by summing up the individual means and variances as in Equation (7).

Development of Semi-Automated Tool

For efficient applications of the procedures explained in the previous section, a semi-automated computing tool was developed using Matlab®. Using the developed code, the following two tasks are performed:

Import HAZUS data: HAZUS is an ArcGIS-based program with a standard MS Windows interface. The HAZUS user-interface is illustrated in Figure 4 (left) while the results database for a HAZUS analysis is shown in Figure 4 (right). The necessary data was manually extracted from ArcGIS and stored in data files. The newly created data files were imported into the computer code and uncertainty calculations were performed.
Quantify uncertainties: The uncertainty analysis code quantifies the uncertainties in the seismic impacts based on the HAZUS data using the procedures discussed in the previous section. Figure 5 shows the input code and the confidence intervals determined within the uncertainty analysis code.

After a single run of HAZUS, it requires less than 10 minutes to complete these calculations for each state in the eight-state study region using a personal computer with 2.6GHz CPU and 2GB RAM memory.

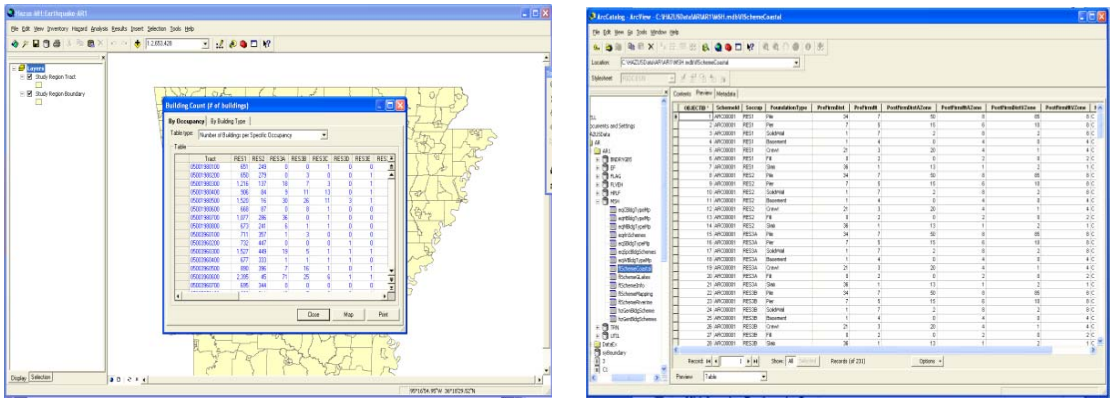

Figure 4: HAZUS User-Interface (Left) and Model Results Database in ArcCatalog (Right)

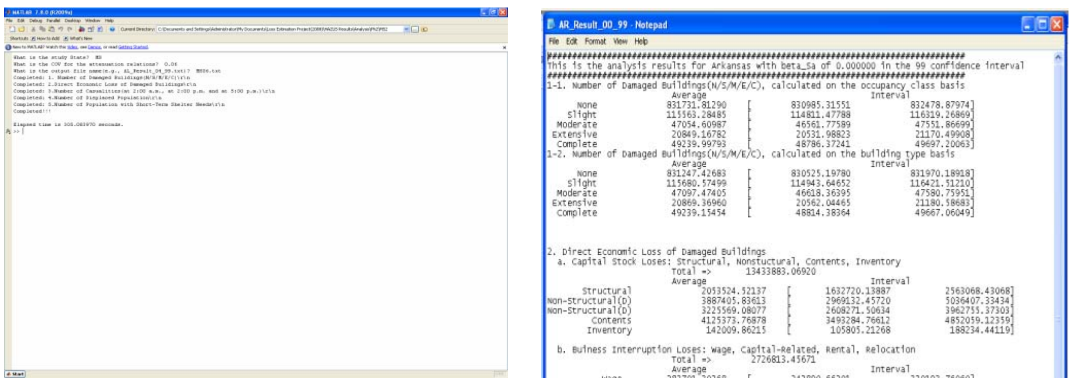

Figure 5: Input (Left) and Output (Right) Matlab® Code for Uncertainty Analysis

Application to the Central US

Using the new uncertainty methodology, the uncertainties in regional loss estimates are quantified for the eight states in the Central US. Substituting the means and standard deviations (i.e. the square roots of the variances) computed by the aforementioned procedures into Equation (1), 90% confidence intervals ($\alpha = 0.10$) are computed for three types of HAZUS regional impacts: number of damaged buildings (five damage states: none, slight, moderate, extensive, complete), capital stock loss (four types), and number of displaced households. The results for the eight states are given in the following tables. In Table 2 thru Table 25, "*SI*" and "*No SI*" indicate the cases in which the uncertainty in the seismic intensity is considered and those in which not considered, respectively. "L/B" and "U/B" denote the lower and upper bounds of the confidence intervals, respectively.

As stated earlier, this study focuses on developing an efficient uncertainty quantification framework for HAZUS and testing its feasibility, rather than investigating the exact level of the uncertainties in the study region. More research efforts are required to quantify the uncertainties that have not been considered in this study and to obtain the realistic values for all parameters with assumed values in this study. It was observed that some of the deterministic loss estimation results in HAZUS do not match with the average values calculated externally based on the methodology outlined in the HAZUS Technical Manual. Various discrepancies between the HAZUS methodology outlined in the Technical Manual and HAZUS model outputs are currently under investigation by the HAZUS developers.

Alabama

Table 2: Number of Damaged Buildings

Damage State	*No SI*			***SI***		
	Mean	L/B	U/B	Mean	L/B	U
None	1,704,917	1,704,612	1,705,223	1,704,814	1,704,508	1,705,120
Slight	38,048	37,774	38,323	25,730	25,482	25,979
Moderate	10,831	10,669	10,993	21,867	21,650	22,085
Extensive	729	686	774	5,376	5,260	5,494
Complete	3,822	3,722	3,923	560	522	600
Total	**1,758,347**	**1,757,463**	**1,759,237**	**1,758,347**	**1,757,422**	**1,759,279**

Table 3: Direct Economic Loss - Capital Stock Loss (in thousands of dollars)

Type	*No SI*			*SI*		
	Mean	L/B	U/B	Mean	L/B	U/B
Structural	196,075	100,854	333,912	133,049	101,923	169,572
Non-Str.	928,536	592,864	1,378,729	597,709	489,732	722,722
Contents	552,814	408,220	726,036	404,150	347,262	466,580
Inventory	17,672	9,241	29,779	13,399	9,857	17,653
Total	**1,695,097**	**1,111,179**	**2,468,456**	**1,148,307**	**948,773**	**1,376,527**

Table 4: Number of Displaced Households

Type	*No SI*			*SI*		
	Mean	L/B	U/B	Mean	L/B	U/B
Displaced HH	3,504	1,100	7,819	40	0	90

Arkansas

Table 5: Number of Damaged Buildings

Damage State	*No SI*			***SI***		
	Mean	L/B	U/B	Mean	L/B	U/B
None	1,013,454	1,012,920	1,013,988	1,056,896	1,056,323	1,057,468
Slight	149,672	149,127	150,218	97,429	96,960	97,900
Moderate	68,446	68,074	68,818	88,685	88,251	89,121
Extensive	23,089	22,862	23,317	43,097	42,785	43,411
Complete	70,699	70,351	71,049	39,253	38,981	39,526
Total	**1,325,360**	**1,323,334**	**1,327,391**	**1,325,360**	**1,323,300**	**1,327,425**

Table 6: Direct Economic Loss - Capital Stock Loss (in thousands of dollars)

Type	*No SI*			*SI*		
	Mean	L/B	U/B	Mean	L/B	U/B
Structural	2,747,869	2,326,131	3,214,819	1,924,215	1,624,070	2,257,121
Non-Str.	9,674,394	8,442,820	11,015,166	6,551,656	5,721,300	7,455,072
Contents	4,687,920	4,206,012	5,203,233	2,908,478	2,628,766	3,206,247
Inventory	163,425	133,060	197,822	86,952	72,034	103,682
Total	**17,273,608**	**15,108,024**	**19,631,040**	**11,471,301**	**10,046,170**	**13,022,121**

Table 7: Number of Displaced Households

Type	*No SI*			*SI*		
	Mean	L/B	U/B	Mean	L/B	U/B
Displaced HH	37,798	26,305	52,027	20,978	11,785	33,640

Illinois

Table 8: Number of Damaged Buildings

Damage State	*No SI*			***SI***		
	Mean	L/B	U/B	Mean	L/B	U/B
None	3,548,303	3,547,830	3,548,777	3,557,095	3,556,618	3,557,572
Slight	62,798	62,371	63,228	46,346	45,942	46,753
Moderate	18,128	17,908	18,351	31,723	31,411	32,039
Extensive	5,224	5,108	5,343	11,239	11,052	11,430
Complete	21,366	21,116	21,619	9,416	9,278	9,557
Total	**3,655,820**	**3,654,335**	**3,657,316**	**3,655,820**	**3,654,301**	**3,657,351**

Table 9: Direct Economic Loss - Capital Stock Loss (in thousands of dollars)

Type	*No SI*			*SI*		
	Mean	L/B	U/B	Mean	L/B	U/B
Structural	983,520	715,893	1,330,148	726,395	575,294	911,879
Non-Str.	4,516,494	3,597,625	5,610,852	2,712,808	2,288,222	3,199,178

Contents	2,503,716	2,136,073	2,908,965	1,810,058	1,591,075	2,047,211
Inventory	46,316	33,079	62,507	34,949	23,725	49,108
Total	**8,050,045**	**6,482,670**	**9,912,472**	**5,284,210**	**4,478,315**	**6,207,376**

Table 10: Number of Displaced Households

Type	*No SI*			*SI*		
	Mean	L/B	U/B	Mean	L/B	U/B
Displaced HH	19,686	11,144	32,020	5,689	2,045	11,868

Indiana

Table 11: Number of Damaged Buildings

Type	*No SI*			***SI***		
	Mean	L/B	U/B	Mean	L/B	U/B
None	2,147,985	2,147,664	2,148,305	2,147,857	2,147,537	2,148,178
Slight	40,096	39,807	40,387	29,415	29,148	29,683
Moderate	6,419	6,295	6,544	18,474	18,271	18,680
Extensive	767	724	812	4,851	4,740	4,963
Complete	6,762	6,634	6,891	1,432	1,378	1,486
Total	**2,202,029**	**2,201,124**	**2,202,940**	**2,202,029**	**2,201,074**	**2,202,990**

Table 12: Direct Economic Loss - Capital Stock Loss (in thousands of dollars)

Type	*No SI*			*SI*		
	Mean	L/B	U/B	Mean	L/B	U/B
Structural	366,867	213,242	576,109	213,533	148,609	293,916
Non-Str.	1,918,063	1,363,772	2,610,769	1,039,256	868,961	1,235,508
Contents	1,140,712	870,520	1,458,435	758,028	661,799	862,632
Inventory	30,738	16,116	51,707	21,257	15,248	28,574
Total	**3,456,380**	**2,463,650**	**4,697,020**	**2,032,075**	**1,694,617**	**2,420,630**

Table 13: Number of Displaced Households

Type	*No SI*			*SI*		
	Mean	L/B	U/B	Mean	L/B	U/B
Displaced HH	6,839	2,859	13,185	501	16	1,905

Kentucky

Table 14: Number of Damaged Buildings

Damage State	*No SI*			***SI***		
	Mean	L/B	U/B	Mean	L/B	U/B
None	1,426,376	1,426,027	1,426,724	1,447,048	1,446,684	1,447,411
Slight	57,067	56,715	57,423	40,111	39,796	40,429
Moderate	27,592	27,374	27,812	27,731	27,480	27,984
Extensive	10,497	10,350	10,644	14,794	14,616	14,973
Complete	22,382	22,174	22,590	14,230	14,074	14,387
Total	**1,543,913**	**1,542,640**	**1,545,193**	**1,543,913**	**1,542,652**	**1,545,184**

Table 15: Direct Economic Loss - Capital Stock Loss (in thousands of dollars)

Type	*No SI*			*SI*		
	Mean	L/B	U/B	Mean	L/B	U/B
Structural	1,564,005	1,309,817	1,847,257	1,098,627	894,197	1,330,297
Non-Str.	5,901,227	5,107,143	6,773,972	4,591,233	3,961,158	5,285,254
Contents	3,046,435	2,754,434	3,358,235	2,149,174	1,929,635	2,384,945
Inventory	98,203	85,013	112,694	62,146	50,952	74,873
Total	**10,609,869**	**9,256,408**	**12,092,157**	**7,901,179**	**6,835,942**	**9,075,368**

Table 16: Number of Displaced Households

Type	*No SI*			*SI*		
	Mean	L/B	U/B	Mean	L/B	U/B
Displaced HH	19,678	11,184	31,379	14,256	7,152	24,663

Mississippi

Table 17: Number of Damaged Buildings

Damage State	*No SI*			*SI*		
	Mean	L/B	U/B	Mean	L/B	U/B
None	943,748	943,391	944,104	945,839	945,479	946,200
Slight	62,822	62,481	63,166	48,441	48,117	48,768
Moderate	27,509	27,283	27,736	34,038	33,767	34,309
Extensive	7,616	7,484	7,749	14,824	14,638	15,012
Complete	22,317	22,093	22,542	20,868	20,684	21,053
Total	**1,064,011**	**1,062,731**	**1,065,296**	**1,064,011**	**1,062,731**	**1,065,342**

Table 18: Direct Economic Loss - Capital Stock Loss (in thousands of dollars)

Type	*No SI*			*SI*		
	Mean	L/B	U/B	Mean	L/B	U/B
Structural	1,116,907	845,603	1,437,383	1,164,621	996,481	1,349,608
Non-Str.	3,803,131	2,948,867	4,802,165	1,953,231	1,576,212	2,383,041
Contents	1,779,599	1,465,427	2,133,159	785,866	655,525	931,441
Inventory	54,610	42,041	69,316	22,424	17,330	28,372
Total	**6,754,247**	**5,301,938**	**8,442,023**	**3,926,142**	**3,245,547**	**4,692,462**

Table 19: Number of Displaced Households

Type	*No SI*			*SI*		
	Mean	L/B	U/B	Mean	L/B	U/B
Displaced HH	21,066	12,343	32,899	3,385	700	8,971

Missouri

Table 20: Number of Damaged Buildings

Damage State	*No SI*			***SI***		
	Mean	L/B	U/B	Mean	L/B	U/B
None	1,926,490	1,925,908	1,927,073	1,944,164	1,943,557	1,944,771
Slight	88,516	87,978	89,058	74,601	74,078	75,127
Moderate	34,890	34,571	35,211	50,204	49,803	50,607
Extensive	8,129	7,980	8,281	20,039	19,790	20,291
Complete	43,818	43,478	44,162	12,836	12,659	13,016
Total	**2,101,844**	**2,099,915**	**2,103,784**	**2,101,844**	**2,099,888**	**2,103,812**

Table 21: Direct Economic Loss - Capital Stock Loss (in thousands of dollars)

Type	*No SI*			*SI*		
	Mean	L/B	U/B	Mean	L/B	U/B
Structural	1,962,947	1,602,509	2,402,227	1,069,467	880,506	1,286,680
Non-Str.	7,299,203	6,136,664	8,668,842	4,018,611	3,497,444	4,596,271
Contents	3,639,147	3,195,093	4,141,954	2,176,614	1,968,615	2,399,459
Inventory	105,794	84,901	132,335	58,871	48,852	70,513
Total	**13,007,091**	**11,019,166**	**15,345,358**	**7,323,563**	**6,395,418**	**8,352,923**

Table 22: Number of Displaced Households

Type	*No SI*			*SI*		
	Mean	L/B	U/B	Mean	L/B	U/B
Displaced HH	37,816	24,857	55,187	12,061	5,627	21,789

Tennessee

Table 23: Number of Damaged Buildings

Damage State	*No SI*			***SI***		
	Mean	L/B	U/B	Mean	L/B	U/B
None	1,604,401	1,603,874	1,604,928	1,649,022	1,648,461	1,649,584
Slight	258,036	257,382	258,692	147,512	146,955	148,070
Moderate	120,266	119,779	120,755	167,233	166,667	167,800
Extensive	37,010	36,721	37,300	85,099	84,668	85,532
Complete	106,914	106,459	107,371	77,762	77,366	78,159
Total	**2,126,628**	**2,124,215**	**2,129,046**	**2,126,628**	**2,124,117**	**2,129,144**

Table 24: Direct Economic Loss - Capital Stock Loss (in thousands of dollars)

Type	*No SI*			*SI*		
	Mean	L/B	U/B	Mean	L/B	U/B
Structural	7,420,497	6,684,018	8,206,145	7,501,085	6,872,165	8,165,108
Non-Str.	26,003,320	23,719,829	28,422,781	18,913,272	17,417,357	20,487,754
Contents	12,319,514	11,487,022	13,189,054	7,032,448	6,550,207	7,536,480
Inventory	388,471	350,043	429,457	180,643	159,528	203,439
Total	**46,131,803**	**42,240,912**	**50,247,436**	**33,627,448**	**30,999,256**	**36,392,782**

Table 25: Number of Displaced Households

Type	*No SI*			*SI*		
	Mean	L/B	U/B	Mean	L/B	U/B
Displaced HH	103,925	80,851	130,762	71,566	50,859	96,910

Conclusion & Discussion

In this study, computational procedures were developed to quantify selected types of uncertainties in the seismic loss estimates completed with HAZUS. For efficient applications, a semi-automated computing tool was developed. In order to test the feasibility of the developed framework, the new methods were applied to seismic loss estimation for eight states in the Central US. In order to quantify the level of uncertainty in seismic loss estimates, further research should be conducted on the following topics:

Effect of spatial correlation: Despite the significant impact of the spatial correlation on the loss estimates of spatially distributed system or structures (Adachi and Ellingwood 2009, Song and Ok 2009), this study did not consider the spatial correlation.
Generalization: The developed framework for uncertainty quantification can be generalized to other types of infrastructure systems (e.g., lifeline networks) and hazard (e.g., flood, wind).
Implementation into HAZUS: In this study, a semi-automated tool was developed for uncertainty quantification HAZUS results, but eventually, such a process should be implemented in HAZUS. This may give rise to some computations, GIS, or database issues, which will require further research efforts.
Other types of uncertainties: This study does not cover other types of uncertainties such as statistical uncertainties of the parameters in loss-estimation models, erroneous or outdated data in inventory databases, and model errors. A sensitivity analysis is needed to identify relatively important uncertainties that must be considered during a regional seismic loss assessment.

Decision makers, intuitively or from experience, understand that any loss estimate is subjected to uncertainties and thus includes the risk of under- or over-estimation. Therefore, it is important for loss assessment software to provide uncertainty quantifications for risk-informed decision making. However, there has not been a great deal of research efforts to systematically quantify the uncertainties in loss estimation software, namely HAZUS. This study demonstrates that it is possible to efficiently quantify the uncertainties without repeated runs of HAZUS. More research efforts are needed to quantifying actual level of the uncertainties and for further implementation in the HAZUS software.

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Appendix 12 – Uncertainty Characterization Method 2

Introduction

The HAZUS (Federal Emergency Management Agency, 2008) impact estimation methodology does not consider uncertainty inherent in performing hazard analysis, collecting inventory data, and evaluating seismic response and capacity of the built environment. In general, it is mandatory to predict the impact of a natural hazard with the consideration of uncertainty. Seismic hazard especially includes large uncertainty in its magnitude, peak ground parameters, frequency content and duration of ground motion, among others. Moreover, seismic hazard in low and moderate seismicity regions includes significant uncertainty due to the relative lack of earthquake data (records) available for statistical analysis. Therefore, it is necessary to include various uncertainties in performing earthquake impact assessments for realistic predictions and better informed decision making.

Uncertainty propagation can be systematically analyzed by probabilistic approaches. For an uncertainty analysis, the Monte Carlo simulation process is widely used since it gives reliable estimates without any approximation of the input distributions. In general, however, it requires large samples and significant computing time. Thus, several different approaches have been proposed as alternative methods for obtaining reliable results with reduced computational effort. This study discusses a simple approximate approach which can be implemented for estimating uncertainty propagation with HAZUS information. This report addresses the proposed probabilistic estimation procedure and shows earthquake impacts for eight states in the Central US using the proposed approach.

Uncertainties in Earthquake Impact Assessment

The limited scientific information for defining the hazard, low quality data used to define the exposed inventory, and limited engineering information available for estimating infrastructure damage result reinforce the need for error bounds when estimating expected impacts. In regions where earthquakes are low-probability, high-consequence events, decision-making should not be based solely on mean estimates of loss, as is the case with HAZUS deterministic scenarios, but should consider the error bounds or confidence limits in addition to calculating the mean value, because there is large uncertainty in the earthquake event (Grossi et al, 1999).

Uncertainties are generally classified as either aleatory or epistemic (Kiureghian and Ditlevsen, 2009). Aleatory uncertainty is due to the natural variability and the inherent randomness of the physical system. The size, location, and time of future earthquakes, as well as the characteristics of the ensuing ground motions, are examples of aleatory uncertainty. Epistemic uncertainty is due to a lack of knowledge or missing information.

The shape of the magnitude distribution for a given seismic source is an example of epistemic uncertainty. The important distinction between the two uncertainties is that aleatory uncertainty cannot be reduced, whereas epistemic uncertainty can be reduced by more knowledge or by more complete data. In some cases, aleatory uncertainty in one model may be epistemic uncertainty in another model, and what appears to be aleatory uncertainty at the present time may be cast into epistemic uncertainty at a later stage of development (Hanks and Cornell, 1994). It is mathematically advantageous to separate uncertainty into aleatory and epistemic types. Separating aleatory and epistemic uncertainties avails of an understanding of how to control uncertainty leading to better informed decision-making (Vose, 2008).

Earthquake impact estimation requires seismic hazard, structural response, damage fragility, inventory data, and cost data for repair and replacement. Uncertainties are included in all steps of the earthquake impact assessment procedure, from seismic hazard analysis to social and economic impact. Sources of uncertainty include: seismic source and path, soil condition, site response, response and capacity of structures and foundations, damage and loss assessment methodology, and inventory information. Regardless of the methodology employed, one of the most important aspects of constructing an earthquake impact model is to identify, quantify and incorporate into the estimates the uncertainties associated with each of the input parameters (Crowley et al, 2005). The major uncertainties embedded in seismic hazard, inventory, fragility, and repair cost are summarized below briefly.

Hazard

The seismic hazard is, in part, defined as the level ground shaking; peak ground acceleration (PGA) or response spectral acceleration (S_a) that is expected to occur at any site as the result of a fault rupture. The hazard can be predicted by physically modeling the source and by studying the recurrence of seismic events at the source, the propagation pattern of seismic waves, and the geological features at the site. The seismic hazard analysis should be accompanied by a measure of uncertainty since large uncertainty in the hazard definition may have a major influence on earthquake damage or loss estimations.

Uncertainty in seismic hazard originates from uncertainties in indentifying earthquake sources (size, source location, boundary definition, source seismicity, and mechanism), modeling the earthquake occurrence (source boundary, occurrence rate, maximum magnitude, and ground motion), estimating ground motion attenuation, and evaluating the effect of site soil amplification. This type of uncertainty is epistemic since it is reduced by gathering more data and improving theories on the physics of the earthquake process. The aleatory uncertainty in seismic hazard includes knowledge of future earthquakes and travel path since these parameters can not be quantified prior to a future event.

The shape of the hazard curve is determined by aleatory uncertainty and alternative hazard curves are given by the epistemic uncertainty. In general, the seismic hazard is modeled as a lognormal distribution (Reiter, 1991; US Department of Housing and Urban Development, 2003). The lognormal standard deviations for the earthquake source, transmission path, and local site response are estimated in previous studies as 0.30 (Newmark et al, 1973), 0.70 (Donovan, 1973), and 0.41 (Hays, 1980). For the New Madrid Seismic Zone (NMSZ) in the Central US, the coefficient of variation (c.o.v.) representing the epistemic uncertainty of PGA and S_a at 0.3 and 1.0 seconds can exceed 0.6, while c.o.v.'s for active seismicity locations in California are approximately 0.3 (Cramer, 2001). The larger c.o.v.'s for the NMSZ reflect greater uncertainties in scientific knowledge about seismic sources, especially the location of future major earthquakes (c.o.v. $\geq$ 0.6), and ground motion attenuation relations (c.o.v. $\approx$ 0.3).

Inventory

Inventory is a core component of earthquake impact assessment and is required to calculate infrastructure damage, direct economic and social losses associated with building stocks and lifelines. Inventory data are collected from many different sources, including the population and housing census, business population reports, energy consumption reports, and financial information from taxes, all of which provide a generalized regional statistical profile of inventory characteristics. HAZUS has a baseline data that consists of a nationwide buildings and essential facilities, transportation systems, lifeline utility systems, and hazardous material facilities inventories. The primary data source for population demographics is the U.S. 2000 Census, while general buildings data is taken from Dun & Bradstreet, and the reports from the Department of Energy (DOE) regarding the housing characteristics and energy consumption. Census data as well as Dun & Bradstreet data were used to develop the general building stock inventory that includes square footage, replacement value, building count, and population demographics metadata. The DOE reports define regional variations in characteristics such as number and size of garages, type of foundation, and number of stories. Building data are grouped by predefined building classes with similar damage and loss characteristics. The primary parameters in classifying damage/loss characteristics include the structural parameters affecting structural capacity and response (i.e., basic structural system, building height, and seismic design criteria), non-structural elements affecting non-structural damage, and occupancy affecting casualties, business interruption losses and damage to contents. In order to estimate total building damage and economic losses, each classification requires damage and loss estimation models that represent the average characteristics of the total population of buildings within each class.

Inventory includes epistemic uncertainties in its data sources and data standardization processes. Databases may include uncertainty due to incomplete or dated demographic, inventory, and economic parameters. Uncertainty contained in census information depends on the number of households that has been surveyed. For example, the margin of error for the number of one-unit detached homes in the American Community Survey (ACS) varied from 2.2% in Chicago, Illinois, to 7.4% in Champaign, Illinois. The margin of error for mobile home counts in Chicago, Illinois, is nearly 70%. The margin of error for the number of housing units according to the construction year is more than 40% in Champaign, Illinois (US Census Bureau, 2008). The population at the county level may increase or decrease with time. For example, there was a population growth of as large as 40% for nine years in San Benito County, California (California Governor's Office of Emergency Services, 2004). The epistemic uncertainty embedded in inventory data can be represented by the standard deviations of a normal distribution.

Fragility

A seismic fragility represents the performance of a structure or component subjected to earthquake ground motions, while fragility curves indicate the conditional probability of reaching or exceeding a limit state for a given seismic hazard level. Fragility curves can be obtained from empirical, judgmental, analytical, and hybrid approaches (Jeong and Elnashai, 2007). Empirical fragility curves (Shinozuka et al, 2000; Rossetto and Elnashai, 2003; Straub and Kiureghian, 2008) are constructed based on statistics of observed damage from past earthquakes. Empirical data are the most realistic though they are highly specific to particular situations and often provide limited statistical data. Thus, the empirical approach is in general very limited. Judgment-based fragility assessment (Applied Technology Council, 1985; National Institute of Building Sciences, 1995) is reliant upon information from experts. This method is not affected by the quantity and quality of damage statistics, but its reliability is unquantifiable due to its dependence on the individual experience of the experts. Analytical fragility curves (Shinozuka et al, 2000; Singhal and Kiremidjian, 1996; Ellingwood. 2001) require the structural response caused by various levels of ground shaking and the structural capacity defined by a damage state. This approach gives a more reliable estimate for different structures through elaborate modeling and comprehensive analyses. Analytical approaches usually adopt simplified models to reduce computation effort for modeling and simulating. Hybrid approaches (Barbat et al, 1996; Singhal and Kiremidjian, 1998; Kim and Shinozuka, 2004) attempt to compensate for the lack of observational data, subjectivity of judgmental data, and modeling deficiencies of analytical procedures by combining proper data from different sources. This method is effective for obtaining more reliable fragility curves when the available empirical data is limited.

All methods for constructing fragility curves contain uncertainties in the assessment procedures and data used. They include measurement uncertainty related to the observations, inconsistency in the quality of the analysis, variability of the ground motions, uncertainty in the judgment of experts, statistical uncertainty inherent in parameter estimates, uncertainty due to simplification of models for the strength and stiffness of structural materials and components, uncertainties in seismic demand and capacity of structures due to variations of their geometry and material properties, and uncertainty in the definition of the limit state.

Seismic fragility is typically modeled by lognormal distribution (Shinozuka et al, 2000; Kennedy and Ravindra, 1984). HAZUS provides baseline medians and standard deviations for four damage states (slight, moderate, extensive, and complete). For instance, uncertainty (i.e., epistemic uncertainty) in the damage-state threshold of the structural system is given by 0.4 for all structural damage states and building types. Variability (i.e., aleatory uncertainty) in capacity properties of the model building types are given by 0.25 for buildings designed with seismic code and 0.30 for buildings designed without seismic provisions.

Repair and Replacement Cost

Direct economic losses for buildings include costs for repair and replacement of structural systems, non-structural components, and building contents. These losses depend on both model building type and building occupancy class defined in inventory databases. Replacement cost of the individual building is estimated as the product of average replacement cost of a building per unit area and total floor area of a building for each combination of model building type and occupancy class. The repair cost and contents value for different damage ratios are expressed as a percentage of structural and non-structural replacement cost for each occupancy class.

Replacement cost is the amount needed to rebuild a building in the same location and with the same features and quality. The cost depends upon many variables such as size, shape, design features, materials, quality, heating, cooling, and geographic location of the building prior to the damage occurring. As a result, average replacement cost of a building is uncertain. Also, replacement cost includes uncertainties due to the variability in material and labor cost, the quality of construction, the productivity of the workers, etc. Moreover, the social and environmental impacts of earthquake damage and the simultaneous demand of materials and labor for post-earthquake reconstruction lead to extraordinary replacement costs. Estimates of replacement cost are dependent upon the year in which the cost data was developed, and thus appropriate inflation rates must be applied when obtaining estimates of future costs.

In order to estimate repair cost of each building component, HAZUS suggests the repair cost ratios of structural to non-structural components as well as damage ratios for building contents at different levels of damage as a percentage of the replacement cost. The repair cost and damage ratios themselves carry epistemic uncertainty, which can be modeled by lognormal distribution (Touran and Wiser, 1992; Touran, 1993). The c.o.v. for total repair costs is assumed to be in the range of 0.15 to 0.20 (RS Means Corp., 1997).

A Framework for Probabilistic Estimation

Direct economic loss estimation procedures for earthquake damage require seismic hazard information, inventory data, fragility curves, and repair cost. Inherently, each of the components must include uncertainty in its data or parameters as discussed previously. Thus, the inclusion of uncertainty in impact assessment seems to be of great importance in order to obtain more realistic estimates. In order to solve an uncertainty propagation problem in seismic impact assessment, recent studies propose a probabilistic estimation procedure that combines inputs of aleatory and epistemic uncertainty in seismic ground motion, building response, damage to building elements, and element repair costs (Baker and Cornell, 2008; Ching et al, 2004). The proposed method may require a large amount of computation time because its framework involves large vectors of dependent random variables. Therefore, a more simple and cost-effective framework is necessary for large-scale estimation. This study proposes a simple framework for probabilistic estimation of several outputs from a HAZUS earthquake impact assessment based on logic trees. The important advantages of the proposed approach are its simplicity and applicability through the use of a powerful numerical method to combine random variables and via information and data given by the HAZUS Technical Manual.

Simplified Framework

The HAZUS framework for earthquake impact assessment was developed for use by state, regional, and local governments. Initially, earthquake ground shaking is determined for each location within a region of interest (i.e., PGA, peak ground velocity (PGV), and S_a response parameters). Subsequently, the damage probabilities of buildings or other infrastructure are determined from fragility curves, either provided in HAZUS software or by the user, for different damage states. Total replacement value is estimated by multiplying the average replacement cost per structure by the number of structures. Repair costs for different damage states are determined by using the repair cost ratios, which are offered as a percentage of replacement cost for different damage states and the total replacement value. Economic loss for each damage state is calculated by multiplying the damage probability times the repair cost for each damage state, and total economic loss is estimated by a summation of repair costs for all damage states.

A proposed, simple framework for probabilistic assessment is developed based on the HAZUS methodology as follows:

$$C_R = \int_p \int_q \int_r \int_s f_{RC}(p)\, f_{IN}(q)\, f_{SF}(r) h_{IM}(s) dp\, dq\, dr\, ds \tag{1}$$

where, C_R is the expected repair cost (i.e., direct economic loss), $f_{RC}(p)$ is the probability density function (PDF) of repair costs given by damage states, $f_{IN}(q)$ is the PDF of inventory data, $f_{SF}(r)$ is the PDF of mean seismic fragility given by damage states, and $h_{IM}(s)$ is the PDF of the seismic intensity.

Fragility Model

Seismic fragility of a structure is defined as the conditional frequency of its failure for a given value of the seismic response parameter such as story drift, stress, moment, or structural acceleration. Fragility analysis evaluates the ground acceleration capacity of a structure and determines when the seismic response of a given structure exceeds its capacity, resulting in damage or failure. There are many sources of variability that may affect the accurate estimation of ground acceleration capacity of a structure. They include randomness (aleatory uncertainty) and uncertainty (epistemic uncertainty) related to the structural design bases, structural configurations, material properties, and seismic response calculated at the design analysis stage. Therefore, the seismic fragility is generally represented by means of a family of fragility curves along with a probability value assigned to each curve to reflect the confidence level associated with the estimation of fragility (Bhargava et al, 2002).

An entire set of fragility curves for a structure corresponding to a particular failure mode can be expressed in terms of the median ground acceleration capacity and two random variables representing the inherent randomness and uncertainty about the median value. The frequency of damage, f_{damage}, during an earthquake with PGA, a, at the confidence level, Q, is derived as follows (Kennedy and Ravindra, 1984):

$$f_{damage}(a,Q) = \Phi\left[\frac{\ln(a/A_m) + \beta_U \Phi^{-1}(Q)}{\beta_R}\right] \tag{2}$$

where A_m is the median (50th percentile) ground acceleration capacity, β_R and β_U are the logarithmic standard deviations of the inherent randomness and the uncertainty in the median ground acceleration capacity, respectively. Φ is the standard Gaussian cumulative distribution function (CDF) and Φ^{-1} is the inverse standard Gaussian CDF.

For the case where knowledge is perfect and complete, i.e., $\beta_U = 0$, only the random variability is utilized to obtain the conditional frequency of damage. The median conditional frequency of damage, f_{median}, for a given PGA level, a, is given by (Kennedy and Ravindra, 1984):

$$f_{median}(a) = \Phi\left[\frac{\ln(a/A_m)}{\beta_R}\right]. \tag{3}$$

The mean conditional frequency of damage, f_{mean}, for a given PGA level, a, is obtained by using the composite variability, β_C, as (Kaplan et al, 1989):

$$f_{mean}(a) = \Phi\left[\frac{\ln(a/A_m)}{\beta_C}\right] \tag{4}$$

where $\beta_C = \sqrt{\beta_R^2 + \beta_U^2}$.

Damage State Probability

The limit state of a structure exposed to an earthquake is a condition in which the resistance is less than demand imposed by the seismic hazard. According to the total probability theorem, the limit state (LS) probability, P_{LS}, can be expressed in terms of discrete random variables, as follows:

$$P_{LS} = \sum_{x=0}^{\infty} P[\mathrm{LS} \mid X = x] P[X = x] = \sum_{x=0}^{\infty} P[R < D \mid X = x] P[X = x] \quad (5)$$

in which R is the resistance and D is the demand imposed by seismic hazard, X. The conditional probability $P[\mathrm{LS} \mid X = x]$ is the probability of reaching or exceeding the damage state at a given hazard level, $X = x$. The term $P[X = x]$ is the marginal hazard probability. For continuous random variables, Eq. (5) can be expressed as:

$$P_{LS} = \int_0^{\infty} F(x) h(x) dx \quad (6)$$

where $F(x)$ is the fragility function in the form of CDF and $h(x)$ is the seismic hazard function in the form of a PDF.

The probabilities of reaching or exceeding different damage states defined in HAZUS, i.e., slight (S), moderate (M), extensive (E), and complete (C) damage states, are calculated as follows:

$$\begin{aligned} P[\mathrm{S} \mid \mathrm{PGA}] &= \int_0^{\infty} F_{\mathrm{slight}}(a) h(a) da \\ P[\mathrm{M} \mid \mathrm{PGA}] &= \int_0^{\infty} F_{\mathrm{moderate}}(a) h(a) da \\ P[\mathrm{E} \mid \mathrm{PGA}] &= \int_0^{\infty} F_{\mathrm{extensive}}(a) h(a) da \\ P[\mathrm{C} \mid \mathrm{PGA}] &= \int_0^{\infty} F_{\mathrm{complete}}(a) h(a) da \end{aligned} \quad (7)$$

where $F_{\mathrm{slight}}(a)$, $F_{\mathrm{moderate}}(a)$, $F_{\mathrm{extensive}}(a)$, and $F_{\mathrm{complete}}(a)$ are the CDFs of fragility functions for slight, moderate, extensive, and complete damage states in terms of the PGA, a, and $h(a)$ is the hazard curve.

Finally, discrete damage probabilities for different damage states can be calculated as follows:

$$
\begin{aligned}
&\text{Probability of no damage:} && P(\text{NONE}) = 1 - P[\text{S} \mid \text{PGA}] \\
&\text{Probability of slight damage:} && P(\text{SLIGHT}) = P[\text{S} \mid \text{PGA}] - P[\text{M} \mid \text{PGA}] \\
&\text{Probability of moderate damage:} && P(\text{MODERATE}) = P[\text{M} \mid \text{PGA}] - P[\text{E} \mid \text{PGA}] \\
&\text{Probability of extensive damage:} && P(\text{EXTENSIVE}) = P[\text{E} \mid \text{PGA}] - P[\text{C} \mid \text{PGA}] \\
&\text{Probability of complete damage:} && P(\text{COMPLETE}) = P[\text{C} \mid \text{PGA}]
\end{aligned} \qquad (8)
$$

Liquefaction Model

Post-earthquake reconnaissance reports describe tilted or settled buildings without any signs of structural damage or distress due to ground shaking, though they also describe damaged buildings subjected to strong ground shaking before the pore water pressure has built up sufficiently for initiation of liquefaction. Numerous buildings collapse as a result of both ground shaking and liquefaction as well. Unfortunately, however, when a building is damaged due to strong ground shaking and then followed by liquefaction, it is impossible to determine the extent of liquefaction-induced deformations. Therefore, building damage caused by both ground shaking and liquefaction still remains a complex and controversial issue (Bird et al, 2006).

When combining damage due to liquefaction and ground shaking, two potential scenarios are taken into account: the two damage types do not interact and the two damage types do interact. This study assumes that the two damages do not interact. The final damage distribution is estimated as follows (Bird et al, 2006):

$$P(\text{DS}) = P(L) \cdot P(\text{DS} \mid \text{Liquefaction}) + (1 - P(L)) \cdot P(\text{DS} \mid \text{Shaking}) \qquad (9)$$

Where, DS stands for the damage state and *P(L)* is the probability of liquefaction. If the occurrence of liquefaction is negligible, then damage will be due to ground shaking only, and if the occurrence of liquefaction is certain, then damage will be due to liquefaction only. The HAZUS Technical Manual presents the conditional liquefaction probability relationships for five susceptibility categories as listed in Table 1 and plotted in Figure 1.

Table 1: Conditional Probability Relationship for Liquefaction Susceptibility Categories

Susceptibility Category	Liquefaction Probability, P[L|PGA= a]
Very High	$0 \leq 9.09\,a - 0.82 \leq 1.0$
High	$0 \leq 7.67\,a - 0.92 \leq 1.0$
Moderate	$0 \leq 6.67\,a - 1.0 \leq 1.0$
Low	$0 \leq 5.57\,a - 1.18 \leq 1.0$
Very Low	$0 \leq 4.16\,a - 1.08 \leq 1.0$
None	0

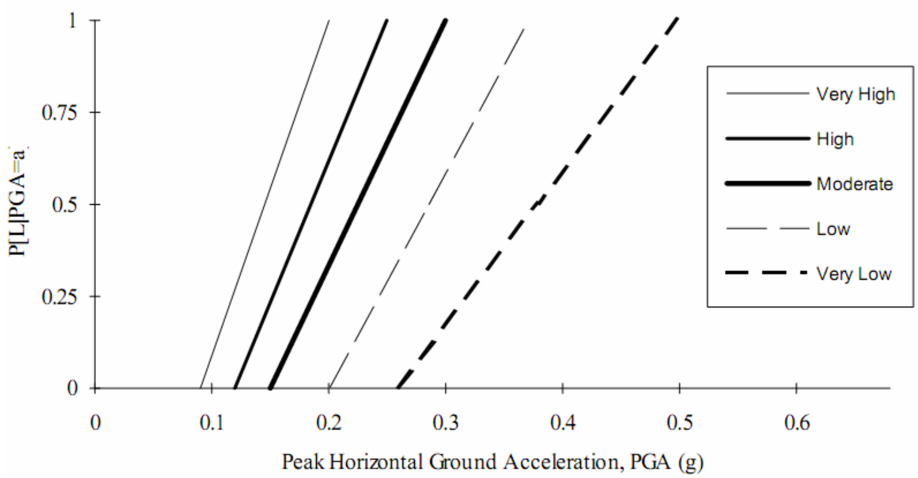

Figure 1: Conditional Liquefaction Probability Relationships for Liquefaction Susceptibility Categories

Fragility curves for liquefaction can be developed through use of the liquefaction potential index (Shinozuka and Kishimoto, 1989). The degree of liquefaction severity is classified in accordance with the liquefaction potential index P_L values as follows:

$$\begin{array}{ll} P_L = 0; & \text{little or no liquefaction} \\ 0 < P_L \leq 5; & \text{minor liquefaction} \\ 5 < P_L \leq 15; & \text{moderate liquefaction} \\ 15 < P_L & \text{major liquefaction} \end{array} \tag{10}$$

The liquefaction potential index is defined by the following expression:

$$P_L = \sum_{i=1}^{n} G_i \times W_i \times H_i \tag{11}$$

where G_i is the severity function of liquefaction, W_i is the weighting function, H_i is the thickness of i-th soil layer in meters, and n is the number of soil layers at which standard penetration test (SPT) is conducted. The severity function of liquefaction G_i and the weighting function W_i are given by Eqs. (12) and (13), respectively.

$$\begin{array}{ll} G_i = 1 - F_{L_i} & \text{for } 0 \leq F_{L_i} \leq 1 \\ G_i = 0 & \text{for } F_{L_i} > 1 \end{array} \tag{12}$$

$$W_i = 10 - 0.5 Z_i \tag{13}$$

where F_{L_i} is the safety factor for liquefaction at the i-th layer and Z_i is the depth from surface at the i-th layer measured in meters with $0 \leq Z_i \leq 20$ m.

Let $P(m_l)$ denote the probability of an earthquake with magnitude ranging in the interval associated with the subscript, *l*. Then, the probability of various degrees of liquefaction severity conditional only to PGA, a , are given by:

$$\begin{aligned}
P(P_L = 0 \mid a) &= \sum_{l=1}^{NL} P(P_L = 0 \mid m_l, a) P(m_l) \\
P(0 < P_L \leq 5 \mid a) &= \sum_{l=1}^{NL} P(0 < P_L \leq 5 \mid m_l, a) P(m_l) \\
P(5 < P_L \leq 15 \mid a) &= \sum_{l=1}^{NL} P(5 < P_L \leq 15 \mid m_l, a) P(m_l) \\
P(15 < P_L \mid a) &= \sum_{l=1}^{NL} P(15 < P_L \mid m_l, a) P(m_l)
\end{aligned} \tag{14}$$

Thus, a fragility curve associated with liquefaction event, E_{minor}, with a degree of severity that are termed "at least minor" is obtained by:

$$F_r(E_{\text{minor}} \mid a) = P(0 < P_L \leq 5 \mid a) + P(5 < P_L \leq 15 \mid a) + P(15 < P_L \mid a) \tag{15}$$

Similarly, the fragility curves associated with "at least moderate" and "major" severity can be expressed respectively as:

$$F_r(E_{\text{moderate}} \mid a) = P(5 < P_L \leq 15 \mid a) + P(15 < P_L \mid a) \tag{16}$$

$$F_r(E_{\text{major}} \mid a) = P(15 < P_L \mid a) \tag{17}$$

Methodology for Uncertainty Propagation

For an analysis of uncertainty propagation, various approximation approaches (Morgan and Henrion, 1990) are commonly used because analytical methods can give results in only a very few cases and they often provide rough results by approximating the given distributions as a normal or a lognormal. In practice, three different approximation methods have been adopted for uncertainty propagation, i.e., Monte Carlo method, the method of moments, and discrete probability distribution. The Monte Carlo method is generally used for uncertainty analyses because it gives relatively reliable results without any approximation to the input distributions. However, this approach requires an extremely large number of samples and abundant computing time to obtain acceptable accuracy in its approximations. The first order method of moments is very useful when a model is simple and the uncertainties are small relative to nonlinearity. By neglecting higher order terms in the expansion of function, it carries relatively large errors when a model is complex and includes large uncertainties. When higher order approximations are used, these rapidly become algebraically complicated as the complexity of the model increases. Discrete probability distributions simplify continuous distributions and allow for a sizeable reduction in computing time through the process of condensation. Thus, approximation approaches using discrete probability distributions are more powerful for complex logic trees. This paper proposes a simple approximation approach using discrete probability distributions.

One of the important issues in discrete probability distributions is to find the optimal way to convert a continuous distribution into a discrete distribution. In the quantile arithmetic method (Dempster, 1969; Abdelhai, 1986), continuous PDFs are approximated by equivalent discrete PDFs with equal probability intervals. This method provides the best estimate at the 50th percentile, while it gives considerably large error at lower values than the 20th percentile and higher values than the 80th percentile. The reason is that it does not define both the start and end points of the distributions. In order to reduce errors near the tail region, a large number of quantiles is used and thus much computing time is required for a complex logic tree.

The proposed method uses two different values of probability interval for converting a continuous PDF into a discrete PDF. By reflecting a rapid slope change near the 20th and 80th percentiles of a CDF curve, a half of probability interval at the 50th percentile is given as a probability interval near the tails of a PDF curve. This modification significantly reduces a computation error near the tails of a PDF curve.

Considering the approximation of the PDF, $f(x)$, of an absolutely continuous random variable, $\boldsymbol{X}$, by a discrete distribution with number of quantiles, N, the discrete PDF, $g(x_i)$, is represented by:

$$g(x)=\begin{cases} \alpha/2 & \text{if } x=x_i, \text{ where } i=2,3,4,5. \\ \alpha & \text{if } x=x_i, \text{ where } i=6,7,\cdots,m-1. \\ 1-(N-7)\cdot\alpha & \text{if } x=x_m, \text{ where } m=\text{median point.} \\ \alpha & \text{if } x=x_{N-i+1}, \text{ where } i=m-1,\cdots,7,6. \\ \alpha/2 & \text{if } x=x_{N-i+1}, \text{ where } i=5,4,3,2. \\ 0 & \text{if } x=x_i, \text{ where } i=1,N. \end{cases} \tag{18}$$

where α is a parameter of the arithmetic which satisfies the condition of $0<\alpha<1/2$ and N is an arbitrary number of quantiles given by $N\geq 10$. For convenience, α is given by $\alpha=1/(N-3)$, and N is adopted as an odd number. The corresponding CDF is calculated by:

$$G(x_i)=\sum_{x_i\leq x} g(x_i) \tag{19}$$

and

$$\sum_{i=1}^{N} g(x_i)=1. \tag{20}$$

An arithmetic function can be defined on the space, $\mathscr{S}$, of all independent random variables of the form, ***X***. The space, $\mathscr{S}$, may be considered as a suitable subset of the space of essentially bounded random variables on the probability space generated by Lebesgue measure restricted to the unit interval (Dempster, 1969).

Let ***X***, ***Y*** $\in \mathscr{S}$ and let $*$ denote any one of the four arithmetic operations. Then the result of performing the binary operation, $*$, on ***X*** and ***Y*** is a random variable, ***Z***, having an N^2-point distribution (Abdelhai, 1986):

$$\begin{aligned} f(z) &= f\left(x_i * y_j\right) \\ &= P\left(\boldsymbol{X} = x_i, \boldsymbol{Y} = y_j\right) \end{aligned} \tag{21}$$

on the sample space $\mathscr{S}\{x_i * y_j : i, j = 1,2,3,\cdots,N\}$. Since ***X*** and ***Y*** are independent, Eq. (21) becomes:

$$\begin{aligned} P\left(\mathrm{X} = x_i,\ \mathrm{Y} = y_j\right) &= P\left(\mathrm{X} = x_i\right) \cdot P\left(\mathrm{Y} = y_j\right) \\ &= p_i \cdot p_j \,. \end{aligned} \tag{22}$$

This can be rewritten as:

$$g(z_k) = \begin{cases} q_k = p_i \cdot p_j & \text{if } z_k = x_i * y_j, \quad \text{where } i, j, k = 1,2,\cdots,N \\ 0 & \text{otherwise} \end{cases} \tag{23}$$

where

$$p_i \text{ and } p_j = \begin{cases} \alpha/2 & \text{for } i, j = 2,3,4,5 \\ & \quad\;\; i, j = N\text{-}4, N\text{-}3, N\text{-}2, N\text{-}1 \\ \alpha & \text{for } i, j = 6,7,\cdots,m-1 \\ & \quad\;\; i, j = m+1, m+2,\cdots,N\text{-}5 \\ 1-(N-7)\cdot\alpha & \text{for } i, j = m, \end{cases} \tag{24}$$

$(x_1, x_2, \cdots, x_N)$ and $(y_1, y_2, \cdots, y_N)$ are the defining quantile points of ***X*** and ***Y***, respectively.

A rule to generate the N quantile points, $w_1, w_2, \cdots, w_N$, defining the operation ***X***$*$***Y*** $\in \mathscr{S}$ is the following:

(i) Order the N^2 numbers z_k in order of increasing magnitude as $z_1, z_2, \cdots, z_{N^2}$, with associated probabilities $q_1, q_2, \cdots, q_{N^2}$;

(ii) For $i = 2,3,4,5$, take w_i to be z_{r+1} such that $\sum_{k=1}^{r} q_k < (i-1)\cdot \alpha/2 \le \sum_{k=1}^{r+1} q_k$

(iii) For $i = 6,7,\cdots,m-1$, take w_i to be z_{r+1} such that $\sum_{k=1}^{r} q_k < (i-3)\cdot \alpha \le \sum_{k=1}^{r+1} q_k$

(iv) For $i = m$, take w_m to be z_{r+1} such that $\sum_{k=1}^{r} q_k < 1/2 \le \sum_{k=1}^{r+1} q_k$

(v) For $i = m+1,\cdots,N-6,N-5$, take w_i to be z_r such that

$$\sum_{k=1}^{r} q_k \le 1-(N-i-2)\cdot \alpha < \sum_{k=1}^{r+1} q_k$$

(vi) for $i = N-4, N-3, N-2, N-1$, take w_i to be z_r such that

$$\sum_{k=1}^{r} q_k \le 1-(N-i)\cdot \alpha/2 < \sum_{k=1}^{r+1} q_k$$

Earthquake Impact Assessment

Direct earthquake losses for the eight states are estimated by the proposed probabilistic approach to reflect the uncertainty included in seismic hazard, building damage fragility, inventory database, and cost data for repair and replacement. The input information used for the estimation and the results are summarized below.

Hazard

For seismic hazard input, the peak ground acceleration map of the New Madrid Seismic Zone (NMSZ) is used. Figure 2 shows a part of the PGA map around fault area. Mean PGA value for a county is estimated by considering PGA values within the county boundary and their corresponding areas. Liquefaction susceptibility is estimated by using liquefaction susceptibility map. The liquefaction susceptibility of a county is also represented by the mean susceptibility level. It is assumed that standard deviations about the mean PGA value are 0.414 for aleatory and 0.25 for epistemic, respectively (Wang, 2007; Campbell, 2003).

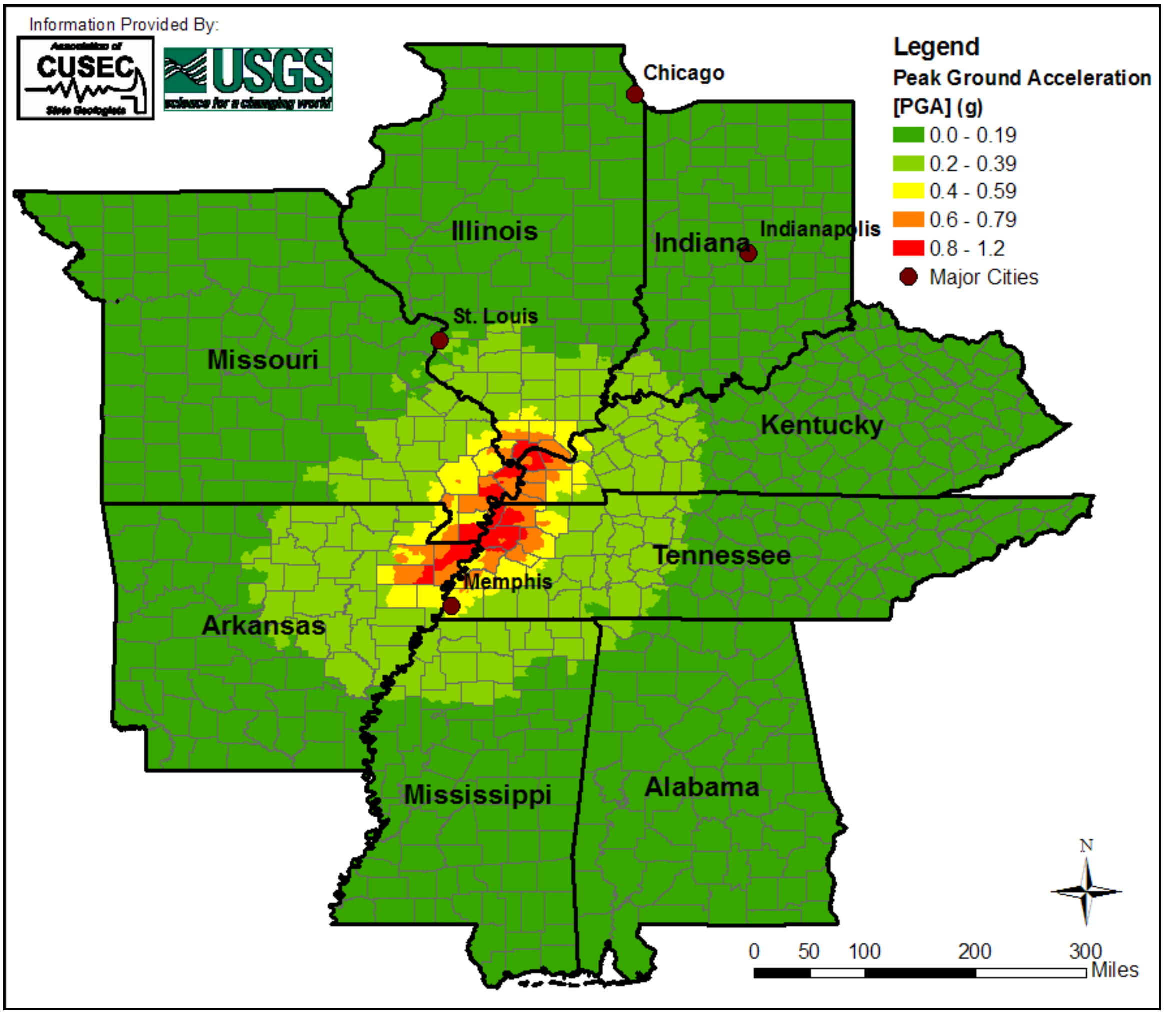

Figure 2: Peak Ground Acceleration Map of the New Madrid Seismic Zone

Inventory

The eight states include more than fifteen building types (structural system types) as listed in Table 2. For simplicity, this demonstration considers three structural types of buildings only, i.e. wood for light frame (W1), low-rise unreinforced masonry bearing walls (URML), and manufactured housing/mobile home (MH), because these three types comprise more than 96% of all general buildings. The coefficient of variation (c.o.v.) of the inventory data is assumed 0.05 for the entire eight-state region.

Table 2: Distribution of Building Structure Types for the Eight States (%)

Building type*	Alabama	Arkansas	Illinois	Indiana	Kentucky	Mississippi	Missouri	Tennessee
W1	72.61	71.01	71.17	71.51	70.41	74.35	67.14	78.62
URML	4.74	11.77	21.42	18.92	10.84	6.01	21.98	10.38
MH	20.42	15.37	4.01	7.28	16.77	17.69	8.81	8.58
W2	0.34	0.49	0.67	0.60	0.53	0.50	0.56	0.67
S3	0.17	0.26	0.36	0.34	0.28	0.07	0.28	0.09
S1L	0.35	0.07	0.09	0.09	0.07	0.13	0.09	0.17
S2L	0.32	0.13	0.16	0.16	0.13	0.28	0.15	0.35
S4L	0.00	0.14	0.20	0.18	0.16	0.15	0.15	0.19
S5L	0.28	0.17	0.24	0.22	0.19	0.18	0.19	0.23
RM1L	0.23	0.11	0.22	0.14	0.11	0.10	0.14	0.15
RM2L	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C1L	0.15	0.03	0.03	0.03	0.03	0.03	0.03	0.03
C2L	0.10	0.18	1.08	0.22	0.19	0.19	0.20	0.23
PC1	0.06	0.21	0.28	0.36	0.23	0.23	0.23	0.27
PC2L	0.02	0.01	0.02	0.02	0.01	0.02	0.01	0.02
W1+URML+MH	97.77	98.15	96.60	97.71	98.02	98.05	97.93	97.58

*Building type:
W1: Wood for Light Frame, URML: Low-rise Unreinforced Masonry, MH: Manufactured Housing, W2: Wood for Commercial and Industrial Buildings, S3: Steel Light Frame, S1L: Low-rise Steel Moment Frame, S2L: Low-rise Steel Braced Frame, S4L: Low-rise Steel Frame with Cast-in-Place Concrete Shear Walls, S5L: Low-Rise Steel Frame with Unreinforced Masonry Infill Walls, RM1L: Low-rise Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms, RM2L: Low-rise Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms, C1L: Low-Rise Concrete Moment Frame, C2L: Low-Rise Concrete Shear Walls, PC1: Precast Concrete Tilt-Up Walls, PC2L: Low-Rise Precast Concrete Frames with Concrete Shear Walls

Fragility

Structural fragility parameters for buildings are derived by modifying the HAZUS values corresponding to soil class D. Fragility curve parameters for liquefaction can be estimated by using soil profiles. This estimation used the liquefaction fragility parameter values at two sites in Memphis, Tennessee (Shinozuka and Kishimoto, 1989). Table 3 and Table 4 list the fragility parameters for the structural damage states of buildings and the severity of liquefaction. Standard deviations about the structural damage state are assumed to be 0.4 for aleatory and 0.5 for epistemic, respectively.

Table 3: Structural Fragility Curve Parameters for Low-Code Seismic Design Level

Building Type	Structural Damage State							
	Slight		Moderate		Extensive		Complete	
	Median PGA (g)	Log(sd)	Median PGA (g)	Log(sd)	Median PGA (g)	Log(sd)	Median PGA (g)	Log(sd)
W1	0.21	0.64	0.36	0.64	0.64	0.64	1.00	0.64
URML	0.15	0.64	0.21	0.64	0.34	0.64	0.48	0.64
MH	0.12	0.64	0.19	0.64	0.33	0.64	0.63	0.64

Table 4: Fragility Curve Parameters for Liquefaction

Susceptibility Category	Liquefaction Severity							
	Minor		Moderate		Extensive		Major	
	Mean PGA (g)	c.o.v.	Mean PGA (g)	c.o.v.	Mean PGA (g)	c.o.v.	Mean PGA (g)	c.o.v.
Very High or High	0.03	0.20	0.06	0.20	0.08	0.20	0.12	0.20
Others	0.05	0.20	0.12	0.20	0.20	0.20	0.30	0.20

Repair and Replacement Cost

Replacement costs for building occupancy classes are delineated in the HAZUS methodology as following:

Single-Family Residential Valuation (RES1):

$$V_{RES1} = A_{RES1} * \sum_{i=1}^{4}\sum_{j=1}^{4} w_i * w_j * C_{i,j} + A_{RES1} * w_l * \sum_{i=1}^{4}\sum_{j=1}^{4} w_i * w_j * C_{i,j,l} + CNT_{RES1} * \sum_{i=1}^{4}\sum_{m=1}^{4} w_i * w_m * C_{i,m} \quad (25)$$

where,

V_{RES1}	is the total estimated valuation for single-family residences (RES1)
A_{RES1}	is the total single-family residential floor area (square feet)
i	the Means construction class (1 = Economy, 2 = Average, 3 = Custom, and 4 = Luxury)
w_i	is the weighting factor for the Means construction class
j	the number of stories class (1 = 1-story, 2 = 2-story, 3 = 3-story, and 4 = split level)
w_j	is the weighting factor for the number of stories class
$C_{i,j}$	is the single-family cost per square foot for the given Means construction class and number of stories class
l	the basement status (1 = yes, 2 = no)
w_l	is the weighting factor for basement
$C_{i,j,l}$	the additional cost, per square foot of the main structure, for a finished basement for the given Means construction class and number of stories class
CNT_{RES1}	the count of RES1 structures
m	the garage combinations for single-family residences (1 = 1-car, 2 = 2-car, 3 = 3-car, 4 = carport, and 5 = none)
w_m	is the weighting factor for the garage type
$C_{i,m}$	the additional replacement cost for a given garage type and the Means construction class

Manufactured Housing (RES2):

$$V_{RES2} = A_{RES2} * C_{RES2} \quad (26)$$

where,

V_{RES2} is the total estimated valuation for manufactured housing (RES2)

A_{RES2} is the total manufactured housing floor area (square feet)

C_{RES2} is the manufactured housing cost per square foot

Multi-Family Residential (RES3):

$$V_{RES3} = A_{RES3} * C_{RES3} \tag{27}$$

where,

V_{RES3} is the total estimated valuation for multi-family residences (RES3)

A_{RES3} is the total multi-family residential floor area (square feet)

C_{RES3} is the multi-family cost per square foot

HAZUS repair cost ratios for the structural damage of buildings are given in Table 5. Additionally, the coefficient of variation (c.o.v.) of the repair cost is assumed 0.2 for all damage states.

Table 5: Structural Repair Cost Ratios (in % of Replacement Cost)

Occupancy Class	Structural Damage State			
	Slight	Moderate	Extensive	Complete
Single Family Dwelling (RES1)	0.5	2.3	11.7	23.4
Mobile Home (RES2)	0.4	2.4	7.3	24.4
Multi Family Dwelling (RES3)	0.3	1.4	6.9	13.8

Uncertainty Quantification of Earthquake Impact Results

An earthquake impact assessment is performed for the ‘impacted counties’ in the eight-state study region. For a demonstration of the proposed framework, only structural damage is considered. Input information used for the estimation and the results are listed in the following, by state:

Alabama

Input

Table 6: Seismic Hazard and Liquefaction Susceptibility for the State of Alabama

County	Mean PGA (g)	Liquefaction Susceptibility Category
Autauga	0.05	Very low
Baldwin	0.05	Moderate
Bibb	0.05	None
Bullock	0.05	Low
Choctaw	0.05	Moderate
Clarke	0.05	Low
Dallas	0.05	Moderate
Elmore	0.05	Very low
Escambia	0.05	Low
Etowah	0.05	None
Fayette	0.05	Low
Geneva	0.05	Low
Hale	0.05	Moderate
Lamar	0.05	Low
Lowndes	0.05	Moderate
Macon	0.05	Moderate
Marengo	0.05	Moderate
Mobile	0.05	Moderate
Pickens	0.05	Low
Russell	0.05	Low
Tuscaloosa	0.05	Low

Table 7: Number of Buildings by Occupancy Class for the State of Alabama

County	W1			URML			MH	Total
	RES1	RES3	Total	RES1	RES3	Total	RES2	
Autauga	11,618	94	11,711	611	33	644	4,594	16,949
Baldwin	44,212	846	45,058	2,327	296	2,623	13,034	60,716
Bibb	4,759	50	4,808	250	17	268	2,830	7,906
Bullock	2,665	63	2,727	140	22	162	1,535	4,425
Choctaw	4,623	35	4,658	243	12	256	2,672	7,586
Clarke	7,695	82	7,777	405	29	434	3,611	11,822
Dallas	12,993	526	13,520	684	184	868	4,051	18,439
Elmore	18,185	166	18,351	957	58	1,015	5,095	24,461
Escambia	10,609	174	10,783	558	61	619	4,061	15,463
Etowah	33,191	616	33,807	1,747	216	1,963	5,979	41,749
Fayette	5,532	94	5,625	291	33	324	1,829	7,778
Geneva	7,925	118	8,043	417	41	458	3,145	11,646
Hale	4,267	64	4,332	225	23	247	2,753	7,332
Lamar	4,720	151	4,871	248	53	301	1,760	6,932
Lowndes	3,196	64	3,260	168	22	191	2,082	5,532
Macon	6,564	253	6,817	345	89	434	1,784	9,034
Marengo	6,019	153	6,172	317	54	370	2,805	9,348
Mobile	114,313	2,947	117,259	6,016	1,031	7,048	15,213	139,520
Pickens	5,874	119	5,993	309	42	351	2,588	8,932
Russell	12,995	612	13,607	684	214	898	4,327	18,832
Tuscaloosa	41,496	1,490	42,986	2,184	521	2,705	10,160	55,851
Total	363,448	8,718	372,166	19,129	3,051	22,180	95,908	490,254

*Occupancy class: RES1: Single Family Dwelling, RES2: Mobile Home, RES3: Multi Family Dwelling

Results

Table 8: Structural Damage of Buildings for the State of Alabama

Statistic	Damage State					Moderate to Complete Damage	Total No. Damaged Buildings
	None	Slight	Moderate	Extensive	Complete		
Mean	461,441	20,798	6,653	1,195	165	8,014	28,812
Standard Deviation	6,768	240	68	13	1	69	249
HAZUS*	484,462	4,222	1,327	82	3,464	4,875	9,097

* HAZUS results represent damage of building for residential occupancy classes of RES1 through RES6.

Table 9: Building Damage for Impacted Counties in the State of Alabama (90% CI)

County	None	Slight	Moderate	Extensive	Complete	Total Damage
Autauga	[14,855 , 16,807]	[749 , 837]	[253 , 285]	[47 , 54]	[6 , 7]	[1,072 , 1,166]
Baldwin	[53,411 , 60,662]	[2,497 , 2,788]	[811 , 906]	[147 , 166]	[20 , 22]	[3,526 , 3,832]
Bibb	[6,891 , 7,742]	[386 , 434]	[138 , 156]	[27 , 31]	[3 , 4]	[564 , 615]
Bullock	[3,862 , 4,336]	[214 , 240]	[76 , 86]	[15 , 17]	[2 , 2]	[312 , 340]
Choctaw	[6,612 , 7,436]	[368 , 414]	[131 , 148]	[26 , 29]	[3 , 3]	[537 , 586]
Clarke	[10,341 , 11,662]	[544 , 610]	[188 , 213]	[36 , 41]	[4 , 5]	[786 , 856]
Dallas	[16,239 , 18,377]	[766 , 853]	[251 , 280]	[46 , 52]	[6 , 7]	[1,084 , 1,176]
Elmore	[21,510 , 24,483]	[996 , 1,113]	[321 , 359]	[58 , 65]	[8 , 9]	[1,403 , 1,526]
Escambia	[13,565 , 15,342]	[677 , 756]	[228 , 256]	[43 , 48]	[5 , 6]	[967 , 1,051]
Etowah	[36,847 , 42,178]	[1,549 , 1,735]	[471 , 523]	[80 , 90]	[12 , 13]	[2,140 , 2,333]
Fayette	[6,836 , 7,749]	[329 , 367]	[108 , 121]	[20 , 23]	[3 , 3]	[467 , 507]
Geneva	[10,211 , 11,544]	[514 , 575]	[174 , 196]	[33 , 37]	[4 , 5]	[736 , 801]
Hale	[6,383 , 7,162]	[365 , 411]	[132 , 150]	[26 , 30]	[3 , 3]	[535 , 584]
Lamar	[6,090 , 6,879]	[300 , 335]	[101 , 113]	[19 , 21]	[2 , 3]	[429 , 466]
Lowndes	[4,817 , 5,401]	[276 , 310]	[99 , 113]	[20 , 23]	[2 , 3]	[404 , 442]
Macon	[7,965 , 9,037]	[364 , 406]	[117 , 130]	[21 , 24]	[3 , 3]	[512 , 556]
Marengo	[8,187 , 9,218]	[428 , 479]	[148 , 167]	[28 , 32]	[4 , 4]	[618 , 672]
Mobile	[123,370 , 141,635]	[4,908 , 5,516]	[1,440 , 1,594]	[236 , 261]	[38 , 42]	[6,704 , 7,331]
Pickens	[7,825 , 8,824]	[404 , 452]	[139 , 156]	[26 , 30]	[3 , 4]	[582 , 633]
Russell	[16,583 , 18,733]	[793 , 883]	[262 , 293]	[48 , 54]	[7 , 7]	[1,126 , 1,222]
Tuscaloosa	[49,267 , 56,007]	[2,200 , 2,454]	[698 , 776]	[124 , 139]	[18 , 20]	[3,081 , 3,347]

Table 10: Building Damage by Occupancy Class for the State of Alabama

Occupancy Class	Damage State									
	None		Slight		Moderate		Extensive		Complete	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Single Family	367,547	6,667	11,801	207	2,797	44	351	5	80	1
Multi Family	11,186	181	409	6	141	2	24	1	8	0
Mobile Home	82,708	1,152	8,588	120	3,716	52	820	12	76	1

Table 11: Building Damage by Structural Type for the State of Alabama

Building Type	Damage State									
	None		Slight		Moderate		Extensive		Complete	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Wood	358,452	6,661	11,131	207	2,308	43	242	4	35	1
Unreinforced Masonry	20,281	336	1,078	18	630	10	134	2	53	1
Mobile Home	82,708	1,152	8,588	120	3,716	52	820	12	76	1

Table 12: Direct Economic Losses Due to Structural Damage of Buildings for the State of Alabama

	Direct Economic Losses ($ millions)	
	Lower Bound	Upper Bound
90% Confidence Interval	37.62	61.31
HAZUS*	123.72	

* HAZUS result includes direct loss for all buildings.

Arkansas

Input

Table 13: Seismic Hazard and Liquefaction Susceptibility for the State of Arkansas

County	Mean PGA (g)	Liquefaction Susceptibility Category
Arkansas	0.14	None
Clay	0.34	Very high
Craighead	0.47	Very high
Crittenden	0.44	Very high
Cross	0.43	Very high
Greene	0.34	Very high
Independence	0.05	Low
Jackson	0.30	Very high
Lawrence	0.30	High
Lee	0.26	Very high
Mississippi	0.74	Very high
Monroe	0.16	None
Phillips	0.16	Moderate
Poinsett	0.56	Very high
Prairie	0.15	Very low
Randolph	0.27	Moderate
Saint Francis	0.30	Very high
White	0.19	Low
Woodruff	0.26	Very high

Table 14: Number of Buildings by Occupancy Class for the State of Arkansas

County	W1			URML			MH	Total
	RES1	RES3	Total	RES1	RES3	Total	RES2	
Arkansas	6,404	1,349	7,753	957	423	1,380	1,804	10,937
Clay	6,008	1,937	7,945	898	607	1,505	1,518	10,968
Craighead	21,683	4,403	26,086	3,240	1,380	4,620	4,167	34,873
Crittenden	12,061	2,848	14,909	1,802	892	2,694	2,652	20,255
Cross	4,706	1,080	5,786	703	338	1,042	2,095	8,922
Greene	10,459	2,110	12,569	1,563	661	2,224	2,621	17,414
Independence	9,498	2,362	11,860	1,419	740	2,159	3,309	17,328
Jackson	5,384	1,346	6,730	805	422	1,226	1,221	9,177
Lawrence	5,685	1,651	7,336	850	517	1,367	1,392	10,095
Lee	2,978	552	3,530	445	173	618	877	5,025
Mississippi	13,367	3,740	17,106	1,997	1,172	3,169	3,408	23,683
Monroe	3,021	1,217	4,238	451	381	833	1,142	6,213
Phillips	6,937	1,805	8,741	1,036	565	1,602	1,443	11,786
Poinsett	7,025	1,480	8,505	1,050	464	1,513	1,917	11,935
Prairie	2,928	1,508	4,435	437	472	910	1,305	6,650
Randolph	5,647	1,172	6,819	844	367	1,211	1,398	9,428
Saint Francis	6,677	1,582	8,259	998	496	1,493	2,185	11,937
White	15,926	4,003	19,929	2,380	1,254	3,634	6,398	29,961
Woodruff	2,587	1,025	3,612	387	321	708	872	5,192
Total	148,981	37,166	186,148	22,262	11,645	33,907	41,724	261,779

*Occupancy class: RES1: Single Family Dwelling, RES2: Mobile Home, RES3: Multi Family Dwelling

Results

Table 15: Structural Damage of Buildings for the State of Arkansas

Statistic	Damage State					Moderate to Complete Damage	Total No. Damaged Buildings
	None	Slight	Moderate	Extensive	Complete		
Mean	77,043	40,695	43,937	28,736	71,370	144,044	184,739
Standard Deviation	816	376	398	260	713	857	936
HAZUS*	87,896	59,529	41,110	16,663	57,885	115,657	175,187

* HAZUS results represent damage of building for residential occupancy classes of RES1 through RES6.

Table 16: Building Damage for Impacted Counties in the State of Arkansas (90% CI)

County	None	Slight	Moderate	Extensive	Complete	Total Damage
Arkansas	[6,496 , 7,258]	[1,968 , 2,182]	[1,257 , 1,376]	[451 , 494]	[188 , 204]	[3,935 , 4,184]
Clay	[1,825 , 2,042]	[1,722 , 1,924]	[1,986 , 2,195]	[1,273 , 1,392]	[3,617 , 3,960]	[8,802 , 9,267]
Craighead	[3,303 , 3,739]	[4,441 , 5,027]	[6,413 , 7,195]	[4,828 , 5,349]	[14,001 , 15,450]	[30,440 , 32,264]
Crittenden	[2,161 , 2,438]	[2,711 , 3,057]	[3,747 , 4,185]	[2,740 , 3,023]	[7,831 , 8,616]	[17,454 , 18,457]
Cross	[920 , 1,033]	[1,150 , 1,288]	[1,626 , 1,803]	[1,292 , 1,422]	[3,488 , 3,821]	[7,735 , 8,157]
Greene	[2,874 , 3,240]	[2,722 , 3,063]	[3,146 , 3,499]	[2,036 , 2,239]	[5,715 , 6,296]	[13,964 , 14,751]
Independence	[15,434 , 17,068]	[721 , 791]	[251 , 275]	[47 , 52]	[9 , 9]	[1,040 , 1,114]
Jackson	[1,854 , 2,082]	[1,512 , 1,695]	[1,592 , 1,764]	[964 , 1,057]	[2,779 , 3,058]	[7,017 , 7,403]
Lawrence	[2,165 , 2,424]	[1,767 , 1,975]	[1,865 , 2,060]	[1,118 , 1,223]	[2,669 , 2,925]	[7,602 , 7,999]
Lee	[1,206 , 1,356]	[842 , 942]	[821 , 908]	[500 , 548]	[1,393 , 1,534]	[3,644 , 3,844]
Mississippi	[789 , 890]	[1,695 , 1,914]	[3,487 , 3,911]	[3,612 , 4,006]	[12,901 , 14,163]	[22,142 , 23,547]
Monroe	[3,308 , 3,655]	[1,228 , 1,350]	[871 , 948]	[348 , 380]	[162 , 175]	[2,656 , 2,804]
Phillips	[6,381 , 7,130]	[2,311 , 2,568]	[1,584 , 1,735]	[599 , 652]	[294 , 318]	[4,879 , 5,182]
Poinsett	[760 , 860]	[1,236 , 1,398]	[2,064 , 2,314]	[1,806 , 1,999]	[5,445 , 5,989]	[10,801 , 11,451]
Prairie	[3,718 , 4,088]	[1,269 , 1,388]	[872 , 947]	[338 , 370]	[249 , 161]	[2,675 , 2,820]
Randolph	[2,665 , 2,997]	[1,962 , 2,200]	[2,035 , 2,253]	[1,218 , 1,337]	[1,047 , 1,141]	[6,419 , 6,775]
Saint Francis	[2,338 , 2,621]	[1,935 , 2,162]	[2,085 , 2,303]	[1,323 , 1,451]	[3,651 , 4,008]	[9,212 , 9,705]
White	[13,401 , 14,924]	[6,378 , 7,062]	[5,113 , 5,603]	[2,339 , 2,568]	[1,215 , 1,319]	[15,359 , 16,237]
Woodruff	[1,252 , 1,391]	[871 , 964]	[852 , 933]	[518 , 564]	[1,453 , 1,585]	[3,777 , 3,964]

Table 17: Building Damage by Occupancy Class for the State of Arkansas

Occupancy Class	Damage State									
	None		Slight		Moderate		Extensive		Complete	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Single Family	53,231	771	27,871	356	28,548	372	16,291	229	45,301	661
Multi Family	15,343	201	7,588	87	7,947	89	4,609	56	13,328	170
Mobile Home	8,468	179	5,236	85	7,442	109	7,837	108	12,741	205

Table 18: Building Damage by Structural Type for the State of Arkansas

Building Type	Damage State									
	None		Slight		Moderate		Extensive		Complete	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Wood	60,685	790	32,216	365	31,225	379	17,161	233	44,864	661
Unreinforced Masonry	7,890	102	3,243	33	5,270	53	3,739	39	13,765	172
Mobile Home	8,468	179	5,236	85	7,442	109	7,837	108	12,741	205

Table 19: Direct Economic Losses Due to Structural Damage of Buildings for the State of Arkansas

Direct Economic Losses ($ millions)		
	Lower Bound	Upper Bound
90% Confidence Interval	3,096.86	6,239.14
HAZUS*	2,359.75	

* HAZUS result includes direct loss for all buildings.

Illinois

Input

Table 20: Seismic Hazard and Liquefaction Susceptibility for the State of Illinois

County	Mean PGA (g)	Liquefaction Susceptibility Category
Alexander	0.50	High
Bond	0.08	Very low
Clinton	0.11	Very low
Fayette	0.05	Very low
Franklin	0.23	Very low
Gallatin	0.24	Very low
Hamilton	0.16	Very low
Hardin	0.30	None
Jackson	0.28	Very low
Jefferson	0.15	Very low
Johnson	0.47	None
Lawrence	0.05	Very low
Madison	0.06	Very low
Marion	0.08	Very low
Massac	0.61	Moderate
Monroe	0.12	Very low
Perry	0.17	Very low
Pope	0.33	Very low
Pulaski	0.80	Moderate
Randolph	0.15	Very low
Saint Clair	0.12	Very low
Saline	0.29	Very low
Union	0.42	Very low
Washington	0.15	Very low
Wayne	0.12	Very low
White	0.15	Very low
Williamson	0.30	Very low

Table 21: Number of Buildings by Occupancy Class for the State of Illinois

County	W1			URML			MH	Total
	RES1	RES3	Total	RES1	RES3	Total	RES2	
Alexander	2,446	86	2,533	699	27	726	765	4,023
Bond	3,868	95	3,964	1,105	30	1,135	1,163	6,262
Clinton	8,209	249	8,458	2,345	77	2,423	1,777	12,658
Fayette	5,196	82	5,278	1,485	25	1,510	1,762	8,550
Franklin	11,251	329	11,580	3,215	102	3,316	1,959	16,855
Gallatin	1,682	48	1,730	480	15	495	702	2,927
Hamilton	2,386	48	2,434	682	15	697	687	3,818
Hardin	1,405	46	1,451	402	14	416	469	2,336
Jackson	11,307	956	12,263	3,231	296	3,527	4,625	20,415
Jefferson	9,292	247	9,538	2,655	76	2,731	2,936	15,206
Johnson	2,669	33	2,702	763	10	773	1,355	4,830
Lawrence	4,089	89	4,179	1,168	28	1,196	1,024	6,399
Madison	66,016	3,298	69,314	18,862	1,022	19,884	4,136	93,334
Marion	10,374	306	10,680	2,964	95	3,059	2,778	16,517
Massac	3,935	91	4,026	1,124	28	1,153	1,338	6,517
Monroe	6,951	221	7,171	1,986	68	2,054	395	9,621
Perry	5,494	190	5,684	1,570	59	1,629	1,352	8,664
Pope	1,260	36	1,296	360	11	371	494	2,161
Pulaski	1,780	59	1,839	509	18	527	768	3,134
Randolph	7,809	229	8,038	2,231	71	2,302	1,973	12,313
Saint Clair	59,265	3,167	62,431	16,933	982	17,914	7,657	88,002
Saline	7,496	130	7,626	2,142	40	2,182	1,709	11,517
Union	4,374	135	4,509	1,250	42	1,292	1,371	7,172
Washington	4,172	41	4,213	1,192	13	1,205	658	6,076
Wayne	4,362	53	4,415	1,246	17	1,263	1,816	7,494
White	4,391	119	4,509	1,254	37	1,291	1,118	6,918
Williamson	15,772	821	16,592	4,506	254	4,761	3,315	24,668
Total	267,252	11,201	278,453	76,358	3,472	79,830	50,102	408,385

*Occupancy class: RES1: Single Family Dwelling, RES2: Mobile Home, RES3: Multi Family Dwelling

Results

Table 22: Structural Damage of Buildings for the State of Illinois

Statistic	Damage State					Moderate to Complete Damage	Total No. Damaged Buildings
	None	Slight	Moderate	Extensive	Complete		
Mean	259,680	58,969	45,883	22,668	21,188	89,739	148,708
Standard Deviation	4,095	643	410	187	180	485	805
HAZUS*	323,594	50,253	15,615	4,817	18,880	39,303	89,561

* HAZUS results represent damage of building for residential occupancy classes of RES1 through RES6.

Table 23: Building Damage for Impacted Counties in the State of Illinois (90% CI)

County	None	Slight	Moderate	Extensive	Complete	Total Damage
Alexander	[324 , 370]	[467 , 533]	[742 , 836]	[633 , 702]	[1,635 , 1,804]	[3,568 , 3,784]
Bond	[4,907 , 5,502]	[610 , 675]	[295 , 324]	[77 , 85]	[22 , 25]	[1,021 , 1,092]
Clinton	[8,668 , 9,774]	[1,793 , 1,999]	[1,024 , 1,126]	[317 , 348]	[125 , 139]	[3,320 , 3,552]
Fayette	[7,541 , 8,427]	[370 , 408]	[137 , 151]	[26 , 29]	[5 , 6]	[546 , 587]
Franklin	[6,233 , 7,091]	[3,640 , 4,127]	[3,274 , 3,651]	[1,580 , 1,740]	[1,130 , 1,248]	[9,871 , 10,517]
Gallatin	[963 , 1,087]	[622 , 698]	[611 , 676]	[340 , 375]	[230 , 253]	[1,848 , 1,956]
Hamilton	[1,985 , 2,242]	[739 , 828]	[544 , 600]	[222 , 244]	[111 , 123]	[1,651 , 1,758]
Hardin	[578 , 655]	[478 , 540]	[535 , 595]	[332 , 366]	[282 , 310]	[1,671 , 1,768]
Jackson	[5,503 , 6,192]	[4,244 , 4,756]	[4,588 , 5,072]	[2,788 , 3,068]	[2,205 , 2,413]	[14,174 , 14,960]
Jefferson	[8,306 , 9,357]	[2,846 , 3,178]	[2,025 , 2,230]	[800 , 880]	[376 , 415]	[6,174 , 6,574]
Johnson	[511 , 581]	[703 , 798]	[1,105 , 1,237]	[978 , 1,084]	[1,269 , 1,394]	[4,168 , 4,400]
Lawrence	[5,658 , 6,343]	[261 , 288]	[95 , 104]	[18 , 20]	[4 , 4]	[383 , 411]
Madison	[80,609 , 91,203]	[4,776 , 5,329]	[1,798 , 1,985]	[348 , 385]	[110 , 125]	[7,136 , 7,720]
Marion	[12,985 , 14,573]	[1,588 , 1,757]	[761 , 835]	[196 , 216]	[59 , 65]	[2,645 , 2,831]
Massac	[375 , 429]	[663 , 759]	[1,230 , 1,391]	[1,236 , 1,376]	[2,652 , 2,922]	[5,935 , 6,293]
Monroe	[6,436 , 7,324]	[1,424 , 1,610]	[805 , 896]	[237 , 262]	[116 , 131]	[2,636 , 2,845]
Perry	[4,314 , 4,875]	[1,724 , 1,934]	[1,301 , 1,437]	[539 , 592]	[291 , 321]	[3,942 , 4,199]
Pope	[450 , 511]	[419 , 474]	[507 , 565]	[345 , 380]	[321 , 352]	[1,635 , 1,727]
Pulaski	[88 , 101]	[204 , 234]	[466 , 529]	[567 , 632]	[1,641 , 1,807]	[2,944 , 3,136]
Randolph	[6,807 , 7,686]	[2,289 , 2,562]	[1,600 , 1,764]	[615 , 675]	[299 , 331]	[4,904 , 5,229]
Saint Clair	[58,218 , 65,828]	[13,318 , 14,931]	[7,767 , 8,569]	[2,414 , 2,647]	[1,095 , 1,222]	[25,070 , 26,891]
Saline	[3,079 , 3,509]	[2,412 , 2,741]	[2,579 , 2,885]	[1,494 , 1,650]	[1,278 , 1,407]	[7,977 , 8,469]
Union	[1,000 , 1,140]	[1,200 , 1,365]	[1,689 , 1,895]	[1,297 , 1,436]	[1,583 , 1,738]	[5,934 , 6,270]
Washington	[3,418 , 3,883]	[1,115 , 1,257]	[757 , 839]	[277 , 304]	[143 , 159]	[2,342 , 2,509]
Wayne	[4,733 , 5,309]	[1,208 , 1,341]	[767 , 845]	[272 , 301]	[101 , 112]	[2,394 , 2,552]
White	[3,823 , 4,317]	[1,286 , 1,440]	[900 , 992]	[346 , 380	[168 , 186]	[2,758 , 2,940]
Williamson	[6,337 , 7,201]	[5,143 , 5,833]	[5,592 , 6,248]	[3,267 , 3,603]	[2,911 , 3,201]	[17,374 , 18,424]

Table 24: Building Damage by Occupancy Class for the State of Illinois

Occupancy Class	Damage State									
	None		Slight		Moderate		Extensive		Complete	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Single Family	229,898	4,078	48,432	630	35,170	391	14,702	157	15,407	162
Multi Family	9,934	205	2,044	33	1,482	21	609	9	607	7
Mobile Home	19,848	308	8,493	118	9,231	123	7,357	100	5,174	77

Table 25: Building Damage by Structural Type for the State of Illinois

Building Type	Damage State									
	None		Slight		Moderate		Extensive		Complete	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Wood	193,710	3,960	41,059	612	25,897	357	9,936	138	7,853	120
Unreinforced Masonry	46,122	998	9,417	156	10,755	160	5,376	75	8,161	110
Mobile Home	19,848	308	8,493	118	9,231	123	7,357	100	5,174	77

Table 26: Direct Economic Losses Due to Structural Damage of Buildings for the State of Illinois

	Direct Economic Losses ($ millions)	
	Lower Bound	Upper Bound
90% Confidence Interval	1,053.12	1,957.62
HAZUS*	868.47	

* HAZUS result includes direct loss for all buildings.

Indiana

Input

Table 27: Seismic Hazard and Liquefaction Susceptibility for the State of Indiana

County	Mean PGA (g)	Liquefaction Susceptibility Category
Crawford	0.05	Very low
Dubois	0.05	Very low
Gibson	0.14	Moderate
Harrison	0.05	Very low
Knox	0.05	Moderate
Lawrence	0.05	Very low
Martin	0.05	Very low
Orange	0.05	Very low
Perry	0.05	Very low
Pike	0.05	Low
Posey	0.15	Moderate
Spencer	0.10	Low
Vanderburgh	0.15	Moderate
Warrick	0.13	Low

Table 28: Number of Buildings by Occupancy Class for the State of Indiana

County	W1			URML			MH	Total
	RES1	RES3	Total	RES1	RES3	Total	RES2	
Crawford	2,761	24	2,785	690	7	698	1,445	4,927
Dubois	9,710	452	10,161	2,427	140	2,567	1,004	13,732
Gibson	8,694	179	8,872	2,173	55	2,229	1,802	12,903
Harrison	8,419	163	8,582	2,105	50	2,155	2,305	13,042
Knox	10,639	512	11,151	2,660	159	2,818	1,173	15,142
Lawrence	12,434	316	12,750	3,109	98	3,206	2,937	18,894
Martin	2,602	65	2,667	650	20	671	1,168	4,505
Orange	4,586	91	4,676	1,146	28	1,175	1,950	7,801
Perry	4,937	119	5,055	1,234	37	1,271	1,207	7,533
Pike	3,257	53	3,309	814	16	830	1,234	5,374
Posey	7,254	121	7,374	1,813	37	1,851	1,170	10,395
Spencer	5,324	116	5,440	1,331	36	1,367	1,052	7,858
Vanderburgh	43,258	2,371	45,629	10,815	735	11,550	2,368	59,547
Warrick	13,415	284	13,699	3,354	88	3,442	1,773	18,913
Total	137,289	4,862	142,150	34,322	1,507	35,829	22,588	200,568

*Occupancy class: RES1: Single Family Dwelling, RES2: Mobile Home, RES3: Multi Family Dwelling

Results

Table 29: Structural Damage of Buildings for the State of Indiana

Statistic	Damage State					Moderate to Complete Damage	Total No. Damaged Buildings
	None	Slight	Moderate	Extensive	Complete		
Mean	155,454	24,199	14,130	4,526	2,262	20,918	45,117
Standard Deviation	1,966	475	261	78	47	277	550
HAZUS*	168,902	25,254	3,768	484	2,770	7,025	32,277

* HAZUS results represent damage of building for residential occupancy classes of RES1 through RES6.

Table 30: Building Damage for Impacted Counties in the State of Indiana

County	None	Slight	Moderate	Extensive	Complete	Total Damage
Crawford	[4,319 , 4,813]	[234 , 259]	[88 , 98]	[17 , 19]	[3 , 3]	[347 , 375]
Dubois	[12,207 , 13,795]	[492 , 545]	[167 , 183]	[29 , 32]	[7 , 8]	[704 , 760]
Gibson	[7,598 , 8,614]	[2,278 , 2,559]	[1,486 , 1,641]	[532 , 584]	[244 , 270]	[4,634 , 4,960]
Harrison	[11,521 , 12,927]	[540 , 596]	[194 , 214]	[36 , 40]	[7 , 8]	[788 , 847]
Knox	[13,460 , 15,199]	[546 , 605]	[186 , 204]	[33 , 36]	[8 , 9]	[782 , 844]
Lawrence	[16,713 , 18,778]	[761 , 840]	[271 , 297]	[50 , 55]	[11 , 12]	[1,107 , 1,190]
Martin	[3,962 , 4,416]	[206 , 228]	[77 , 85]	[15 , 17]	[3 , 3]	[305 , 328]
Orange	[6,862 , 7,657]	[353 , 390]	[131 , 145]	[25 , 28]	[5 , 5]	[521 , 561]
Perry	[6,663 , 7,482]	[305 , 337]	[109 , 120]	[20 , 22]	[4 , 5]	[444 , 478]
Pike	[4,734 , 5,289]	[237 , 262]	[87 , 97]	[17 , 19]	[3 , 3]	[349 , 376]
Posey	[5,864 , 6,671]	[1,915 , 2,162]	[1,283 , 1,423]	[467 , 513]	[233 , 259]	[3,983 , 4,272]
Spencer	[5,671 , 6,413]	[993 , 1,109]	[525 , 577]	[151 , 165]	[54 , 60]	[1,753 , 1,881]
Vanderburgh	[34,525 , 39,330]	[10,803 , 12,258]	[6,913 , 7,716]	[2,305 , 2,545]	[1,276 , 1,423]	[21,776 , 23,463]
Warrick	[11,895 , 13,529]	[3,094 , 3,490]	[1,872 , 2,074]	[610 , 670]	[281 , 313]	[5,977 , 6,427]

Table 31: Building Damage by Occupancy Class for the State of Indiana

Occupancy Class	Damage State									
	None		Slight		Moderate		Extensive		Complete	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Single Family	134,631	1,950	20,276	472	11,419	257	3,367	75	1,917	46
Multi Family	4,803	90	828	24	495	14	153	4	93	3
Mobile Home	16,020	235	3,095	48	2,216	40	1,006	22	252	6

Table 32: Building Damage by Structural Type for the State of Indiana

Building Type	Damage State									
	None		Slight		Moderate		Extensive		Complete	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Wood	114,558	1,911	17,116	463	7,928	235	1,919	60	635	20
Unreinforced Masonry	24,877	394	3,988	95	3,986	106	1,601	46	1,375	42
Mobile Home	16,020	235	3,095	48	2,216	40	1,006	22	252	6

Table 33: Direct Economic Losses Due to Structural Damage of Buildings for the State of Indiana

Direct Economic Losses ($ millions)	Lower Bound	Upper Bound
90% Confidence Interval	191.99	259.85
HAZUS*	158.86	

* HAZUS result includes direct loss for all buildings.

Kentucky

Input

Table 34: Seismic Hazard and Liquefaction Susceptibility for the State of Kentucky

County	Mean PGA (g)	Liquefaction Susceptibility Category
Ballard	0.86	Moderate
Caldwell	0.30	Very low
Calloway	0.28	Low
Carlisle	0.63	Low
Crittenden	0.30	Very low
Daviess	0.15	Moderate
Fulton	0.55	Moderate
Graves	0.37	Low
Henderson	0.15	Moderate
Hickman	0.53	Low
Hopkins	0.17	Very low
Livingston	0.31	Low
Lyon	0.30	Low
McCracken	0.62	Low
Marshall	0.32	Moderate
Muhlenberg	0.15	Very low
Trigg	0.28	Low
Union	0.22	Moderate
Webster	0.19	Low

Table 35: Number of Buildings by Occupancy Class for the State of Kentucky

County	W1			URML			MH	Total
	RES1	RES3	Total	RES1	RES3	Total	RES2	
Ballard	2,512	32	2,543	342	10	352	758	3,653
Caldwell	4,235	98	4,333	577	31	608	862	5,803
Calloway	9,173	550	9,723	1,251	172	1,423	2,933	14,079
Carlisle	1,683	13	1,695	229	4	233	493	2,422
Crittenden	2,701	52	2,752	368	16	384	1,081	4,218
Daviess	25,004	1,199	26,204	3,410	376	3,785	2,567	32,556
Fulton	2,497	155	2,652	341	48	389	184	3,225
Graves	10,928	290	11,218	1,490	91	1,581	2,522	15,321
Henderson	11,486	680	12,166	1,566	213	1,779	2,348	16,293
Hickman	1,617	25	1,641	220	8	228	451	2,321
Hopkins	13,223	392	13,614	1,803	123	1,926	3,372	18,912
Livingston	2,863	11	2,873	390	3	394	1,382	4,649
Lyon	2,447	65	2,513	334	20	354	1,076	3,943
McCracken	18,750	892	19,642	2,557	279	2,836	3,406	25,884
Marshall	9,629	149	9,777	1,313	47	1,360	2,882	14,019
Muhlenberg	8,583	133	8,715	1,170	42	1,212	3,050	12,977
Trigg	4,384	71	4,455	598	22	620	1,387	6,462
Union	3,922	95	4,017	535	30	565	1,173	5,755
Webster	4,110	45	4,155	561	14	575	1,214	5,944
Total	139,746	4,944	144,690	19,056	1,549	20,605	33,141	198,436

*Occupancy class: RES1: Single Family Dwelling, RES2: Mobile Home, RES3: Multi Family Dwelling

Results

Table 36: Structural Damage of Buildings for the State of Kentucky

Statistic	Damage State					Moderate to Complete Damage	Total No. Damaged Buildings
	None	Slight	Moderate	Extensive	Complete		
Mean	72,624	38,481	37,735	23,357	26,241	87,334	125,815
Standard Deviation	1,095	438	394	254	348	584	729
HAZUS*	103,857	36,798	25,532	9,809	23,018	58,359	95,159

* HAZUS results represent damage of building for residential occupancy classes of RES1 through RES6.

Table 37: Building Damage for Impacted Counties in the State of Kentucky (90% CI)

County	None	Slight	Moderate	Extensive	Complete	Total Damage
Ballard	[93 , 107]	[233 , 270]	[545 , 627]	[658 , 744]	[1,906 , 2,124]	[3,428 , 3,679]
Caldwell	[1,530 , 1,759]	[1,256 , 1,439]	[1,312 , 1,482]	[752 , 837]	[590 , 650]	[4,023 , 4,294]
Calloway	[3,889 , 4,429]	[3,006 , 3,406]	[3,119 , 3,485]	[1,855 , 2,053]	[1,390 , 1,525]	[9,623 , 10,216]
Carlisle	[144 , 166]	[266 , 308]	[491 , 561]	[484 , 544]	[890 , 989]	[2,196 , 2,338]
Crittenden	[1,038 , 1,185]	[880 , 999]	[969 , 1,085]	[617 , 686]	[465 , 512]	[3,013 , 3,199]
Daviess	[18,881 , 21,627]	[6,014 , 6,848]	[3,723 , 4,167]	[1,252 , 1,380]	[581 , 639]	[11,825 , 12,779]
Fulton	[278 , 320]	[438 , 506]	[701 , 804]	[568 , 645]	[1,033 , 1,157]	[2,830 , 3,022]
Graves	[2,761 , 3,177]	[2,902 , 3,330]	[3,594 , 4,073]	[2,487 , 2,776]	[2,632 , 2,911]	[11,973 , 12,730]
Henderson	[9,232 , 10,500]	[3,055 , 3,445]	[1,983 , 2,200]	[722 , 795]	[313 , 342]	[6,201 , 6,654]
Hickman	[205 , 236]	[318 , 366]	[513 , 585]	[452 , 507]	[693 , 768]	[2,037 , 2,164]
Hopkins	[9,519 , 10,851]	[3,834 , 4,333]	[2,757 , 3,066]	[1,127 , 1,245]	[522 , 572]	[8,427 , 9,029]
Livingston	[1,034 , 1,180]	[925 , 1,049]	[1,074 , 1,202]	[741 , 825]	[603 , 666]	[3,438 , 3,646]
Lyon	[940 , 1,071]	[804 , 910]	[903 , 1,008]	[597 , 662]	[471 , 519]	[2,852 , 3,022]
McCracken	[1,696 , 1,956]	[3,059 , 3,531]	[5,450 , 6,241]	[5,000 , 5,644]	[9,083 , 10,109]	[23,297 , 24,819]
Marshall	[2,930 , 3,362]	[2,668 , 3,048]	[3,143 , 3,540]	[2,201 , 2,449]	[2,231 , 2,469]	[10,550 , 11,198]
Muhlenberg	[7,091 , 8,051]	[2,474 , 2,779]	[1,697 , 1,882]	[673 , 748]	[267 , 294]	[5,224 , 5,590]
Trigg	[1,776 , 2,034]	[1,376 , 1,567]	[1,430 , 1,604]	[855 , 949]	[635 , 698]	[4,416 , 4,698]
Union	[2,103 , 2,400]	[1,233 , 1,397]	[1,117 , 1,247]	[590 , 653]	[367 , 403]	[3,392 , 3,615]
Webster	[2,660 , 3,037]	[1,262 , 1,428]	[990 , 1,104]	[446 , 494]	[222 , 244]	[2,991 , 3,199]

Table 38: Building Damage by Occupancy Class for the State of Kentucky

Occupancy Class	Damage State									
	None		Slight		Moderate		Extensive		Complete	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Single Family	63,459	1,088	31,895	430	29,085	381	15,372	233	18,992	329
Multi Family	2,604	49	1,216	18	1,154	16	628	10	893	17
Mobile Home	6,561	113	5,371	78	7,496	100	7,357	100	6,357	110

Table 39: Building Damage by Structural Type for the State of Kentucky

Building Type	Damage State									
	None		Slight		Moderate		Extensive		Complete	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Wood	60,116	1,084	30,472	429	26,302	377	13,455	231	14,349	316
Unreinforced Masonry	5,947	109	2,639	40	3,938	53	2,545	34	5,536	95
Mobile Home	6,561	113	5,371	78	7,496	100	7,357	100	6,357	110

Table 40: Direct Economic Losses Due to Structural Damage of Buildings for the State of Kentucky

Direct Economic Losses ($ millions)

	Lower Bound	Upper Bound
90% Confidence Interval	1,199.00	2,001.76
HAZUS*	1,501.98	

* HAZUS result includes direct loss for all buildings.

Mississippi

Input

Table 41: Seismic Hazard and Liquefaction Susceptibility for the State of Mississippi

County	Mean PGA (g)	Liquefaction Susceptibility Category
Alcorn	0.15	None
Benton	0.15	Moderate
Bolivar	0.07	None
Coahoma	0.15	None
Desoto	0.30	Moderate
Lafayette	0.15	None
Marshall	0.23	Moderate
Panola	0.15	None
Pontotoc	0.12	None
Prentiss	0.15	None
Quitman	0.15	None
Sunflower	0.05	None
Tallahatchie	0.11	None
Tate	0.27	Moderate
Tippah	0.15	Moderate
Tishomingo	0.15	None
Tunica	0.23	Very high
Union	0.14	None
Yalobusha	0.14	None

Table 42: Number of Buildings by Occupancy Class for the State of Mississippi

County	W1			URML			MH	Total
	RES1	RES3	Total	RES1	RES3	Total	RES2	
Alcorn	11,060	274	11,334	706	86	792	2,377	14,503
Benton	2,563	11	2,575	164	4	167	687	3,429
Bolivar	9,941	415	10,355	635	130	764	1,783	12,903
Coahoma	7,856	357	8,213	501	112	613	941	9,767
Desoto	30,990	508	31,498	1,978	159	2,137	2,932	36,567
Lafayette	9,102	595	9,697	581	186	767	3,009	13,473
Marshall	8,498	98	8,596	542	31	573	3,561	12,730
Panola	7,957	170	8,127	508	53	561	4,315	13,003
Pontotoc	7,382	135	7,517	471	42	513	2,323	10,353
Prentiss	7,509	175	7,683	479	55	534	1,639	9,857
Quitman	2,819	58	2,877	180	18	198	602	3,677
Sunflower	7,871	190	8,060	502	59	562	648	9,270
Tallahatchie	3,829	48	3,877	244	15	259	1,362	5,498
Tate	6,304	174	6,478	402	55	457	2,019	8,954
Tippah	6,340	81	6,421	405	25	430	1,650	8,501
Tishomingo	6,939	125	7,064	443	39	482	1,587	9,133
Tunica	1,953	94	2,047	125	29	154	817	3,018
Union	7,489	183	7,672	478	57	535	1,942	10,149
Yalobusha	3,927	92	4,020	251	29	280	1,661	5,960
Total	150,328	3,781	154,108	9,595	1,185	10,780	35,855	200,743

*Occupancy class: RES1: Single Family Dwelling, RES2: Mobile Home, RES3: Multi Family Dwelling

Results

Table 43: Structural Damage of Buildings for the State of Mississippi

Statistic	Damage State					Moderate to Complete Damage	Total No. Damaged Buildings
	None	Slight	Moderate	Extensive	Complete		
Mean	110,836	38,075	28,793	13,658	9,385	51,835	89,910
Standard Deviation	1,168	474	409	213	184	497	686
HAZUS*	116,496	42,819	19,404	5,951	16,572	41,927	84,747

* HAZUS results represent damage of building for residential occupancy classes of RES1 through RES6.

Table 44: Building Damage for Impacted Counties for the State of Mississippi (90% CI)

County	None	Slight	Moderate	Extensive	Complete	Total Damage
Alcorn	[8,225 , 9,441]	[2,742 , 3,117]	[1,728 , 1,934]	[626 , 695]	[237 , 260]	[5,453 , 5,887]
Benton	[1,916 , 2,199]	[653 , 741]	[421 , 471]	[159 , 177]	[58 , 64]	[1,320 , 1,423]
Bolivar	[10,683 , 12,198]	[937 , 1,051]	[354 , 392]	[76 , 84]	[16 , 17]	[1,403 , 1,524]
Coahoma	[5,686 , 6,544]	[1,823 , 2,083]	[1,093 , 1,230]	[364 , 403]	[147 , 161]	[3,503 , 3,801]
Desoto	[9,288 , 10,800]	[7,629 , 8,853]	[7,923 , 9,111]	[4,709 , 5,349]	[4,446 , 5,026]	[25,568 , 27,479]
Lafayette	[7,476 , 8,489]	[2,581 , 2,901]	[1,704 , 1,893]	[659 , 733]	[243 , 267]	[5,300 , 5,680]
Marshall	[4,267 , 4,880]	[2,727 , 3,092]	[2,586 , 2,898]	[1,483 , 1,656]	[887 , 984]	[7,897 , 8,416]
Panola	[6,895 , 7,804]	[2,535 , 2,841]	[1,786 , 1,993]	[755 , 850]	[259 , 288]	[5,462 , 5,845]
Pontotoc	[6,696 , 7,636]	[1,657 , 1,865]	[942 , 1,049]	[314 , 351]	[93 , 102]	[3,068 , 3,305]
Prentiss	[5,585 , 6,410]	[1,865 , 2,119]	[1,177 , 1,317]	[428 , 475]	[161 , 177]	[3,712 , 4,006]
Quitman	[2,086 , 2,394]	[695 , 790]	[438 , 490]	[159 , 176]	[60 , 66]	[1,382 , 1,492]
Sunflower	[8,210 , 9,461]	[306 , 346]	[86 , 96]	[13 , 15]	[3 , 3]	[414 , 455]
Tallahatchie	[3,715 , 4,226]	[815 , 915]	[445 , 496]	[143 , 160]	[38 , 42]	[1,471 , 1,584]
Tate	[2,459 , 2,822]	[1,865 , 2,126]	[1,935 , 2,178]	[1,211 , 1,350]	[930 , 1,032]	[6,115 , 6,512]
Tippah	[4,763 , 5,463]	[1,616 , 1,834]	[1,040 , 1,163]	[389 , 433]	[143 , 158]	[3,261 , 3,515]
Tishomingo	[5,160 , 5,922]	[1,730 , 1,965]	[1,097 , 1,228]	[402 , 447]	[150 , 165]	[3,456 , 3,729]
Tunica	[812 , 924]	[508 , 574]	[466 , 520]	[300 , 333]	[755 , 843]	[2,087 , 2,214]
Union	[5,996 , 6,861]	[1,835 , 2,077]	[1,127 , 1,258]	[402 , 448]	[140 , 154]	[3,582 , 3,860]
Yalobusha	[3,409 , 3,871]	[1,101 , 1,237]	[718 , 800]	[278 , 312]	[92 , 102]	[2,239 , 2,401]

Table 45: Building Damage by Occupancy Class for the State of Mississippi

Occupancy Class	Damage State									
	None		Slight		Moderate		Extensive		Complete	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Single Family	94,502	1,154	29,953	464	20,490	395	8,253	199	6,725	179
Multi Family	2,989	35	854	10	622	8	255	4	247	4
Mobile Home	13,345	176	7,268	95	7,680	105	5,149	77	2,412	44

Table 46: Building Damage by Structural Type for the State of Mississippi

Building Type	Damage State									
	None		Slight		Moderate		Extensive		Complete	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Wood	92,486	1,154	29,297	464	19,211	394	7,491	198	5,627	176
Unreinforced Masonry	5,004	57	1,510	19	1,902	27	1,018	19	1,345	31
Mobile Home	13,345	176	7,268	95	7,680	105	5,149	77	2,412	44

Table 47: Direct Economic Losses Due to Structural Damage of Buildings for the State of Mississippi

	Direct Economic Losses ($ millions)	
	Lower Bound	Upper Bound
90% Confidence Interval	526.83	1,281.85
HAZUS*	878.10	

* HAZUS result includes direct loss for all buildings.

Missouri

Input

Table 48: Seismic Hazard and Liquefaction Susceptibility for the State of Missouri

County	Mean PGA (g)	Liquefaction Susceptibility Category
Bollinger	0.28	Low
Butler	0.30	High
Cape Girardeau	0.32	Low
Carter	0.17	Low
Dunklin	0.51	Very high
Iron	0.11	Very low
Jefferson	0.05	Very low
Madison	0.15	Very low
Mississippi	0.63	Very high
New Madrid	0.61	Very high
Oregon	0.13	Low
Pemiscot	0.68	Very high
Perry	0.23	Low
Reynolds	0.14	Low
Ripley	0.19	Low
St. Charles	0.05	Moderate
St. Francois	0.14	None
St. Louis	0.05	Low
Ste. Genevieve	0.15	None
Scott	0.50	High
Stoddard	0.47	High
Wayne	0.23	Low
City of St. Louis	0.08	Moderate

Table 49: Number of Buildings by Occupancy Class for the State of Missouri

County	W1			URML			MH	Total
	RES1	RES3	Total	RES1	RES3	Total	RES2	
Bollinger	3,109	27	3,136	982	8	990	1,191	5,317
Butler	10,581	404	10,986	3,342	127	3,468	2,541	16,995
Cape Girardeau	15,654	935	16,589	4,944	293	5,236	2,497	24,322
Carter	1,623	23	1,646	513	7	520	754	2,920
Dunklin	8,873	310	9,183	2,802	97	2,899	1,693	13,775
Iron	2,739	66	2,805	865	21	886	984	4,675
Jefferson	42,813	1,029	43,842	13,520	322	13,842	12,656	70,340
Madison	3,246	77	3,322	1,025	24	1,049	957	5,328
Mississippi	3,602	162	3,764	1,137	51	1,188	492	5,444
New Madrid	4,723	262	4,985	1,492	82	1,574	1,304	7,863
Oregon	2,847	45	2,892	899	14	913	1,032	4,837
Pemiscot	5,008	221	5,228	1,581	69	1,650	1,016	7,895
Perry	4,662	118	4,780	1,472	37	1,509	989	7,278
Reynolds	2,180	28	2,207	688	9	697	702	3,606
Ripley	3,414	40	3,454	1,078	12	1,091	1,631	6,175
St. Charles	64,419	1,708	66,127	20,343	535	20,878	5,325	92,330
St. Francois	13,065	455	13,520	4,126	142	4,268	3,488	21,276
St. Louis	247,090	9,692	256,781	78,028	3,037	81,065	1,007	338,853
Ste. Genevieve	4,530	60	4,590	1,431	19	1,449	1,289	7,329
Scott	9,847	354	10,201	3,109	111	3,220	2,219	15,640
Stoddard	8,054	247	8,300	2,543	77	2,621	1,575	12,496
Wayne	3,693	45	3,738	1,166	14	1,180	2,367	7,285
City of St. Louis	58,534	18,955	77,489	18,485	5,939	24,424	255	102,168
Total	524,307	35,258	559,565	165,570	11,048	176,618	47,964	784,147

*Occupancy class: RES1: Single Family Dwelling, RES2: Mobile Home, RES3: Multi Family Dwelling

Results

Table 50: Structural Damage of Buildings for the State of Missouri

Statistic	Damage State					Moderate to Complete Damage	Total No. Damaged Buildings
	None	Slight	Moderate	Extensive	Complete		
Mean	618,117	57,881	43,068	22,921	42,164	108,153	166,034
Standard Deviation	13,356	612	373	199	433	605	861
HAZUS*	640,381	69,176	30,259	7,624	39,044	76,930	146,110

* HAZUS results represent damage of building for residential occupancy classes of RES1 through RES6.

Table 51: Building Damage for Impacted Counties in the State of Missouri (90% CI)

County	None	Slight	Moderate	Extensive	Complete	Total Damage
Bollinger	[1,398 , 1,583]	[1,080 , 1,218]	[1,189 , 1,321]	[740 , 816]	[614 , 676]	[3,720 , 3,934]
Butler	[3,469 , 3,939]	[2,826 , 3,202]	[3,124 , 3,485]	[1,947 , 2,147]	[4,677 , 5,175]	[12,917 , 13,665]
Cape Girardeau	[5,591 , 6,355]	[4,857 , 5,516]	[5,557 , 6,223]	[3,398 , 3,756]	[3,517 , 3,876]	[17,817 , 18,882]
Carter	[1,387 , 1,557]	[585 , 652]	[470 , 517]	[213 , 235]	[107 , 117]	[1,405 , 1,490]
Dunklin	[1,044 , 1,194]	[1,512 , 1,732]	[2,396 , 2,712]	[1955 , 2,180]	[6,081 , 6,746]	[12,256 , 12,057]
Iron	[3,138 , 3,514]	[686 , 760]	[411 , 452]	[135 , 149]	[50 , 55]	[1,306 , 1,392]
Jefferson	[62,147 , 69,451]	[2,967 , 3,268]	[1,100 , 1,211]	[209 , 232]	[45 , 50]	[4,380 , 4,702]
Madison	[2,916 , 3,284]	[993 , 1,108]	[709 , 780]	[278 , 306]	[135 , 150]	[2,160 , 2,299]
Mississippi	[264 , 303]	[474 , 545]	[869 , 990]	[788 , 886]	[2,732 , 3,037]	[4,985 , 5,336]
New Madrid	[388 , 443]	[681 , 778]	[1,246 , 1,407]	[1,183 , 1,317]	[3,937 , 4,346]	[7,212 , 7,683]
Oregon	[2,914 , 3,271]	[824 , 915]	[548 , 602]	[201 , 222]	[84 , 93]	[1,690 , 1,799]
Pemiscot	[309 , 354]	[602 , 691]	[1,182 , 1,344]	[1,166 , 1,306]	[4,190 , 4,645]	[7,308 , 7,818]
Perry	[2,637 , 2,993]	[1,555 , 1,757]	[1,432 , 1,593]	[715 , 787]	[517 , 570]	[4,326 , 4,599]
Reynolds	[2,071 , 2,331]	[644 , 719]	[444 , 489]	[169 , 186]	[76 , 85]	[1,362 , 1,451]
Ripley	[2,618 , 2,941]	[1,280 , 1,428]	[1,104 , 1,218]	[540 , 597]	[297 , 327]	[3,297 , 3,494]
St. Charles	[82,034 , 92,716]	[3,288 , 3,652]	[1,149 , 1,270]	[203 , 226]	[57 , 65]	[4,762 , 5,247]
St. Francois	[12,356 , 13,909]	[3,773 , 4,209]	[2,560 , 2,816]	[949 , 1,043]	[445 , 493]	[7,886 , 8,402]
St. Louis	[301,874 , 342,770]	[11,029 , 12,396]	[3,712 , 4,156]	[624 , 706]	[205 , 236]	[15,812 , 17,252]
Ste. Genevieve	[4,013 , 4,526]	[1,363 , 1,524]	[972 , 1,071]	[381 , 418]	[186 , 206]	[2,963 , 3,156]
Scott	[1,296 , 1,481]	[1,846 , 2,111]	[2,901 , 3,277]	[2,377 , 2,645]	[6,336 , 7,010]	[13,822 , 14,681]
Stoddard	[1,188 , 1,358]	[1,581 , 1,809]	[2,363 , 2,670]	[1,836 , 2,043]	[4,812 , 5,332]	[10,883 , 11,562]
Wayne	[2,387 , 2,678]	[1,521 , 1,696]	[1,529 , 1,690]	[892 , 991]	[565 , 662]	[4,621 , 4,884]
City of St. Louis	[83,271 , 92,571]	[8,599 , 9,511]	[3,760 , 4,121]	[833 , 916]	[356 , 398]	[13,755 , 14,739]

Table 52: Building Damage by Occupancy Class for the State of Missouri

Occupancy Class	Damage State									
	None		Slight		Moderate		Extensive		Complete	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Single Family	557,228	13,305	48,133	599	34,367	361	16,296	184	33,854	418
Multi Family	38,358	1,002	3,625	88	2,096	37	811	11	1,421	16
Mobile Home	22,531	601	6,124	88	6,606	83	5,814	76	6,890	111

Table 53: Building Damage by Structural Type for the State of Missouri

Building Type	Damage State									
	None		Slight		Moderate		Extensive		Complete	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Wood	461,902	12,784	39,644	561	24,959	323	11,546	170	21,518	365
Unreinforced Masonry	133,684	3,819	12,113	230	11,504	165	5,561	71	13,756	206
Mobile Home	22,531	601	6,124	88	6,606	83	5,814	76	6,890	111

Table 54: Direct Economic Losses Due to Structural Damage of Buildings for the State of Missouri

Direct Economic Losses ($ millions)

	Lower Bound	Upper Bound
90% Confidence Interval	1,699.67	3,488.51
HAZUS*	1,801.92	

* HAZUS result includes direct loss for all buildings.

Tennessee

Input

Table 55: Seismic Hazard and Liquefaction Susceptibility for the State of Tennessee

County	Mean PGA (g)	Liquefaction Susceptibility Category
Benton	0.29	Very low
Carroll	0.30	Low
Chester	0.30	Low
Crockett	0.52	Low
Dyer	0.85	High
Fayette	0.29	Low
Gibson	0.49	Low
Hardeman	0.25	Low
Hardin	0.15	Low
Haywood	0.36	Low
Henderson	0.30	Low
Henry	0.28	Low
Lake	0.89	Very high
Lauderdale	0.52	Moderate
Madison	0.30	Low
McNairy	0.23	Low
Obion	0.70	Moderate
Shelby	0.38	Moderate
Tipton	0.45	Moderate
Weakley	0.35	Low

Table 56: Number of Buildings by Occupancy Class for the State of Tennessee

County	W1			URML			MH	Total
	RES1	RES3	Total	RES1	RES3	Total	RES2	
Benton	5,132	50	5,181	570	16	586	2,493	8,260
Carroll	8,750	201	8,951	972	63	1,035	2,551	12,537
Chester	3,892	99	3,991	432	31	463	1,306	5,760
Crockett	4,459	83	4,541	495	26	521	784	5,846
Dyer	11,057	515	11,572	1,229	161	1,390	1,350	14,312
Fayette	7,769	95	7,864	863	30	893	1,913	10,670
Gibson	14,853	518	15,370	1,650	162	1,812	2,141	19,324
Hardeman	6,914	147	7,061	768	46	814	2,315	10,190
Hardin	8,638	146	8,784	960	46	1,006	2,481	12,271
Haywood	5,433	264	5,697	604	83	686	805	7,189
Henderson	6,841	162	7,003	760	51	811	3,134	10,948
Henry	9,433	236	9,668	1,048	74	1,122	3,947	14,737
Lake	1,693	112	1,805	188	35	223	241	2,269
Lauderdale	6,858	295	7,153	762	92	854	1,532	9,539
Madison	24,738	1,451	26,190	2,749	455	3,203	2,509	31,902
McNairy	7,735	98	7,832	859	31	890	2,093	10,815
Obion	9,406	425	9,831	1,045	133	1,178	2,128	13,137
Shelby	230,702	10,877	241,578	25,634	3,408	29,041	4,140	274,759
Tipton	13,350	237	13,587	1,483	74	1,558	2,916	18,060
Weakley	9,356	474	9,830	1,040	149	1,188	2,337	13,356
Total	397,006	16,483	413,489	44,112	5,165	49,276	43,116	505,881

*Occupancy class: RES1: Single Family Dwelling, RES2: Mobile Home, RES3: Multi Family Dwelling

Results

Table 57: Structural Damage of Buildings for the State of Tennessee

Statistic	Damage State					Moderate to Complete Damage	Total No. Damaged Buildings
	None	Slight	Moderate	Extensive	Complete		
Mean	106,942	101,151	119,465	78,082	100,247	297,794	398,945
Standard Deviation	2,488	2,600	2,964	1,784	2,088	4,041	4,805
HAZUS*	79,351	191,196	103,227	32,191	101,343	236,766	427,959

* HAZUS results represent damage of building for residential occupancy classes of RES1 through RES6.

Table 58: Building Damage for Impacted Counties in the State of Tennessee (90% CI)

County	None	Slight	Moderate	Extensive	Complete	Total Damage
Benton	[2,087 , 2,382]	[1,729 , 1,960]	[1,886 , 2,110]	[1,216 , 1,356]	[853 , 942]	[5,845 , 6,207]
Carroll	[3,148 , 3,612]	[2,637 , 3,012]	[2,839 , 3,197]	[1,754 , 1,951]	[1,390 , 1,533]	[8,871 , 9,443]
Chester	[1,425 , 1,632]	[1,202 , 1,369]	[1,309 , 1,471]	[827 , 919]	[650 , 716]	[4,102 , 4,361]
Crockett	[569 , 659]	[859 , 994]	[1,333 , 1,529]	[1,093 , 1,235]	[1,618 , 1,806]	[5,066 , 5,401]
Dyer	[375 , 434]	[925 , 1,073]	[2,077 , 2,399]	[2,254 , 2,577]	[7,758 , 8,752]	[13,355 , 14,460]
Fayette	[2,864 , 3,296]	[2,290 , 2,623]	[2,374 , 2,682]	[1,399 , 1,558]	[1,072 , 1,183]	[7,343 , 7,837]
Gibson	[2,160 , 2,499]	[3,051 , 3,529]	[4,498 , 5,158]	[3,482 , 3,936]	[4,883 , 5,453]	[16,448 , 17,541]
Hardeman	[3,281 , 3,753]	[2,230 , 2,533]	[2,131 , 2,386]	[1,181 , 1,311]	[749 , 825]	[6,461 , 6,885]
Hardin	[6,813 , 7,769]	[2,329 , 2,628]	[1,546 , 1,719]	[592 , 657]	[233 , 256]	[4,804 , 5,156]
Haywood	[1,421 , 1,636]	[1,432 , 1,647]	[1,689 , 1,921]	[1,083 , 1,214]	[1,107 , 1,228]	[5,479 , 5,842]
Henderson	[2,602 , 2,969]	[2,237 , 2,536]	[2,508 , 2,807]	[1,669 , 1,857]	[1,288 , 1,422]	[7,921 , 8,404]
Henry	[3,942 , 4,499]	[3,111 , 3,527]	[3,293 , 3,684]	[2,053 , 2,284]	[1,466 , 2,617]	[10,200 , 10,835]
Lake	[49 , 56]	[126 , 145]	[294 , 338]	[332 , 378]	[1,327 , 1,492]	[2,128 , 2,305]
Lauderdale	[862 , 994]	[1,307 , 1,505]	[2,061 , 2,351]	[1,772 , 1,991]	[2,951 , 3,284]	[8,345 , 8,877]
Madison	[8,655 , 9,965]	[6,997 , 8,044]	[7,093 , 8,066]	[3,853 , 4,320]	[3,231 , 3,581]	[21,820 , 23,364]
McNairy	[3,953 , 4,534]	[2,391 , 2,724]	[2,109 , 2,366]	[1,064 , 1,181]	[624 , 686]	[6,352 , 6,793]
Obion	[602 , 695]	[1,234 , 1,426]	[2,426 , 2,781]	[2,479 , 2,800]	[5,592 , 6,240]	[12,075 , 12,903]
Shelby	[49,696 , 57,594]	[52,391 , 60,785]	[62,780 , 72,386]	[39,747 , 45,516]	[50,965 , 57,652]	[213,361 , 228,871]
Tipton	[2,179 , 2,519]	[2,841 , 3,279]	[4,045 , 4,618]	[3,222 , 3,621]	[4,631 , 5,164]	[15,220 , 16,201]
Weakley	[2,657 , 3,047]	[2,634 , 3,011]	[3,129 , 3,533]	[2,096 , 2,333]	[2,031 , 2,241]	[10,185 , 10,823]

Table 59: Building Damage by Occupancy Class for the State of Tennessee

Occupancy Class	Damage State									
	None		Slight		Moderate		Extensive		Complete	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Single Family	97,714	2,484	91,321	2,596	104,621	2,958	63,471	1,776	83,994	2,079
Multi Family	4,208	117	4,084	123	5,052	143	3,258	88	5,049	118
Mobile Home	5,020	76	5,746	76	9,792	125	11,354	142	11,205	147

Table 60: Building Damage by Structural Type for the State of Tennessee

Building Type	Damage State									
	None		Slight		Moderate		Extensive		Complete	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Wood	95,504	2,483	90,441	2,596	99,857	2,949	58,683	1,763	69,009	2,010
Unreinforced Masonry	6,418	151	4,964	129	9,816	267	8,046	227	20,033	546
Mobile Home	5,020	76	5,746	76	9,792	125	11,354	142	11,205	147

Table 61: Direct Economic Losses Due to Structural Damage of Buildings for the State of Tennessee

Direct Economic Losses ($ millions)

	Lower Bound	Upper Bound
90% Confidence Interval	4,766.44	7,170.25
HAZUS*	7,251.58	

* HAZUS result includes direct loss for all buildings.

Summary of Results

Table 62 and Table 63 summarize estimates of structurally damaged buildings and their ratios to total number of buildings for the eight states, respectively. Table 64 shows the lower and upper bounds for the 90% confidence interval of direct economic loss due to structural damage. It is shown that the proposed framework gives consistent and reasonable estimates when compared to the HAZUS results. For high-hazard states, such as Arkansas, Missouri, and Tennessee, the differences between the probabilistic estimates and the HAZUS results are not significant. This indicates that both approaches can give fairly reasonable estimates in a high-seismicity area.

Table 62: Summary of Structural Damage of Buildings for the Eight States

State	Statistics	Damage State					Moderate to Complete Damage	Total No. Damaged Buildings
		None	Slight	Moderate	Extensive	Complete		
Alabama	Mean	461,441	20,798	6,653	1,195	165	8,014	28,812
	St. Dev.	6,768	240	68	13	1	69	249
	HAZUS*	484,462	4,222	1,327	82	3,464	4,875	9,097
Arkansas	Mean	77,043	40,695	43,937	28,736	71,370	144,044	184,739
	St. Dev.	816	376	398	260	713	857	936
	HAZUS*	87,896	59,529	41,110	16,663	57,885	115,657	175,187
Illinois	Mean	259,680	58,969	45,883	22,668	21,188	89,739	148,708
	St. Dev.	4,095	643	410	187	180	485	805
	HAZUS*	323,594	50,253	15,615	4,817	18,880	39,303	89,561
Indiana	Mean	155,454	24,199	14,130	4,526	2,262	20,918	45,117
	St. Dev.	1,966	475	261	78	47	277	550
	HAZUS*	168,902	25,254	3,768	484	2,770	7,025	32,277
Kentucky	Mean	72,624	38,481	37,735	23,357	26,241	87,334	125,815
	St. Dev.	1,095	438	394	254	348	584	729
	HAZUS*	103,857	36,798	25,532	9,809	23,018	58,359	95,159
Mississippi	Mean	110,836	38,075	28,793	13,658	9,385	51,835	89,910
	St. Dev.	1,168	474	409	213	184	497	686
	HAZUS*	116,496	42,819	19,404	5,951	16,572	41,927	84,747
Missouri	Mean	618,117	57,881	43,068	22,921	42,164	108,153	166,034
	St. Dev.	13,356	612	373	199	433	605	861
	HAZUS*	640,381	69,176	30,259	7,624	39,044	76,930	146,110
Tennessee	Mean	106,942	101,151	119,465	78,082	100,247	297,794	398,945
	St. Dev.	2,488	2,600	2,964	1,784	2,088	4,041	4,805
	HAZUS*	79,351	191,196	103,227	32,191	101,343	236,766	427,959

* HAZUS results represent damage of building for residential occupancy classes of RES1 through RES6.

Table 63: Summary of Percentage of Building Damage for the Eight States

State	Mean		HAZUS	
	Moderate to Complete	Damaged Building	Moderate to Complete	Damaged Building
Alabama	1.6	5.9	1.0	1.8
Arkansas	55.0	70.6	44.0	66.6
Illinois	22.0	36.4	9.5	21.7
Indiana	10.4	22.5	3.5	16.0
Kentucky	44.0	63.4	29.3	47.8
Mississippi	25.8	44.8	20.8	42.1
Missouri	13.8	21.2	9.8	18.6
Tennessee	58.9	78.9	46.7	84.4

Table 64: Summary of Direct Economic Losses due to Structural Damage of Buildings for the Eight States (90% CI)

Direct Economic Losses ($ millions)

State	Lower Bound	Upper Bound	HAZUS*
Alabama	37.62	61.31	123.72
Arkansas	3,096.86	6,239.14	2,359.75
Illinois	1,053.12	1,957.62	868.47
Indiana	191.99	259.85	158.86
Kentucky	1,199.00	2,001.76	1,501.98
Mississippi	526.83	1,281.85	878.10
Missouri	1,699.67	3,488.51	1,801.92
Tennessee	4,766.44	7,170.25	7,251.58

* HAZUS results represent direct loss for all buildings.

Conclusions and Discussion

Earthquake impact assessment contains various sources of uncertainty. The uncertainties should be considered in impact assessment procedures so that decision-making includes allowances for the potential variation of impact results and also so that future efforts are focused on reducing this variation. In order to consider the effect of uncertainty, this study proposes a simple probabilistic framework which adopts a modified quantile arithmetic method. It is demonstrated that the proposed procedure for probabilistic loss estimation gives consistent and reasonable estimates.

A simplified framework for uncertainty propagation analysis has a simple procedure and requires little information input. Also, it is quite convenient to use in practice because it directly utilizes standard outputs from loss assessment tools HAZUS. In addition, it requires much less computational effort than Monte Carlo simulation by adopting approximation of uncertainty propagation. Thus, the proposed procedure will be a powerful tool used to obtain reliable estimates for a complex system.

A reliable estimation will be accomplished by using objectively acceptable uncertainty included in the earthquake loss estimation procedures. Since reliability of the information and data used in the assessment depends upon the uncertainty in the definitions various components from seismic sources to the estimation of economic loss, more efforts to understand the physical phenomena of the seismic hazard and fragility and to collect the reliable and sufficient inventory data should be undertaken for better decision-making.

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Appendix 13 – Comparison with Previous Study

The earthquake impact assessment modeling discussed in this report built upon work completed in a previous Central US earthquake impact assessment study by the same research team. A report published by the Mid-America Earthquake (MAE) Center in 2008, *Impact of Earthquakes on the Central USA* (Elnashai et al., 2008), details HAZUS models and impact assessment results for a variety of seismic events in the New Madrid Seismic Zone (NMSZ), Wabash Valley Seismic Zone (WVSZ), and East Tennessee Seismic Zone (ETSZ). Though the previous study was the most comprehensive of its kind at the time it was published this new study presents results which are based on further improvement to the model components discussed in the 2008 MAE Center report. This appendix compares results from the current NMSZ impact assessment with results from the previous MAE Center NMSZ impact assessments detailed in Elnashai et al. (2008). Only the results of HAZUS models for NMSZ scenarios are considered. Scenarios for WVSZ and ETSZ events were not completed in both studies and thus no comparisons are made. Furthermore, various additional models discussed in this report, such as network and flood risk models, threshold value damage estimations, and uncertainty analyses were not included in the previous MAE Center study and thus no comparisons are available. Differences between the results of each study are presented as well as likely explanations for these differences.

General Building Damage

Estimates of damage to general buildings do not show a consistent trend of more or less damage in one particular study. For example, total building damage in Alabama is greater in the 2009 study than the 2008 study, due, in part, to more damaged wood structures. Similar trends are evident in Arkansas, as over 50,000 more buildings are damaged in the 2009 study than the 2008 study. Conversely, fewer total buildings are damaged in the 2009 study than the 2008 study for the State of Kentucky. Roughly 14,000 fewer wood structures are damaged and nearly 1,000 fewer damaged unreinforced masonry buildings (URMs). In other states, such as Illinois, Indiana, and Missouri, damage estimates are very similar in both the 2008 and 2009 studies.

There are numerous factors that contribute to these differences including improvements to the hazard, inventory, and fragility characterizations employed in each study. The 2009 study employs a new scenario event (see Appendix 1) that was designed to be nationally catastrophic. In 2008, the worst case scenario for each state was used, meaning the rupture source was moved closer to each state, thus increasing the shaking intensity in certain parts of each state. The slightly lower levels of shaking near the rupture zone may lead to less damage. Conversely, new liquefaction characterizations for the entire eight-state study region were used in the 2009 study, though only limited liquefaction data was used in the 2008 study. A full set of liquefaction data likely increases damage estimates.

The 2008 study utilized the MR2 version of HAZUS while the MR3 version was used in the 2009 study. The new MR3 version has more current building data and higher building counts than the MR2 version. The addition of more building inventory may lead to more damage, depending up on where the new inventory is located.

Lastly, building fragility relationships were updated for all building types in HAZUS (see Appendix 3). New fragility relationships alter the distribution of building damage among the four damage states (slight, moderate, extensive, and complete) (Gencturk et al., 2008). By adjusting the dispersion measures associated with each fragility buildings that were classified as 'moderately' damaged, for example, in the 2008 study may be classified as 'slightly' damaged in the 2009 study. Since damage counts include only moderate, extensive, and complete damage the resulting building damage estimates would be lower in the 2009 study than the 2008 study. Conversely, the adjustment of dispersion values may lead to more cases of damage, particularly complete damage, as is the case with certain structure types. Overall, it is difficult to determine one single factor that causes the difference in building damage estimates. Instead, there are multiple factors that contribute to the variations shown in Table 1.

Table 1: Building Damage Comparison[1]

State	Wood Structures		URM Structures		Total Buildings	
	2008	2009	2008	2009	2008	2009
Alabama	100	3,000	500	400	6,300	15,400
Arkansas	57,900	68,800	20,700	29,100	111,600	162,200
Illinois	16,700	17,700	12,700	10,100	46,300	44,500
Indiana	200	4,800	2,900	2,600	16,600	14,200
Kentucky	50,100	36,100	10,300	9,400	81,600	68,400
Mississippi	10,600	19,900	5,800	5,000	46,700	57,400
Missouri	33,600	40,200	27,300	26,800	84,600	86,800
Tennessee	166,400	163,600	48,100	48,900	258,000	264,200

Essential Facilities Damage

Variations in essential facilities damage are similar to those shown in building damage estimates (see Table 2). Certain states, such as Illinois, Indiana, Arkansas, and Mississippi, show substantially more damaged facilities in the 2009 study than the 2008 study. Conversely, Tennessee and Missouri experience fewer damaged facilities in the 2009 study. As previously mentioned, it is difficult to identify only one cause for these differences.

New characterizations of hazard, inventory, and fragility factor into the new damage estimations in the 2009 study. The adjustment of rupture location and new liquefaction susceptibility data affect the level of ground shaking and ground deformation at each individual facility. In the case of Tennessee, intense shaking was likely closer to Memphis in the 2008 leading to more damaged facilities. Since liquefaction data was

[1] All damaged buildings are those in the 'moderate', 'extensive', and 'complete' damage states, as reported by the HAZUS model. Those buildings classified as 'slightly' damaged are not included in the damage estimates shown as damage is not severe.

available in the Memphis area for both studies, the adjustments to liquefaction may not have been as critical in this portion of the study region.

Extensive inventory improvements were completed in the 2009 study. Numerous new essential facilities were added to state inventories though these new facilities were not evenly distributed throughout the eight states. Certain states saw larger numbers of new facilities than others. For example, Illinois' inventory was fairly comprehensive in the 2008 study. The inventory in Indiana was greatly improved in the 2009 study, however, with many new facilities.

Finally, new fragility relationships are employed in the damage assessment of essential facilities damage. The building fragilities employed in the building damage estimates are also used in the essential facilities damage calculations as they share the same building types. Improvements to these fragility relationships alter the damage state probabilities for essential facilities in the 2009 study, leading to more cases of damage in certain circumstances and fewer occurrences of damage in other situations.

Table 2: Essential Facilities Damage Comparison[2]

State	Hospitals		Schools		Police Stations		Fire Stations	
	2008	2009	2008	2009	2008	2009	2008	2009
Alabama	0	0	0	0	0	0	0	0
Arkansas	18	24	188	219	94	107	151	216
Illinois	3	15	83	333	21	100	38	158
Indiana	0	5	0	6	0	2	0	4
Kentucky	6	9	98	99	23	22	77	71
Mississippi	11	15	110	140	30	42	81	104
Missouri	8	7	185	136	61	53	116	69
Tennessee	43	12	602	608	124	51	256	242

Transportation Lifeline Damage

There are fewer factors affecting damage estimations for transportation lifelines than building damage and essential facilities. Extensive hazard and inventory improvements were made in the 2009 study, though fragilities were largely unchanged, with the exception of bridge fragilities, which were updated. Estimates of bridge damage are far greater for some states in the 2009 study, namely Arkansas, Kentucky, and Tennessee, though far less in others such as Illinois, Missouri, and Mississippi. Other transportation facilities show lesser variations between the two studies. Kentucky damage estimates are generally less in the 2009 study, while most facility types in Arkansas incur more damage. Estimates in Tennessee are largely unchanged between the 2008 and 2009 studies, as shown in Table 3.

[2] For tables in this section the following method is used to determine the number of facilities in a damage category. HAZUS assigns each facility a probability of reaching a specific damage level (at least moderate, complete, etc.). In order to provide quantities of facilities at various damage levels, all those facilities that experience a damage probability of 50% or greater for a given damage level are counted as 'damaged.' Therefore, the facilities that are not 50% likely to incur damage at a specific damage level are deemed 'undamaged.'

The aforementioned improvements to the scenario event and resulting ground shaking distribution, as well as liquefaction susceptibility data affect the damage estimations in the 2009 study. Extensive inventory improvements to all transportation facilities are also a major factor as certain facility types have greater inventories in the 2009 study. This is particularly relevant to bridges since the National Bridge Inventory (NBI) from 2008 was added to the regional inventory in the 2009 study. There are multiple factors that contribute to variations in damage estimates, and as with previously discussed infrastructure damage, it is impossible to attribute variations to only a single factor.

Table 3: Transportation Lifeline Damage Comparison[3]

State	Highway Bridges		Railway Bridges		Ports		Airports	
	2008	2009	2008	2009	2008	2009	2008	2009
Alabama	0	0	0	0	0	0	0	0
Arkansas	688	1,082	4	11	17	12	36	37
Illinois	264	157	6	11	20	17	30	16
Indiana	0	0	0	0	0	0	0	0
Kentucky	197	262	3	3	86	61	19	13
Mississippi	73	6	0	0	1	0	5	0
Missouri	1,363	1,004	2	2	49	51	33	28
Tennessee	878	1,035	4	2	81	82	50	45

Utility Lifeline Damage

Estimates of utility facility damage show more cases of damage in the 2009 study than the 2008 study, generally. Waste water, electric power, and communication facilities damage estimates are greater in each of the eight states while oil facilities damage is greater in seven of the eight states. Variations in damage estimates are far more straight-forward with utility facilities than with the aforementioned infrastructure types. Though all hazard improvements previously discussed apply to utility facility damage estimations, the improvements to the inventory overshadow the hazard improvements. In many states, hundreds or thousands of facilities have been added to the 2009 inventory and many of these new facilities are located in areas of intense shaking. This leads to far more cases of damage and the larger damage estimates shown in Table 4. Utility fragility relationships are unchanged between the 2008 and 2009 studies.

Utility pipeline damage estimate are largely influenced by ground shaking and ground deformation, thus the adjustments to the scenario event and liquefaction susceptibility data are major factors in damage estimate variations. Several states require fewer repairs in the 2008 study than the 2009 study, specifically Alabama, Arkansas, Illinois, and Kentucky. Conversely, Indiana, Mississippi, Missouri, and Tennessee require more repairs in the 2009 study, though some variations are larger than others (see Table 5). Several hundred additional repairs are needed in Indiana, while each pipe type requires up to 8,100 more repairs in the 2009 study. These larger estimates are due, in part, to the improvements in liquefaction susceptibility. In states like Tennessee, liquefaction data was not available for the entire state in the 2008 study, though a comprehensive state liquefaction map was used in the 2009 study.

[3] Please reference footnote 2.

Table 4: Utility Facility Damage Comparison[4]

State	Waste Water		Oil		Electric Power		Communication	
	2008	2009	2008	2009	2008	2009	2008	2009
Alabama	0	0	0	0	0	0	0	0
Arkansas	66	349	2	14	8	147	59	633
Illinois	461	616	3	755	59	75	1,450	1,715
Indiana	0	0	0	0	0	0	0	0
Kentucky	523	650	6	175	132	202	1,044	1,373
Mississippi	102	145	1	4	24	36	290	467
Missouri	88	519	8	7	96	117	1,573	1,536
Tennessee	375	453	32	43	63	96	3,468	4,024

Table 5: Local Utility Pipeline Damage Comparison

State	Potable Water		Waste Water		Natural Gas	
	2008	2009	2008	2009	2008	2009
Alabama	902	752	714	595	762	636
Arkansas	49,440	47,181	39,103	37,316	41,800	39,889
Illinois	10,849	9,768	8,612	7,725	9,206	8,167
Indiana	1,481	1,807	1,172	1,429	1,253	1,528
Kentucky	15,087	11,406	11,933	9,022	12,755	9,644
Mississippi	5,685	10,735	4,497	8,490	4,807	9,076
Missouri	35,461	36,581	28,047	28,933	29,981	30,928
Tennessee	31,244	39,309	24,711	31,089	26,415	33,234

Table 6: Utility Service Outage Comparison at Day 1

State	Electric Power Outages		Potable Water Outages	
	2008	2009	2008	2009
Alabama	0	230,000	0	0
Arkansas	95,300	330,000	175,600	193,000
Illinois	69,600	235,000	70,800	95,000
Indiana	0	222,000	44,100	15,000
Kentucky	77,300	329,000	108,600	76,000
Mississippi	32,600	233,000	41,800	80,000
Missouri	100,100	310,000	146,400	124,000
Tennessee	426,600	709,000	446,900	507,000

Utility service outage estimates are vastly different in the 2008 and 2009 studies, particularly electric power outages. Every state in the study region shows far greater electric power outages in the 2009 study. This substantial increase is due, in large part, to the improvement of regional inventory. Additional electric power facilities were added to many states which affects the determination of electric outages. Also, previous inventory improvements were adjusted to reflect the appropriate facility types. These improvements also affected the power outages model leading to numerous additional outages. Estimates of potable water outages are greater in the 2009 study for many states. Only Indiana, Kentucky, and Missouri report fewer outages in the 2009 study, while estimates in Alabama are unchanged (see Table 6). The adjustments to hazard lead to variation in pipeline damage which feeds the water outage model. It is likely that pipeline damage estimates decreased in areas of intense shaking leading to fewer water outages. It is relevant to note that pipeline damage estimates may be reduced in areas of intense shaking and increase in areas of less intense shaking since liquefaction susceptibility information was available for these outlying areas in the 2009 study and was not available in the 2008 study. Though state totals may increase or decrease in the 2009

[4] Please reference footnote 2.

study, variations throughout each state are not discussed explicitly and affect the outages estimated in the model.

Induced Damage, Casualties, Direct Economic Loss

Debris estimates are greater in the 2009 study for all states. The newer version of HAZUS used in the 2009 study, MR3 version, has a more substantial building inventory than the MR2 version used in the 2008 study. All forms of building damage and bridge damage are included in the debris calculation and greater inventory generates greater damage, especially when slight damage is considered, as it is in the estimations shown in Table 7. Some states show small increases, such as Illinois, Kentucky, Missouri, and Tennessee, while other states show significant increases (Alabama, Arkansas, and Indiana). Greater estimates of truckloads[5] are also required to remove the increased estimates of debris reported in the 2009 study.

Table 7: Debris Generation Comparison

State	Total Debris (Tons)		Truckloads	
	2008	2009	2008	2009
Alabama	112,000	559,000	4,480	22,360
Arkansas	7,000,000	9,391,000	280,000	375,640
Illinois	2,570,000	2,762,000	102,800	110,480
Indiana	282,000	1,049,000	11,280	41,960
Kentucky	4,000,000	4,818,000	160,000	192,720
Mississippi	2,000,000	3,408,000	80,000	136,320
Missouri	6,000,000	6,450,000	240,000	258,000
Tennessee	20,000,000	21,619,000	800,000	864,760

Table 8: Casualties Comparison

State	Fatalities		Total Casualties	
	2008	2009	2008	2009
Alabama	2	28	88	949
Arkansas	574	641	13,977	15,305
Illinois	276	271	6,250	6,284
Indiana	3	80	145	1,976
Kentucky	593	287	9,740	6,840
Mississippi	208	183	3,977	6,056
Missouri	760	687	15,639	14,125
Tennessee	4,088	1,319	63,038	34,230

Casualty estimates are also related to building damage and thus many states that show less building damage in the 2009 study also show fewer fatalities and total casualties, though this is not a direct correlation, so this is not applicable in every case. In addition, the 2008 studies reported the greatest casualty estimate of the three times of day modeled. The 2009 study reported only the 2:00AM casualty estimate since that was the time of day chosen for the scenario event. Generally, fatality estimates are less in the 2009 study, which may be due to fewer completely damaged buildings. Table 8 shows, however, that total casualties increase in several states. Alabama, Arkansas, Indiana, Mississippi, and Illinois to a lesser degree, show greater total casualty estimates in the 2009 study. All other states show far fewer total casualties, particularly Tennessee where nearly 30,000

[5] Truckload estimates assume a 25-ton truck.

fewer casualties occur. It should also be noted that a social impact model such as the casualty model, is highly uncertain due to the uncertainties in all models and input components that are used within the casualty model itself. Improving the model components and inputs that feed the casualty model reduce the level of uncertainty, though not completely.

Direct economic losses are divided into losses by infrastructure group: buildings, transportation lifelines, and utility lifelines. A comparison of building losses shows that building losses are greater in the 2009 study than the 2008 study. While this is due, in part, to some increases in building damage, the increase in building value is also relevant. The MR2 version of HAZUS used building valuation data from 2005. The MR3 version used in the 2009 study was updated to more current building valuations. Similar amounts of damage in both studies would result in more economic loss in the 2009 study than the 2008 study. The largest differences, in terms of total dollars or percentage increases, in building-related economic loss occur in Alabama, Indiana, Mississippi, Illinois, and Tennessee.

Table 9: Direct Economic Loss Comparison ($ millions)

State	Building		Transportation		Utility		Total	
	2008	2009	2008	2009	2008	2009	2008	2009
Alabama	$404	$1,758	$96	$274	$569	$11,626	$1,068	$13,658
Arkansas	$12,597	$18,167	$2,155	$2,347	$4,127	$18,515	$18,879	$39,029
Illinois	$5,451	$8,105	$1,883	$1,303	$26,779	$34,764	$34,114	$44,172
Indiana	$613	$3,472	$158	$464	$648	$8,355	$1,419	$12,291
Kentucky	$9,443	$11,369	$1,291	$1,131	$35,292	$40,261	$46,026	$52,761
Mississippi	$3,770	$7,305	$280	$660	$5,442	$8,759	$9,492	$16,724
Missouri	$11,811	$13,512	$1,773	$1,789	$25,138	$33,700	$38,722	$49,001
Tennessee	$40,316	$49,392	$1,746	$2,898	$14,576	$16,121	$56,639	$68,411

Transportation lifeline losses are also greater in all eight states. Improvements to inventory and greater damage estimations are main factors in those increases. Utility lifeline losses show substantial increases in all eight states as well. Alabama, for example, shows $11 billion more utility loss in the 2009 study than the 2008 study, which is extremely large, considering the 2008 study estimated on $570 million in utility losses. Improvements to the inventory and the addition of liquefaction data are largely responsible for this change. Arkansas, Illinois, Kentucky, and Missouri also show significant increases in utility loss. Overall, direct economic losses are far greater in the 2009 study, as is detailed by the total losses shown in Table 9. Losses in Arkansas more than doubled in the 2009 study. Tennessee shows a $12 billion increase while both Illinois and Missouri report at least $10 billion in new economic losses. Though total economic losses in all states should not be added in the 2008 study, due to the different scenario events employed for each state, rough estimates indicated total regional losses up to $200 billion. The 2009 study reports nearly $300 billion in total direct economic losses for the eight-state region. This is a substantial increase that is directly related to the improvements made to the model components discussed previously.

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