Understanding Interdependent Infrastructure Systems: Modeling Insights and Practical Challenges

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Network Analysis: Complexity of Interdependence
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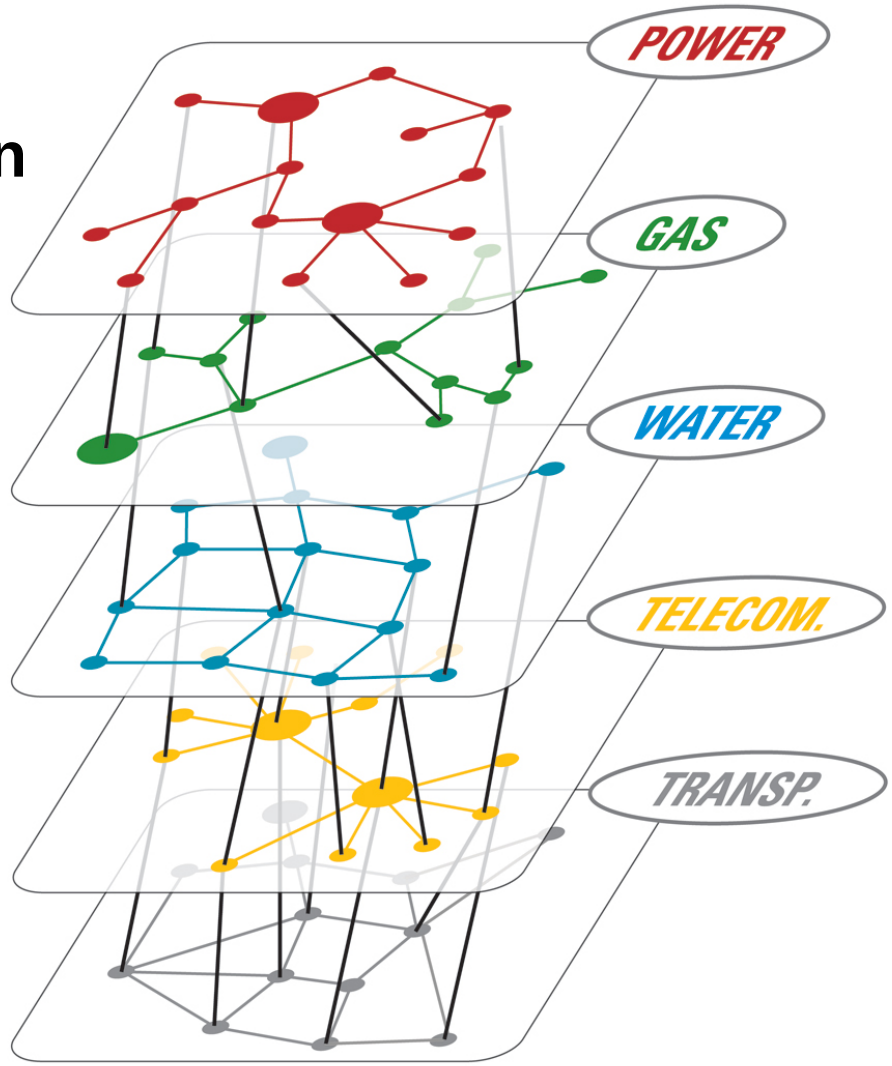
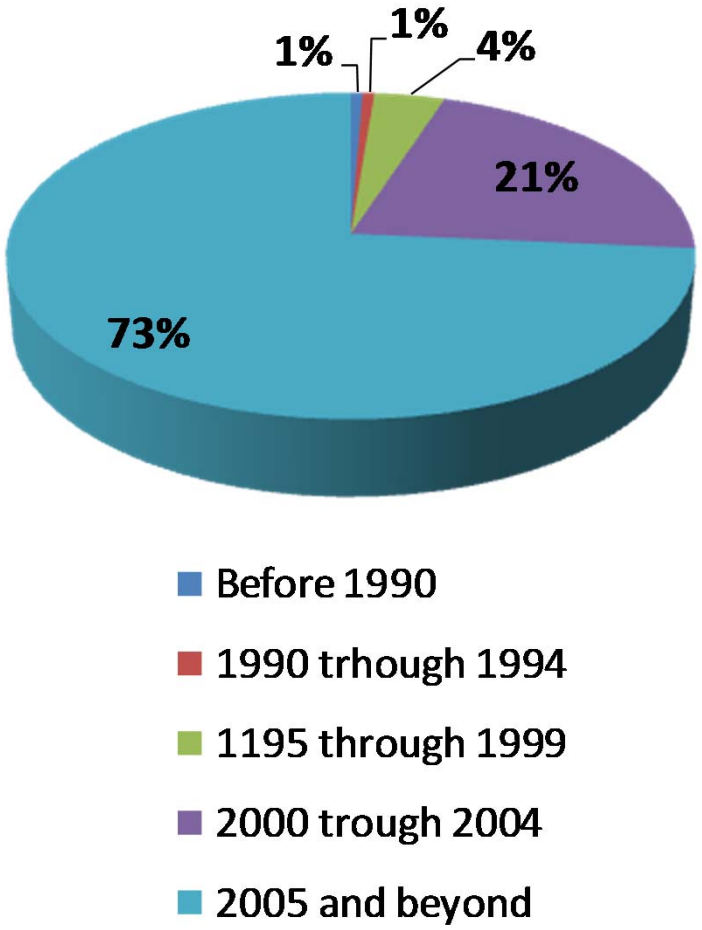
Motivation (1/3)

- **Contemporary complex infrastructure systems**
  - **Essential to support modern society's functions**
  - **Large scale and high exposure systems**
  - **Reached accelerated phase of aging and deterioration**
  - **Increased interdependence for optimized operation**



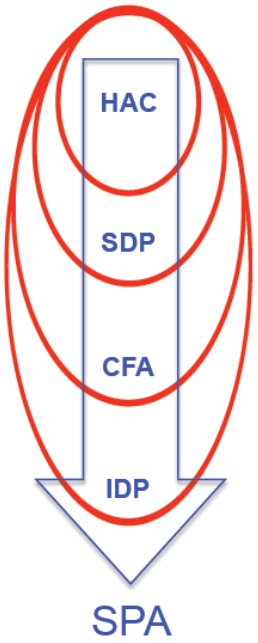
Motivation (2/3)

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

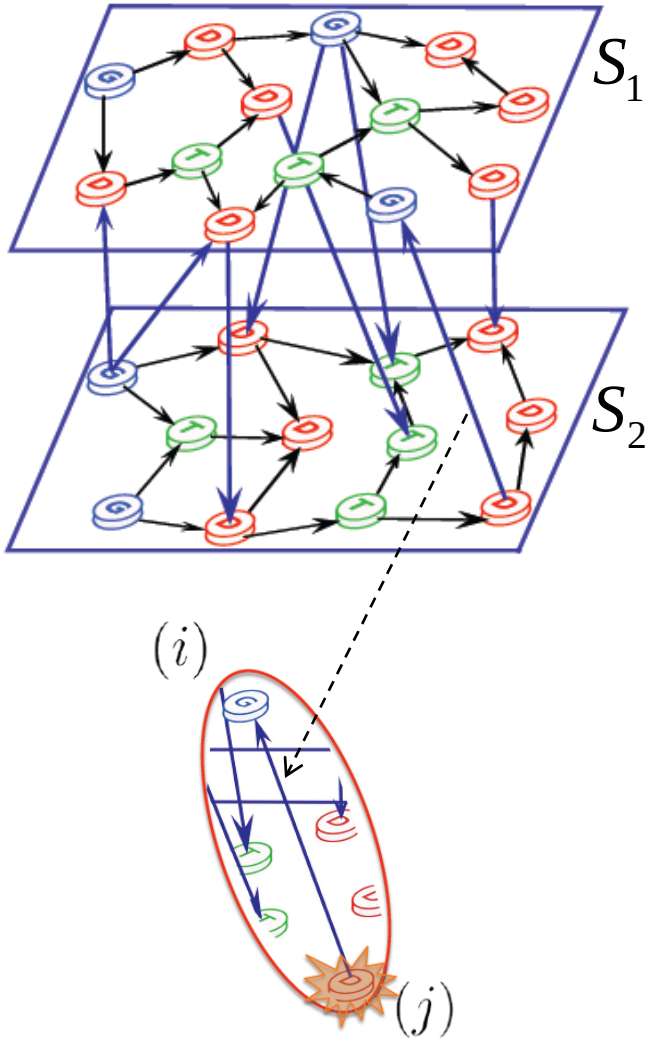


Motivation (3/3)

- **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

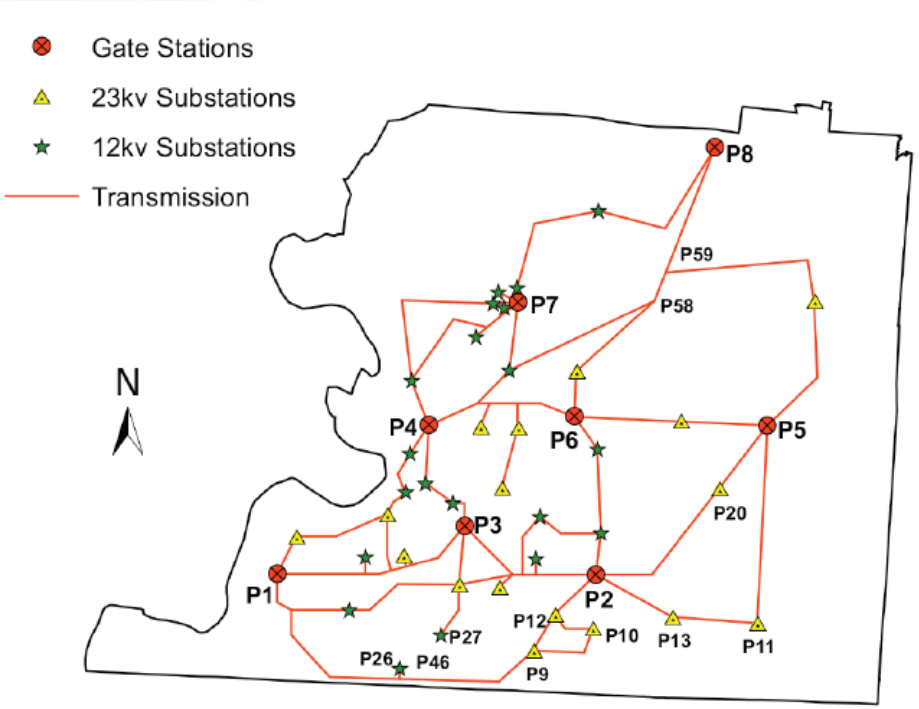
1. Research insights from network modeling approaches of infrastructure systems

2. Recent field observations of interdependence

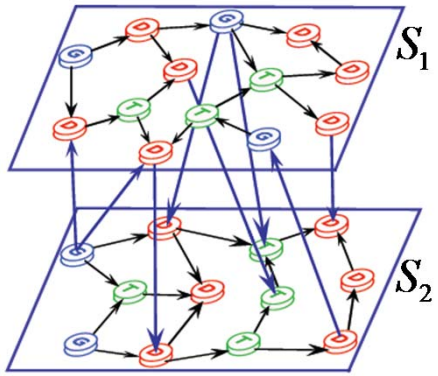
3. Concluding remarks and future work

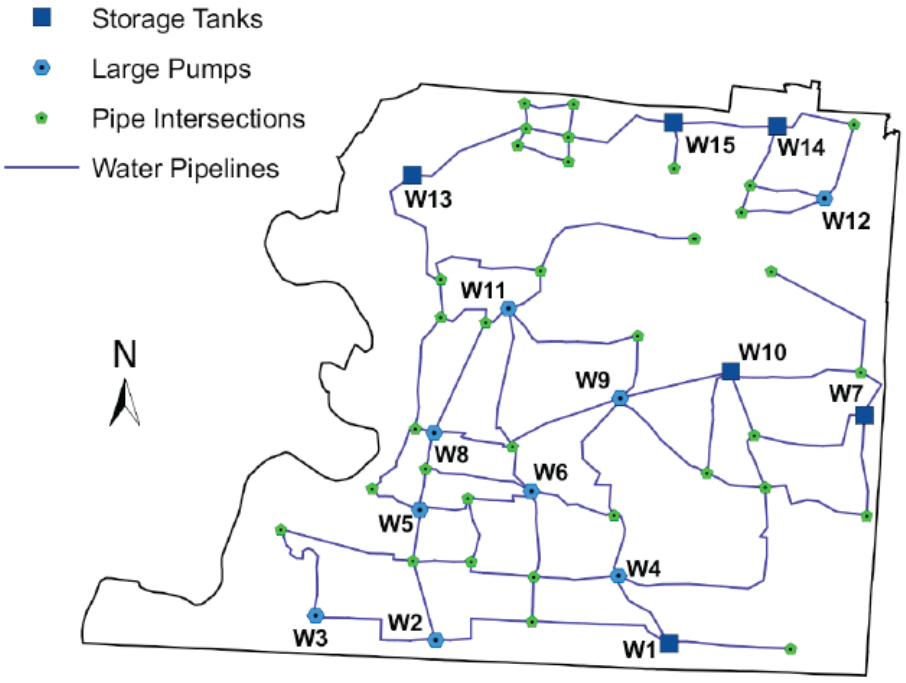
1. Insights from Modeling (1/8)

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



Power System S_1





Water Network S_2

$S_1 \rightarrow S_2$ Power effects on Water

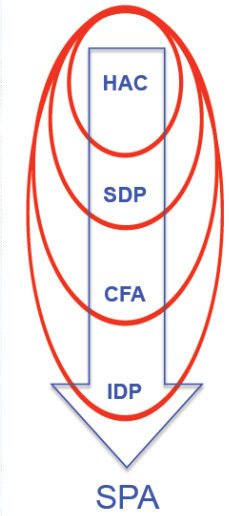
$S_2 \rightarrow S_1$ Water effects on Power

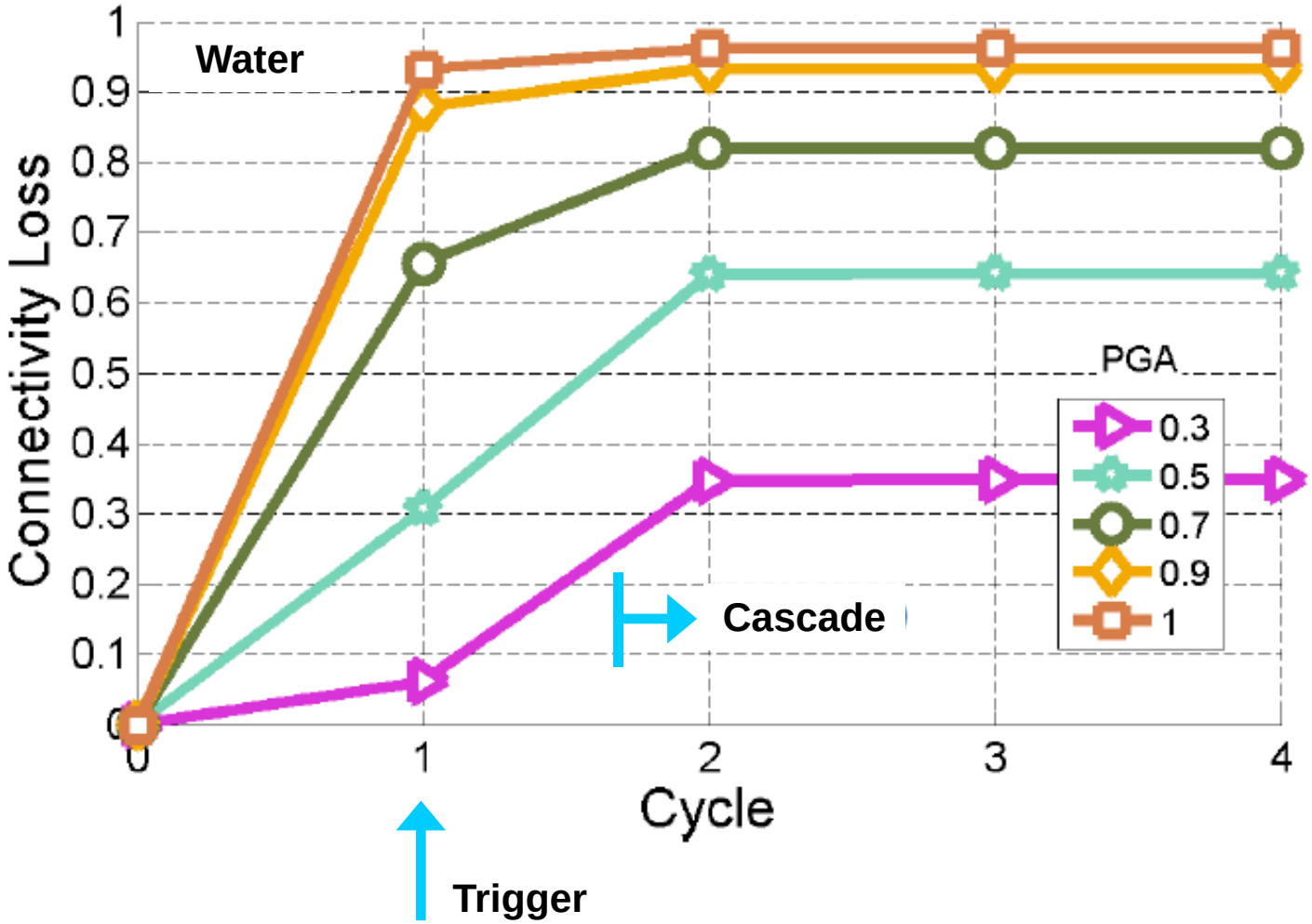
1. Insights from Modeling (2/8)

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

$S_1 \rightarrow S_2$

$Istr = 0.30$

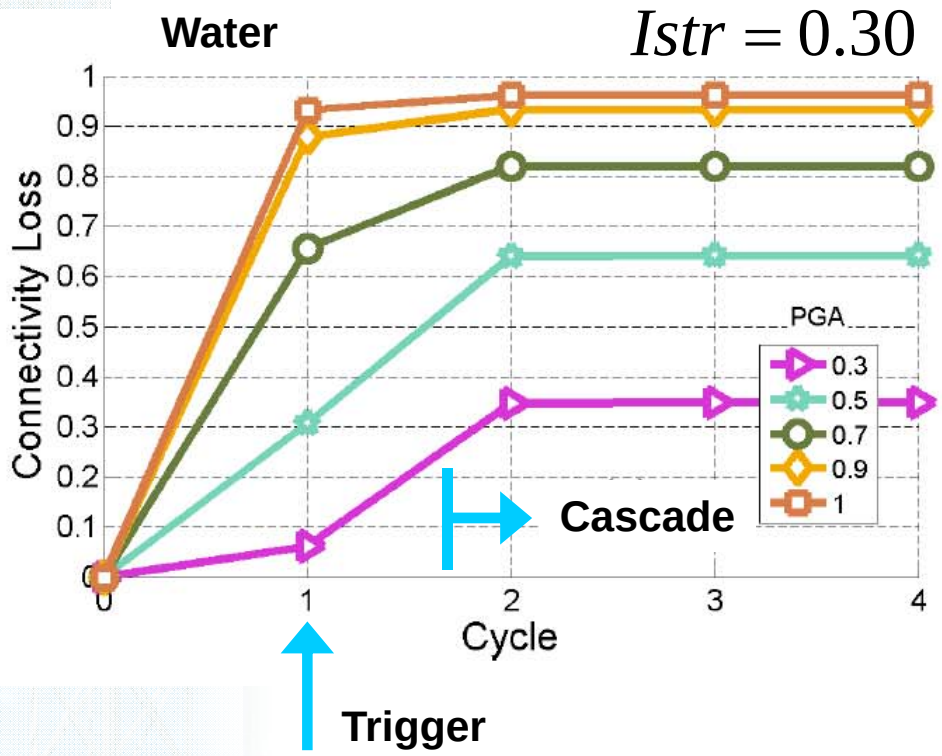


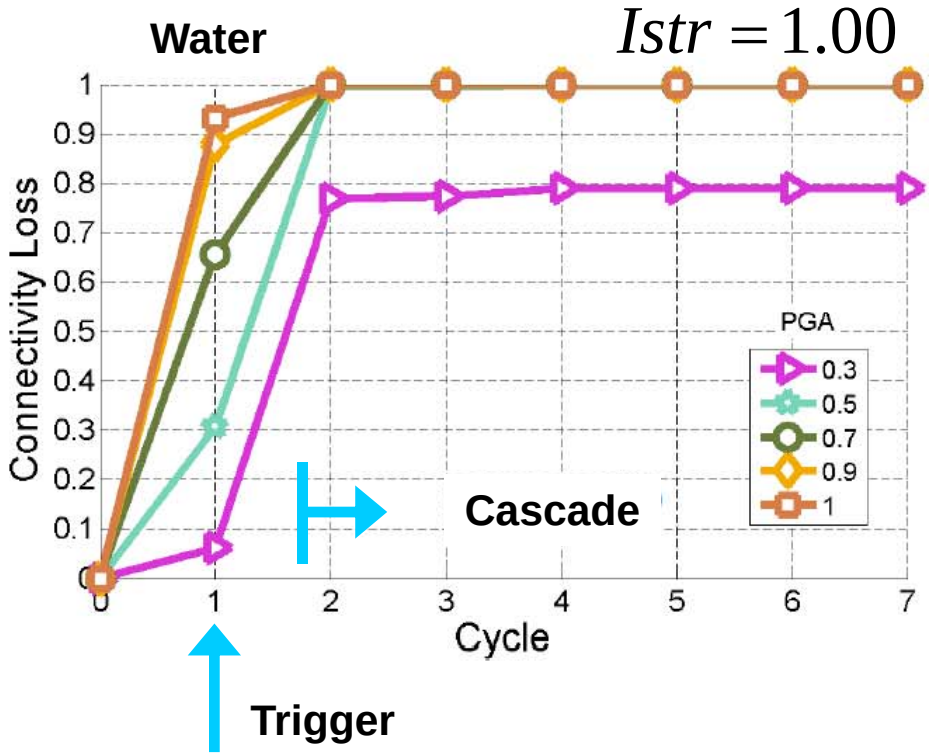


1. Insights from Modeling (3/8)

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

$S_1 \rightarrow S_2$

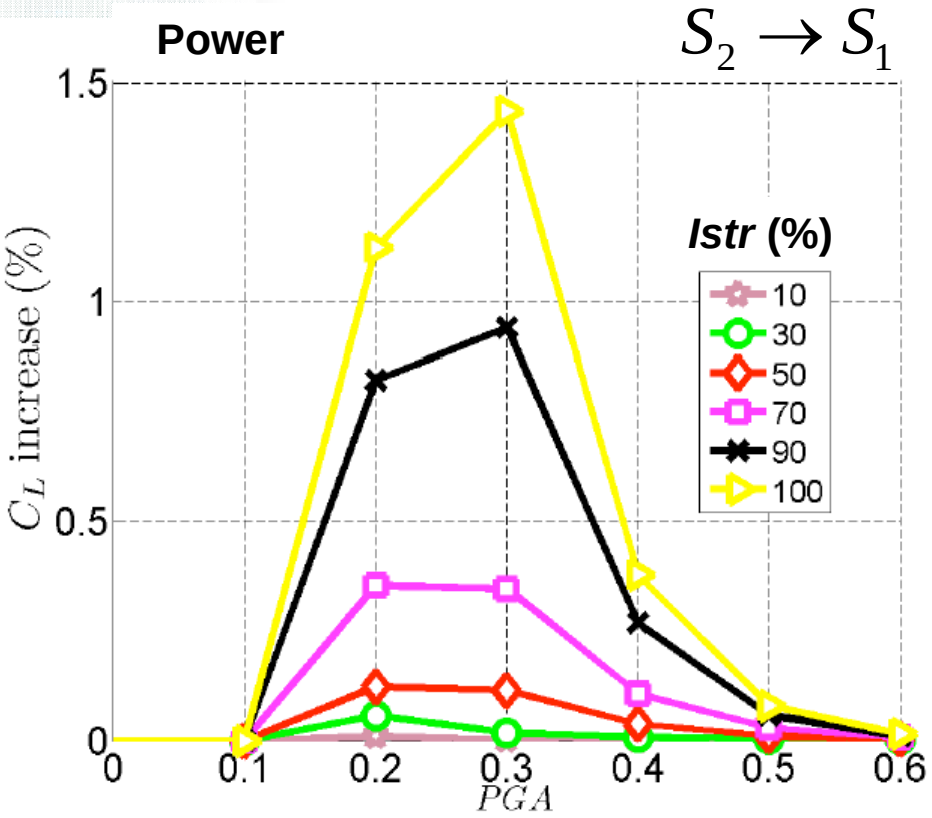


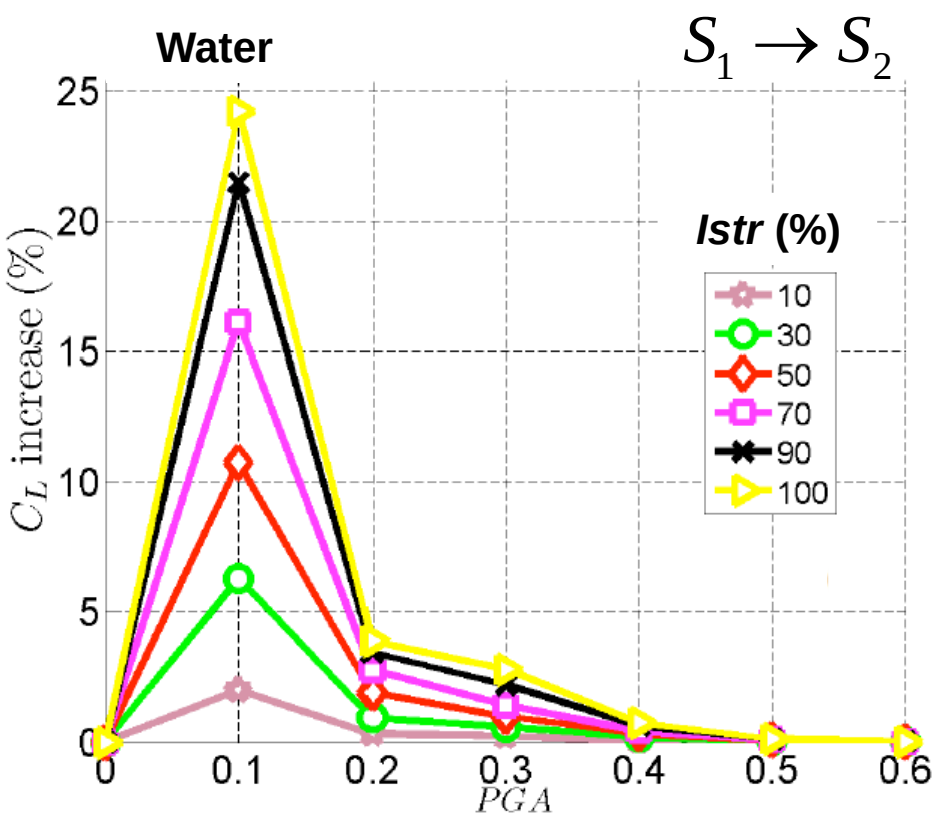


- **Coupling contributes significantly to water fragility**
- **Interdependence control must be activated early**

1. Insights from Modeling (4/8)

- **Added Connectivity Loss C_L from interdependencies**





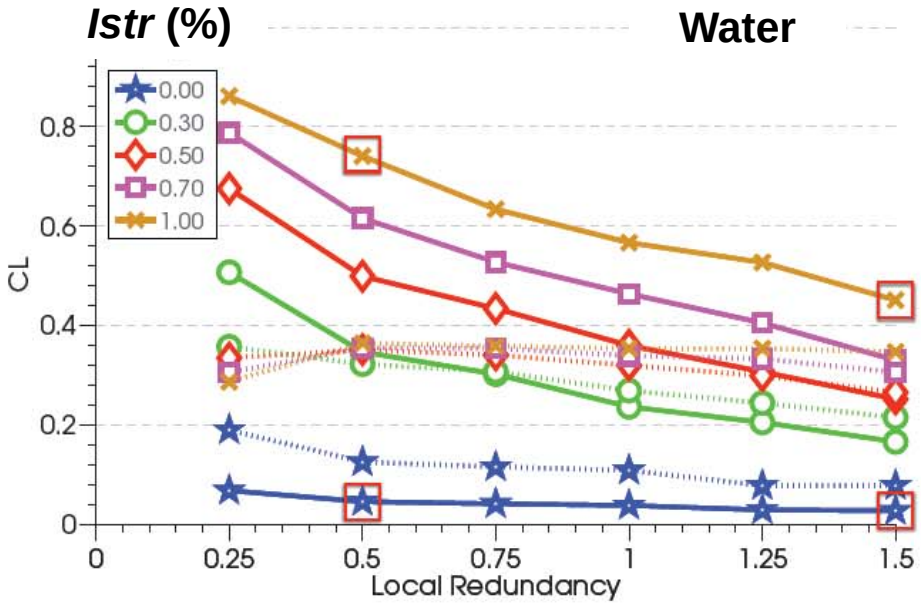
- **Power system is less sensitive to coupling**
- **Interdependencies manifest at select hazard levels**

1. Insights from Modeling (5/8)

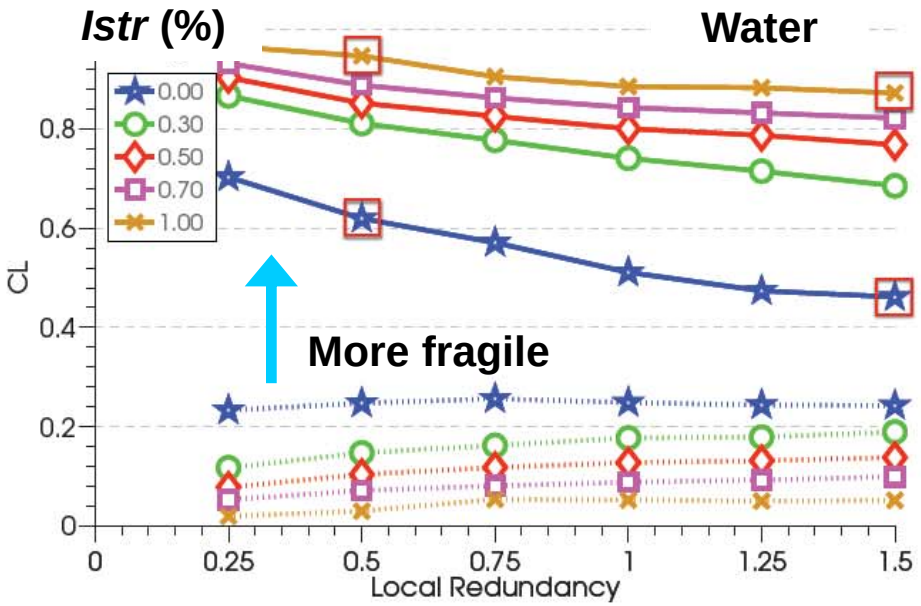
- **Effects of capacity increase of congested elements on C_L**

$S_1 \rightarrow S_2$

$PGA = 0.20$



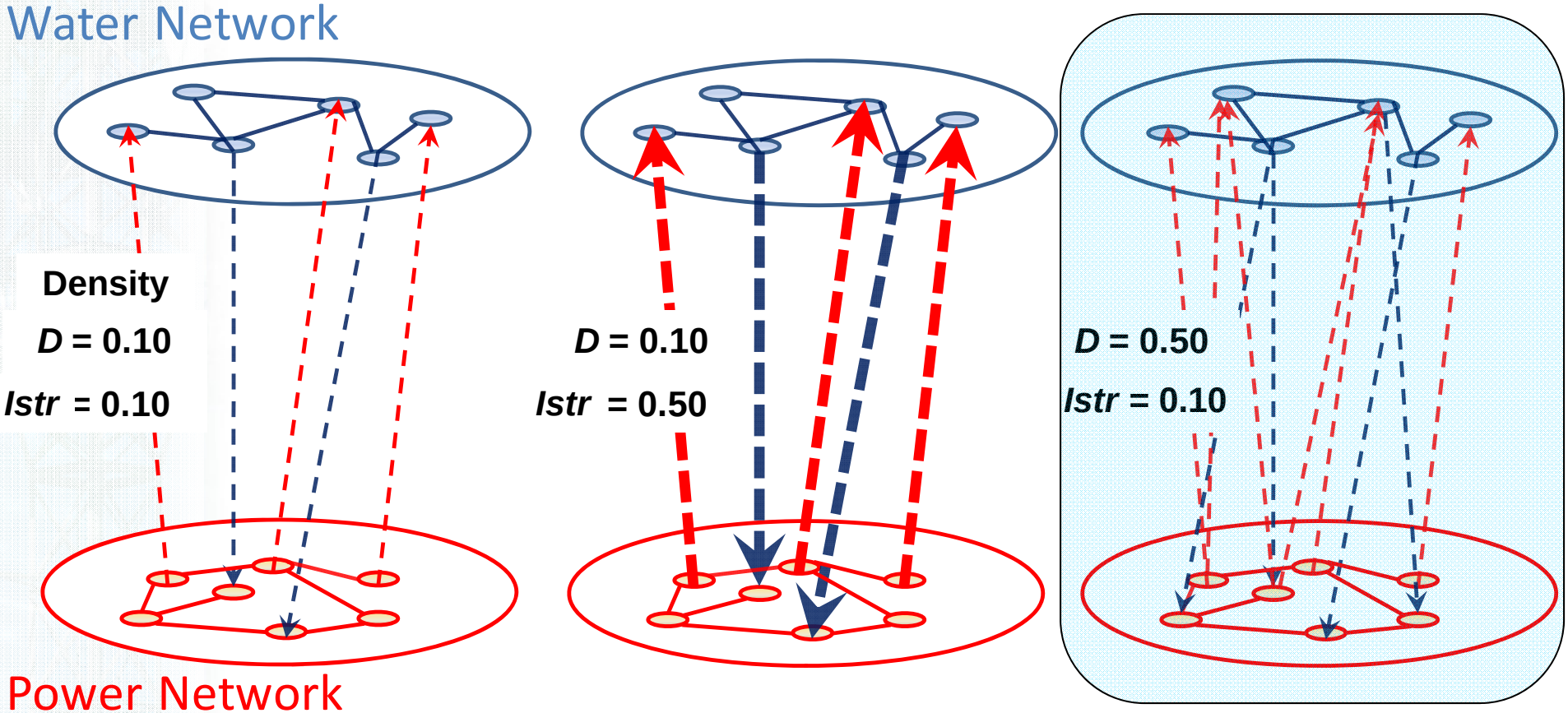
$PGA = 0.50$



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

1. Insights from Modeling (6/8)

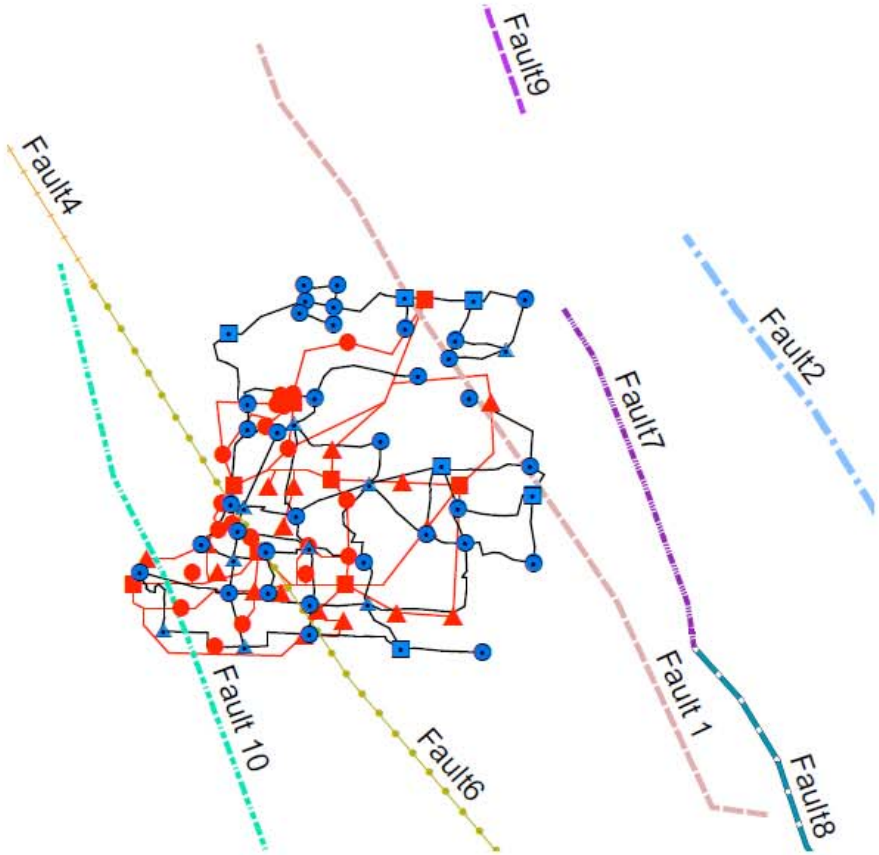
- **Effects of interface and network topology**

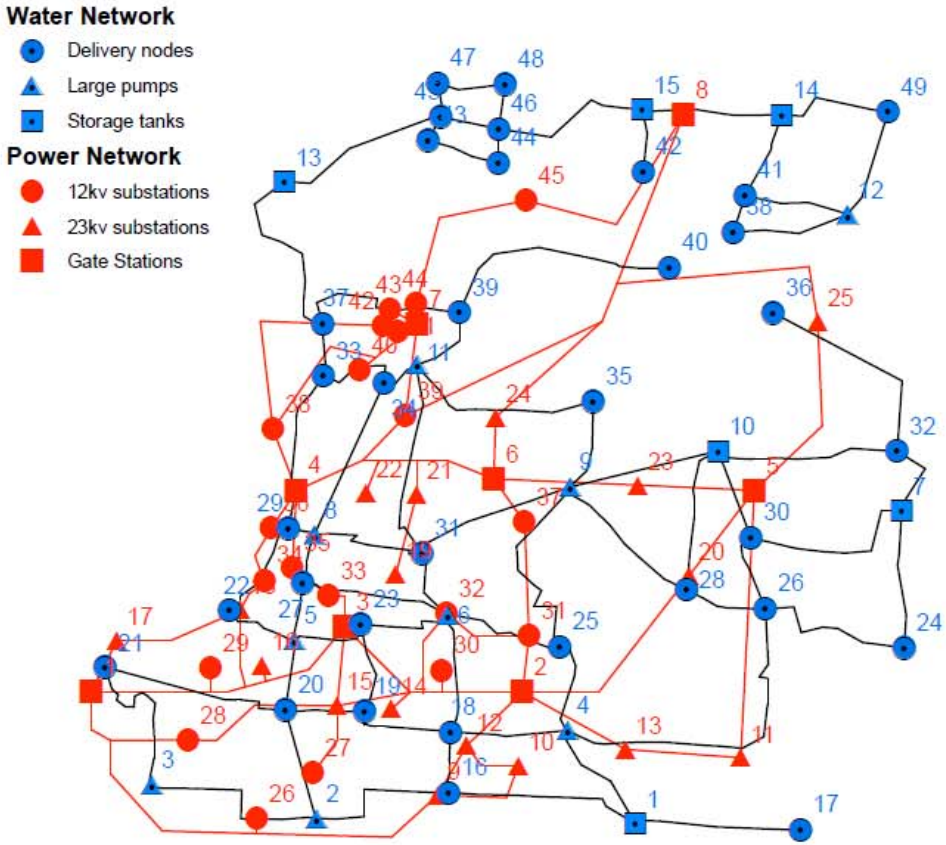


  - **Optimal interfaces exhibit high *D* and low *Istr***
  - **Strengthen power nodes and water links**

1. Insights from Modeling (7/8)

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

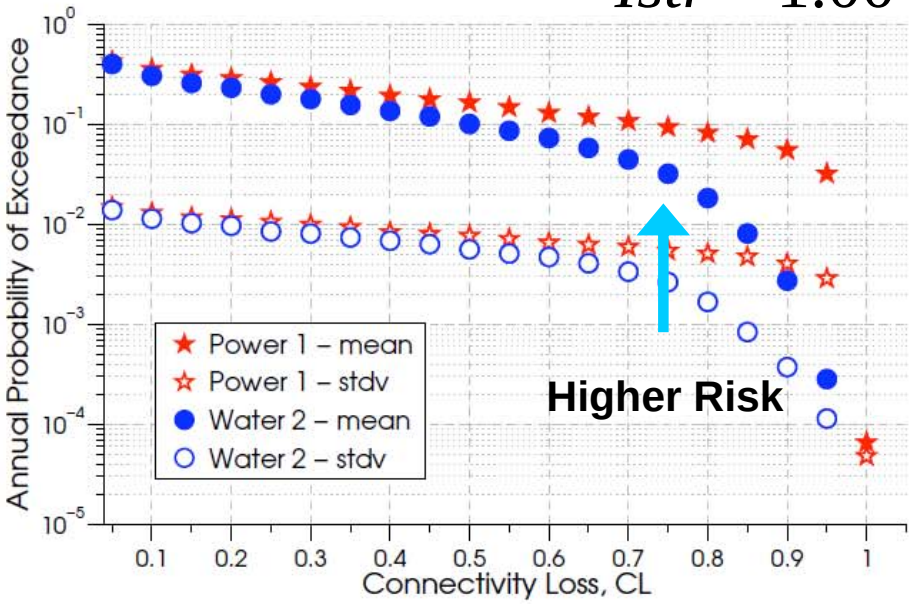




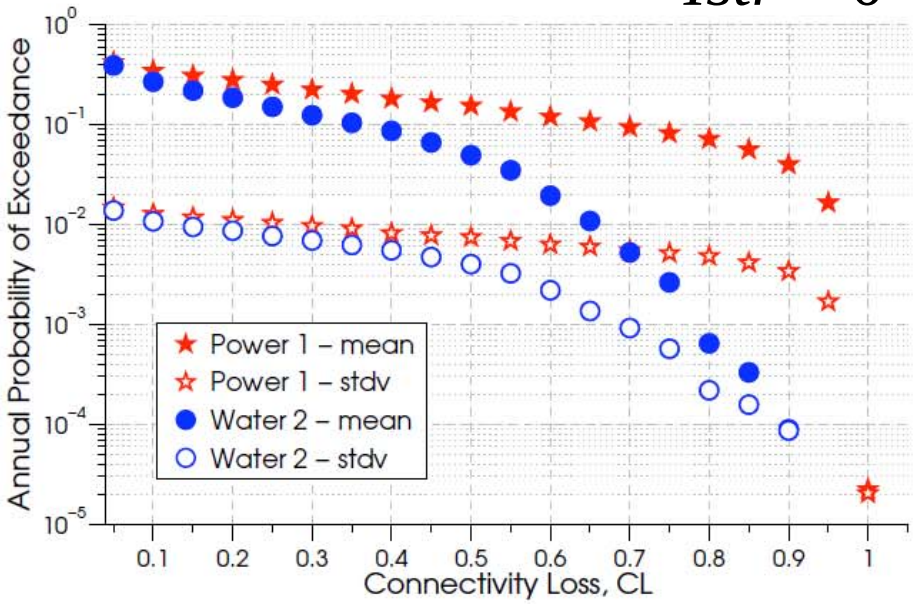
1. Insights from Modeling (8/8)

- **Risk-level effects of interdependence**

$Istr = 1.00$



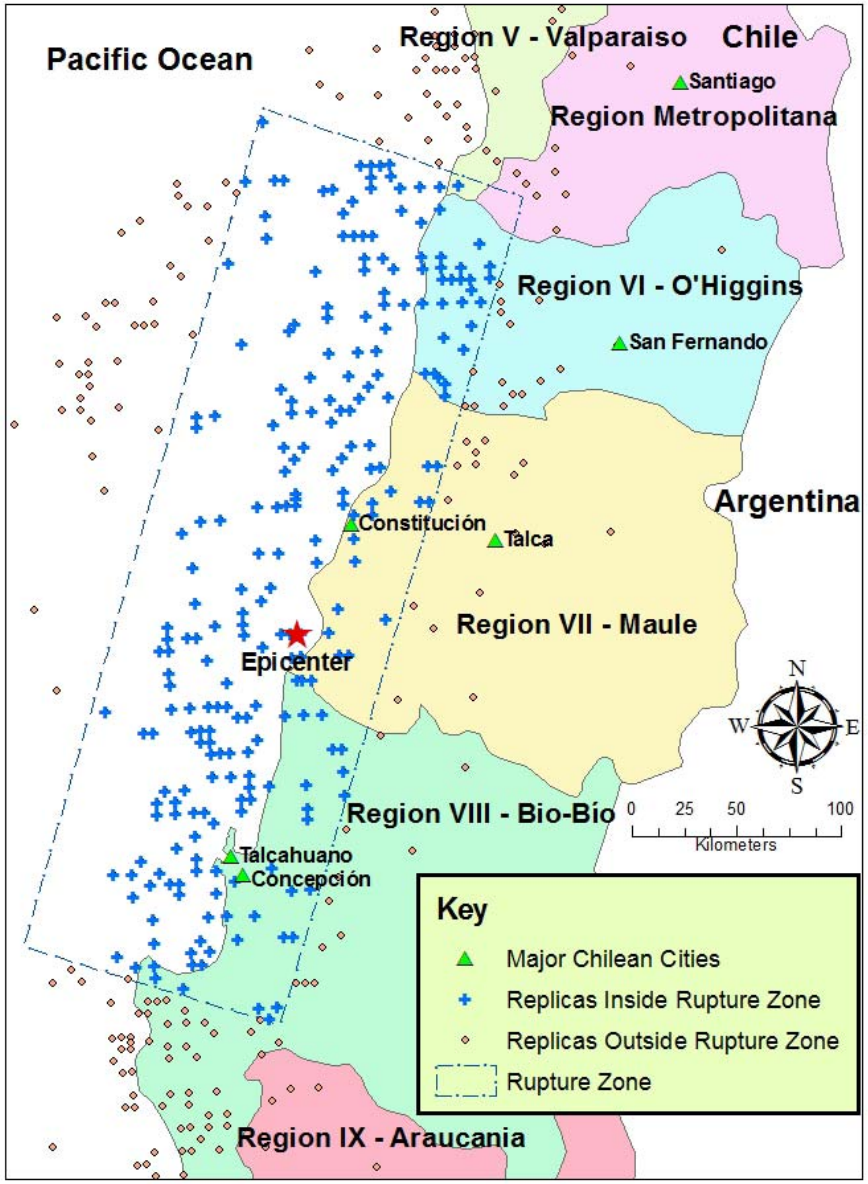
$Istr = 0$



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

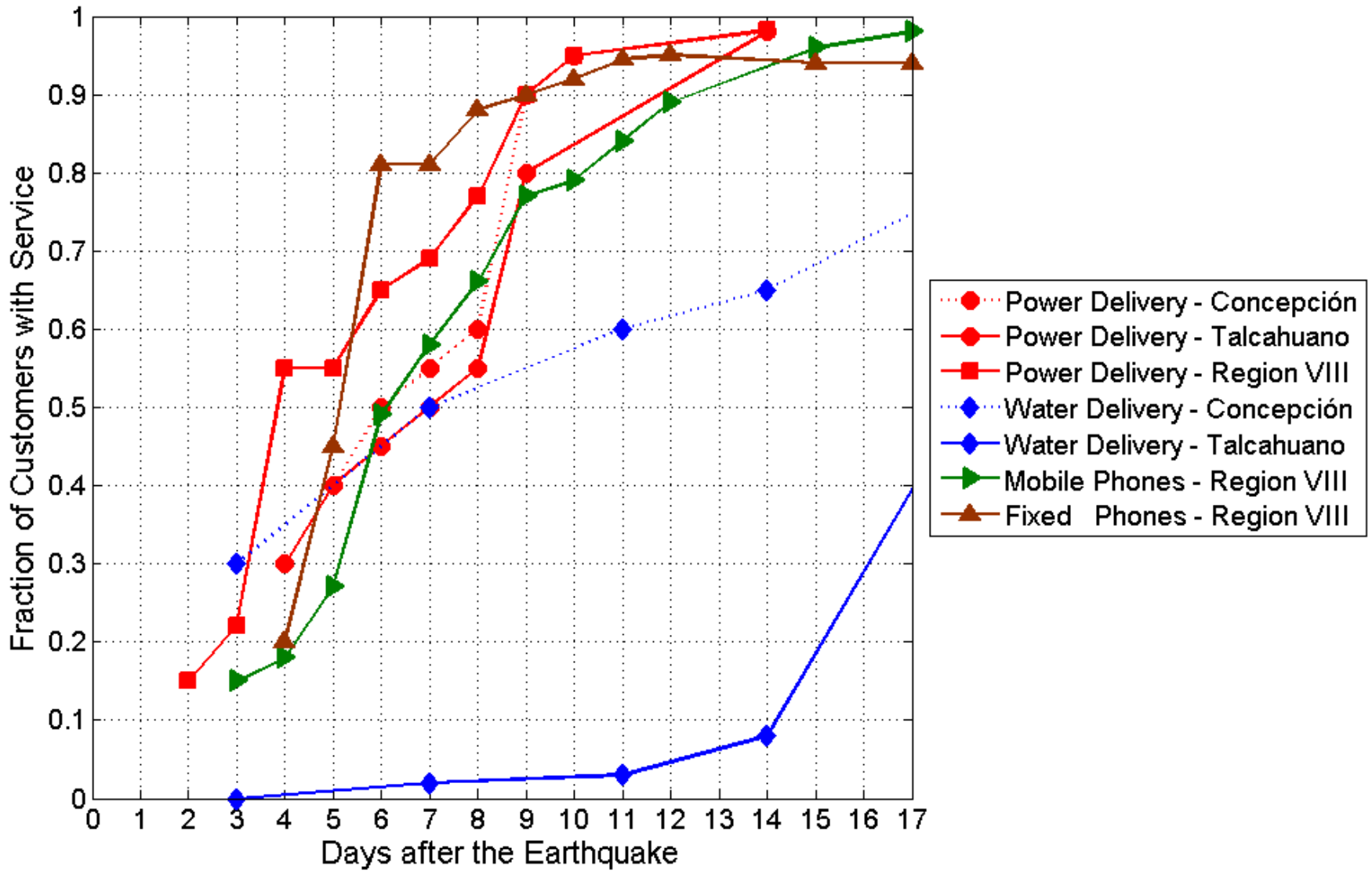
2. Recent Field Observations (1/8)

Geographical and seismological context of Chile 2010 Earthquake



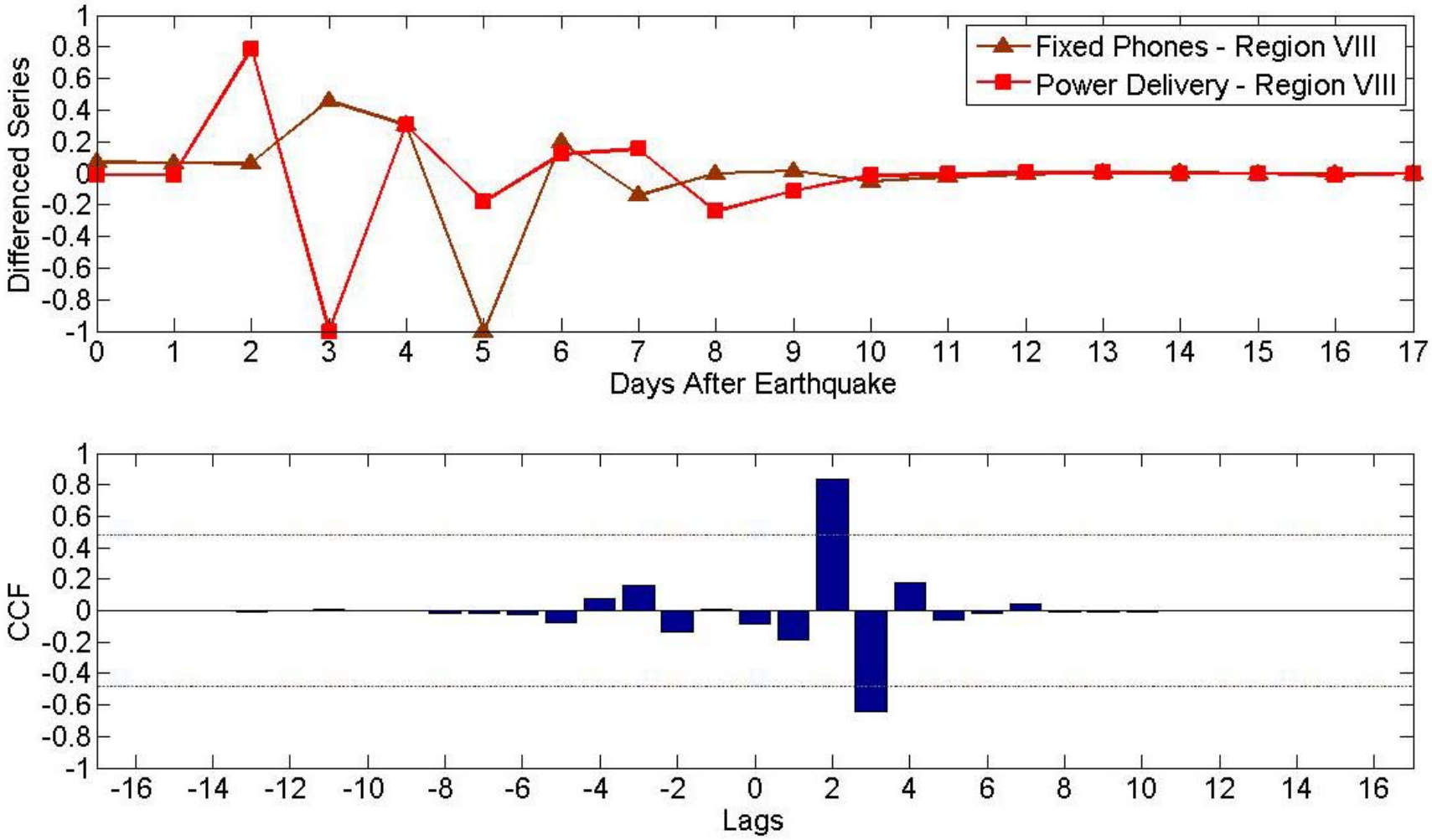
2. Recent Field Observations (2/8)

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



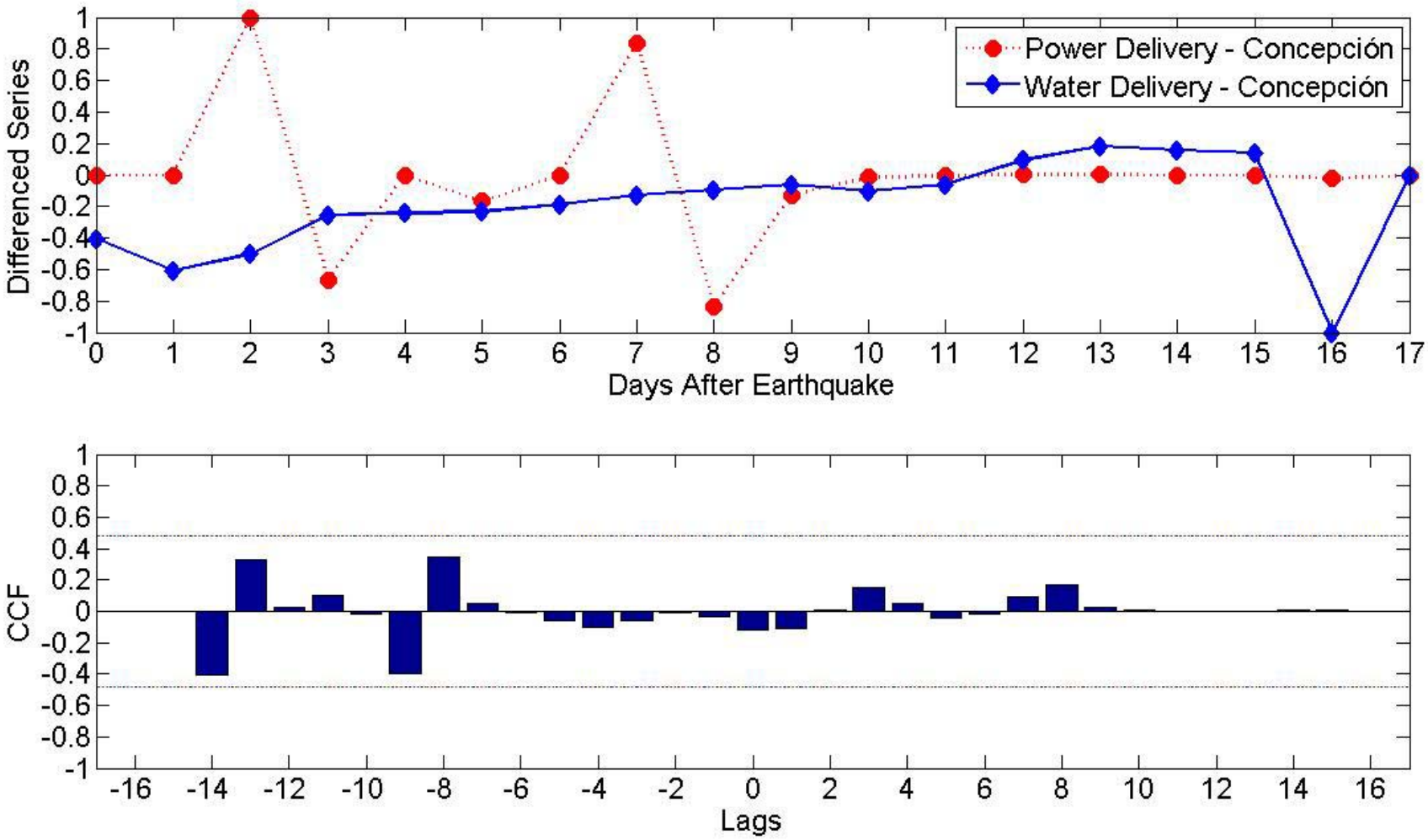
2. Recent Field Observations (3/8)

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



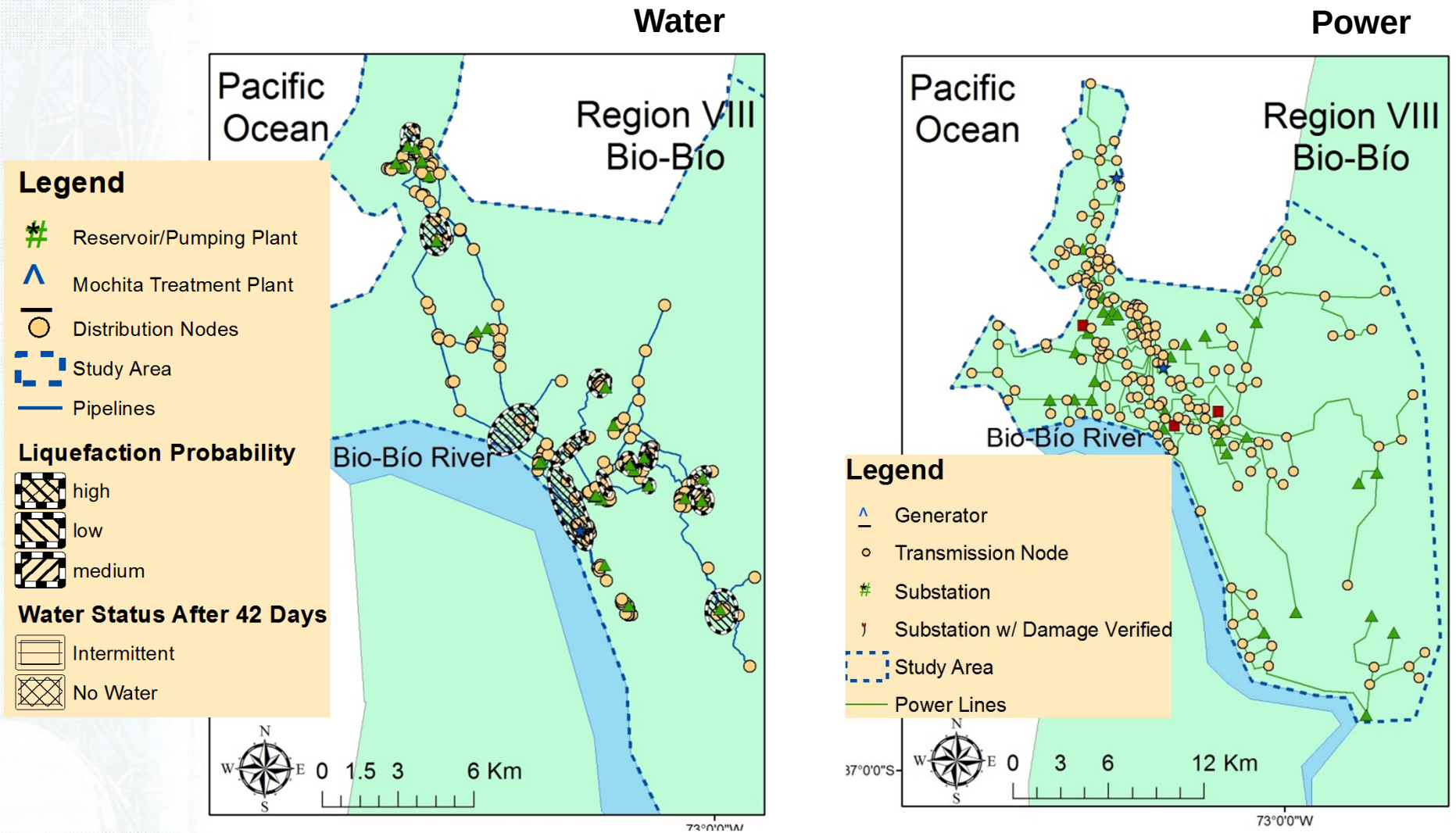
2. Recent Field Observations (4/8)

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



2. Recent Field Observations (5/8)

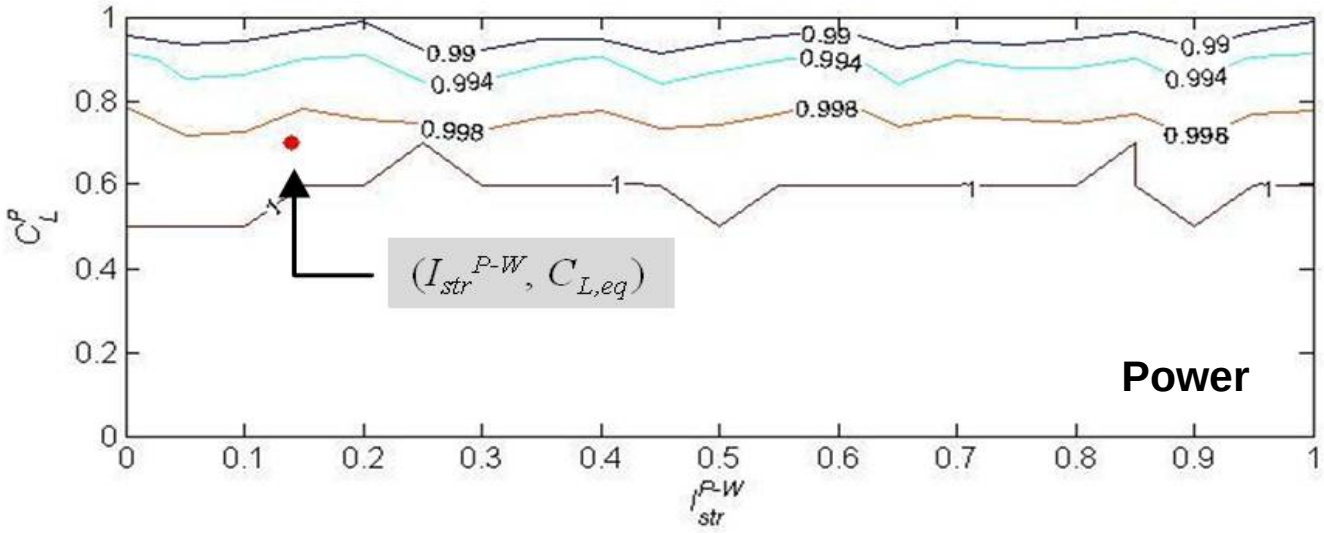
- **Water and power systems in Concepcion, Chile**



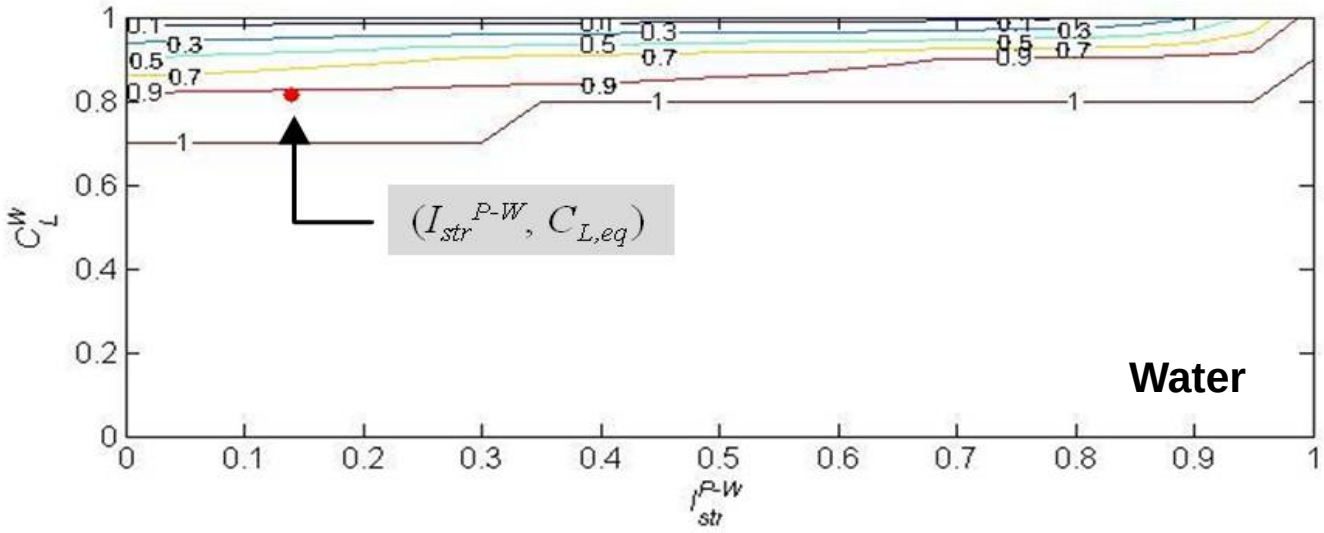
2. Recent Field Observations (6/8)

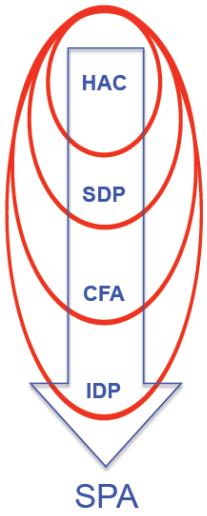
- **Fragility point validation**

$S_2 \rightarrow S_1$



$S_1 \rightarrow S_2$

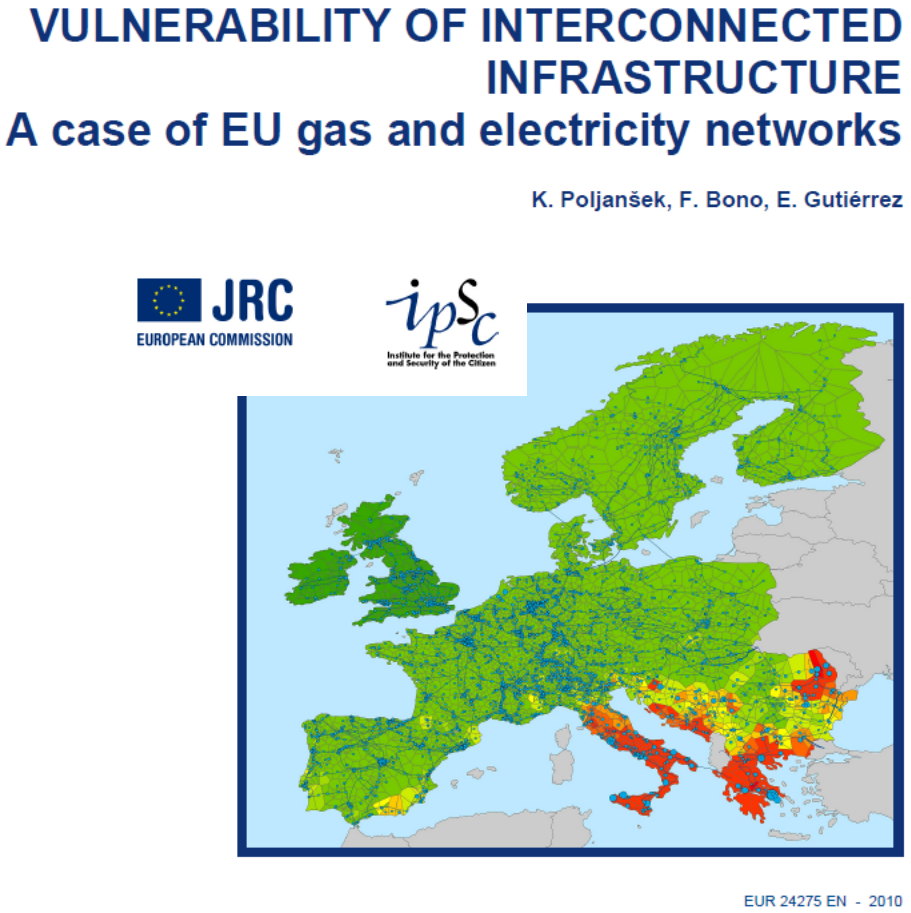




2. Recent Field Observations (7/8)

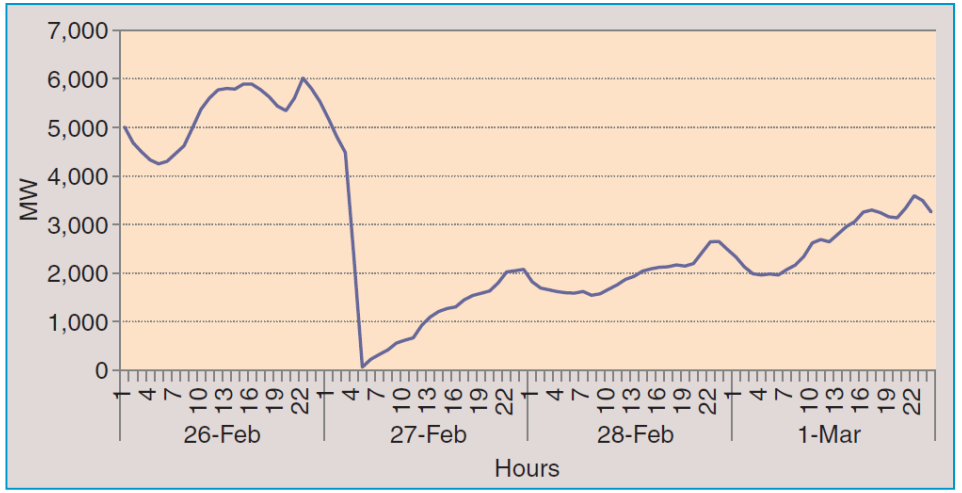
- **Current initiatives for infrastructure system management**

ASCE AMERICAN SOCIETY OF CIVIL ENGINEERS



2. Recent Field Observations (8/8)

- **Main interdependent effects on power systems**
  - **Disrupted transportation systems**
  - **Impaired public telecommunication networks**
  - **Outdated SCADA signals**
  - **Insufficient emergency power at key locations**



Rudnick et al. 2011

3. Conclusions and Future Work

- 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*
- Most *salient interdependence effects* are between *power, telecommunications, and transportation systems*.

- Expand analyses of interdependence effects to system *resilience assessment*
- *Prioritize critical components* 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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