Lifeline System Interdependencies: Field Observations and Modeling Challenges

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Meeting # 8: Lifeline Interdependencies During Post-Disaster Recovery

San Francisco, California

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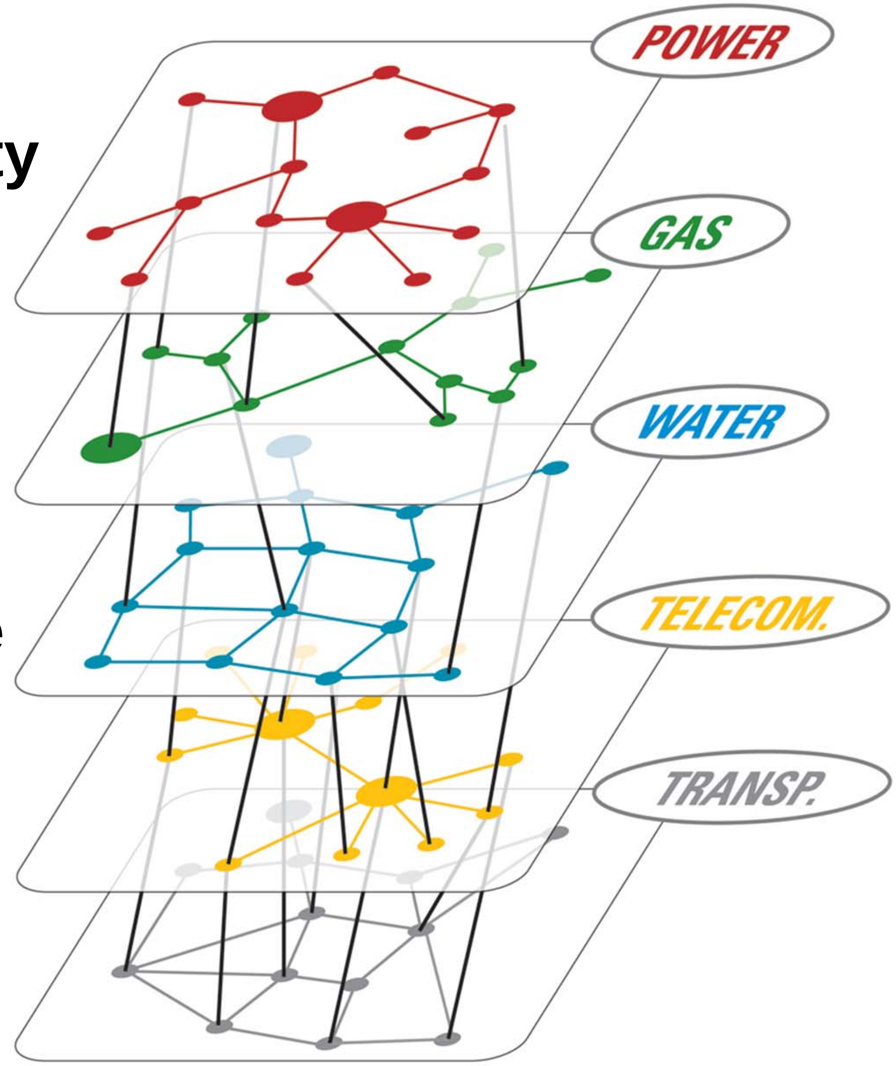
Motivation (1/7)

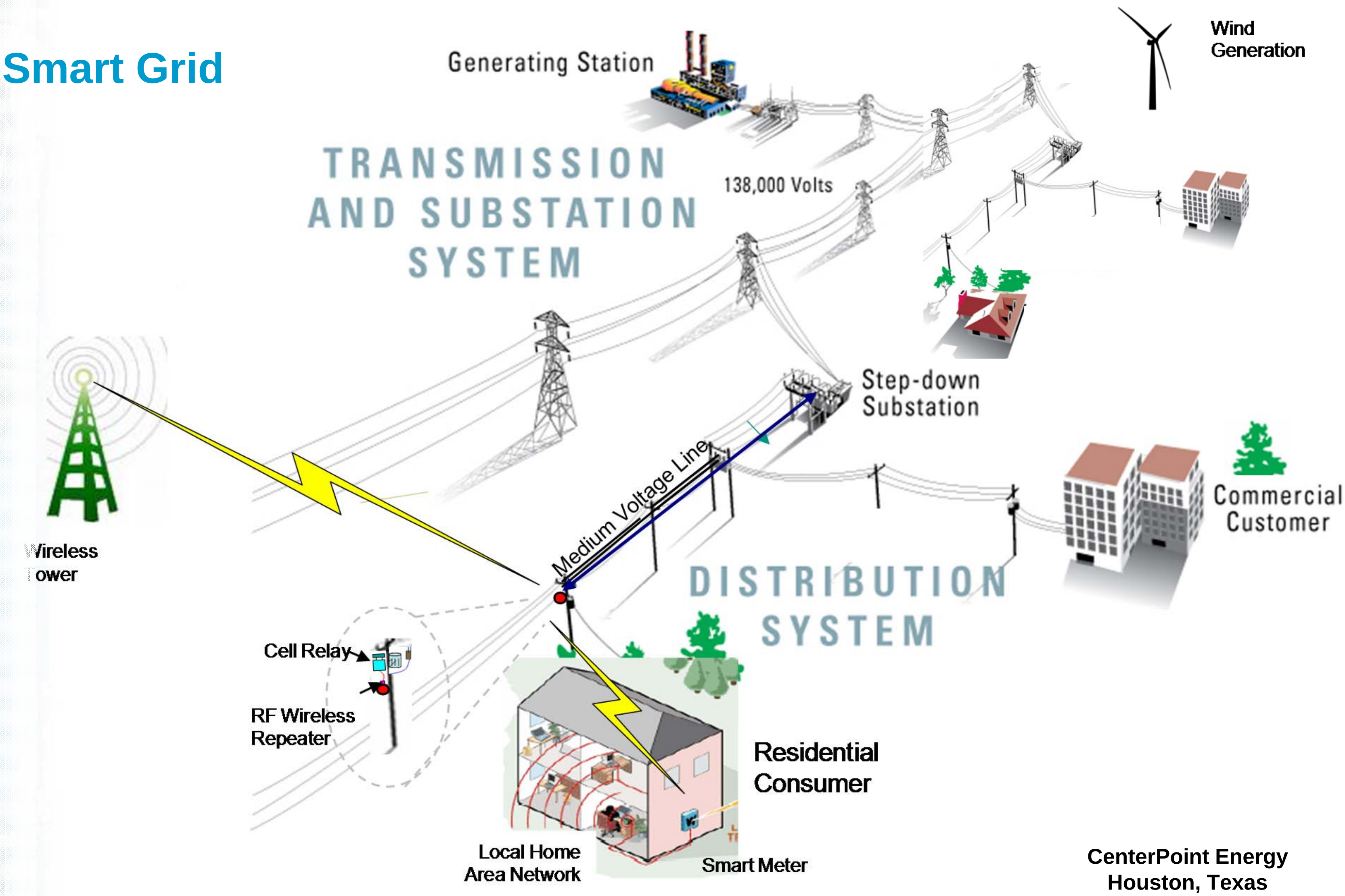
- **Contemporary complex infrastructure systems**
  - **Essential for modern society function**
  - **Large scale and high exposure systems**
  - **Reached accelerated phase of aging and deterioration**
  - **More interdependent for optimized operation**



Motivation (2/7)

- **Emerging complex infrastructure systems**

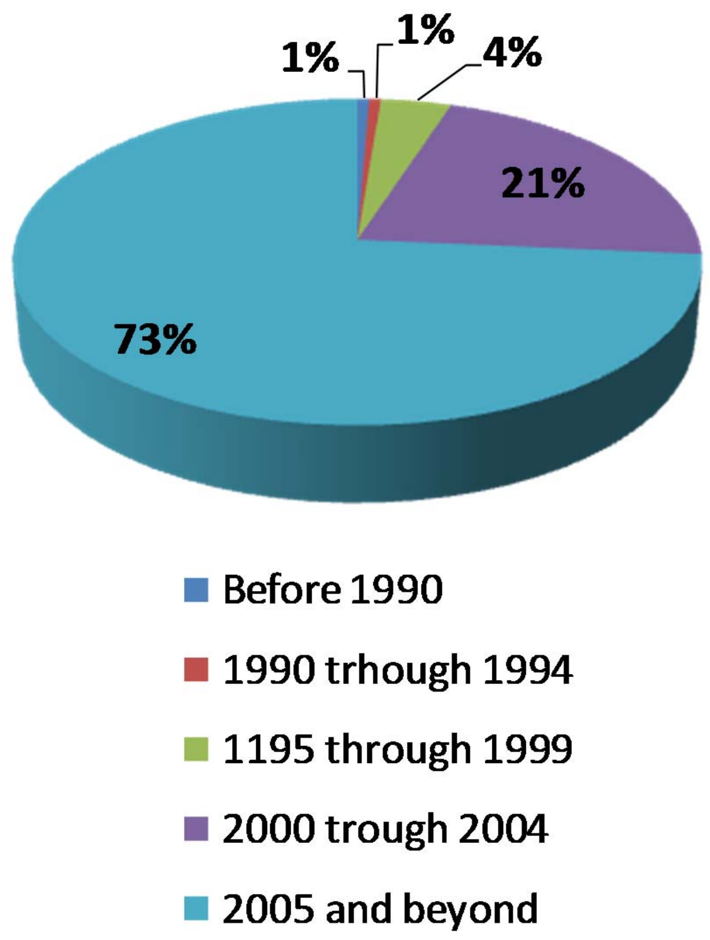
Smart Grid



CenterPoint Energy
Houston, Texas

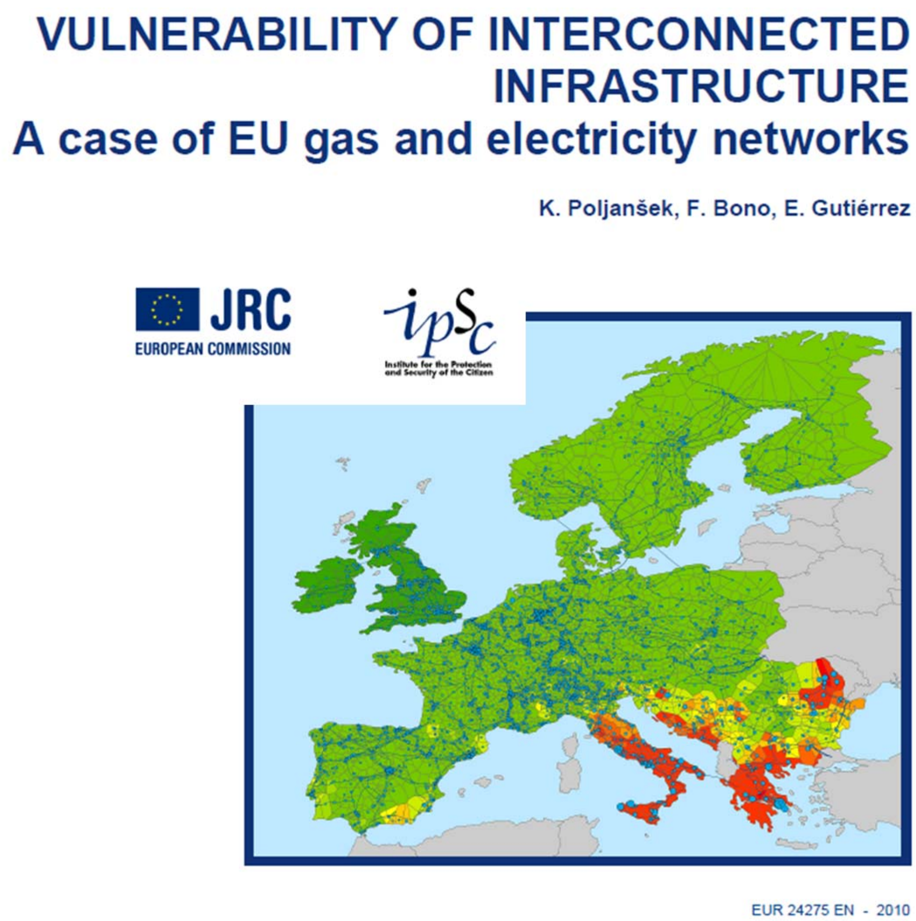
Motivation (3/7)

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



Motivation (4/7)

- **Efforts to understand interdependencies and quantify their strength of coupling in practice**
  - **European Union's Institute for the Protection and Safety of Citizens**
  - **U.S. Department of Homeland Security**
  - **Technical Council on Lifeline Earthquake Engineering**
  - **San Francisco's SPUR initiative**


VULNERABILITY OF INTERCONNECTED INFRASTRUCTURE
A case of EU gas and electricity networks

K. Poljanšek, F. Bono, E. Gutiérrez

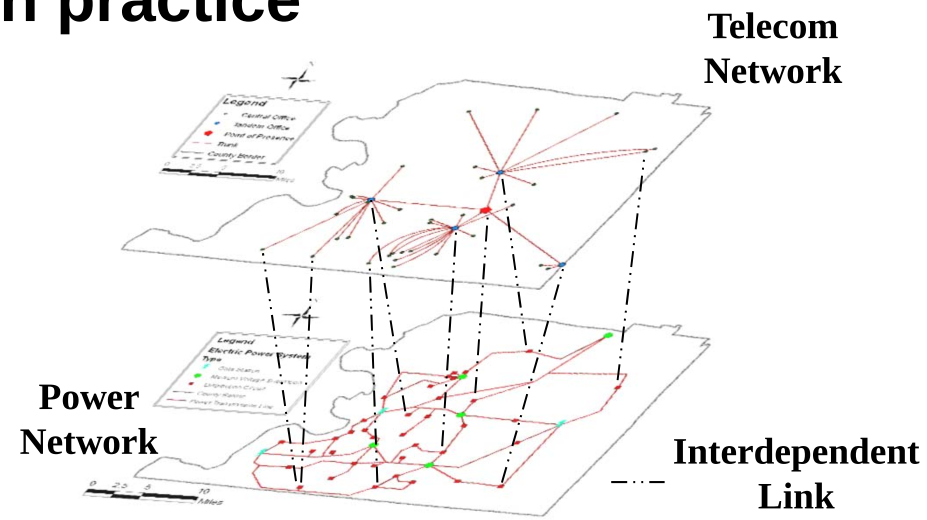
JRC
EUROPEAN COMMISSION

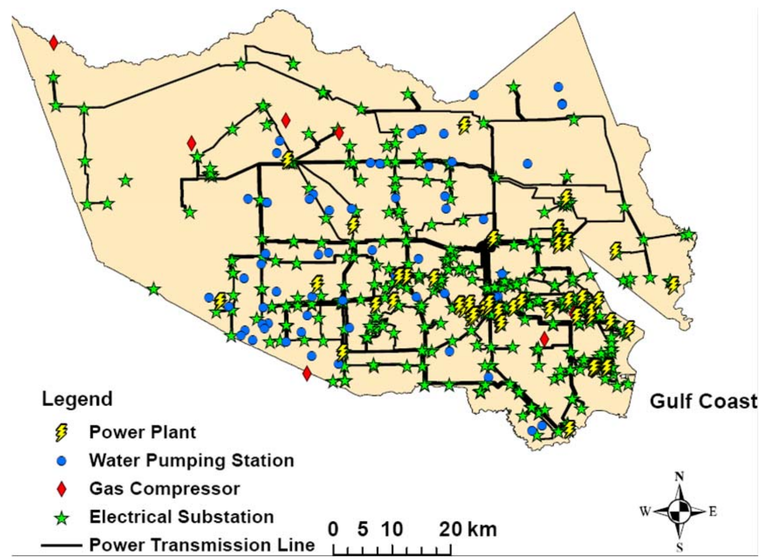
ipSc
Institute for the Protection and Security of the Citizen

EUR 24275 EN - 2010

Motivation (5/7)

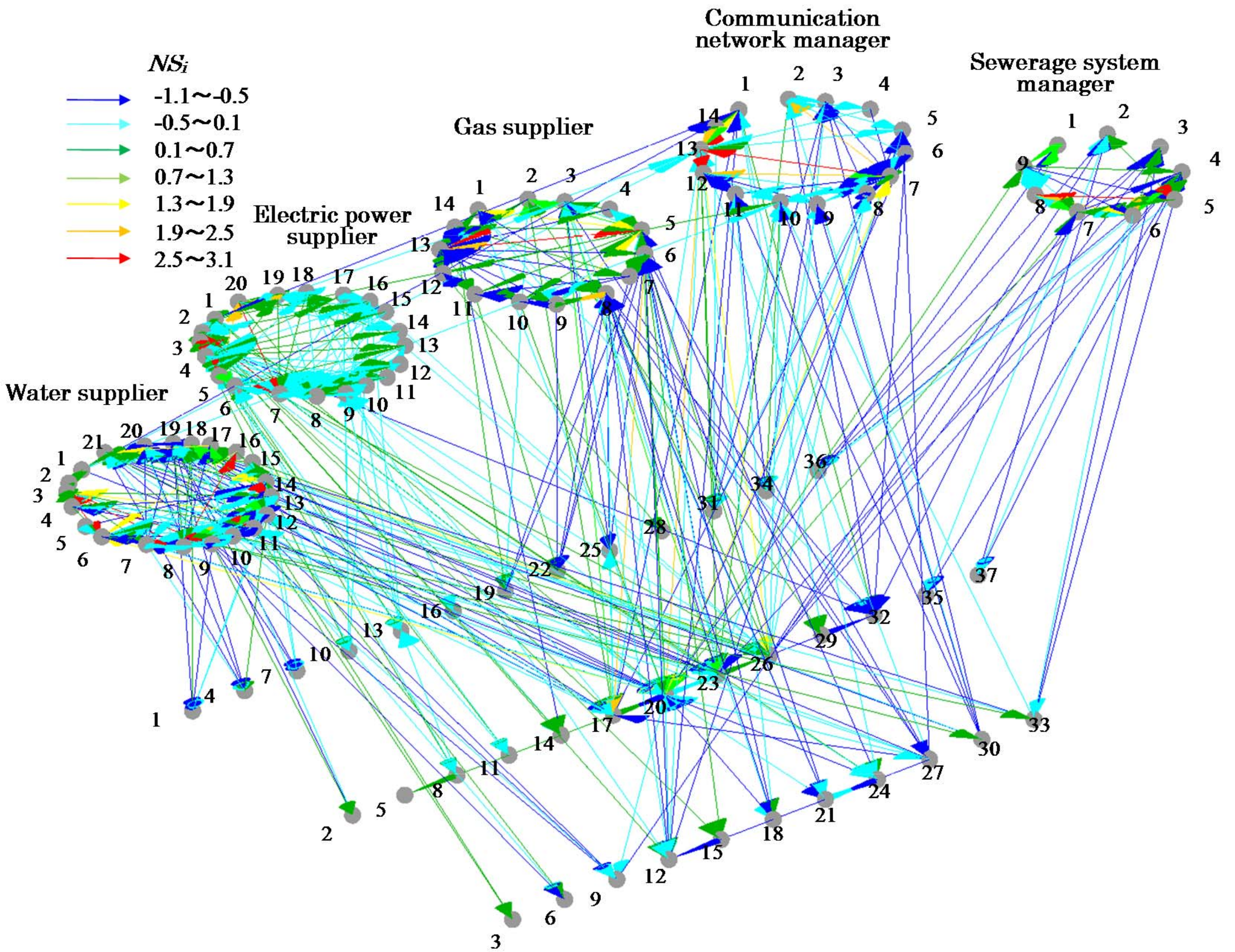
- **Implementations to cope with potential interdependencies and their cascading effects in practice**
  - **MLGW's ring of telecommunications**
  - **British Columbia's Olympic games scenarios**
  - **Houston's water and gas decoupling from grid**





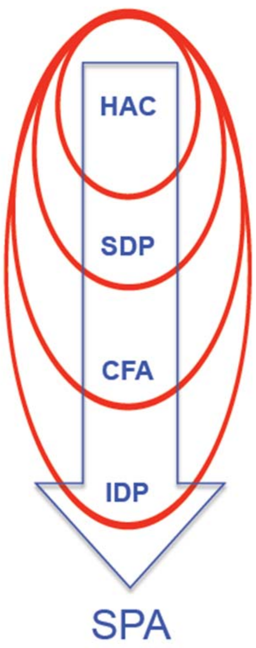
Motivation (6/7)

- **Japanese efforts to link interdependence with resilience**

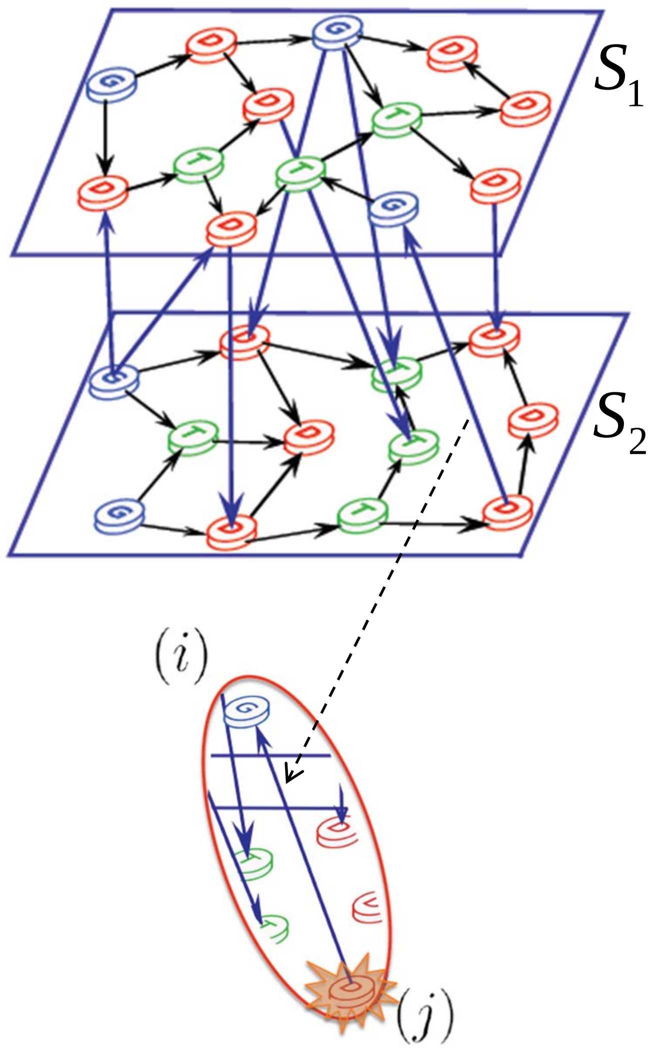


Motivation (7/7)

- **Simulation-based network modeling approach**



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



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

Istr: Interdependence Strength

Presentation Outline

1. Recent field observations of lifeline system interdependencies

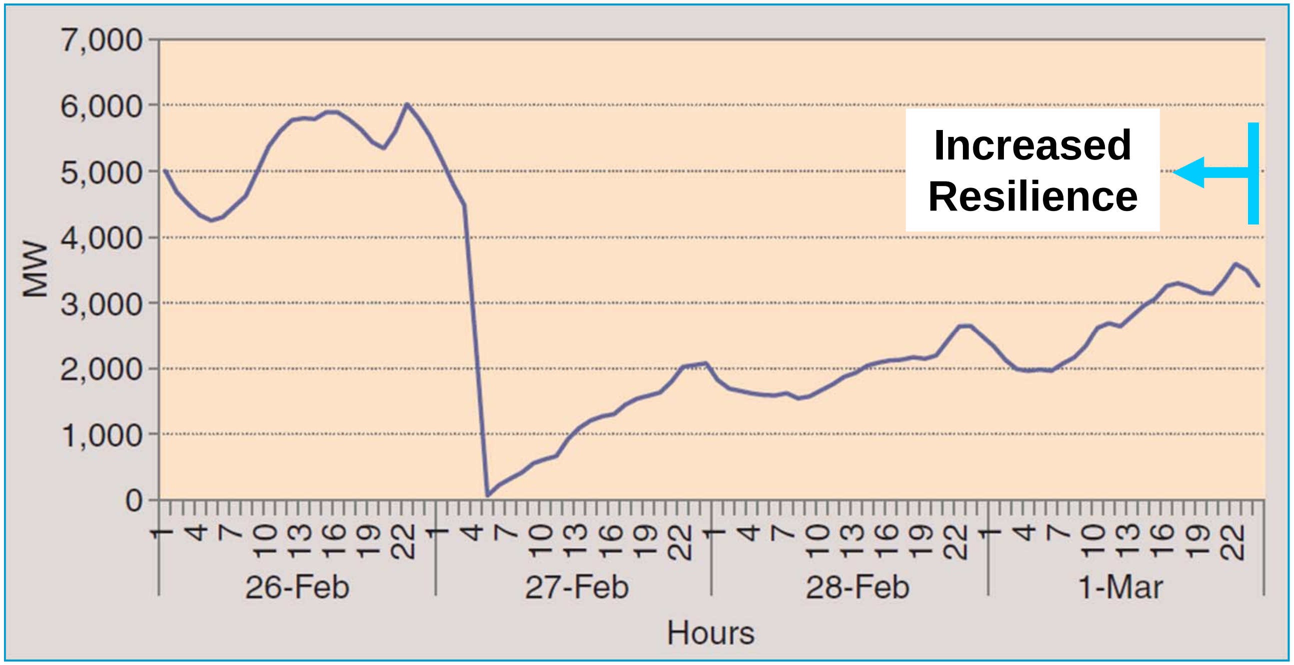
2. Modeling of infrastructure interdependence

3. Quantification of coupling strengths

4. Concluding remarks and future research / implementation

1. Recent Field Observations (1/2)

- **Power system after the 2010 Chilean Earthquake**

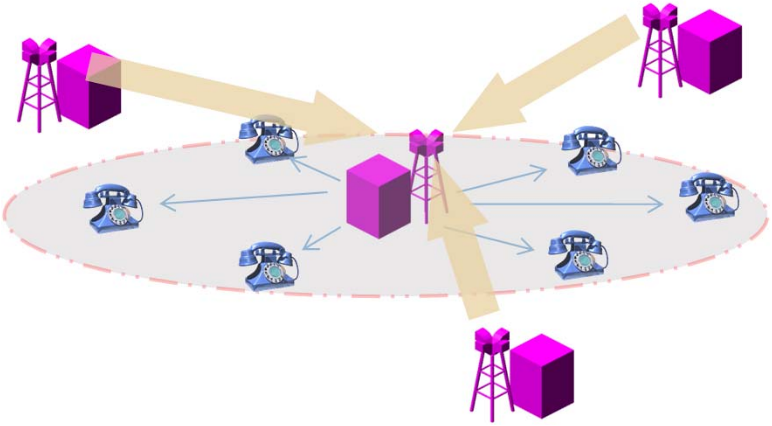


  - **Chilean Interconnected Systems (CIS) back in 48 hours**
    - ***N*-1 security**
    - **Emergency plans**

1. Recent Field Observations (2/2)

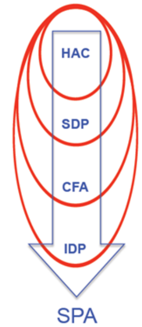
- **Observed interdependencies that delayed restoration**
  - **Road infrastructure**
  - **Telecommunication systems**
  - **Logistics**

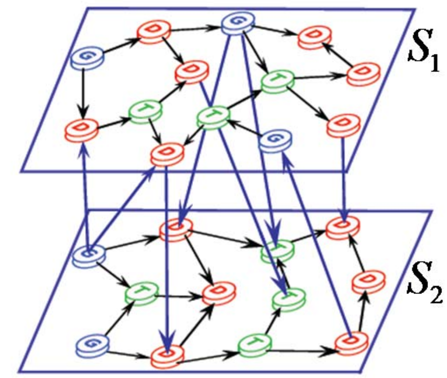
- **Observed actions to cope with interdependencies that delayed restoration**
  - **Private telecommunications**
  - **Transmission autonomy**
  - **Decentralized dispatch**
  - **Mobile generation**

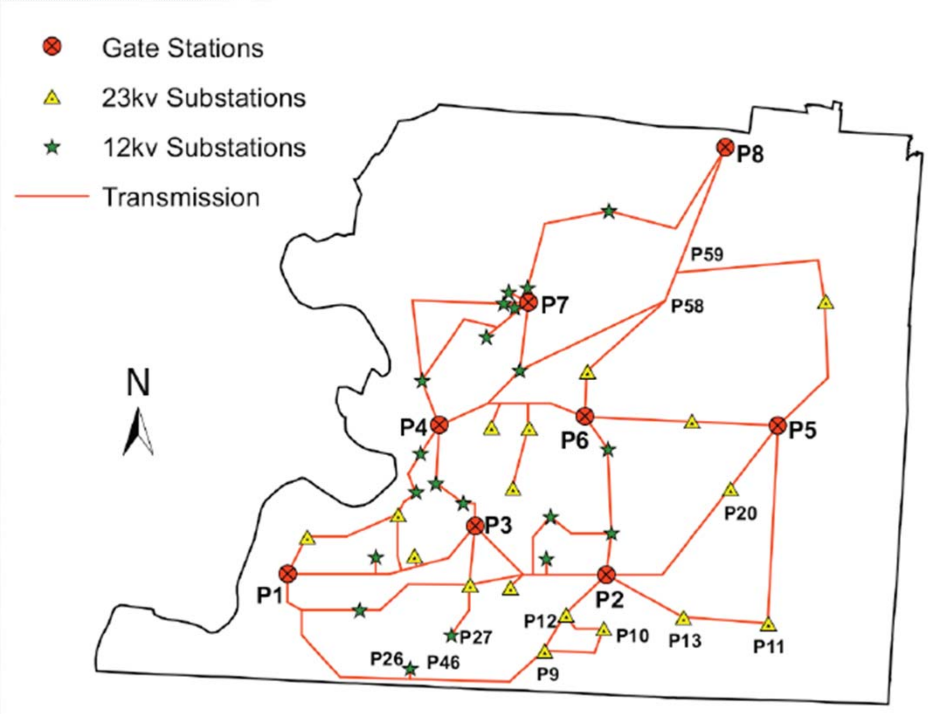


2. Insights from Modeling (1/8)

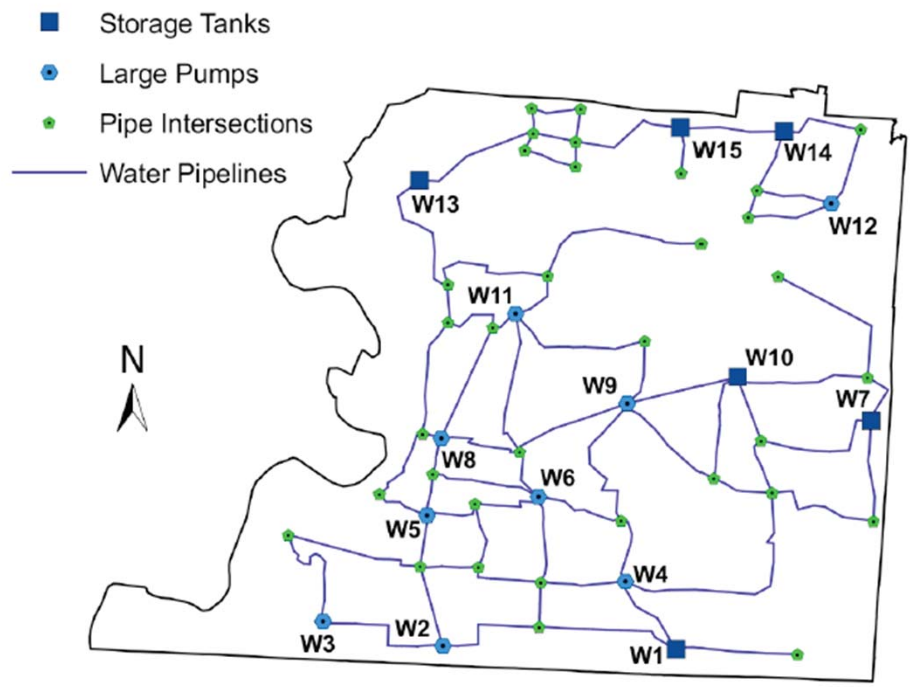
- **A set of realistic yet streamlined systems**







Power System S_1



Water Network S_2

$S_1 \rightarrow S_2$ Power effects on Water

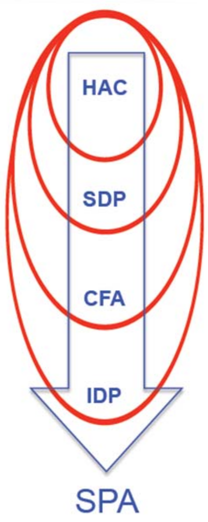
$S_2 \rightarrow S_1$ Water effects on Power

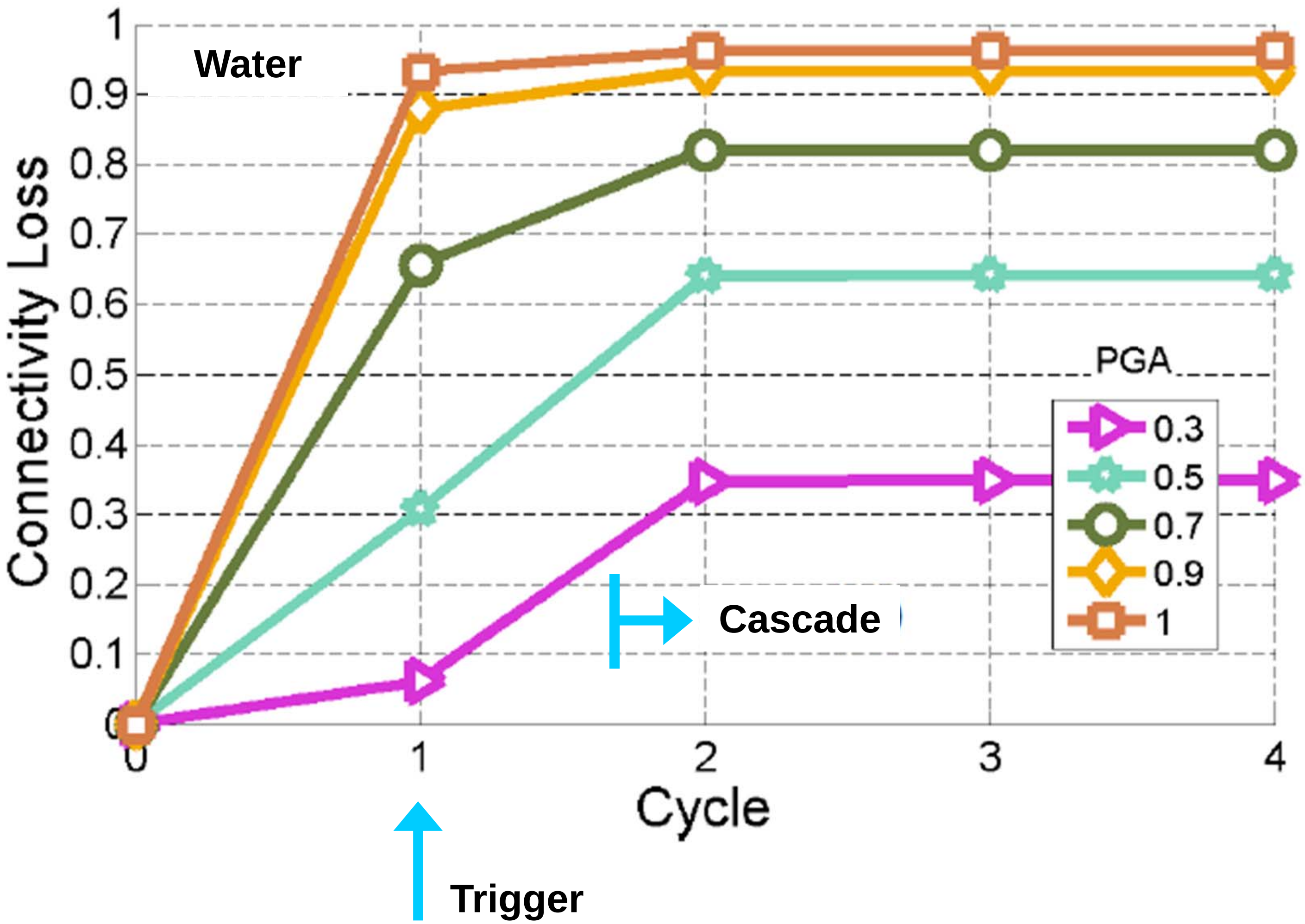
2. Insights from Modeling (2/8)

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

$S_1 \rightarrow S_2$

$Istr = 0.30$

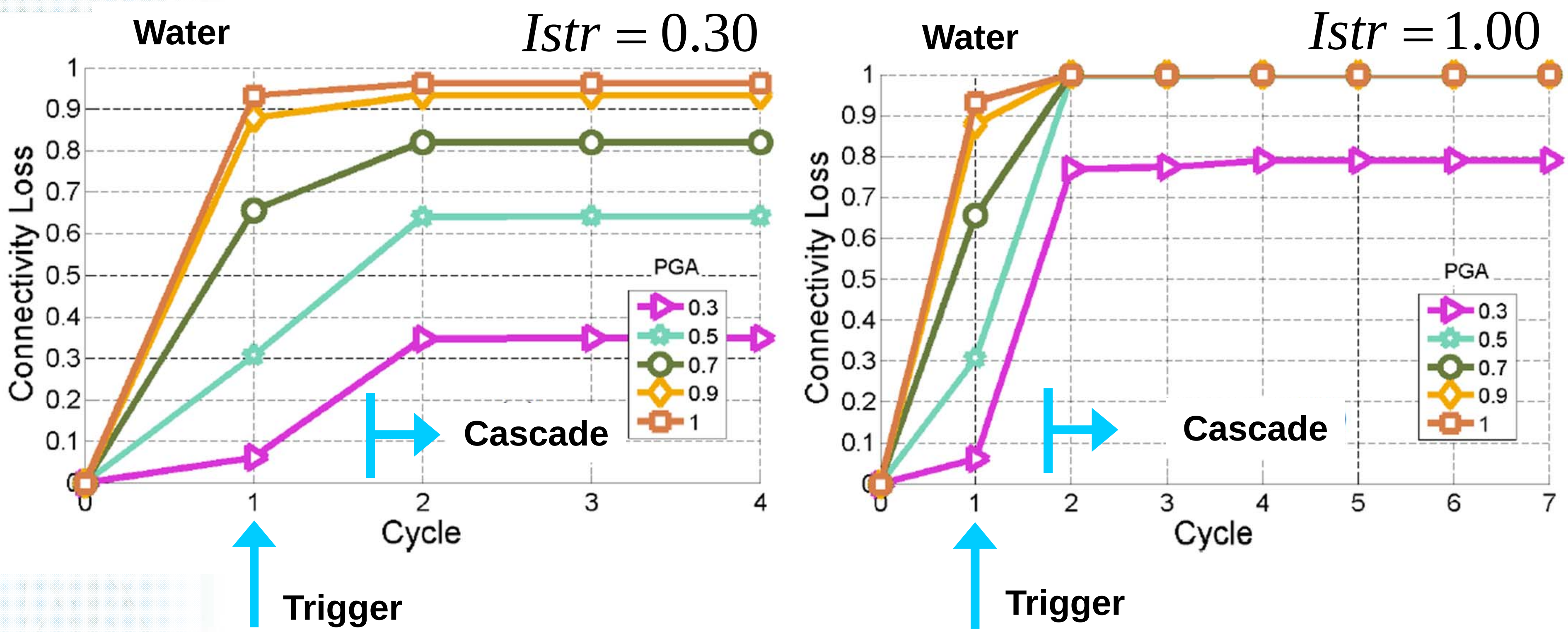




2. Insights from Modeling (3/8)

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

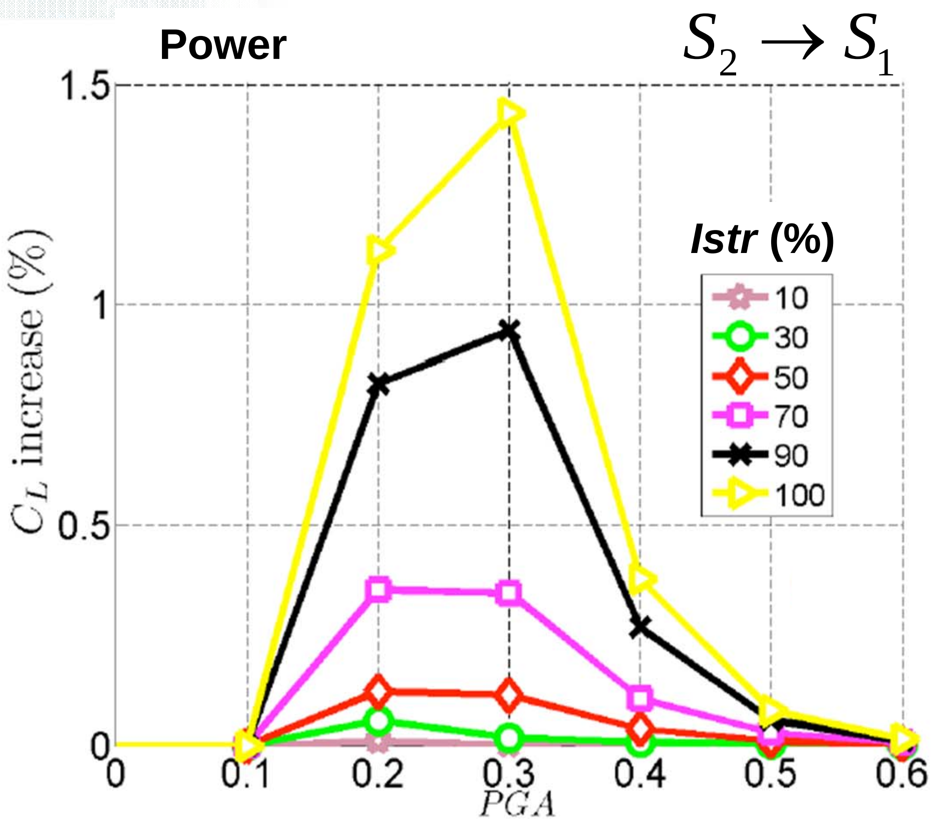
$S_1 \rightarrow S_2$

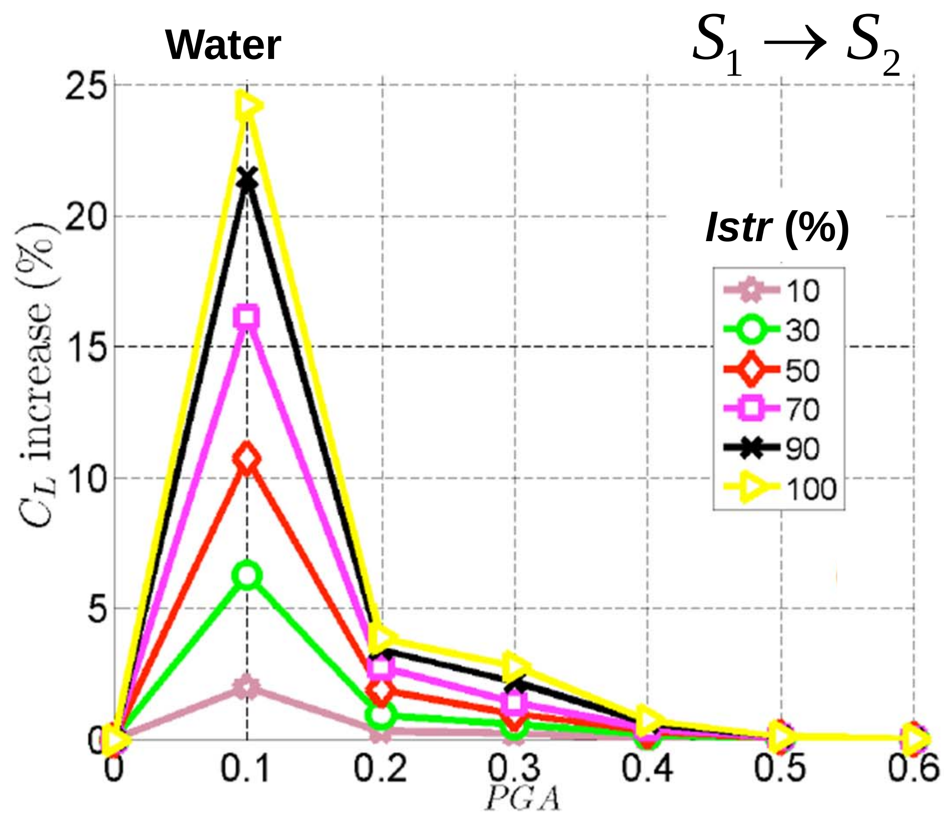


- **Coupling contributes significantly to water fragility**
- **Interdependence control must be activated early**

2. Insights from Modeling (4/8)

- **Added Connectivity Loss C_L from interdependencies**



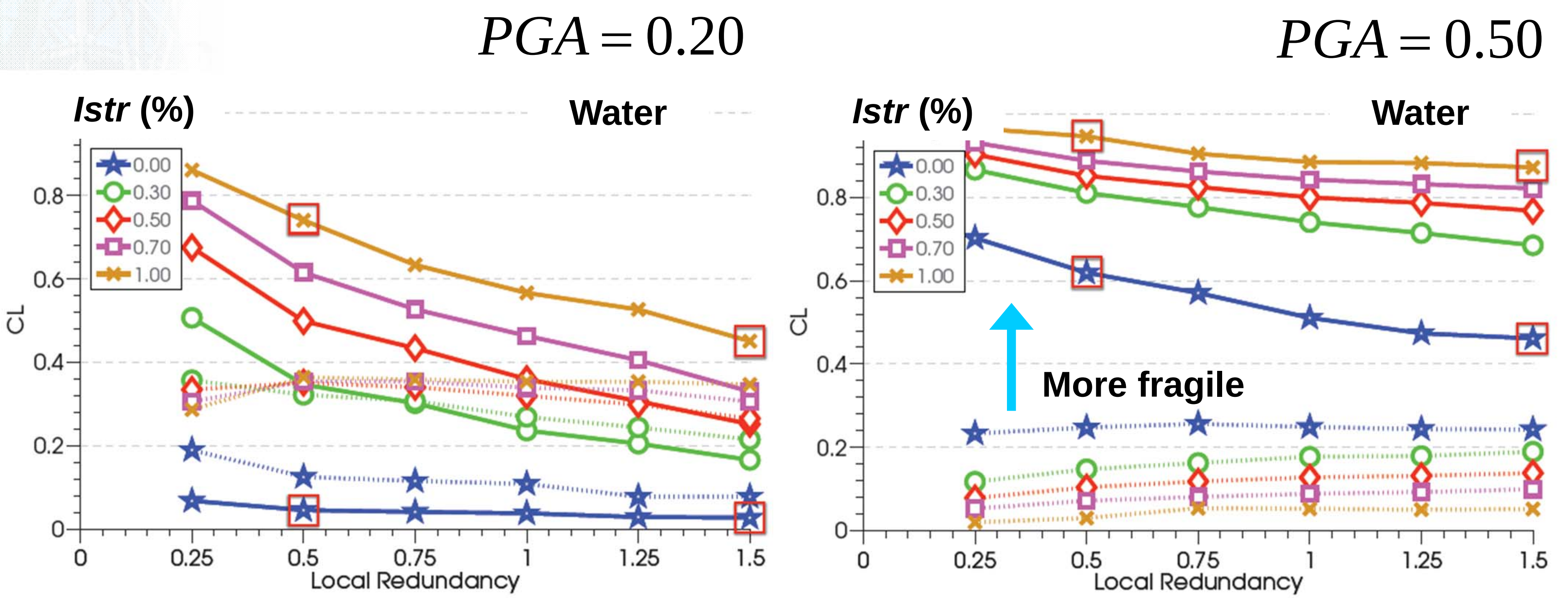


- **Power system is less sensitive to coupling**
- **Interdependencies manifest at select hazard levels**

2. Insights from Modeling (5/8)

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

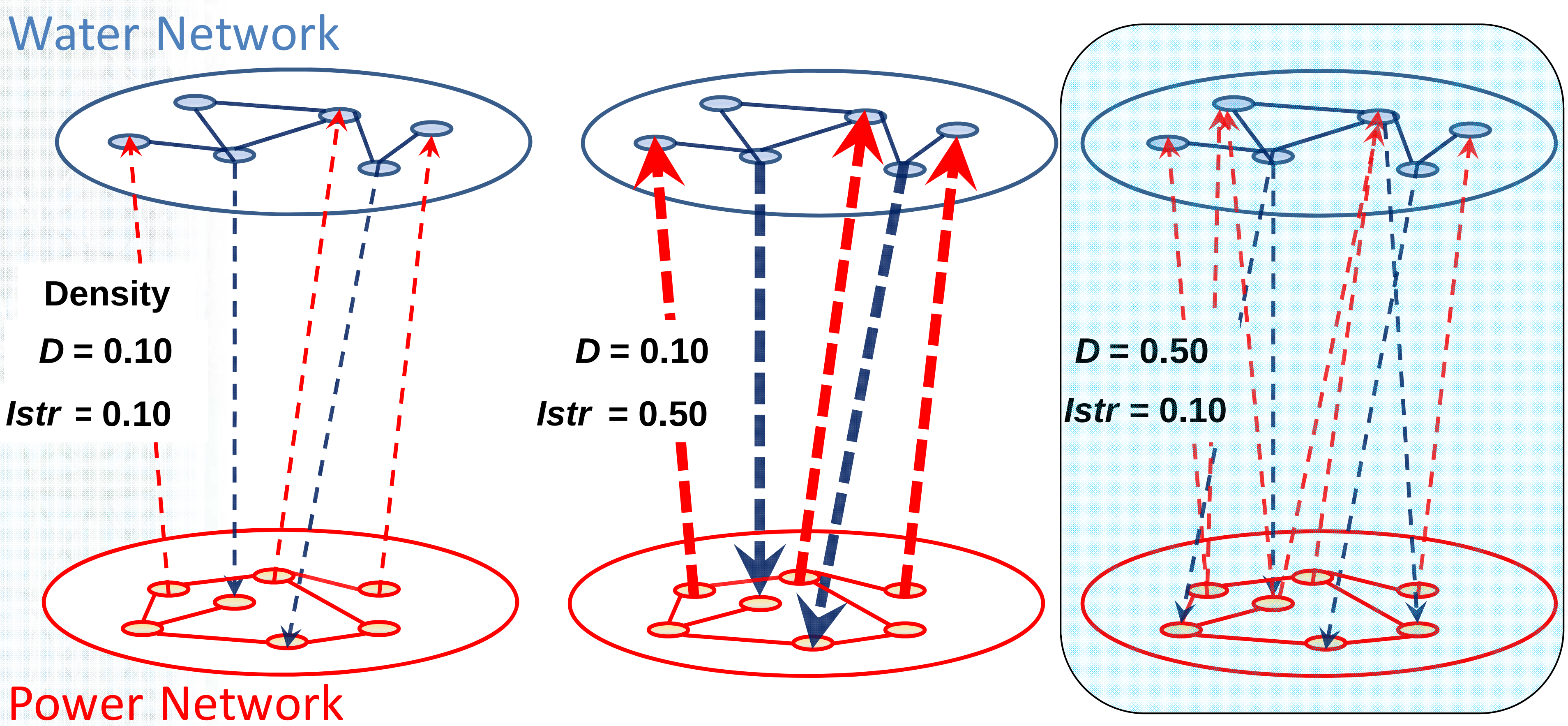
$S_1 \rightarrow S_2$



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

2. Insights from Modeling (6/8)

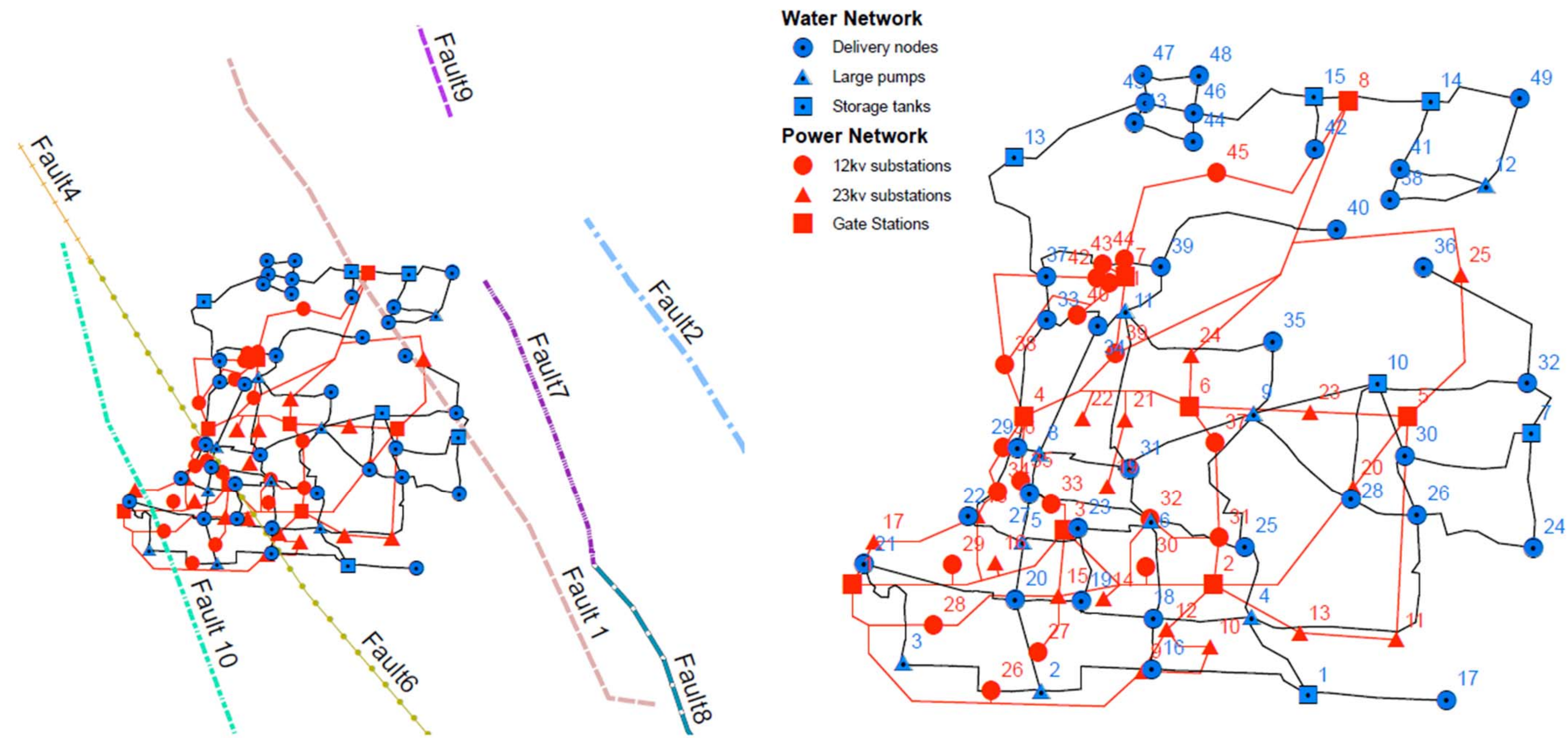
- **Effects of interface topology across systems**



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

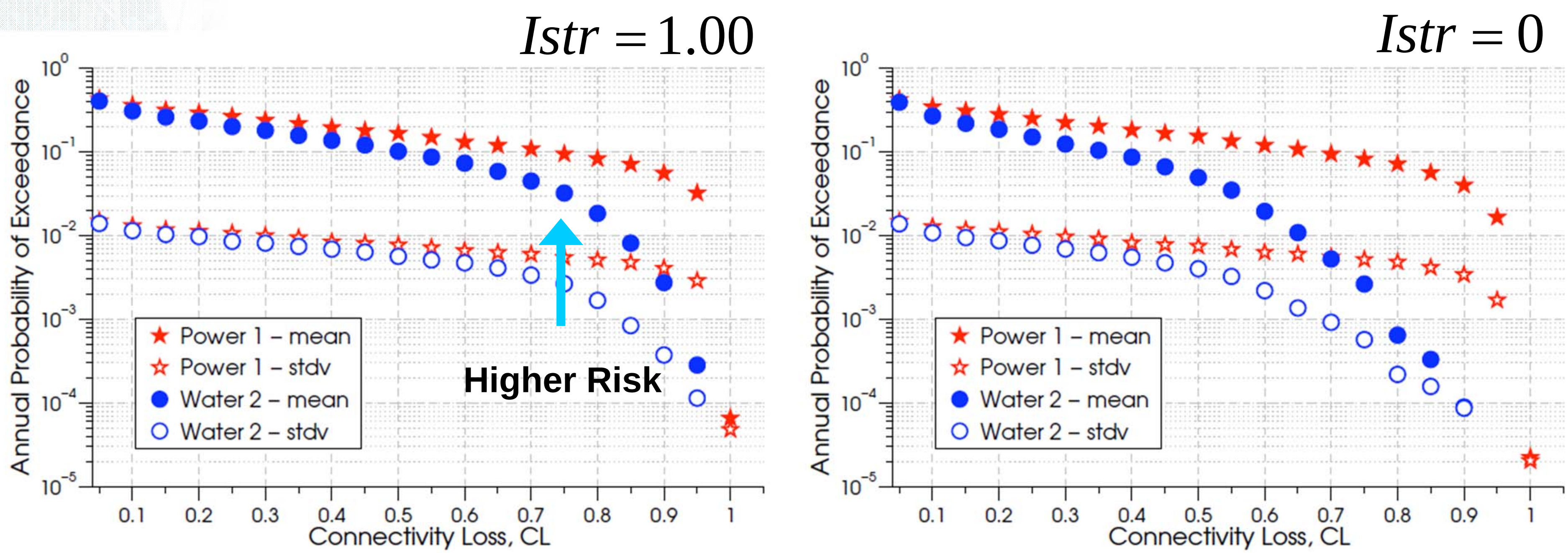
2. Insights from Modeling (7/8)

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



2. Insights from Modeling (8/8)

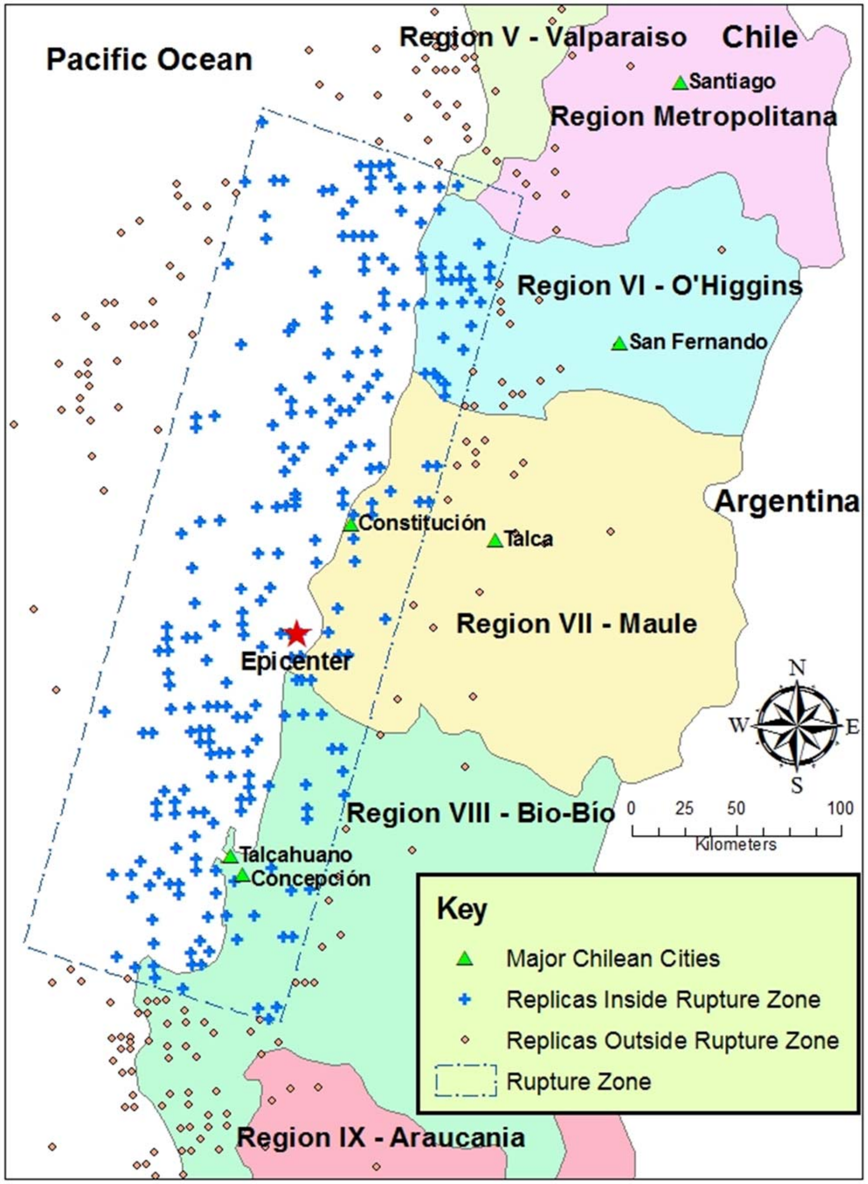
- **Risk-level effects of interdependence**



  - **Interdependence effects persist after convolution of fragility with seismic hazards**

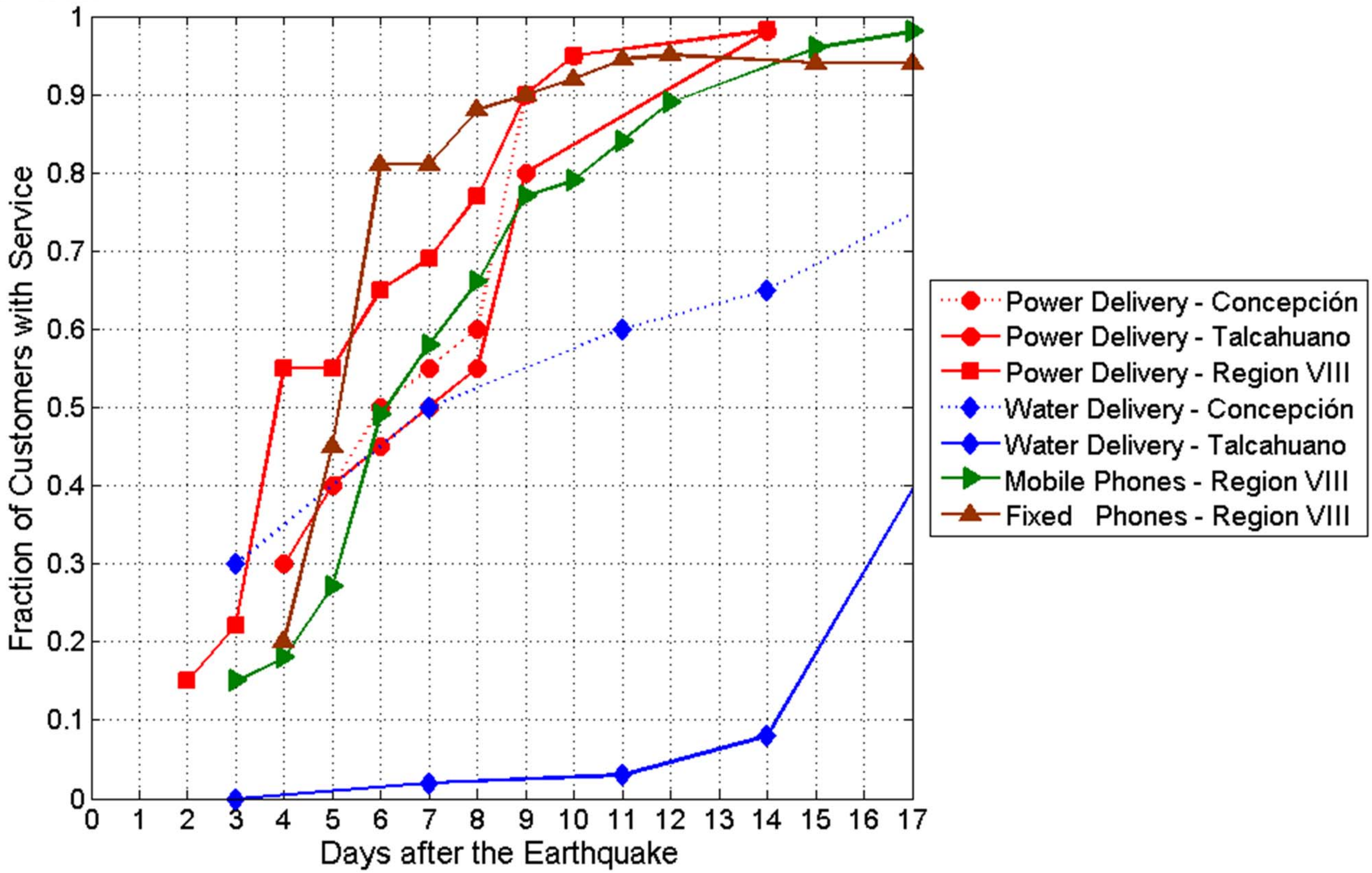
3. Coupling Strength Quantification (1/8)

Geographical and seismological context of Chile 2010 Earthquake



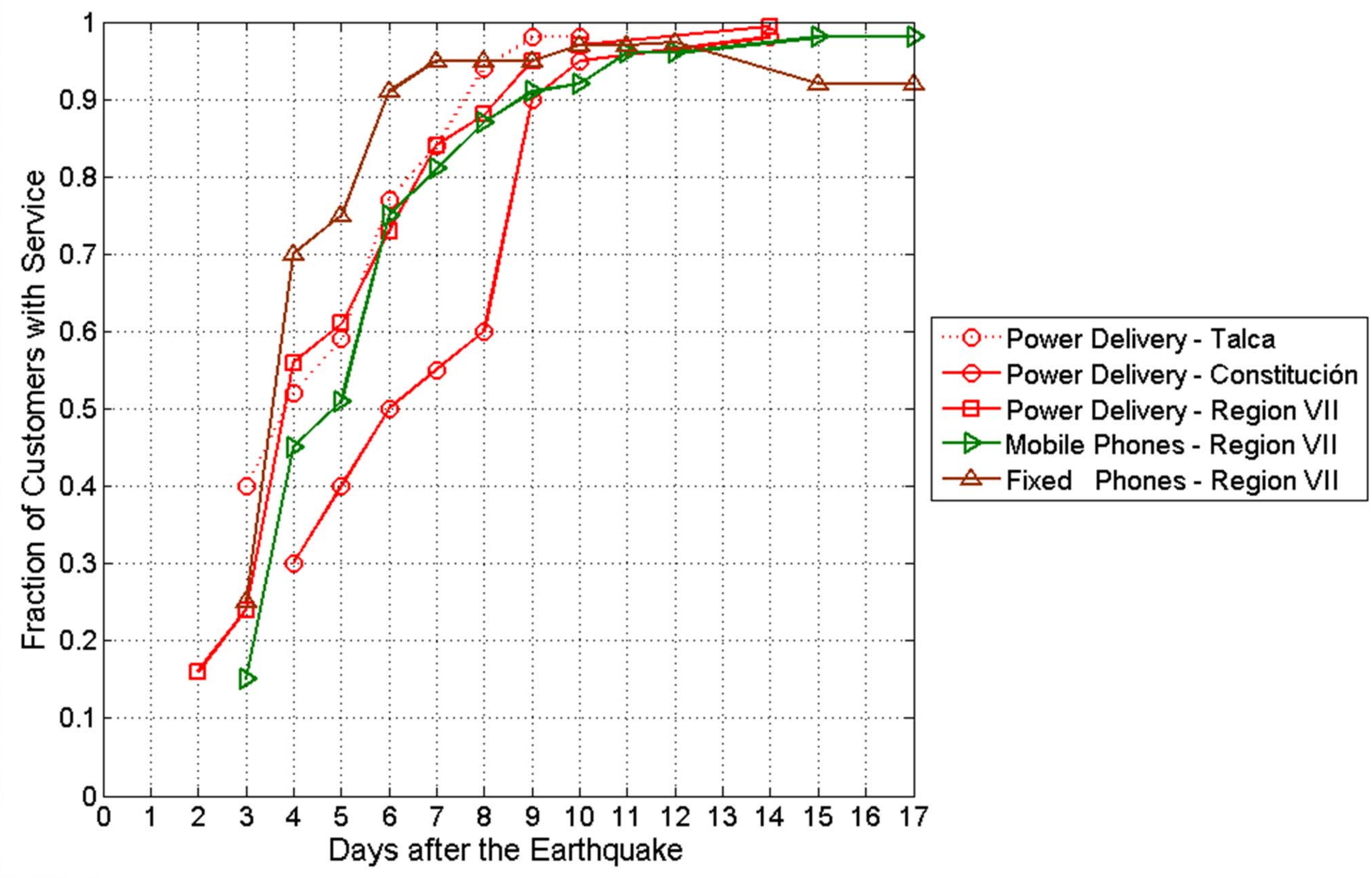
3. Coupling Strength Quantification (2/8)

- **Restoration time series in the Bio-Bio Region VIII**



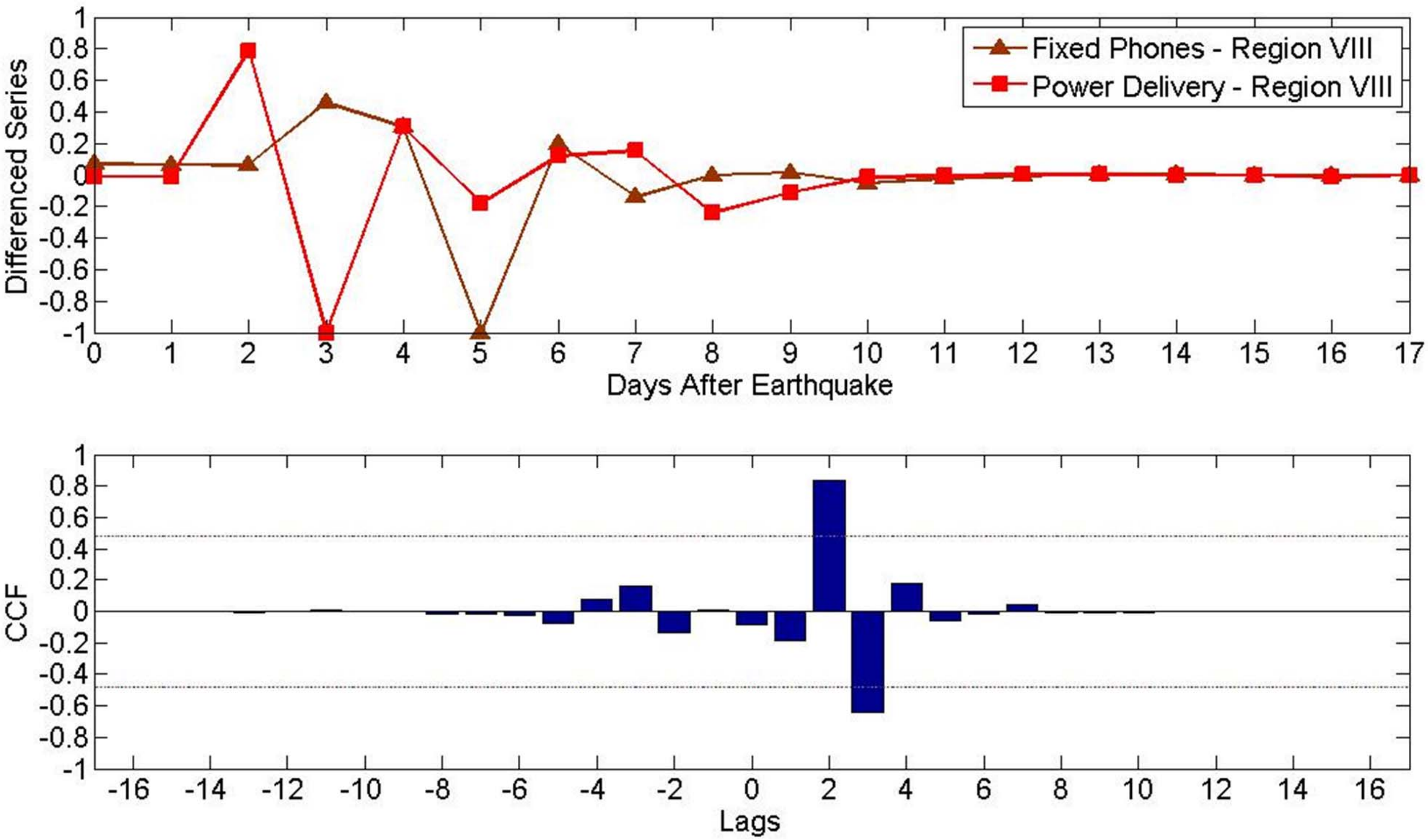
3. Coupling Strength Quantification (3/8)

- **Restoration time series in the Maule Region VII**



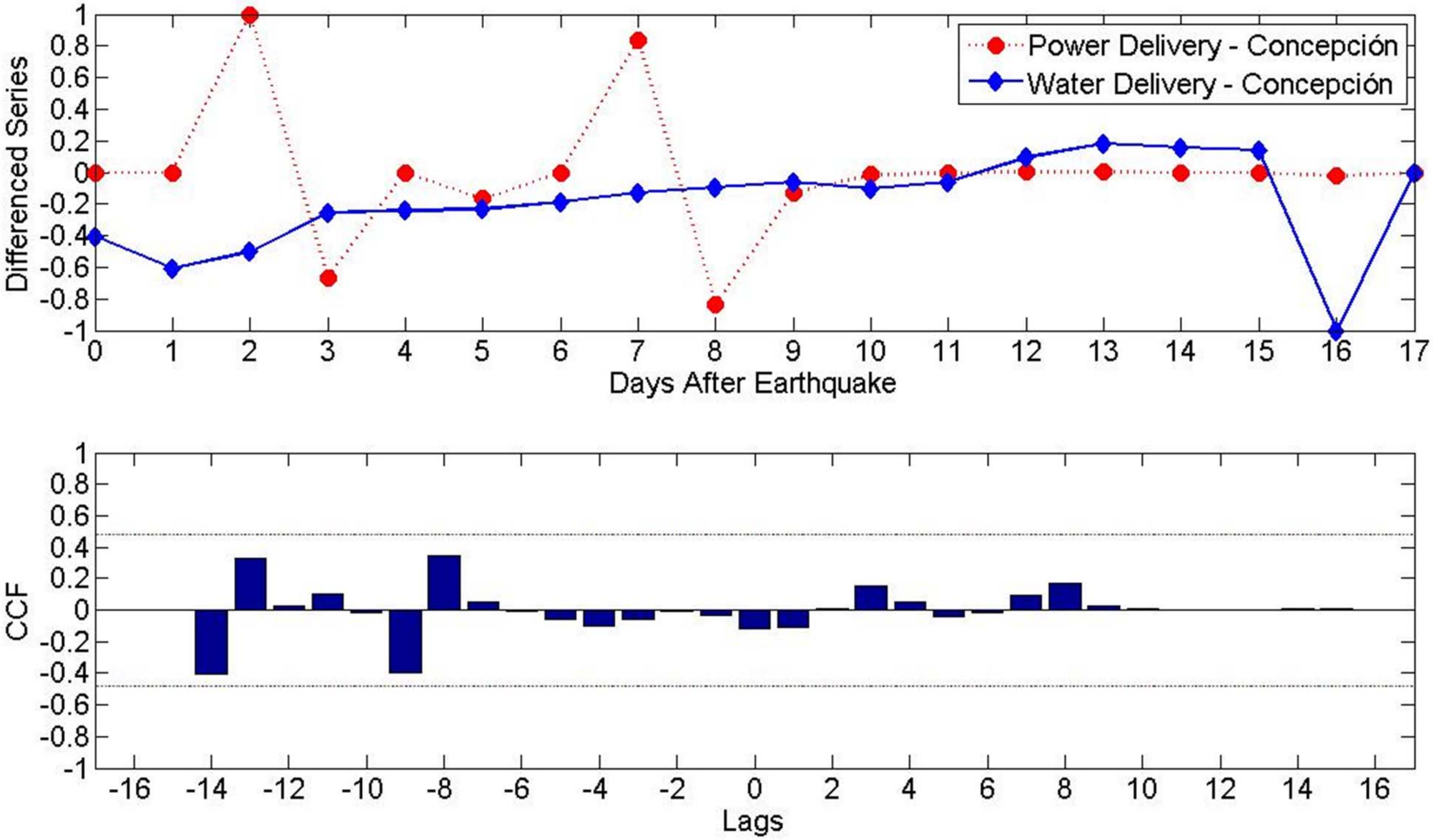
3. Coupling Strength Quantification (4/8)

- **Sample of *strong* cross-correlation (coupling strength)**



3. Coupling Strength Quantification (5/8)

- **Sample of *weak* cross-correlation (coupling strength)**



3. Coupling Strength Quantification (6/8)

- **Pair-wise cross-correlations CCFs in Region VIII**

Series	F_VIII		M_VIII		P_VIII		P_C_VIII		P_T_VIII		W_C_VIII		W_T_VIII	
	Peak ρ	Lag h	Peak ρ	Lag h	Peak ρ	Lag h	Peak ρ	Lag h	Peak ρ	Lag h	Peak ρ	Lag h	Peak ρ	Lag h
F_VIII	1.00	0.00	0.74	0.00	**0.84**	2.00	0.53	2.00	0.74	-3.00	0.66	-11.00	**0.96**	-11.00
M_VIII	0.74	0.00	1.00	0.00	0.73	2.00	0.64	2.00	**0.83**	-3.00	0.48	-11.00	0.74	-11.00
P_VIII	**0.84**	-2.00	0.73	-2.00	1.00	0.00	0.79	0.00	**0.89**	-5.00	0.56	-13.00	0.79	-13.00
P_C_VIII	0.53	-2.00	0.64	-2.00	0.79	0.00	1.00	0.00	0.68	-5.00	0.35	-8.00	0.53	-8.00
P_T_VIII	0.74	3.00	**0.83**	3.00	**0.89**	5.00	0.68	5.00	1.00	0.00	0.50	-8.00	0.75	-8.00
W_C_VIII	0.66	11.00	0.48	11.00	0.56	13.00	0.35	8.00	0.50	8.00	1.00	0.00	0.70	0.00
W_T_VIII	**0.96**	11.00	0.74	11.00	0.79	13.00	0.53	8.00	0.75	8.00	0.70	0.00	1.00	0.00

F: Fixed lines
M: Mobile lines
P: Power

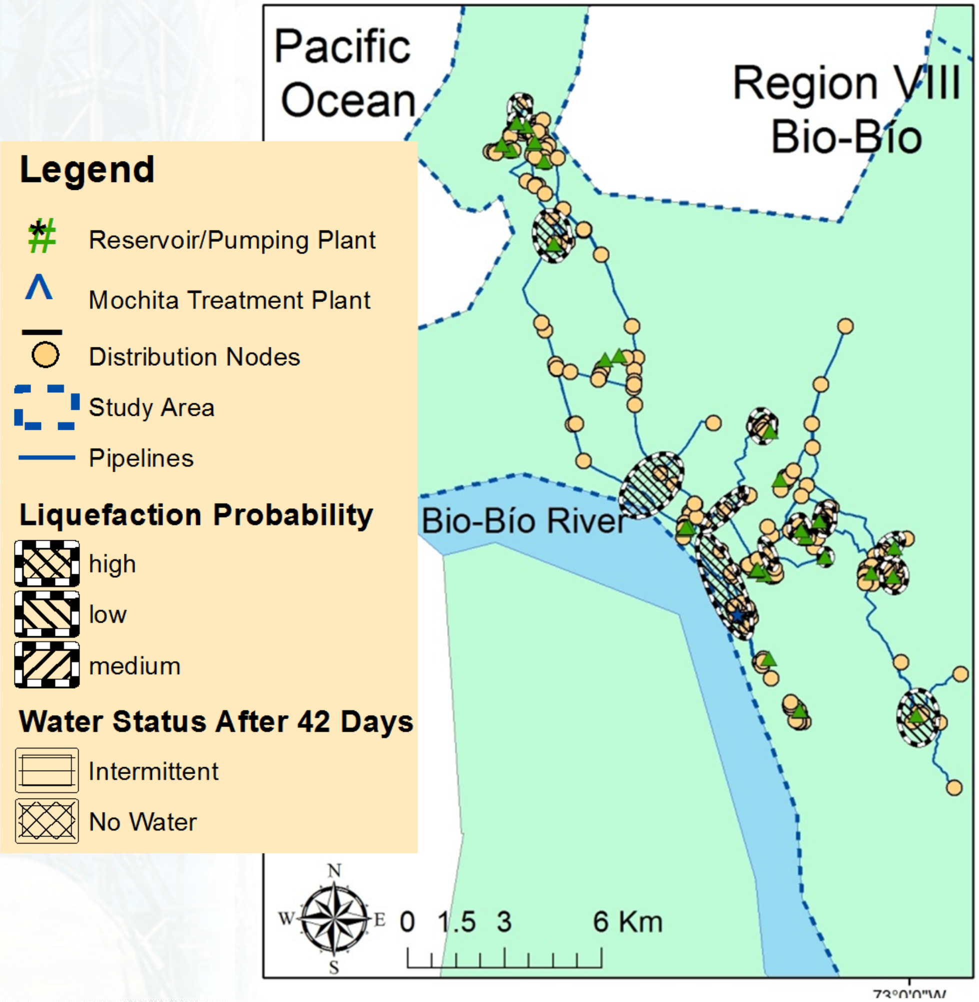
W: Water
C: Concepción
T: Talcahuano

- **Strong operational coupling between telecommunication systems and with power systems**
- **Measurable logistical coupling with water systems**

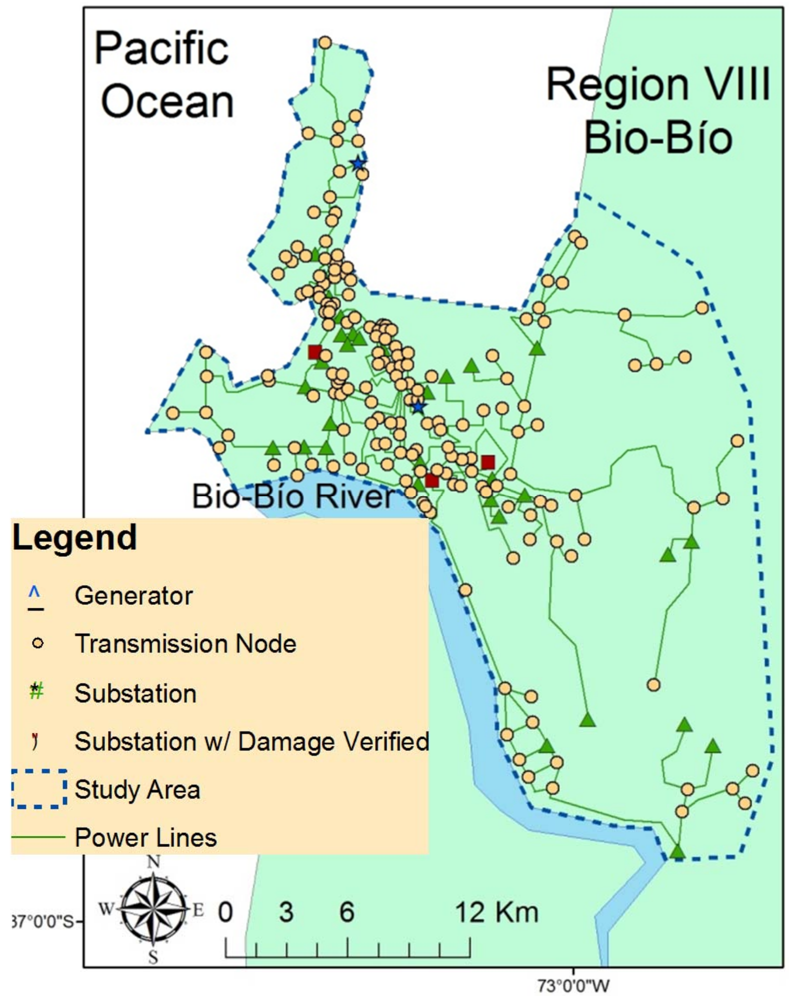
3. Coupling Strength Quantification (7/8)

- **Water and power systems in Concepcion, Chile**

Water



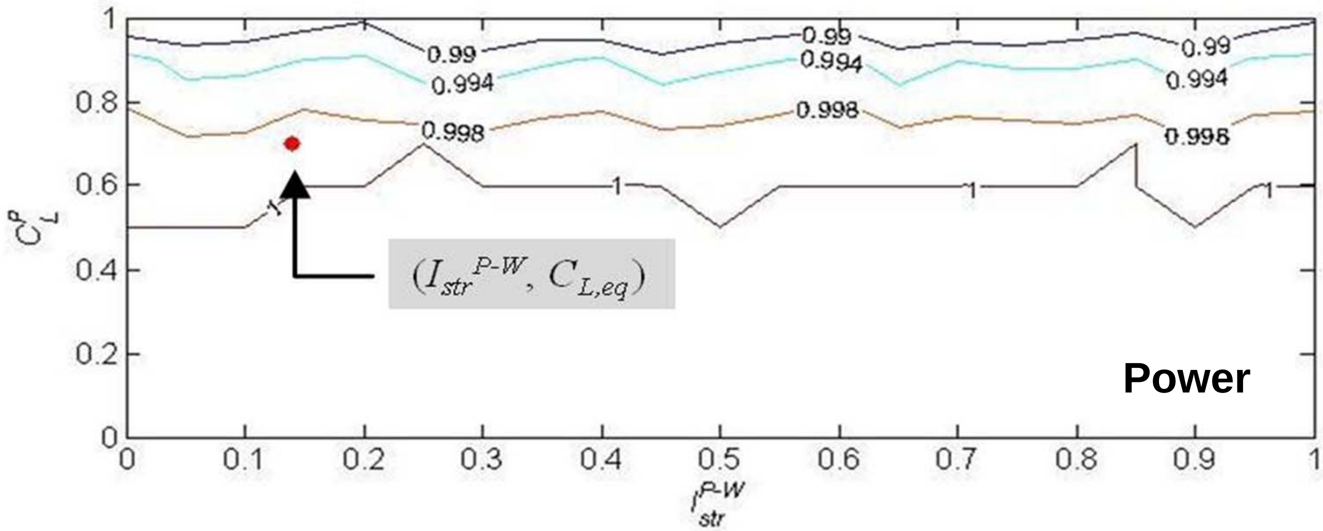
Power



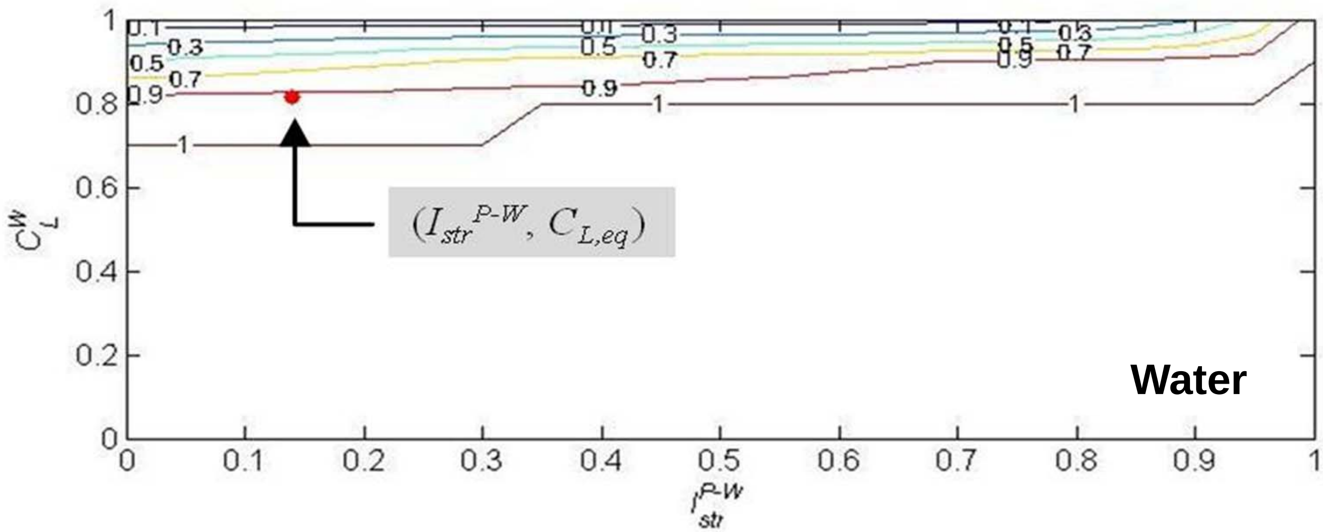
3. Coupling Strength Quantification (8/8)

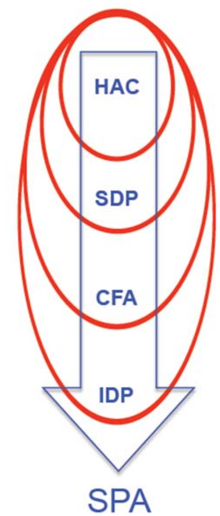
- **Fragility point validation**

$S_2 \rightarrow S_1$



$S_1 \rightarrow S_2$





4. Conclusions and Future Work

- There is a need for modeling tools with predictive capabilities that merge *physical and institutional* systems
- Interdependencies are significant at *specific ranges of hazard* intensities and tend to *quickly propagate main effects*
- Infrastructure interfaces that promote coordination and prevent propagation are *denser and weaker than current designs*
- Time-series analyses of restoration curves enable *coupling strength quantification* and interdependence *model validations*

- Expand analyses of interdependence effects to system *resilience assessment*
- *Prioritize critical components and restoration tasks* to achieve target multi-system performance levels

Thank you!

Support from:

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Technical Council on Lifeline Earthquake Engineering (TCLEE)

Rice University

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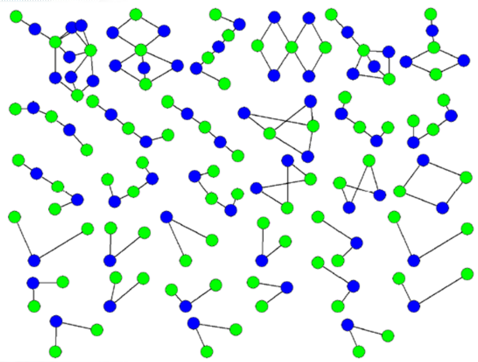
Insights from Modeling

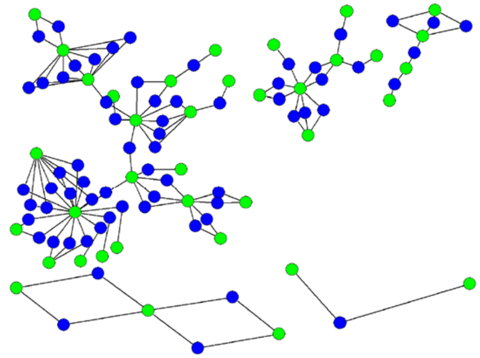
- **Effects of interface topology on performance**

● Water node

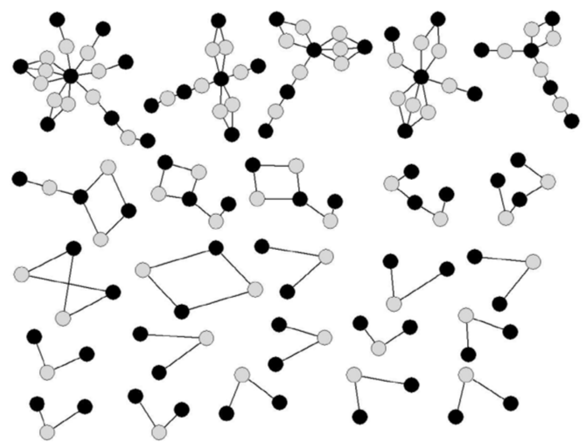
● Power node



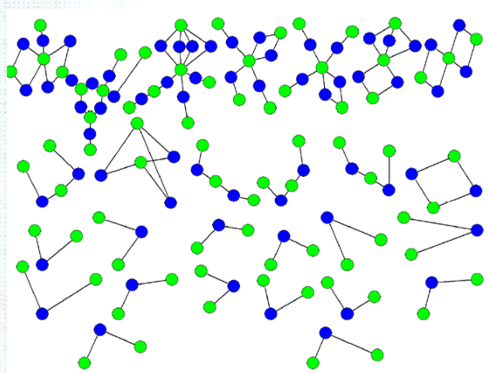
Distance



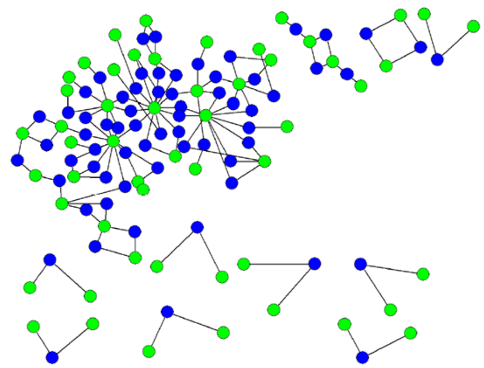
Clustering



Hybrid Distance-Betweenness



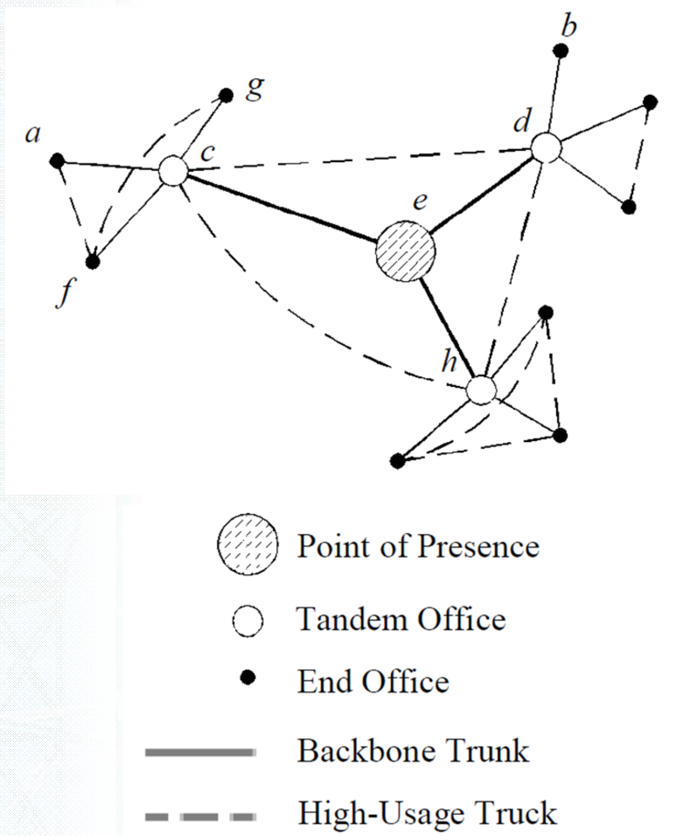
Degree

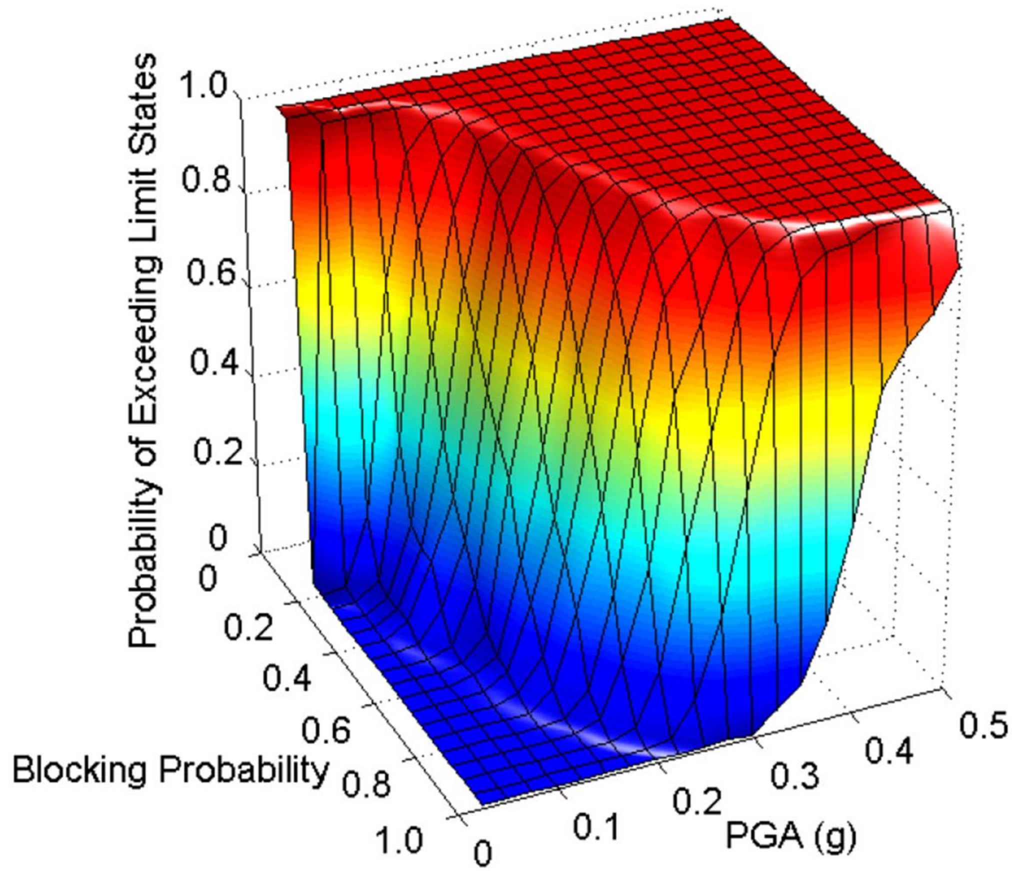


Betweenness

Insights from Modeling

- **Systems with distinct physical operating principles**





  - **Congestion is a dominant failure mode for telecommunication systems**

Recent Field Observations

- **Autocorrelation (ACF) in power systems**