# Modeling and Analysis of Complex Infrastructure Systems

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**Rethinking Network Science for Critical Infrastructure**
University of Vermont - Santa Fe Institute - MITRE Corporation

**McLean, Virginia**
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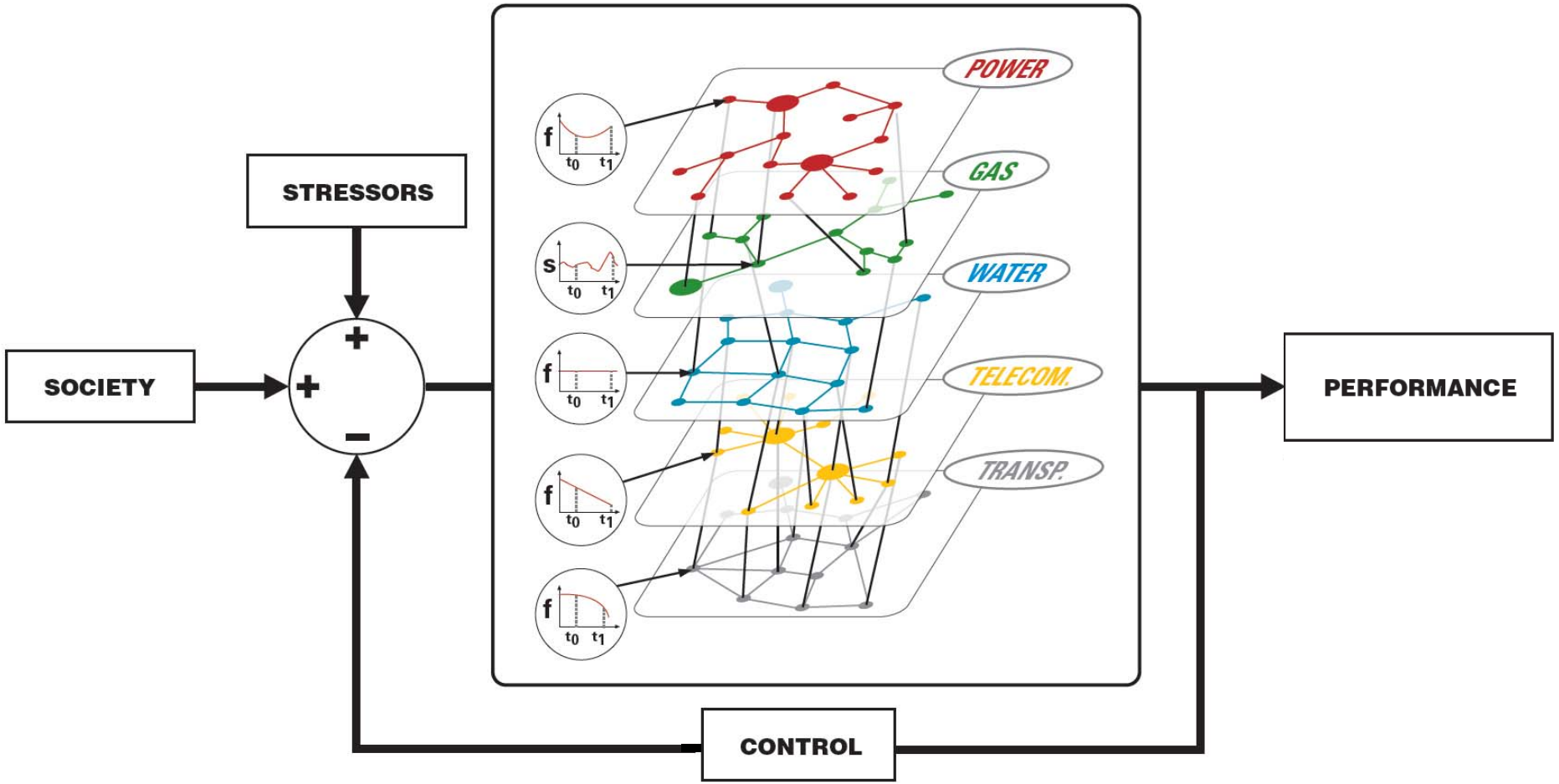
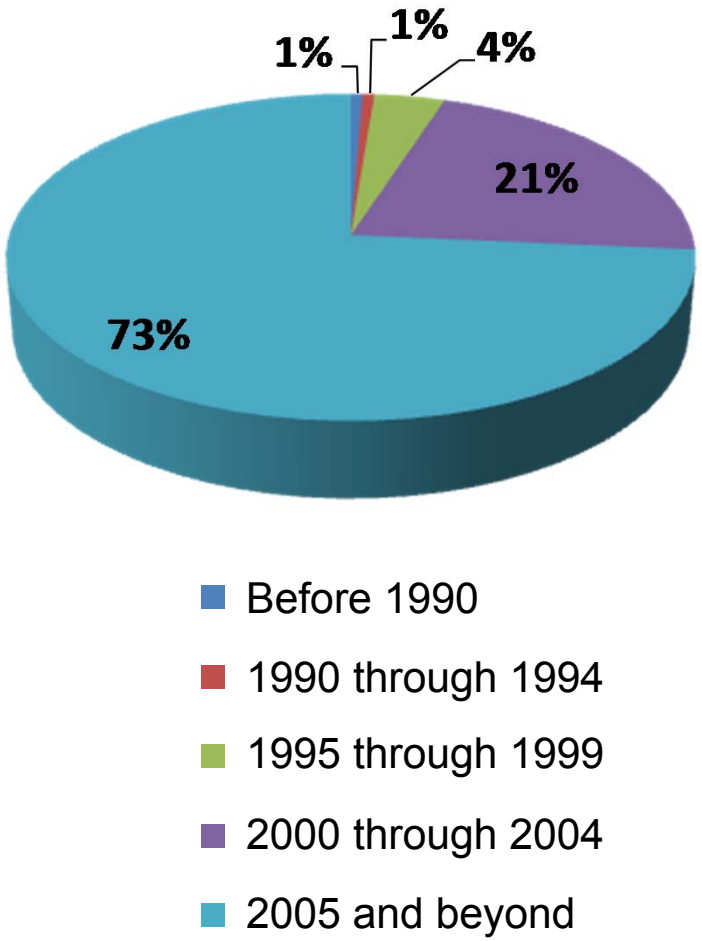
# Motivation (1/3)

- **Contemporary complex infrastructure systems**



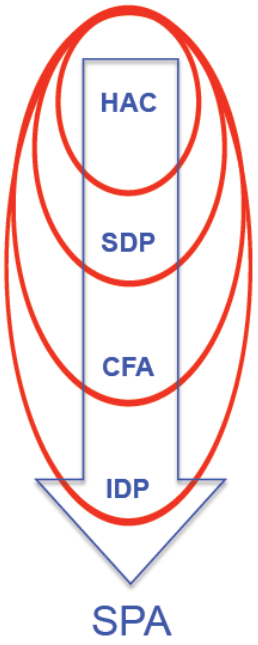
# Motivation (2/3)

- **Research on interdependent infrastructure systems**
  - **Inoperability input-output Leontief methods**
  - **Agent-based modeling**
  - **Network- and reliability-theory approaches**
  - **Data-based methods**

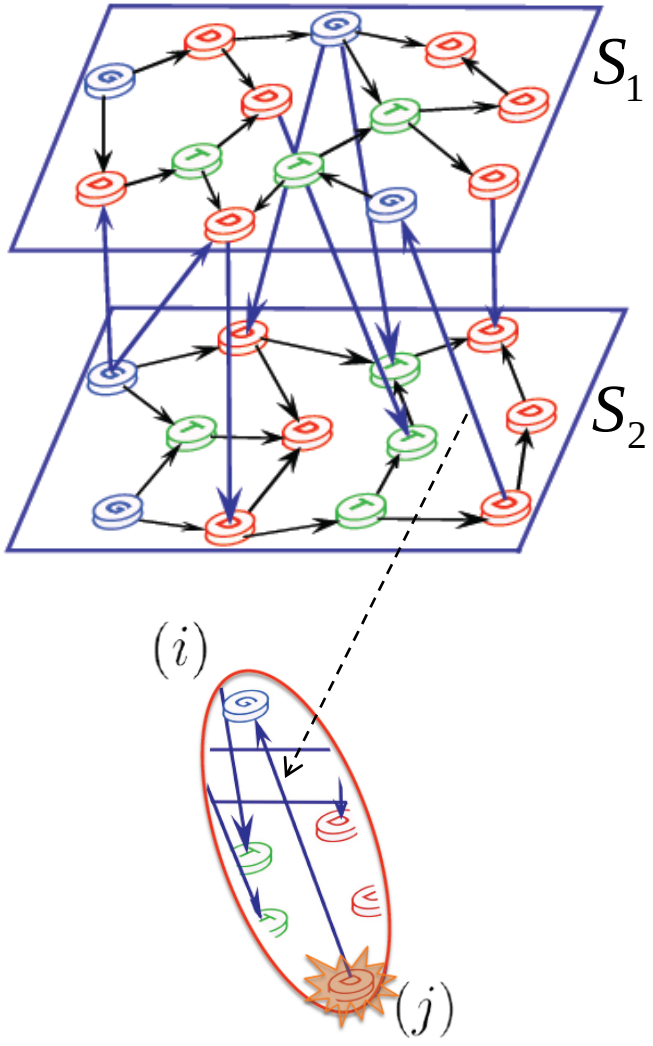


# Motivation (3/3)

- **Risk assessment approach for of interdependent infrastructures**




  - **Hazard and Action on Components (HAC)**
  - **Systemic Damage Propagation (SDP) and Cascading Failures Assessment (CFA)**
  - **Interdependence Damage Propagation (IDP)**
  - **Systemic Performance Assessment (SPA)**




$$Istr = P(F(i)|F(j))$$

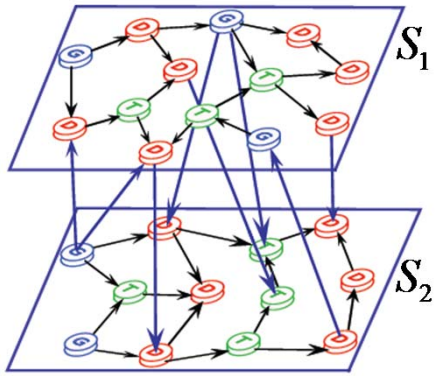
*Istr*: Interdependence Strength

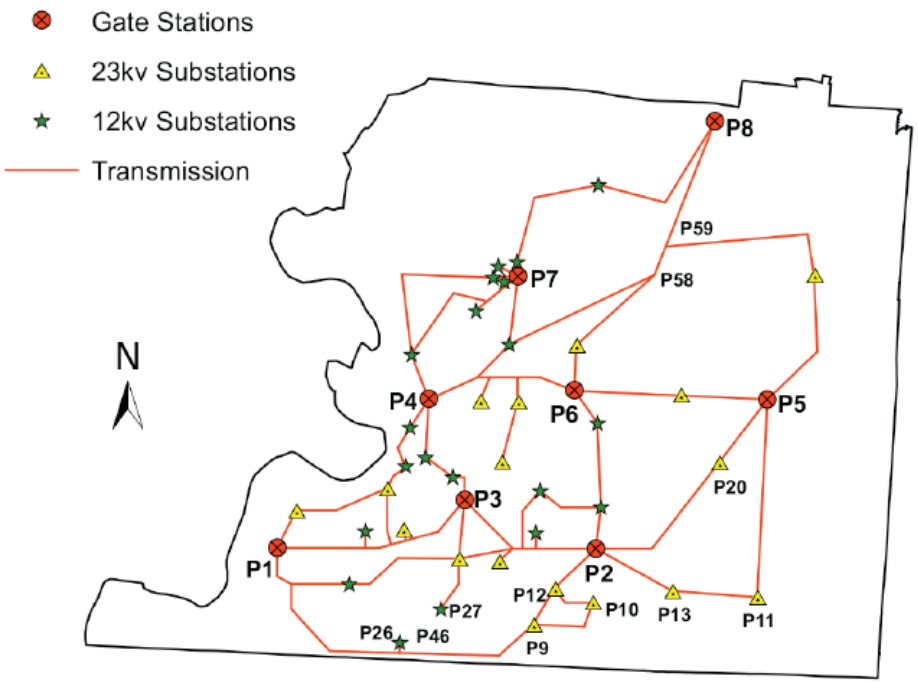
# Presentation Outline

1. Insights from interdependent infrastructure model abstractions
2. Approaches to capture socio-technical interactions
3. Quantification of infrastructure system coupling strengths
4. Prospective applications
5. Concluding remarks

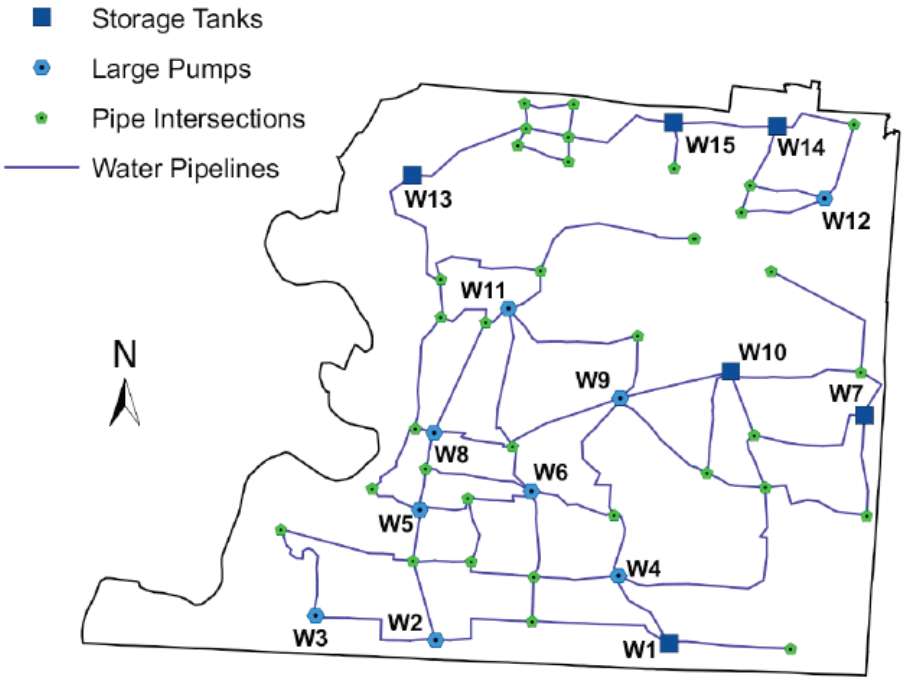
# 1. Insights from Modeling (1/7)

- **A set of realistic yet streamlined systems**




Power System $S_1$



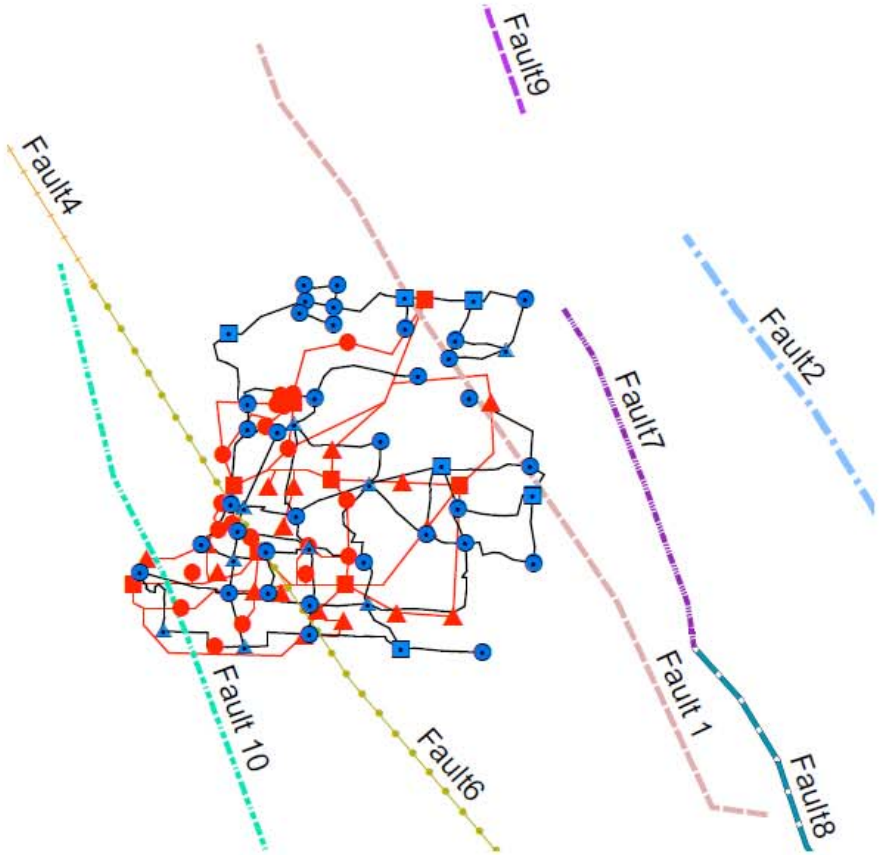

Water Network $S_2$

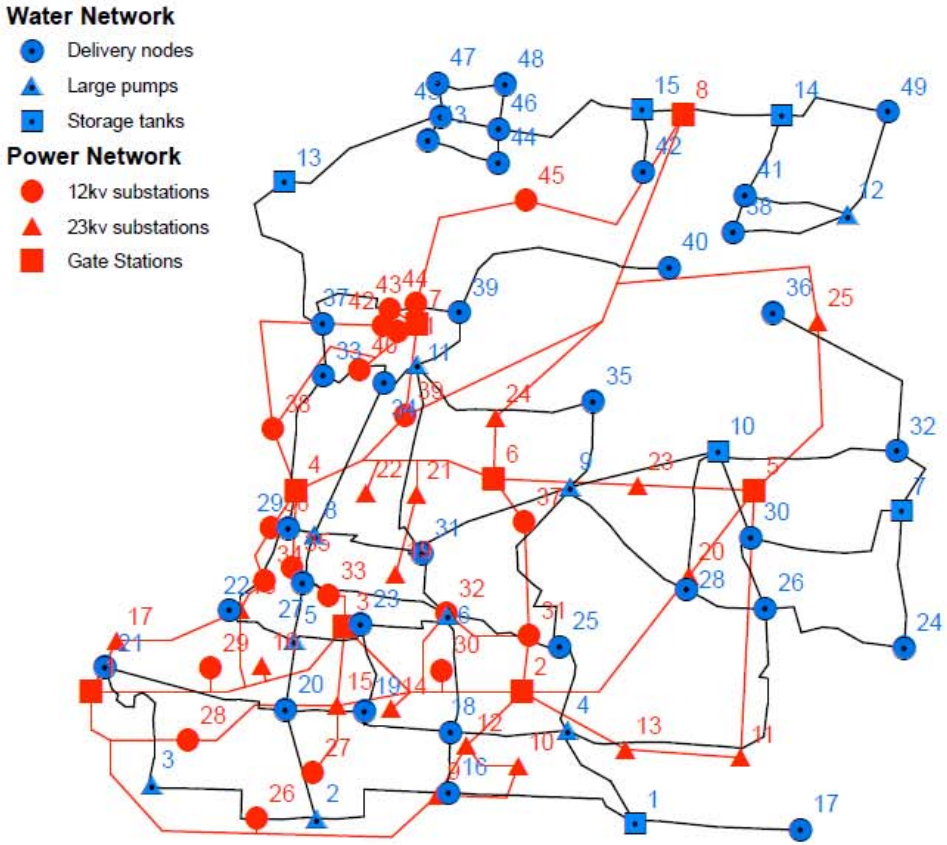
$S_1 \rightarrow S_2$ Power effects on Water

$S_2 \rightarrow S_1$ Water effects on Power

# 1. Insights from Modeling (2/7)

- **Assess the effects of probabilistic seismic hazards**

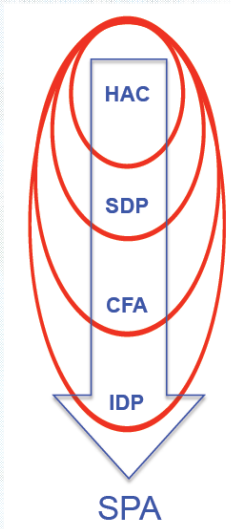


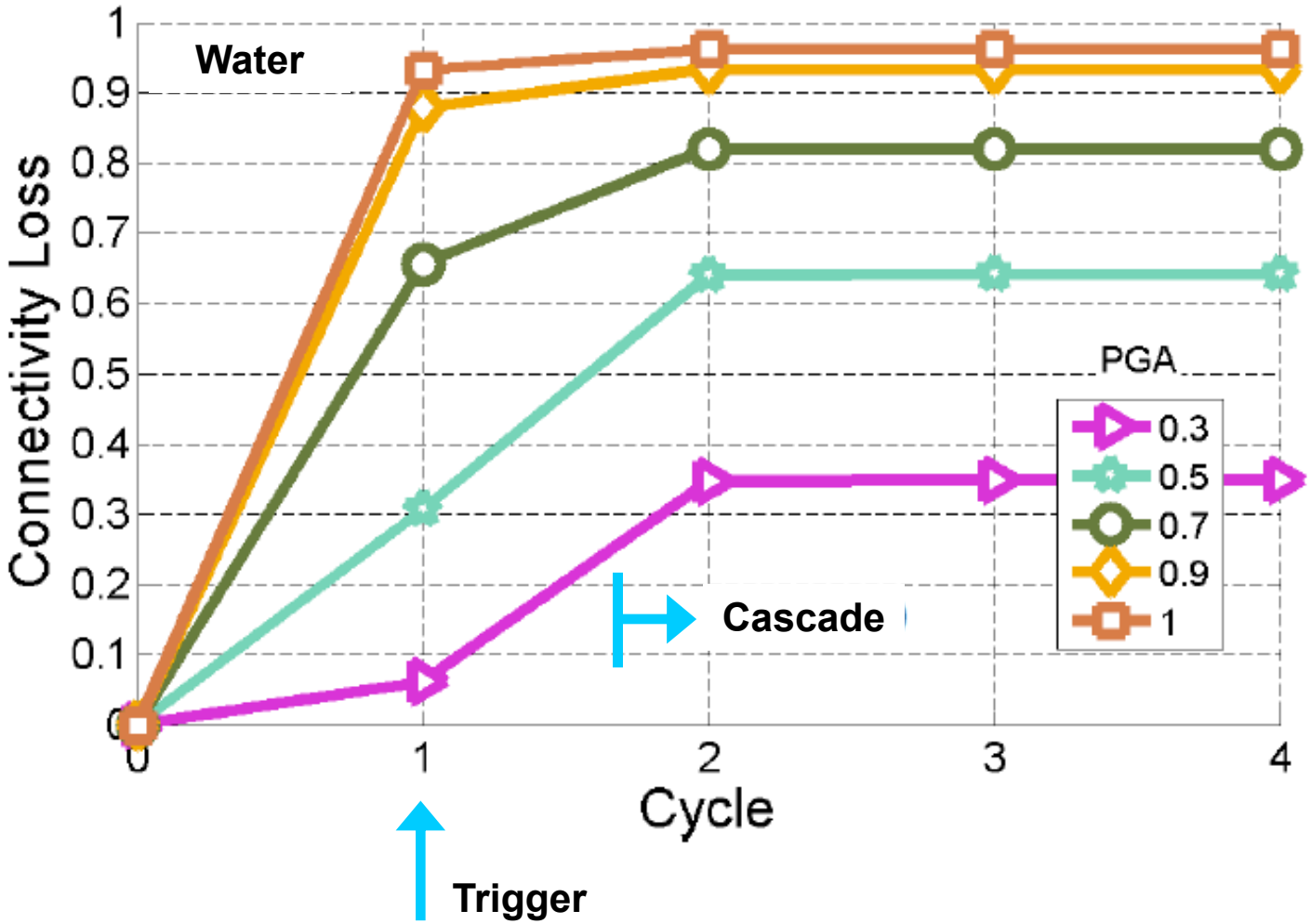
# 1. Insights from Modeling (3/7)

- **Water Connectivity Loss from interdependence with power**

$S_1 \rightarrow S_2$



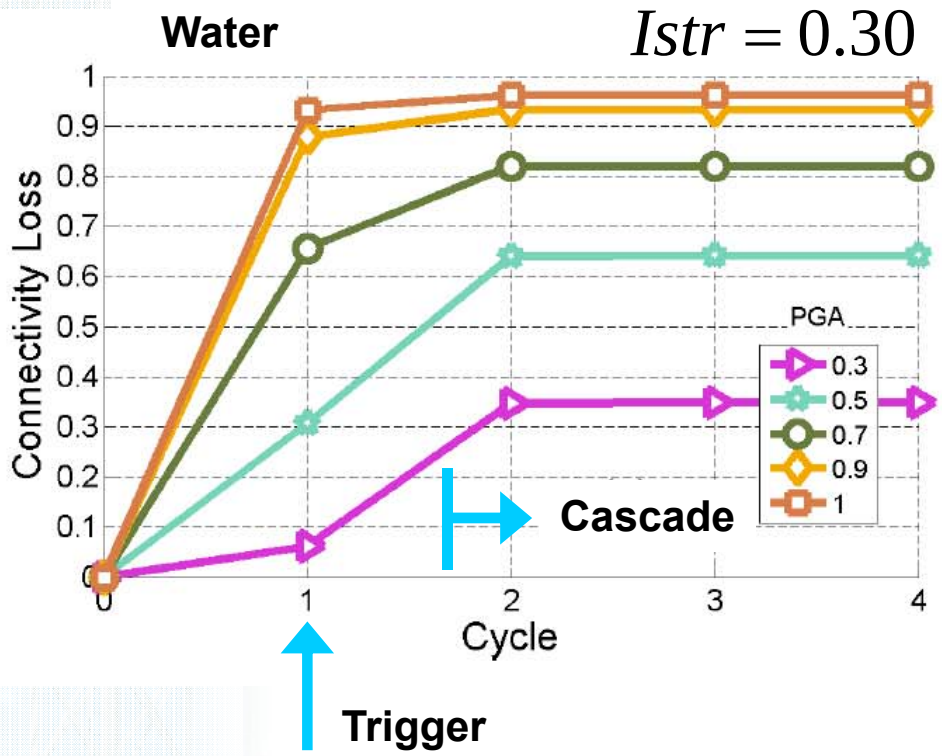

$Istr = 0.30$

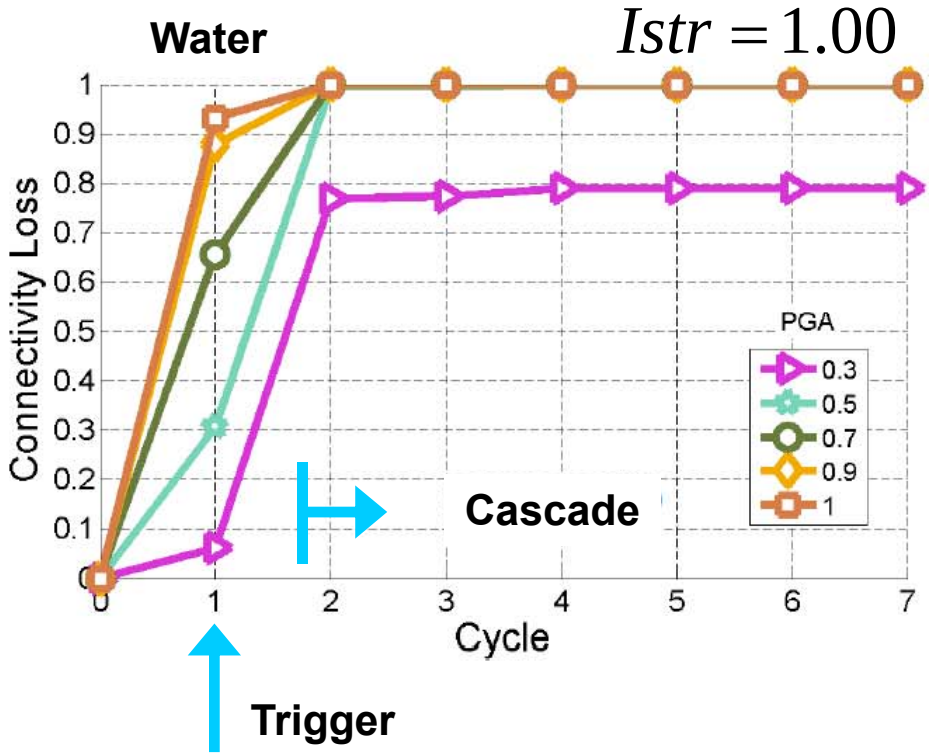


# 1. Insights from Modeling (4/7)

- **Water Connectivity Loss from interdependence with power**

$S_1 \rightarrow S_2$

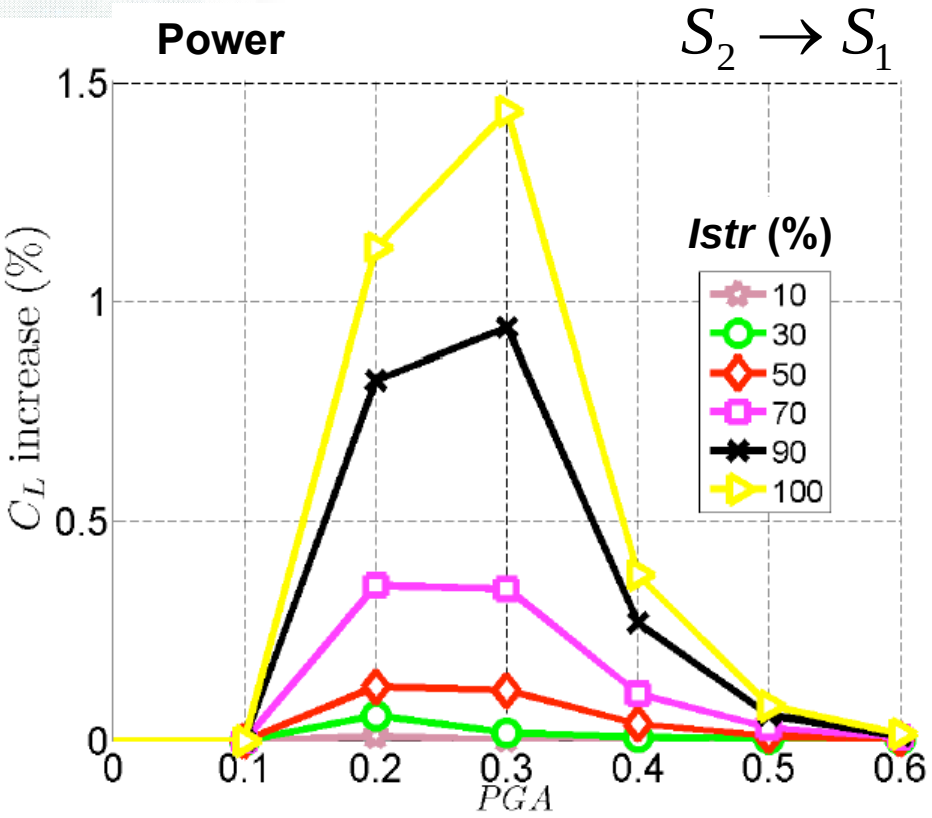


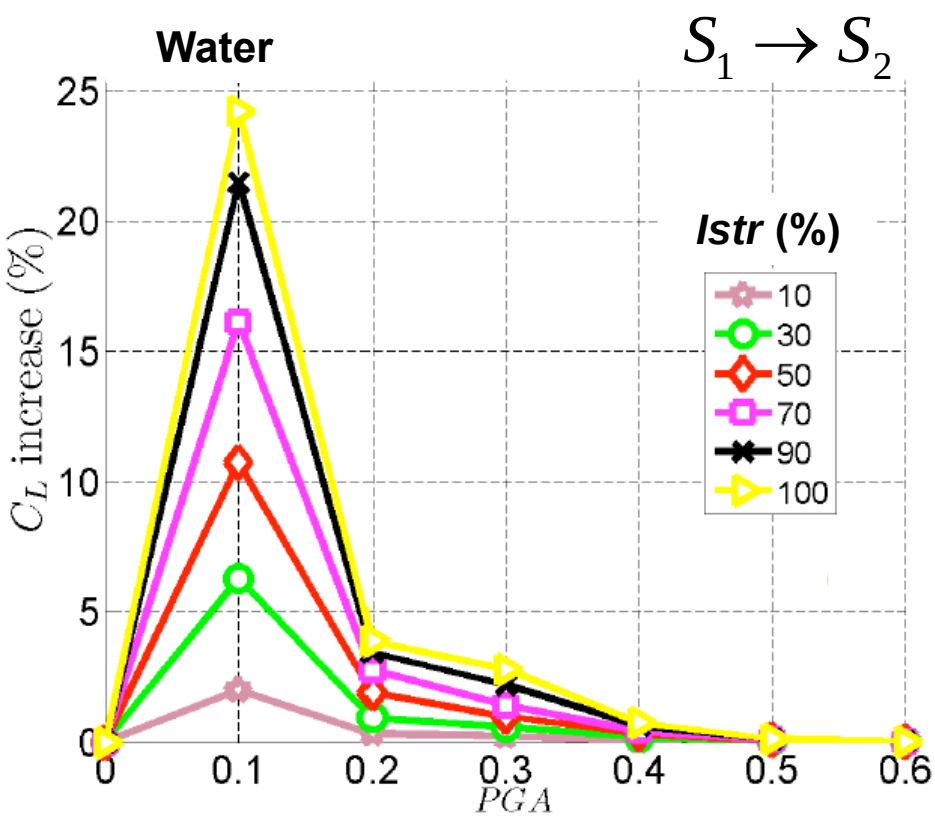




- **Coupling contributes significantly to water fragility**
- **Interdependence control must be activated early**

# 1. Insights from Modeling (5/7)

- **Added Connectivity Loss $C_L$ from interdependencies**



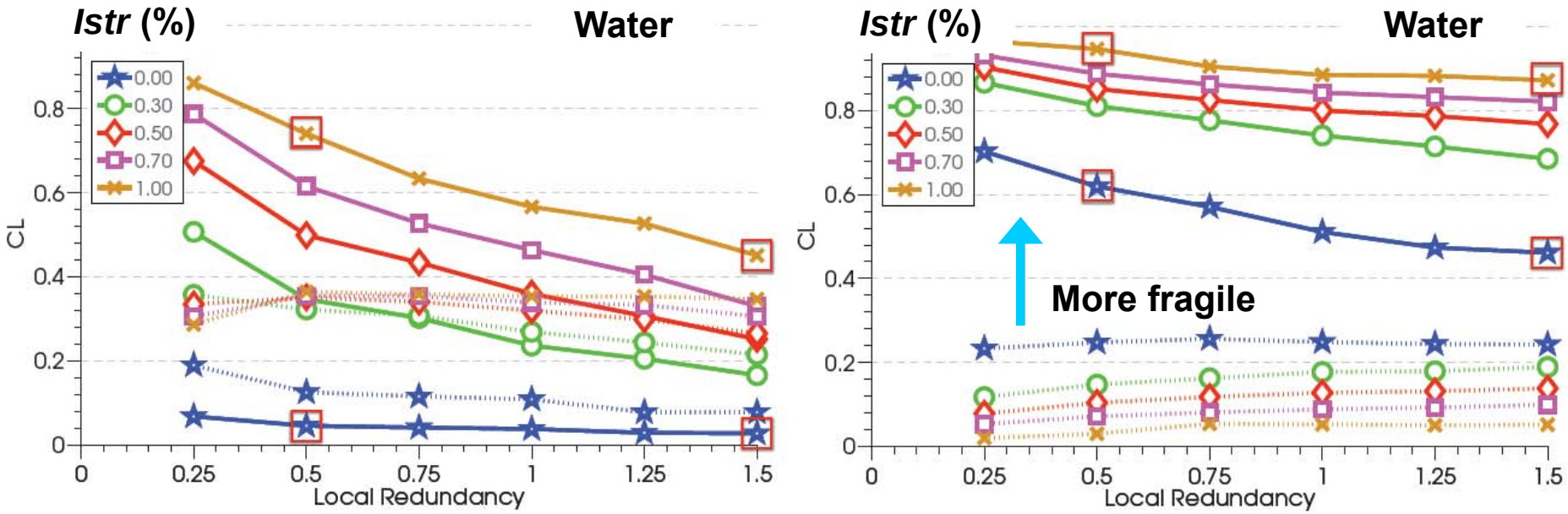

- **Power system is less sensitive to coupling**
- **Interdependencies manifest at select hazard levels**

# 1. Insights from Modeling (6/7)

- **Effects of capacity increase of congested elements on $C_L$**

$S_1 \rightarrow S_2$

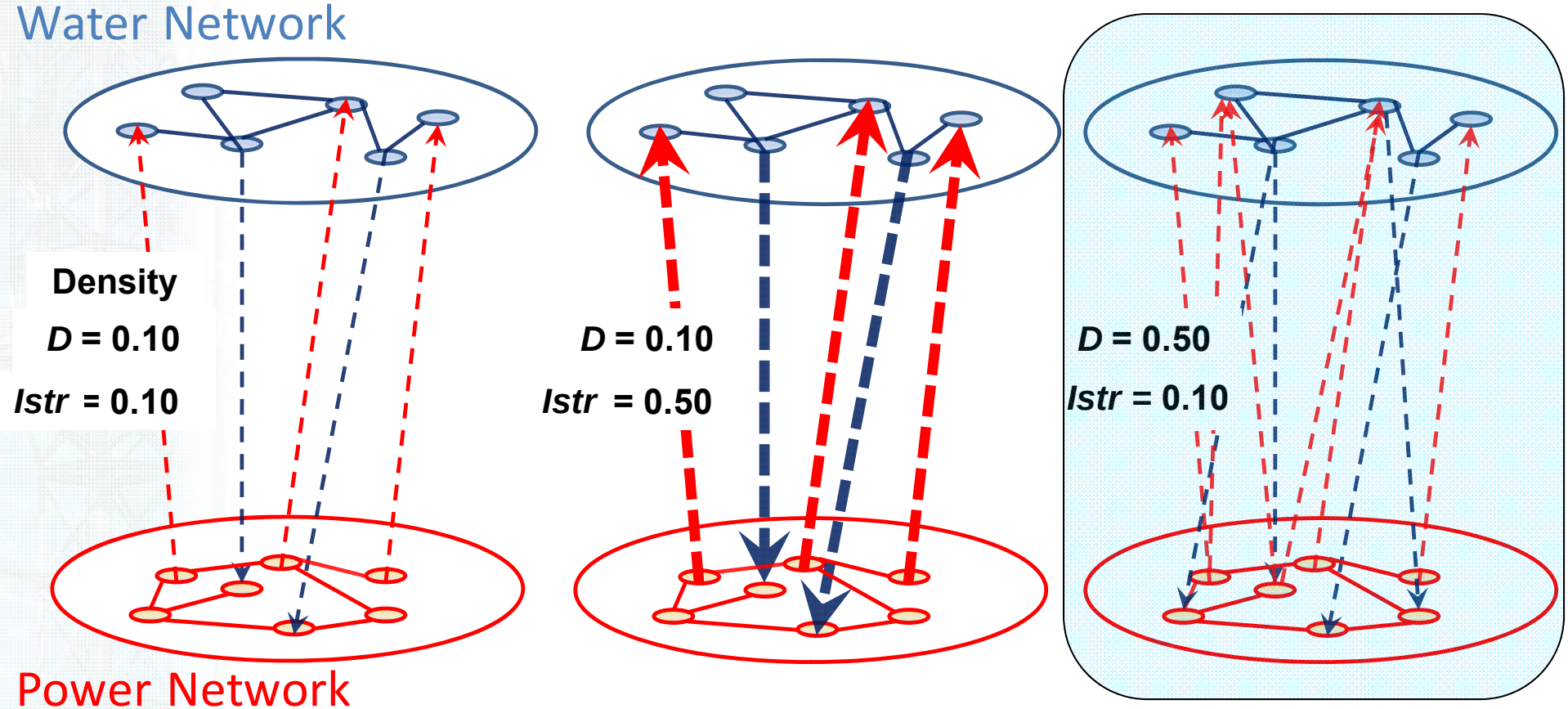
$PGA = 0.20$ $PGA = 0.50$




- **Local capacity increase to manage intra- and inter-dependent cascades is insufficient to control $C_L$**

# 1. Insights from Modeling (7/7)

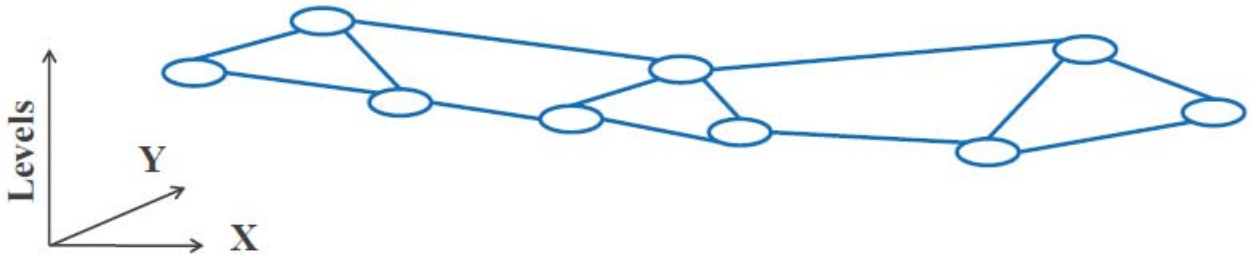
- **Effects of interface topology across systems**




- **Optimal interfaces exhibit high *D* and low *Istr***
- **Strengthen power nodes and water links**

# 2. Socio-Technical Interactions (1/3)

- **Hierarchical representations for decision-support**



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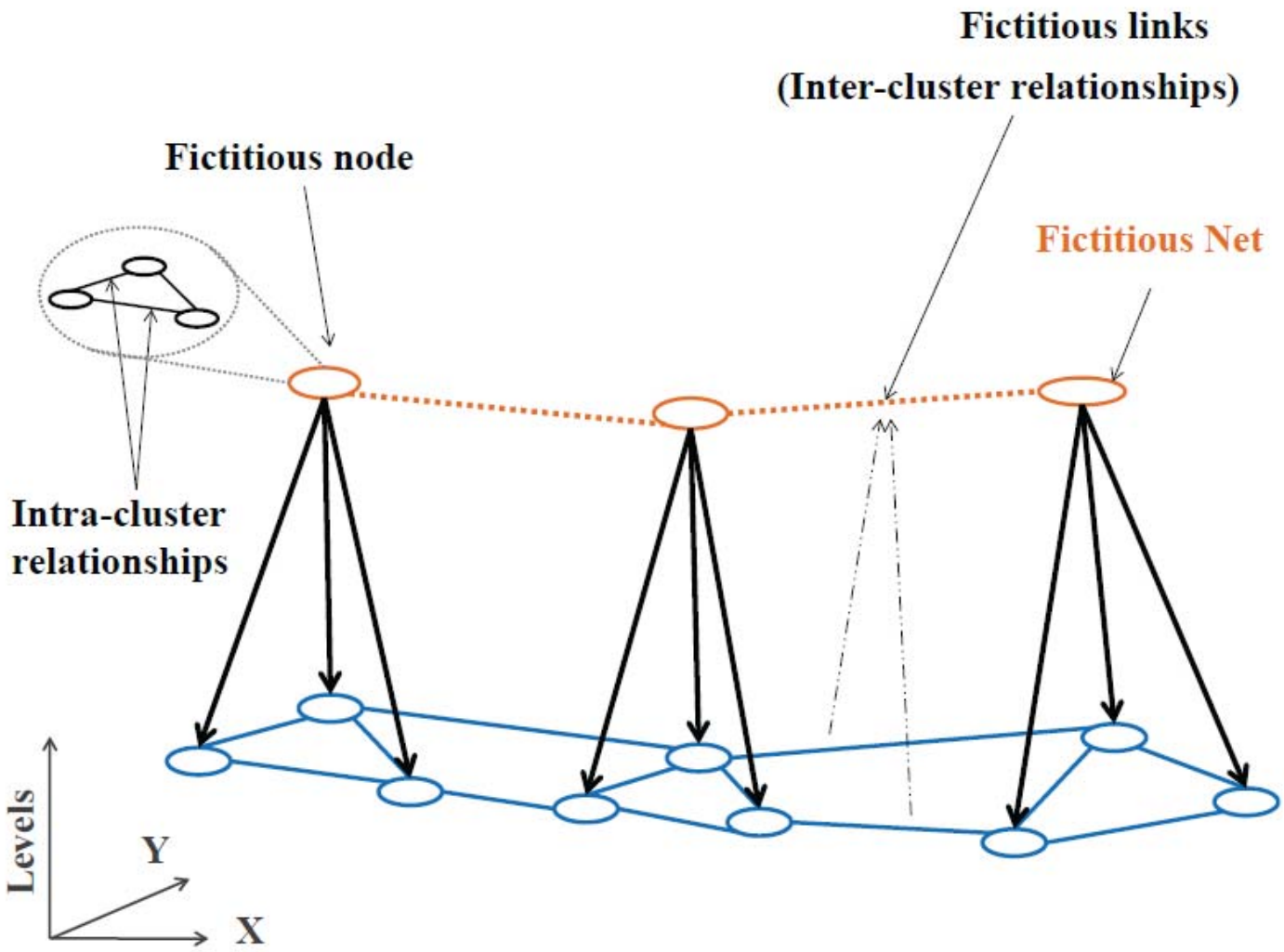

# 2. Socio-Technical Interactions (1/3)

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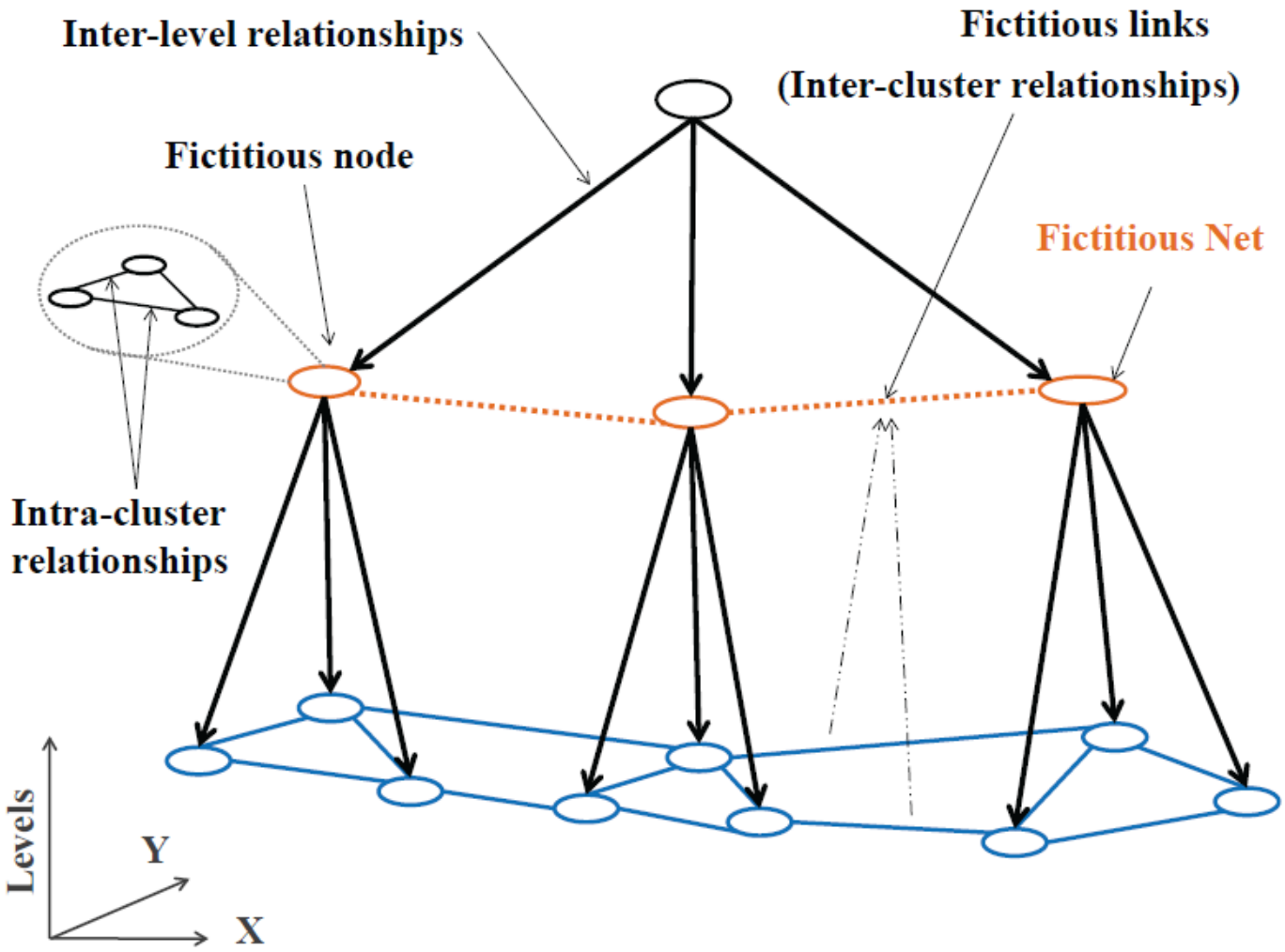
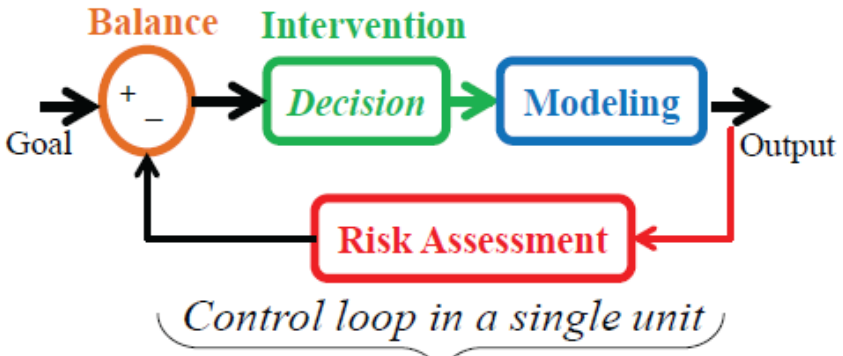
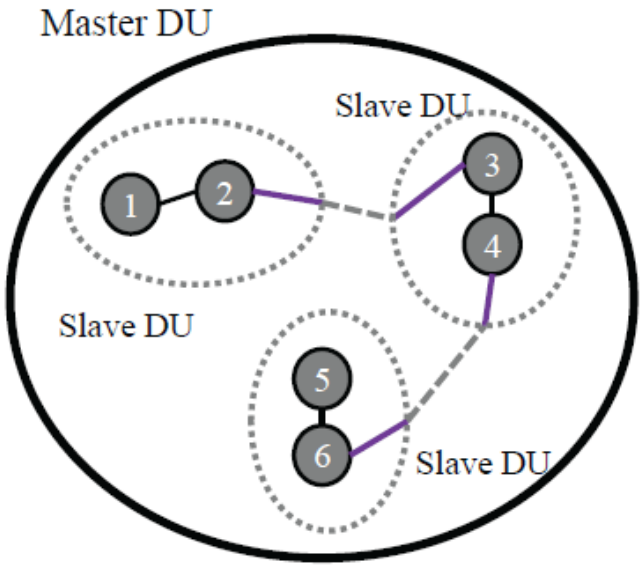


# 2. Socio-Technical Interactions (2/3)

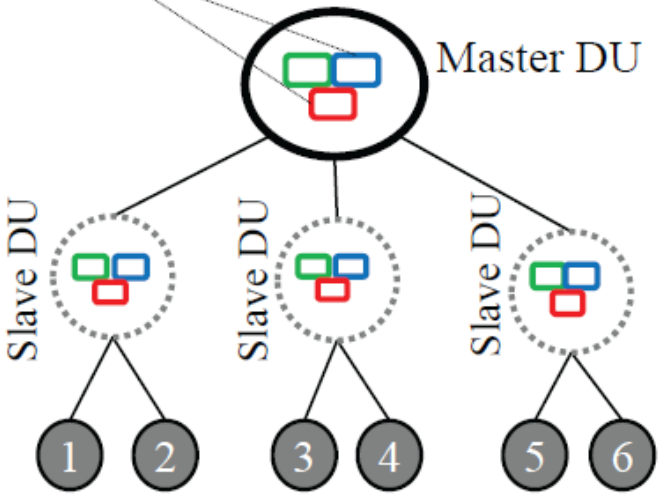
- **Control based on decentralized coordination**




*Control loop in a single unit*



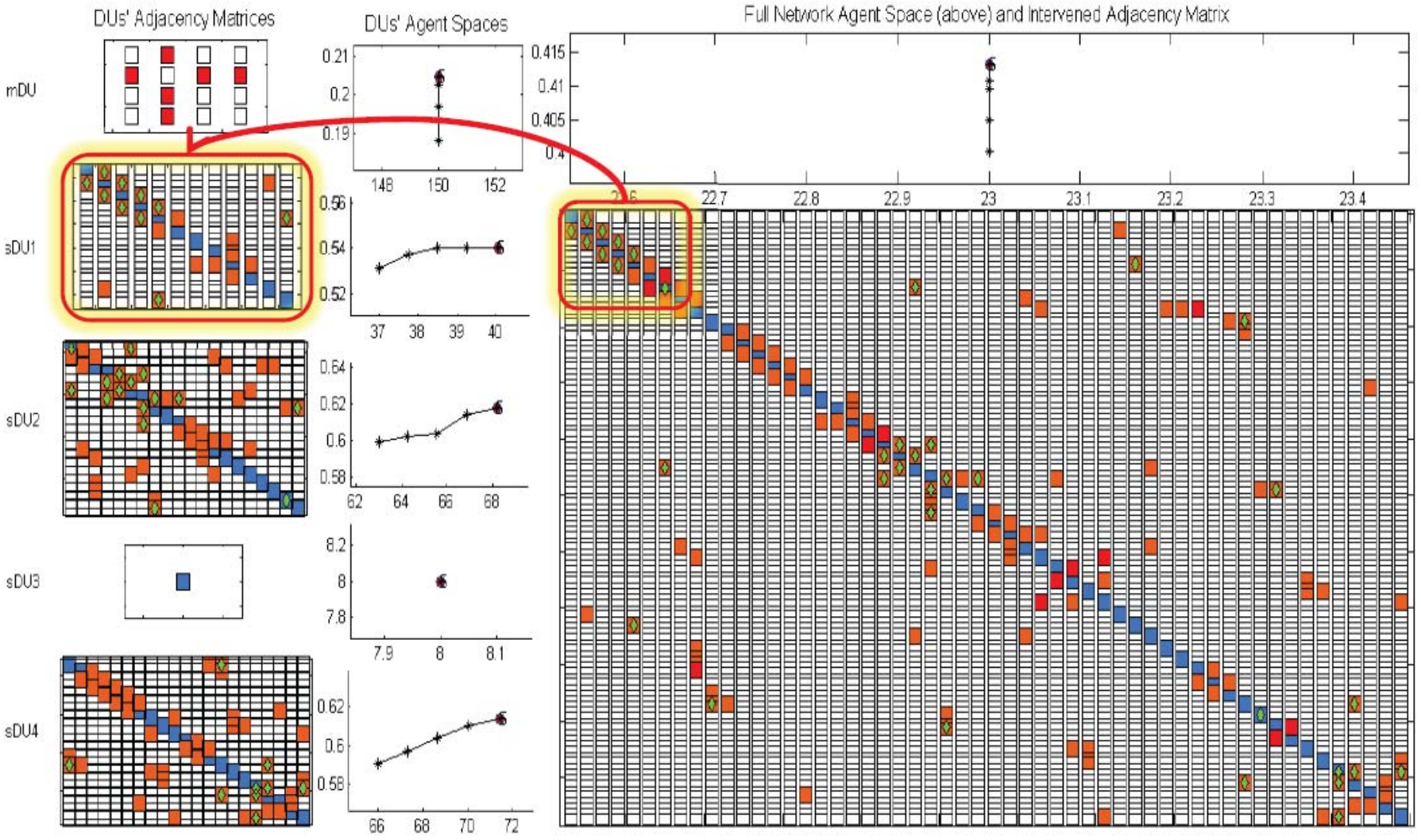

*Clustered Network (top view)*




*Hierarchical view of the clustered network and control loops in DUs*

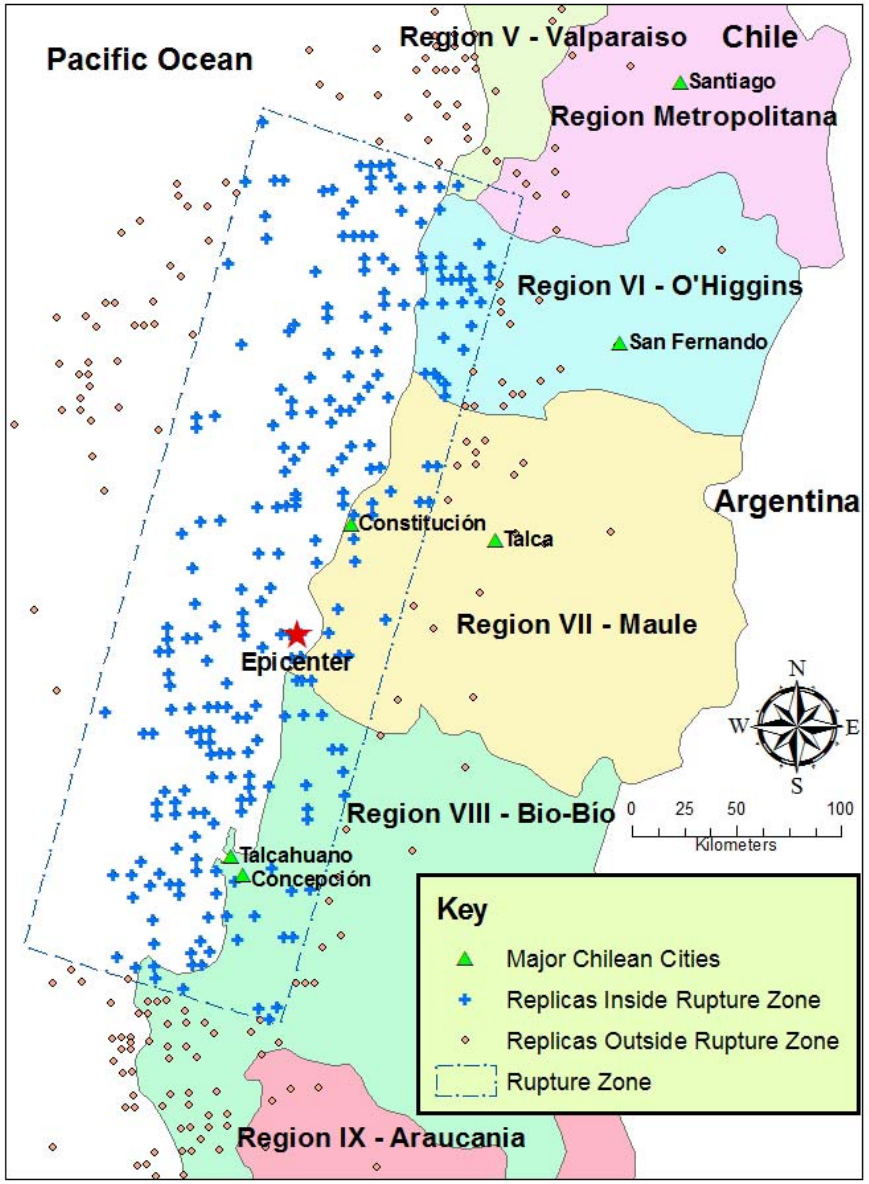
# 2. Socio-Technical Interactions (3/3)

- **Distributed matrix view:**



# 3. Field-Informed Advances (1/6)

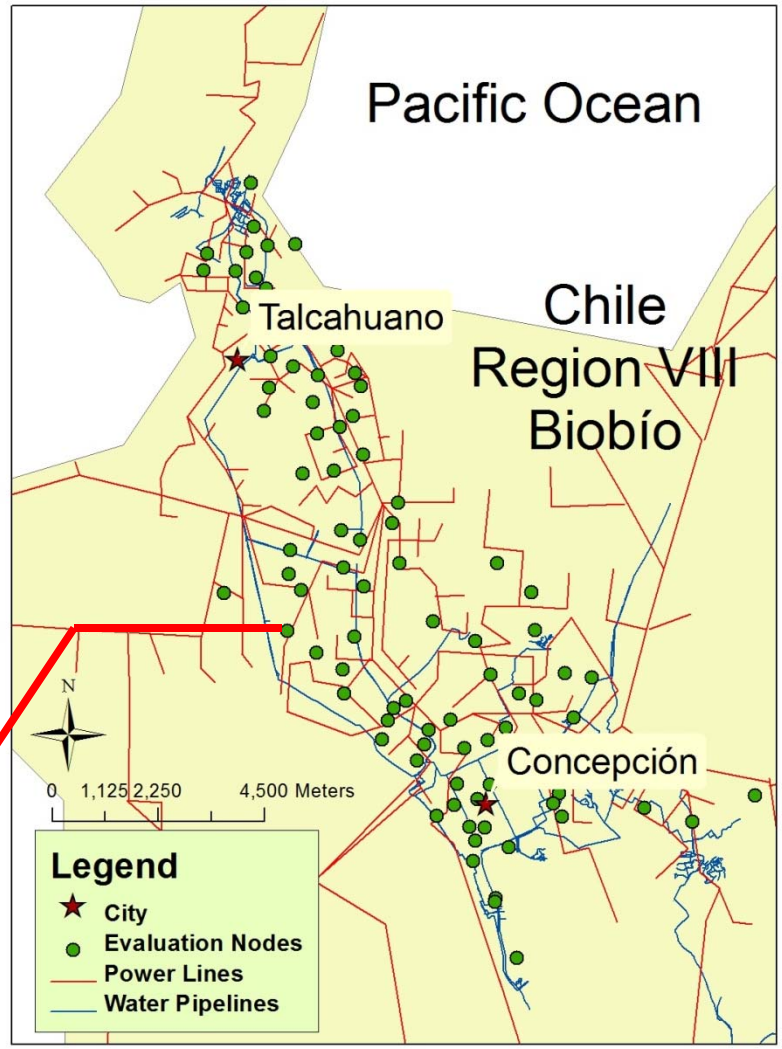
**Geographical and seismological context of Chile 2010 Earthquake**



# 3. Field-Informed Advances (2/6)

- **Available geographically distributed field data**
  - Spatially distributed points (**evaluation nodes**)
  - Each node contains restoration information (**ψ**)

  **ψ** = days of repair

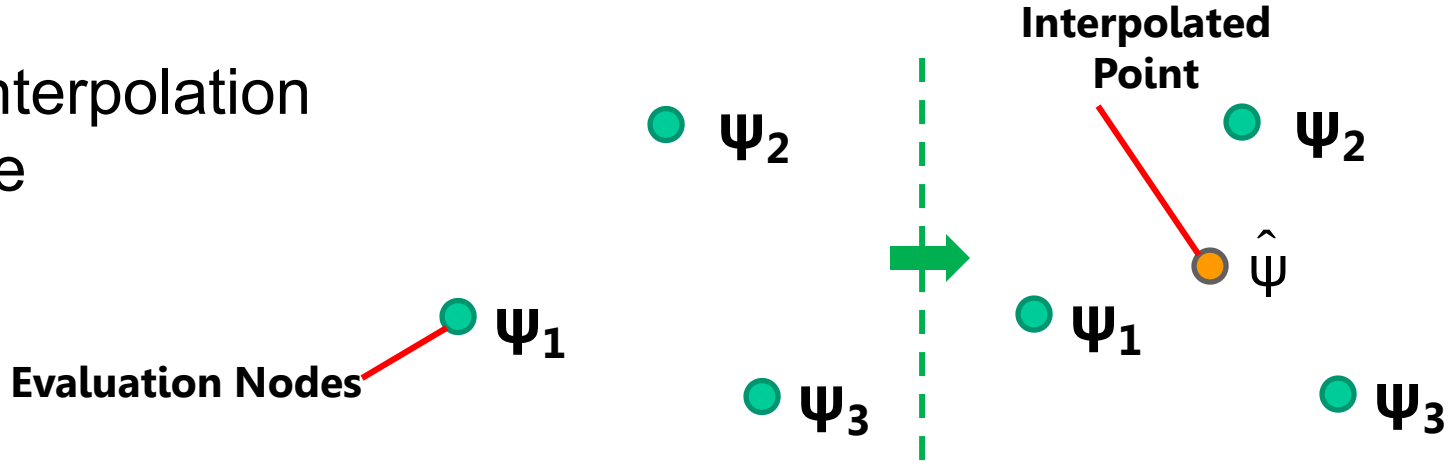



$\psi^{Power} = 8$

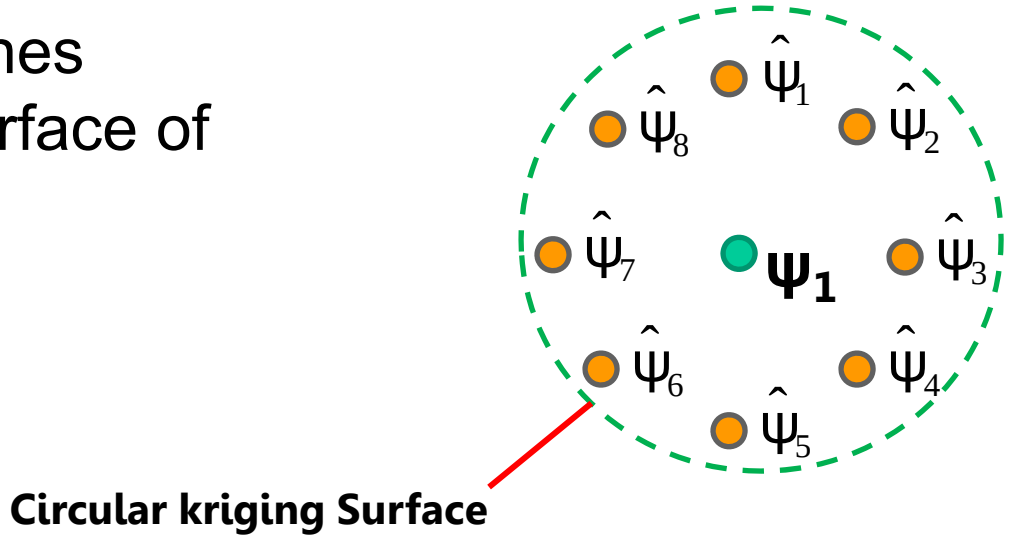
$\psi^{Water} = 12$

# 3. Field-Informed Advances (3/6)

- **Ordinary point kriging approaches**
  - Spatial interpolation technique

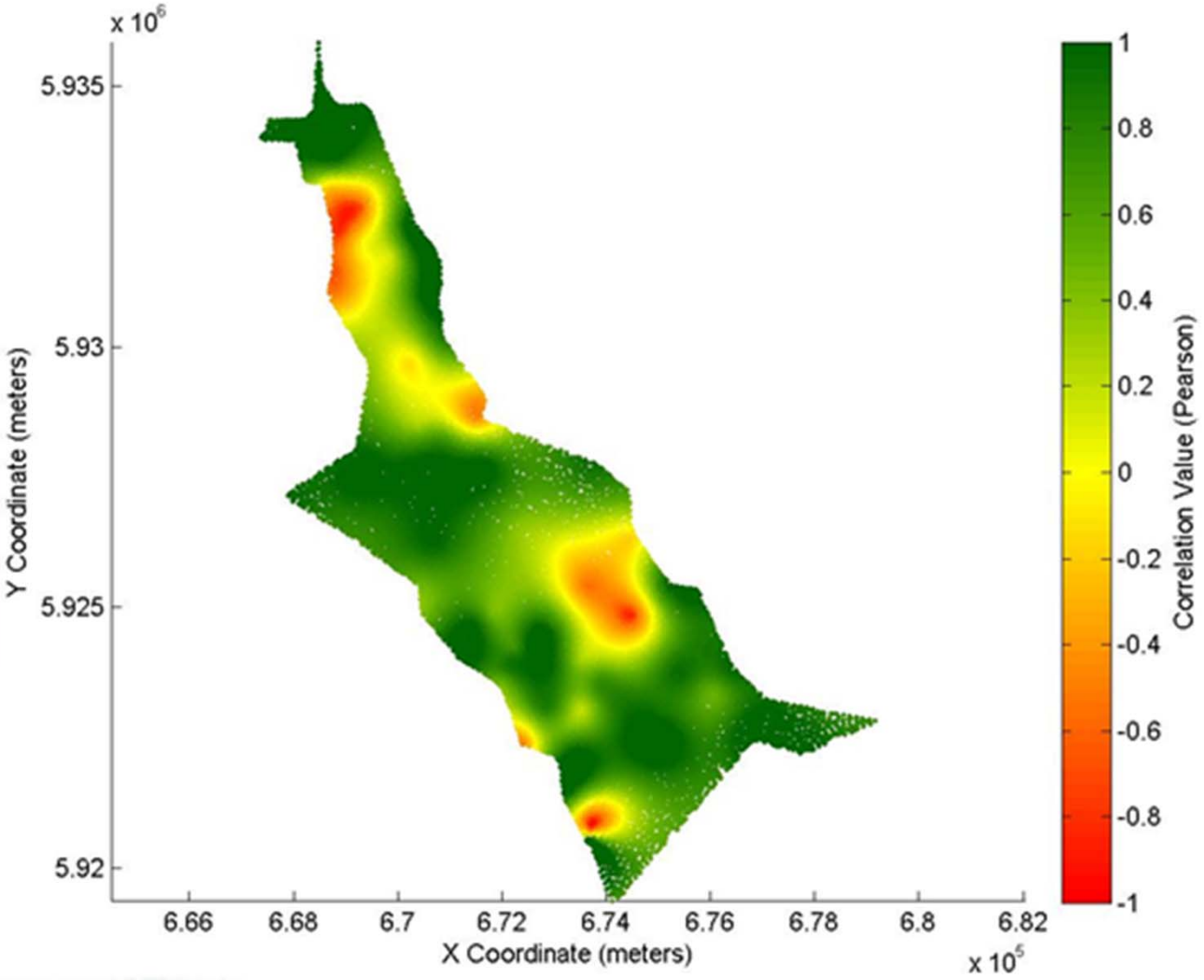


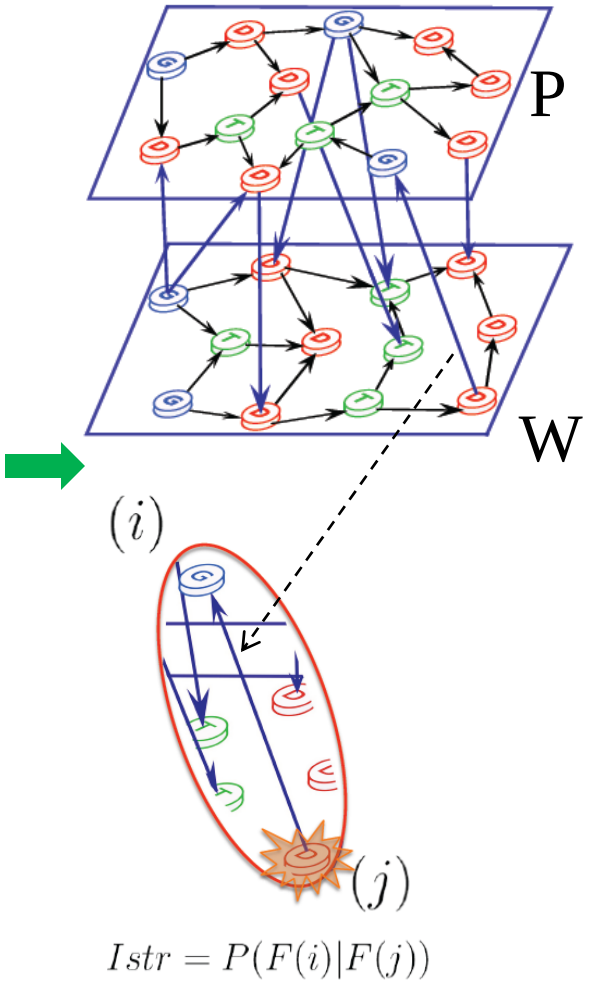

  - Interpolation over restoration meshes yields kriging surface of coupling



# 3. Field-Informed Advances (4/6)

- **Richness of local interdependencies**



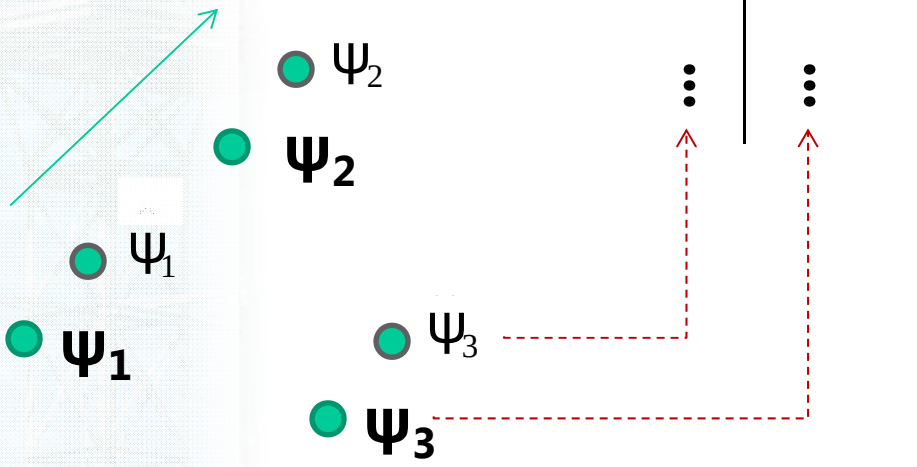




$$Istr = P(F(i)|F(j))$$

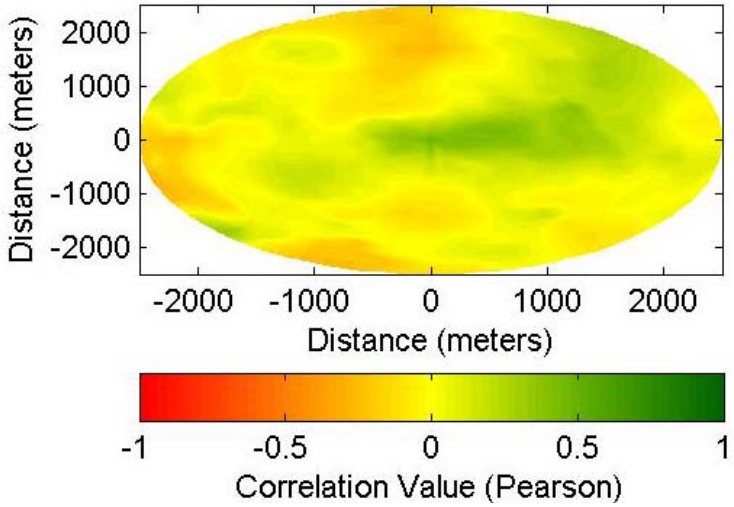
*Istr*: Interdependence Strength

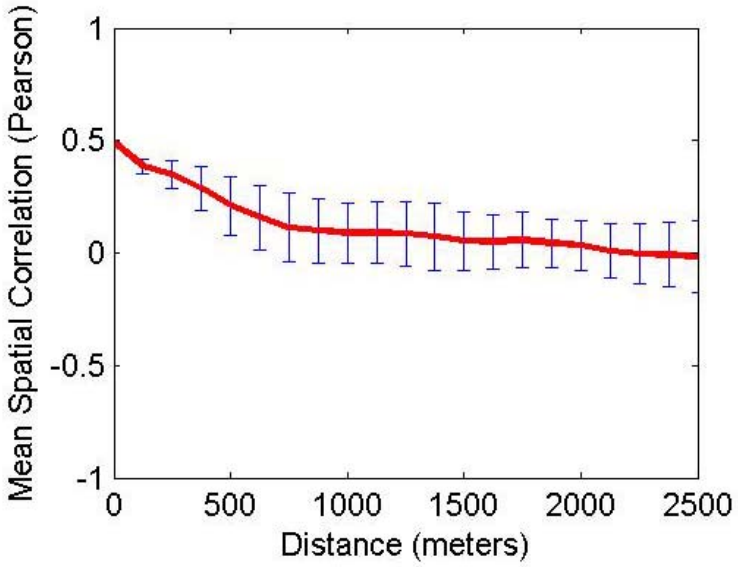
# 3. Field-Informed Advances (5/6)

- **Synthesis for global coupling trend assessment**



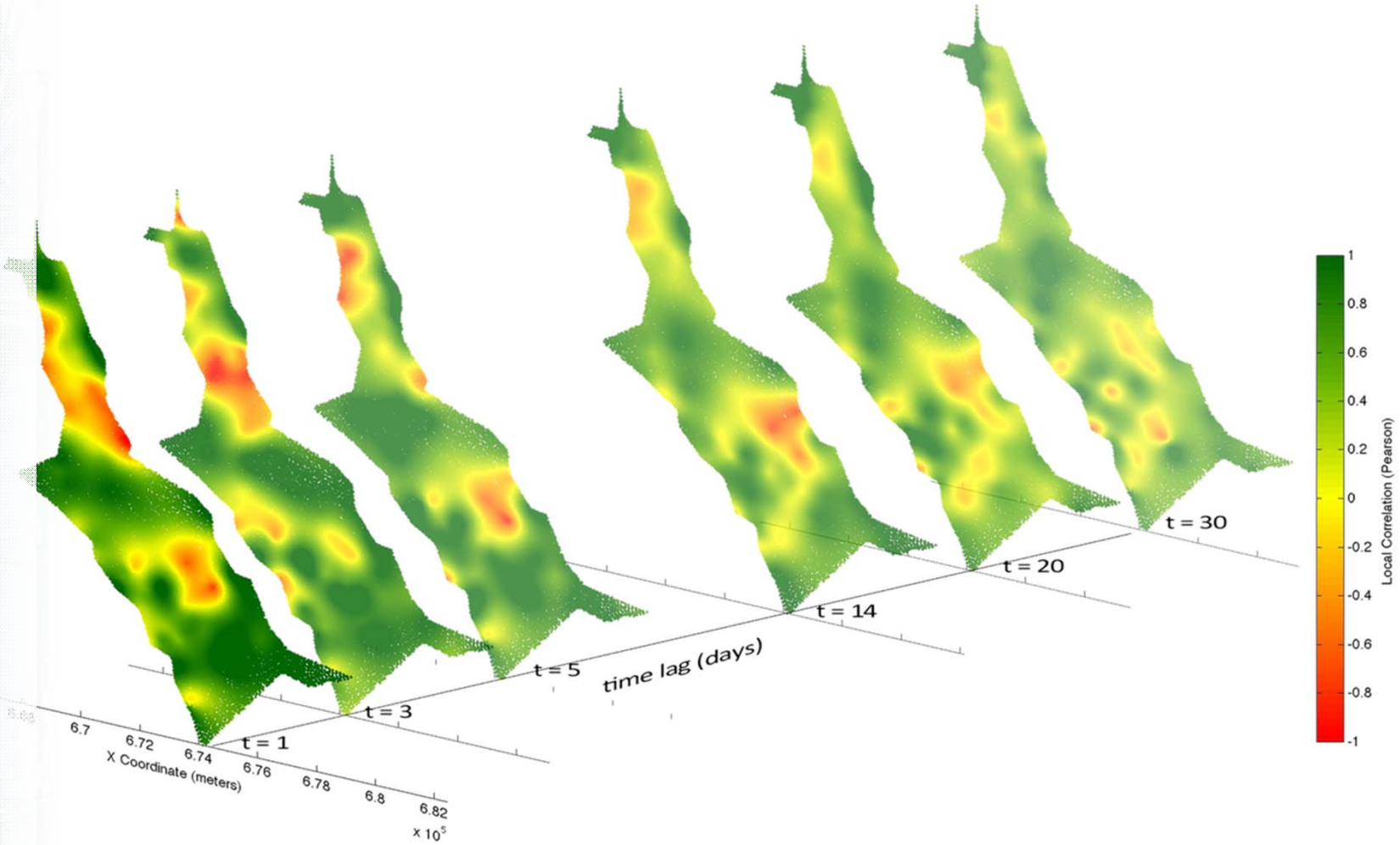

| $\psi^P$ | $\psi^W$ |
|---|---|
| 8 | 12 |
| 4 | 17 |
| 12 | 13 |
| 16 | 14 |
| ⋮ | ⋮ |



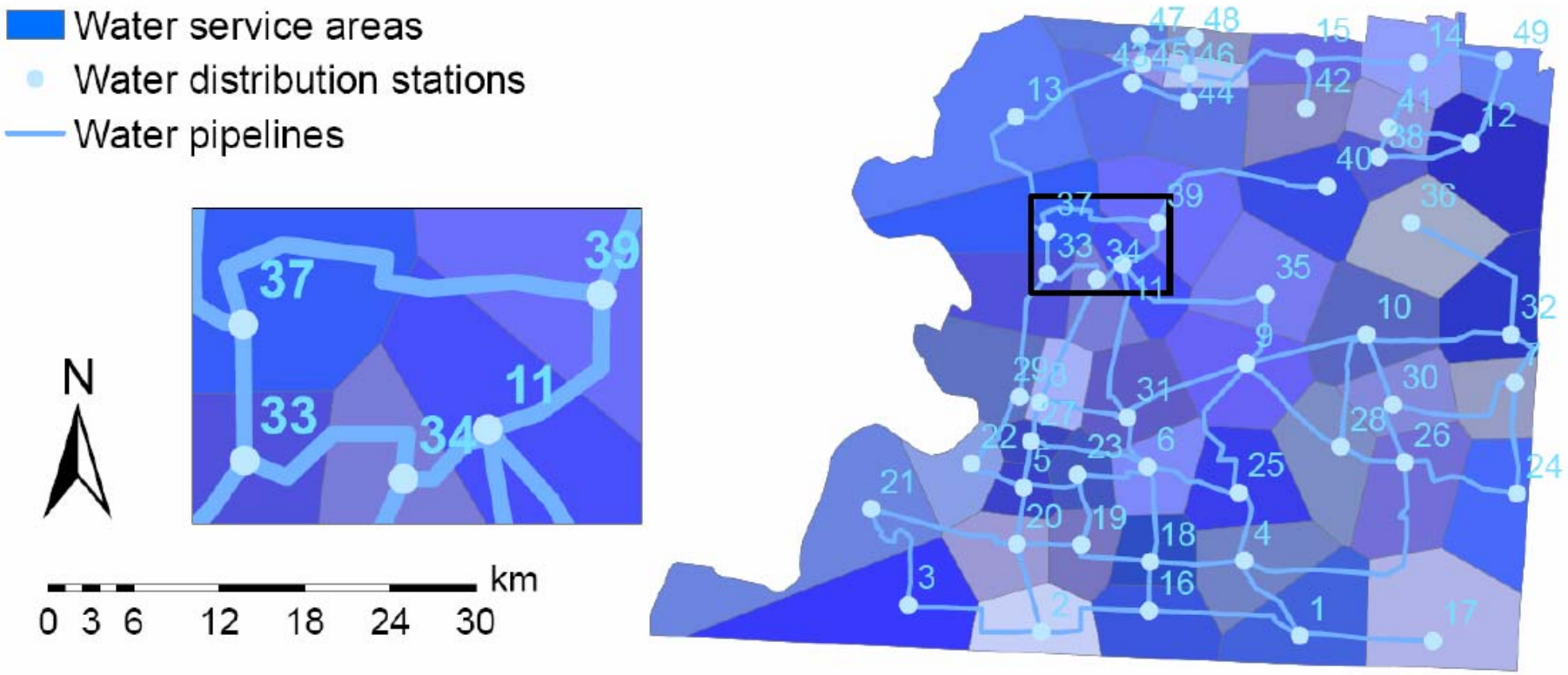
# 3. Field-Informed Advances (6/6)

- **Can we trace the evolution of interdependence across time and space?**



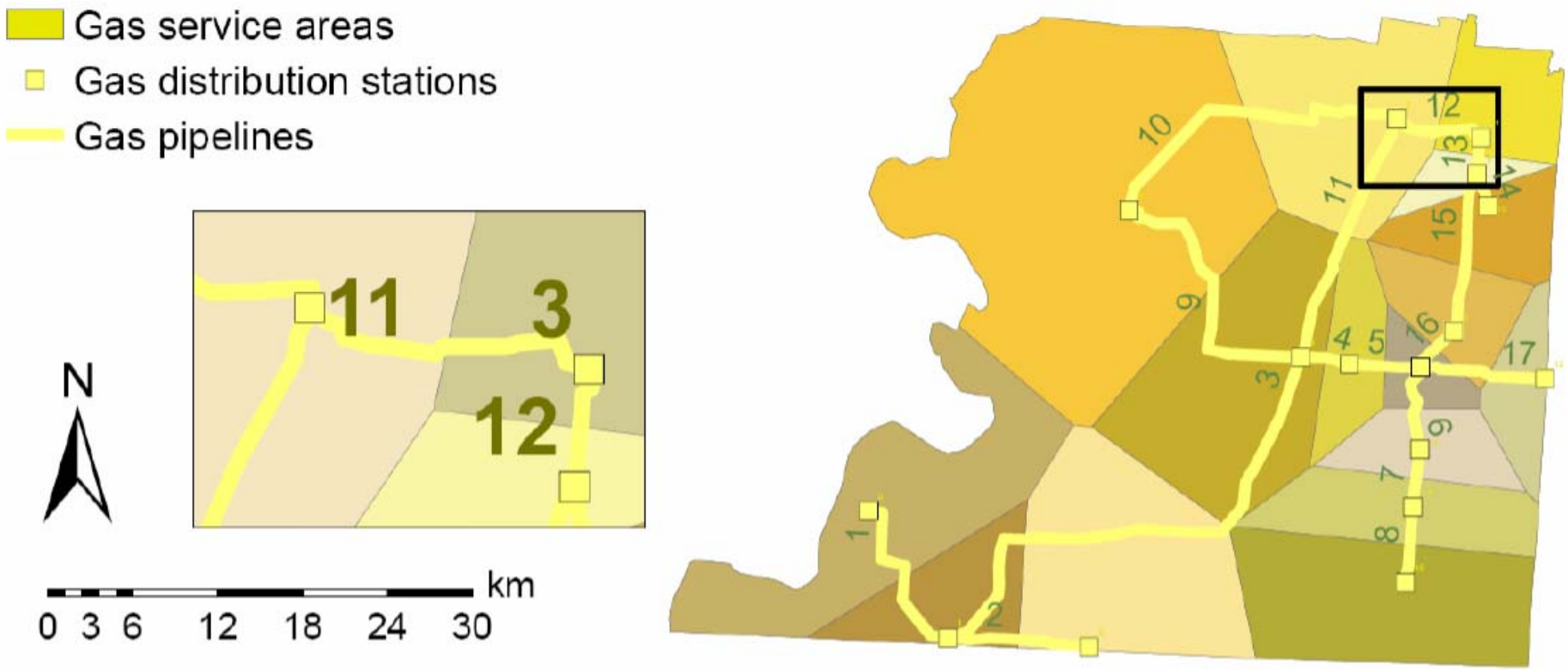
# 4. Prospective Applications (1/5)

- **Restoration of interdependent infrastructure systems (Water)**



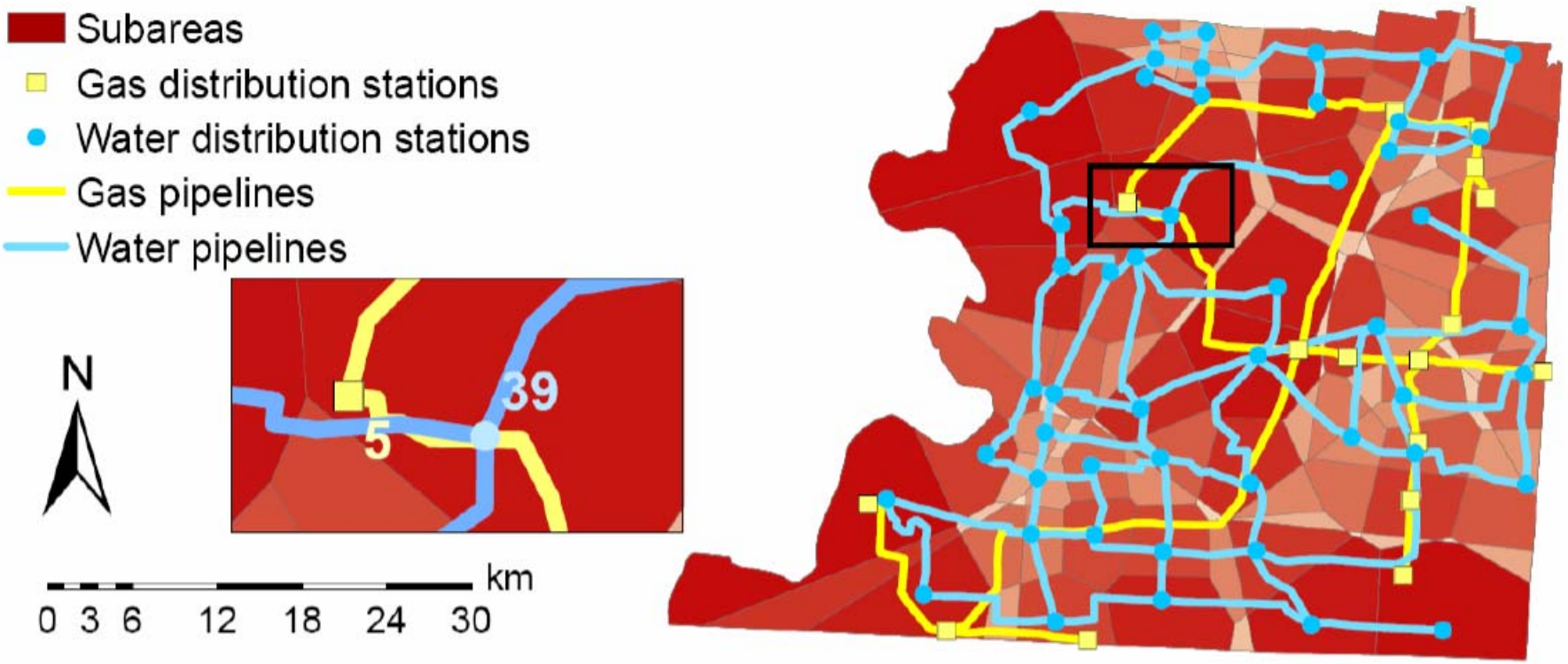
# 4. Prospective Applications (2/5)

- **Restoration of interdependent infrastructure systems (Gas)**



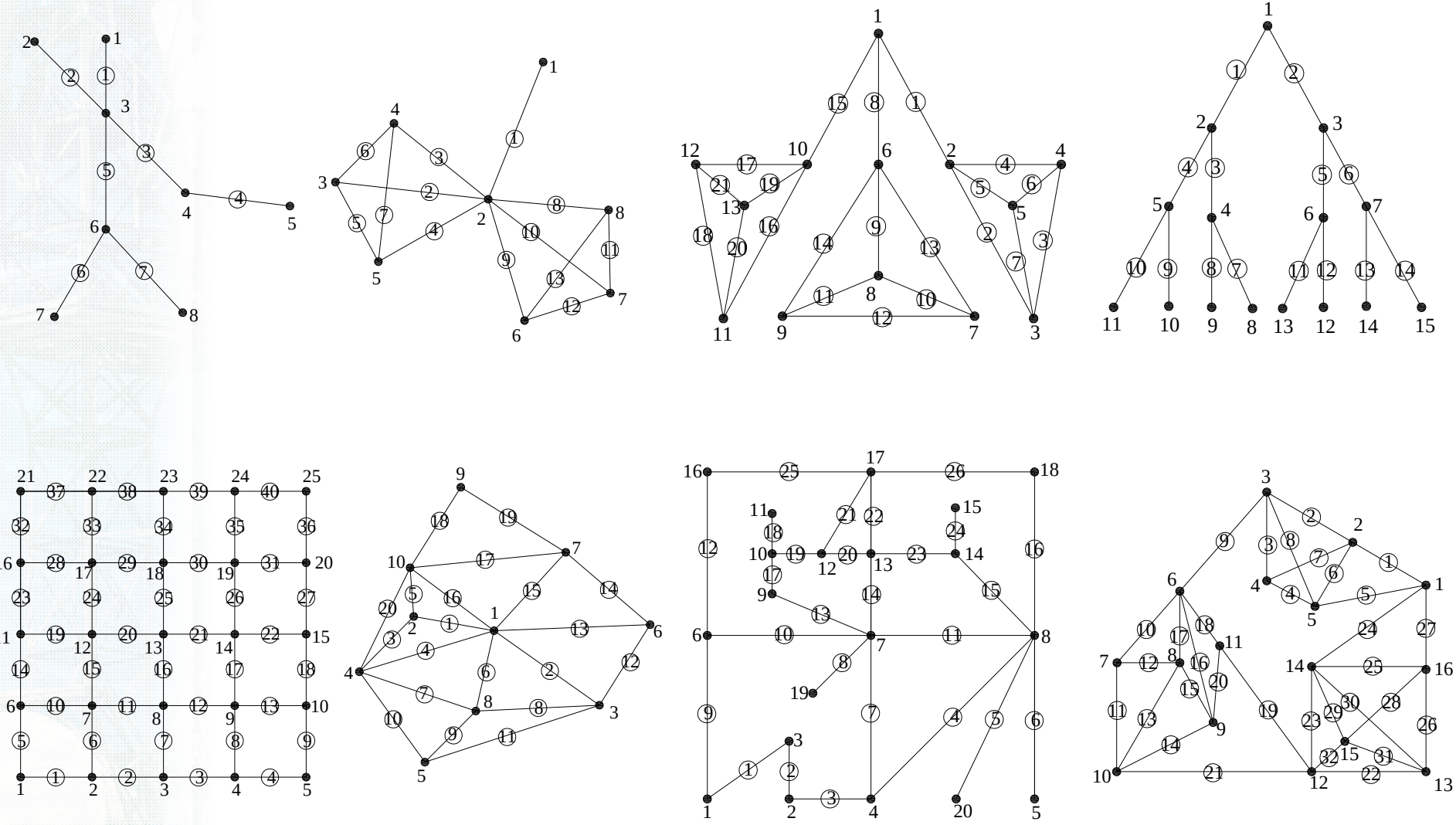
# 4. Prospective Applications (3/5)

- **Restoration of interdependent infrastructure systems**



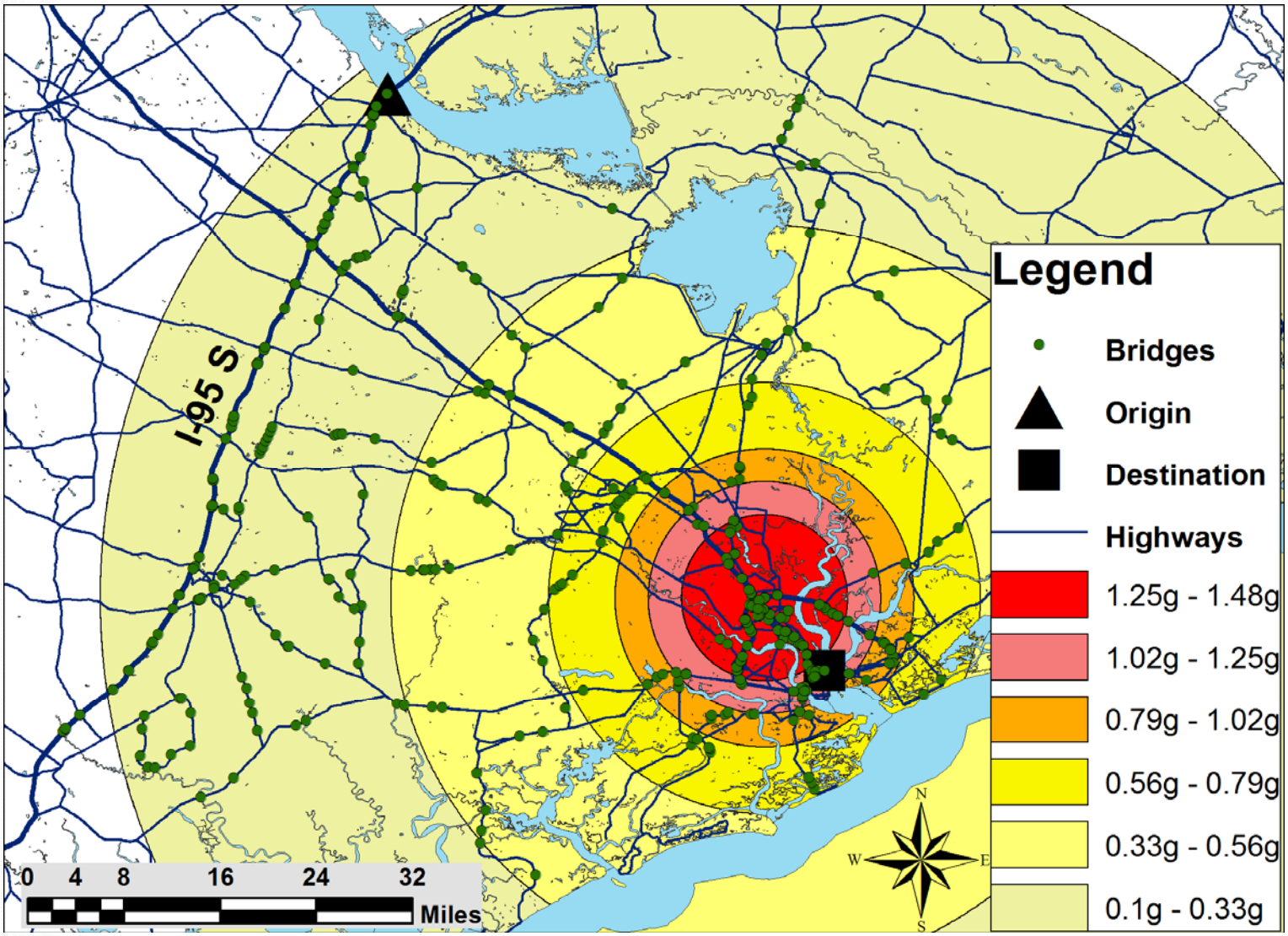
# 4. Prospective Applications (4/5)

- **Joint ranking and prioritization of network elements**



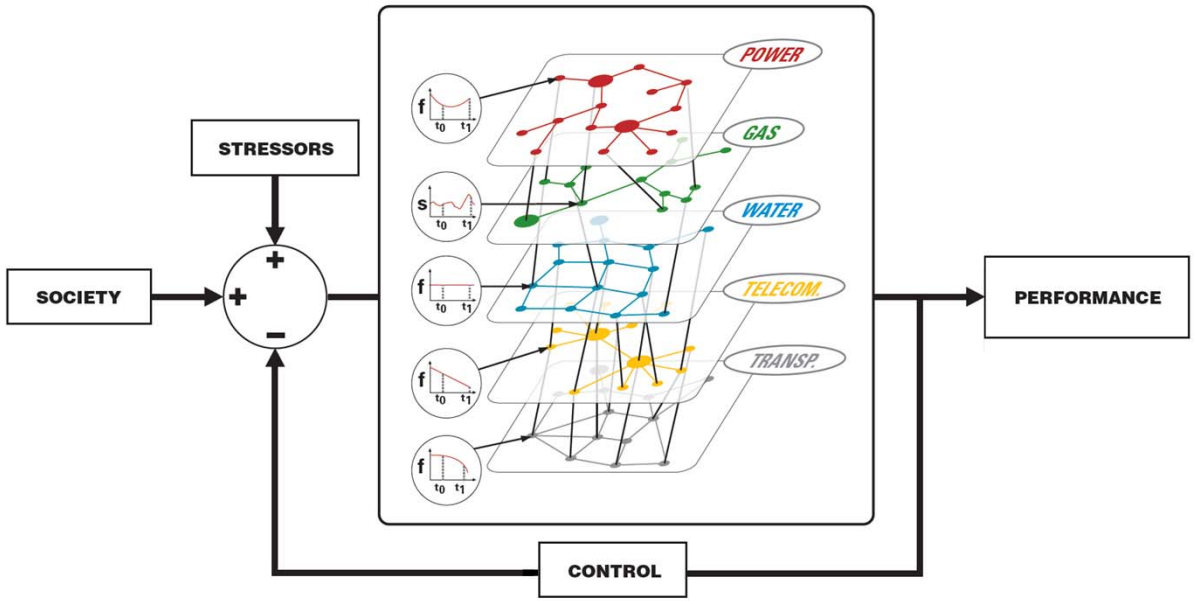
# 4. Prospective Applications (5/5)

- **Transportation networks**



# 5. Conclusions

- Network science and engineering have a productive partnership addressing complex infrastructure problems under uncertainty
- Significant research opportunities await in the field of spatial-temporal network control of infrastructure systems
- Practical applications including best practices and guidelines are in motion informed by trend-level analyses



# Thank you!

**Support from:**

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Technical Council on Lifeline Earthquake Engineering (TCLEE)

Rice University

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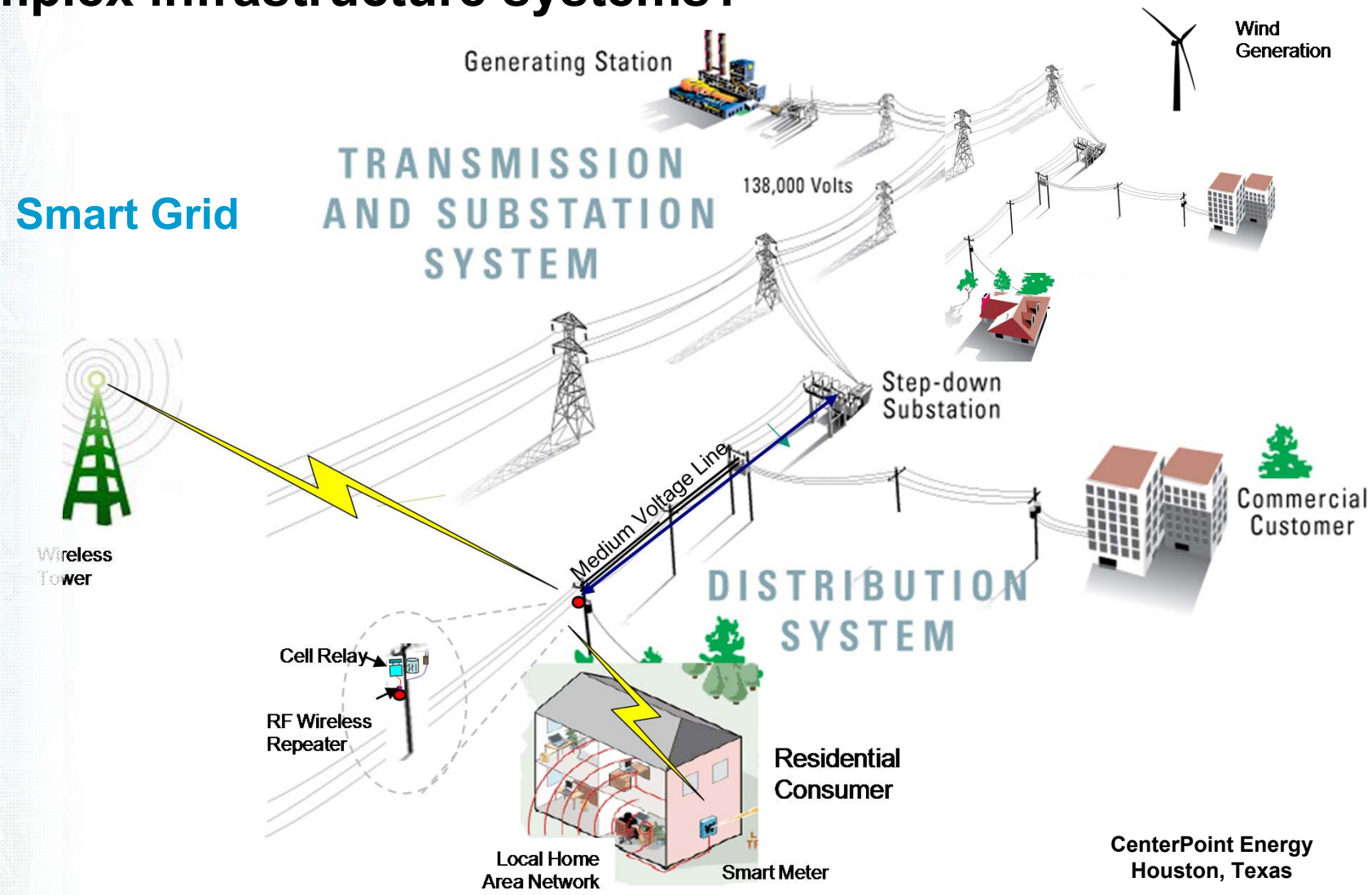
# Applications

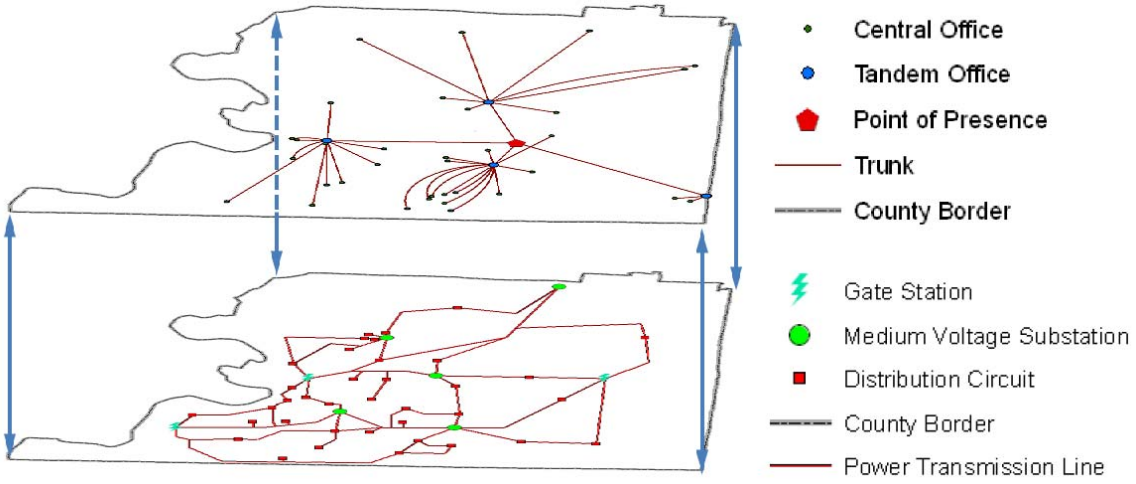
- **Can we assess the risk and resilience of emerging complex infrastructure systems?**

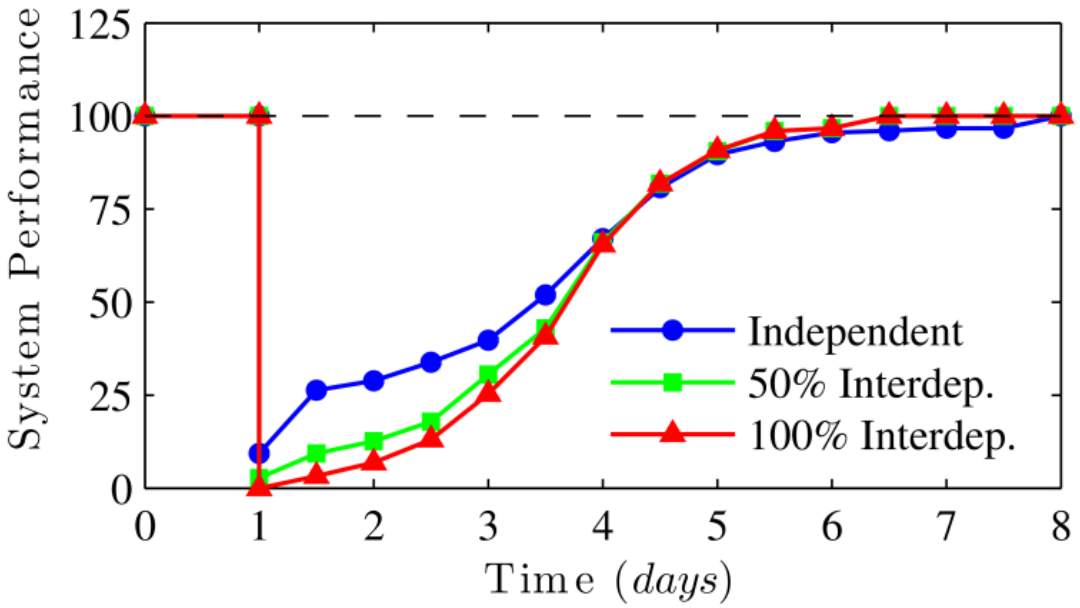


# Applications

- **Include restoration resources and prioritization criteria**

**Power and Telecommunication systems**




**MLGW's restoration sequence and resource mobilization**