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# Modeling and Analysis of Infrastructure Dependencies: an example for natural disaster planning

**Theresa Brown**

**Distinguished Member of Technical Staff**

**Policy and Decision Analytics Dept.**

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# Critical Infrastructures are Massively Interconnected

Figure is illustration of concept; it is not inclusive


- **Dependency**: Each infrastructure, while important on its own, is also dependent on other infrastructures to function successfully. Transportation, Telecommunications, Petroleum, Water (and others) require electric power to function.
- **Interdependency**: The dynamic of being mutually dependent upon each other. For example, transportation is dependent upon electric power to pump fuel and electric power is dependent on transportation and petroleum to deliver fuel for power generating plants. Such dynamic feedback loops can exist within a single infrastructure or among multiple infrastructures.
- **Cascade**: A series of infrastructure dependencies in which a stress in one sector or on one element causes disruption in the next. In the example above, loss of electric power causes the loss of wastewater treatment which causes a public health emergency.

# What I want to know about interdependencies is…

- Have interdependencies increased the risks or have they changed them?
- Are there any time bombs?
- Are there any weak points we don't know about?
- What conditions have to exist to cause cascading failures?
- What size of event has to occur to initiate cascading failures?
- Are certain systems, networks, parts of the country more at risk than others? Why?
- Are there trends in the evolution of the infrastructures toward more vulnerable conditions or configurations?
- Are we repeating any mistakes from the past or have we really learned from them?
- How do the risks to infrastructures impact national security?
- How can we reduce the risks to infrastructures?
- Can we afford to reduce those risks? Over what timeframe?

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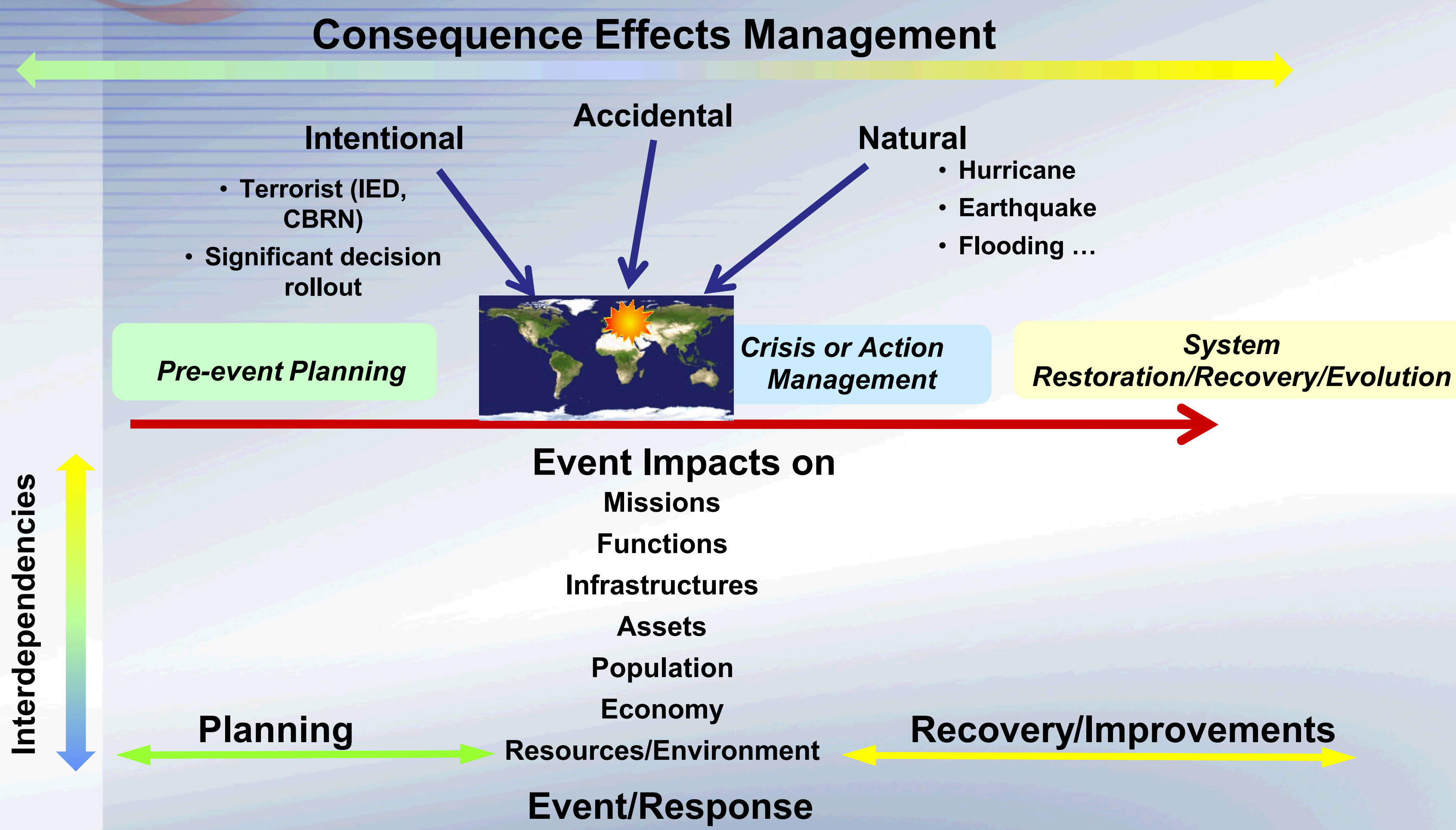
# There are different decision and analysis lifecycles

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# There are a range of data, modeling and analysis capabilities needed for this class of problems

| System Mapping | Quantitative Modeling | Hypothesis Testing | Uncertainty Analysis | Forecasting and Optimization |
|---|---|---|---|---|
| Qualitative Inductive<br><br>Provides situational awareness of relationships, potentially causal relationships, linkages and interdependencies | Quantitative Descriptive<br><br>Formulation and simulation requires specification of rules and governing relationships to represent and track consequences | Quantitative Deductive<br><br>Problem focused, statement of hypothesis of system behavior. Goal is to improve understanding of system under specified conditions. | Quantitative Exploratory<br><br>Examines behavioral and quantitative sensitivity, allows testing of model robustness and hypotheses, quantification of risks and identification of leverage points | Quantitative Predictive<br><br>Identification of future system behavior, optimal or robust solutions. |

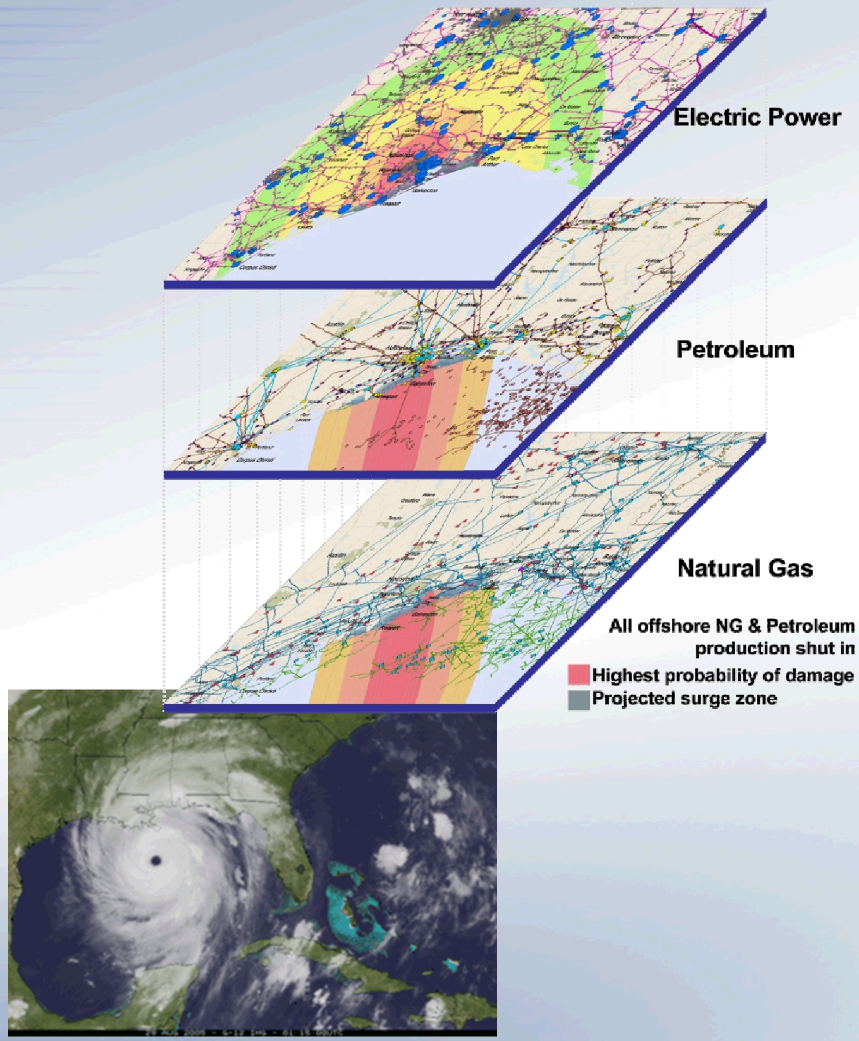
Table based on : “Levels of Confidence in System Dynamics Modeling: A Pragmatic Approach to Assessment of Dynamic Models” by Aldo A. Zagonel and Thomas F. Corbet, CI Modeling and Simulation Department, Published in the International System Dynamics Conference Proceedings, 2006.

# National Infrastructure Simulation and Analysis Center (NISAC) Capabilities

- **Interdependencies and System Modeling**
  - The interdependencies and system modeling capability provides the foundation for all NISAC products including asset prioritization, earthquake planning scenario, and other impact analyses.
- **Economic and Human Consequences**
  - NISAC uses a mixture of proprietary commercial software and in-house modeling and simulation capability to provide first-in-class estimates of population and economic impacts.
- **Asset and Facility Operations Modeling**
  - Infrastructure operators interact with infrastructure systems by making decisions based on constraints and opportunities. Modeling these interactions allows prediction of likely infrastructure operator responses to external events and the possible infrastructure impacts caused by those decisions.
- **Fast Integrated Hazards Analysis**
  - NISAC uses a common integrated simulation environment to provide consistent consequence estimates across event analyses and to expand event scenarios to multiple cascading events. This capability significantly improves NISAC's ability to provide timely and cost-effective analysis of event implications during a real event.
- **Integrating Architecture**
  - Integrating architecture supports systems analyses, fast turnaround analyses for events of national concern, and exercise support. NISAC's integrating architecture also improves coordination with other stakeholders in infrastructure protection including sector-specific agencies, FEMA, and state agencies.

# Infrastructure Modeling and Analysis Mission

- **Improve the understanding, preparation, and mitigation of the consequences of infrastructure disruption**
- **Provide a common, comprehensive view of U.S. infrastructure and its response to disruptions**
  - **Scale & resolution appropriate to the issues**
  - **All threats**
- **Built an operations-tested DHS capability to respond quickly to urgent infrastructure protection issues**
  - **Rapid analysis and collaboration**
  - **24/7 when needed**

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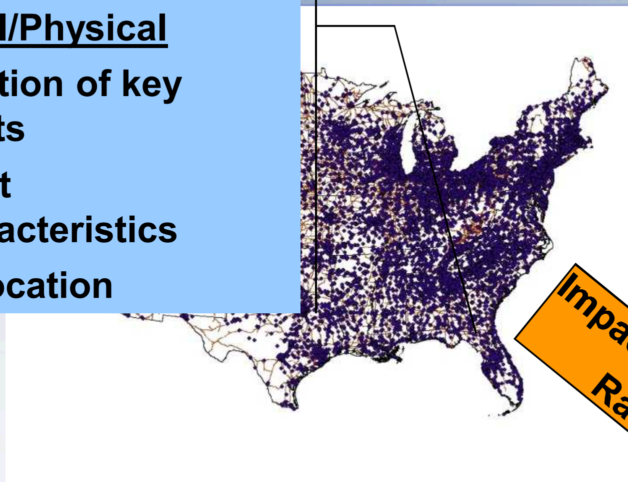
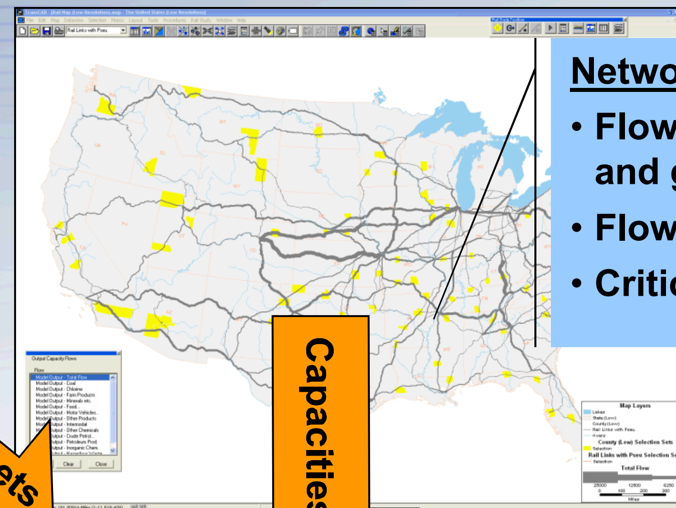
# Multiple Viewpoints Are Used to Understand Critical Infrastructures

**Spatial/Physical**
- Location of key assets
- Asset Characteristics
- Co-location

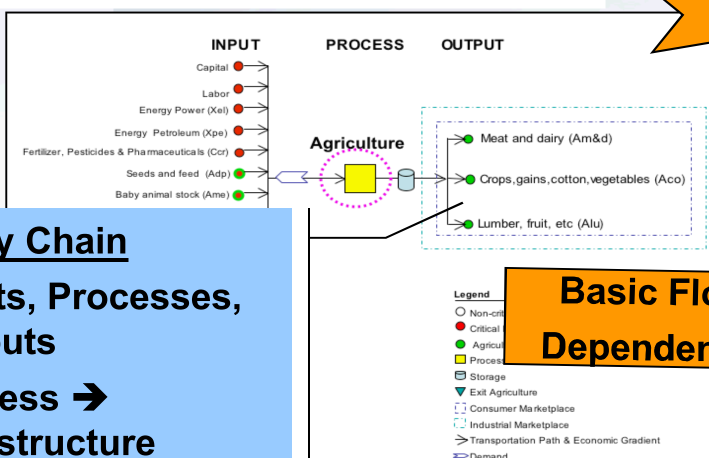




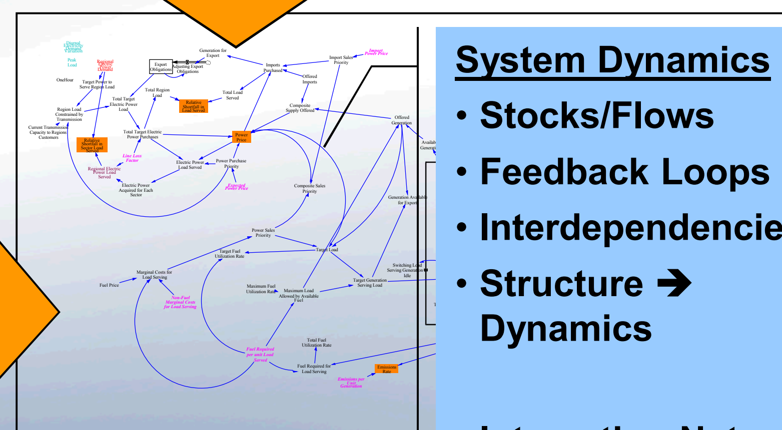
**Network**
- Flow of resources and goods
- Flow Capacity
- Critical Nodes

Impacted Assets Ratios

Capacities



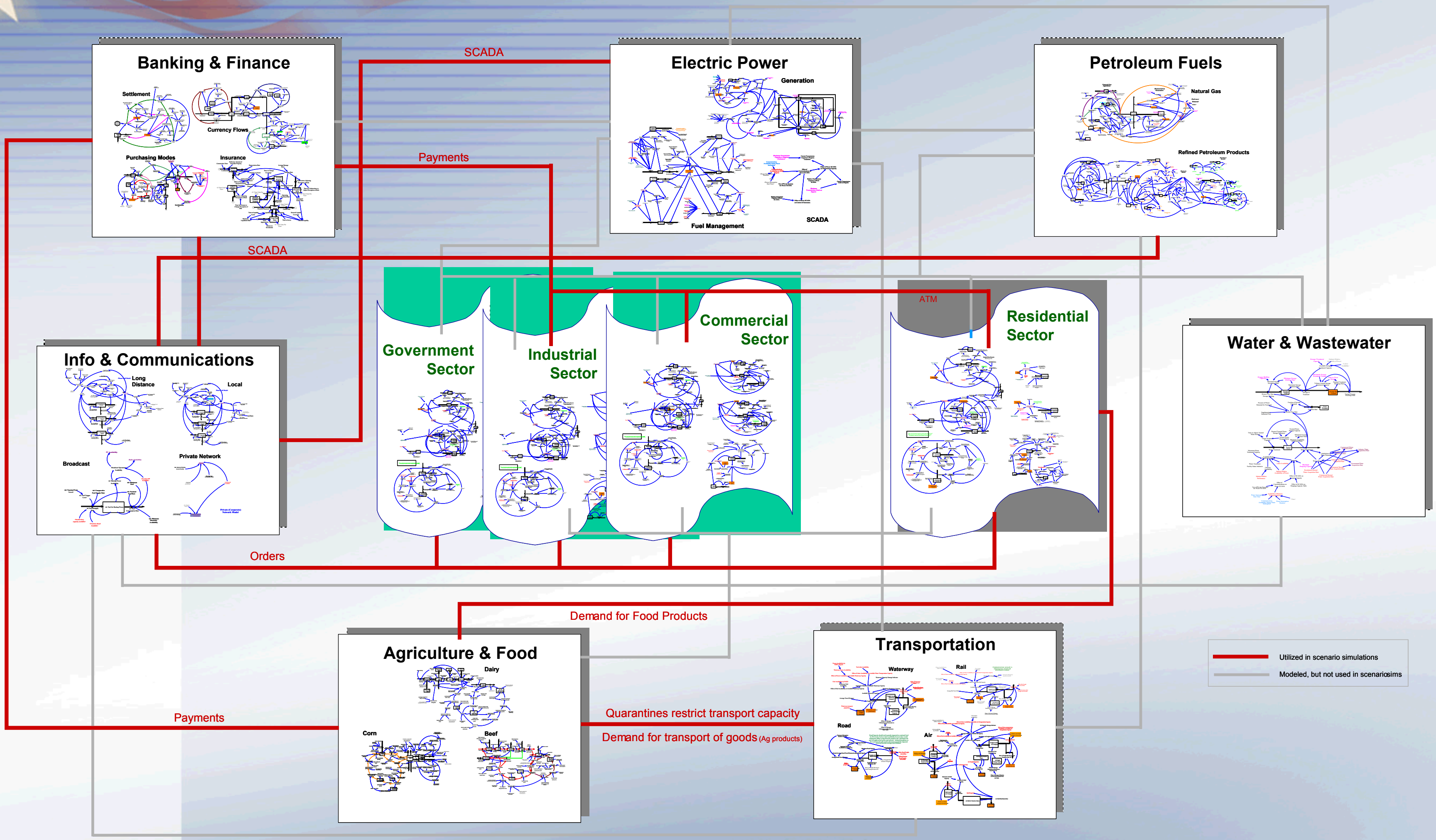

Basic Flows Dependencies



**Supply Chain**
- Inputs, Processes, Outputs
- Process ➔ Infrastructure
- Dependencies

**System Dynamics**
- Stocks/Flows
- Feedback Loops
- Interdependencies
- Structure ➔ Dynamics
- Interacting Networks

# Major Infrastructure Interdependencies – Short Timescale

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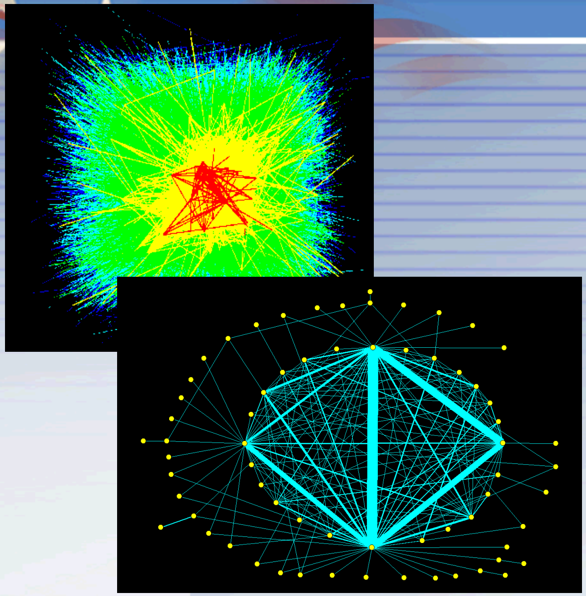
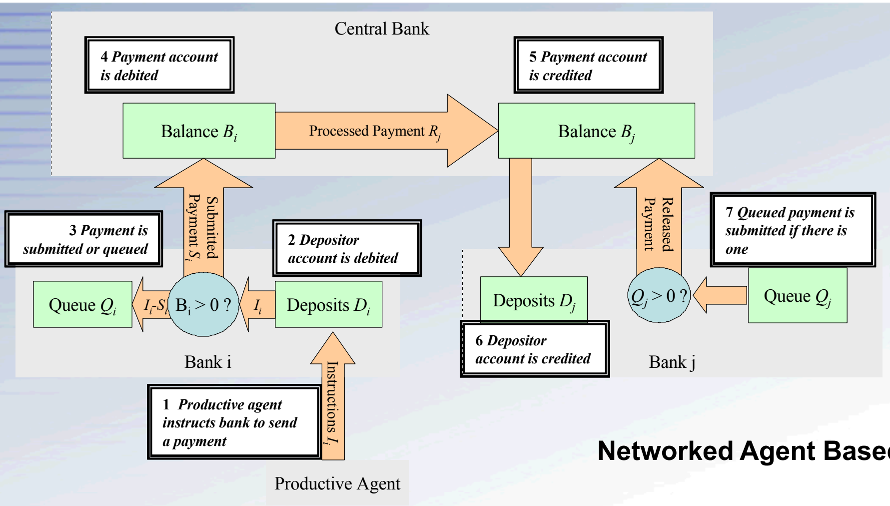
# Understanding Congestion and Cascades in Payment Systems



Payment system network



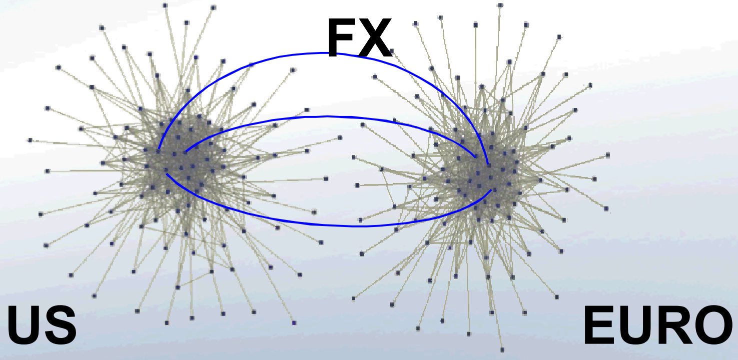

Networked Agent Based Model

**For Details see:**

***The Topology of Interbank Payment Flows*, Soramäki, et al, *PhysicaA,* 1 June 2007; vol.379, no.1, p.317-33.**

***Congestion and Cascades in Payment Systems*, Beyeler, et al, *PhysicaA,* 15 Oct. 2007; v.384, no.2, p.693-718.**

***Congestion and Cascades in Coupled Payment Systems*, Renault, et al, Joint Bank of England/ECB Conference on Payments and monetary and financial stability, Nov, 12-13 2007.**




Global interdependencies

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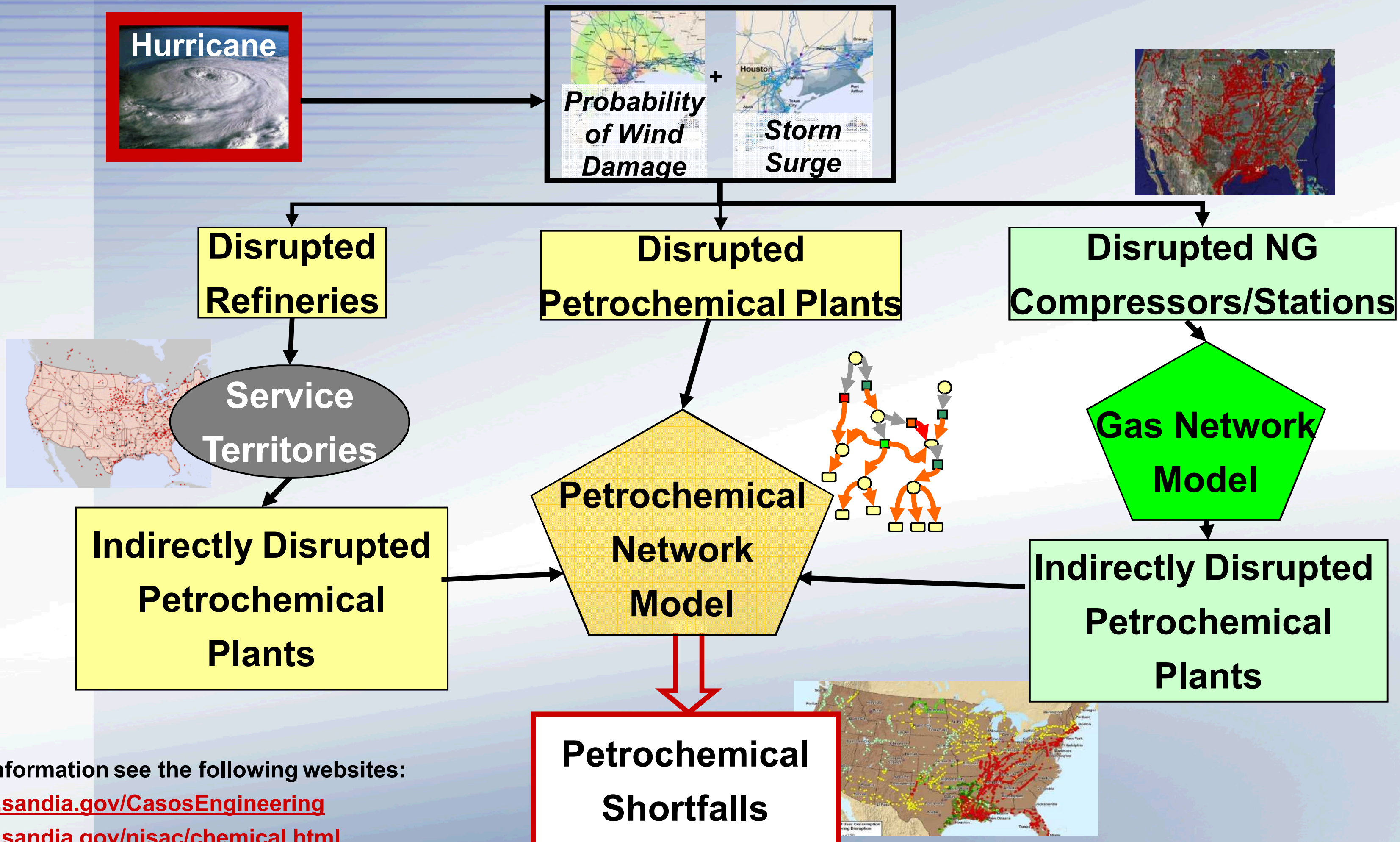
# Disaster Planning: understanding and quantifying dependency effects to improve protection &/or response

## Example – Hurricane Impacts on Petrochemical Supplies




For more information see the following websites:

http://www.sandia.gov/CasosEngineering

http://www.sandia.gov/nisac/chemical.html

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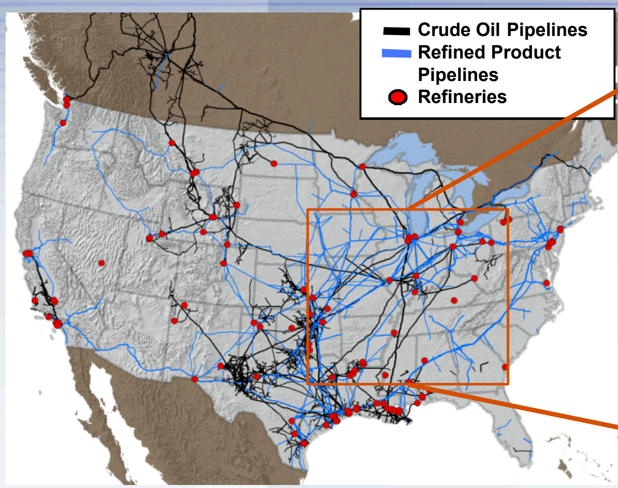
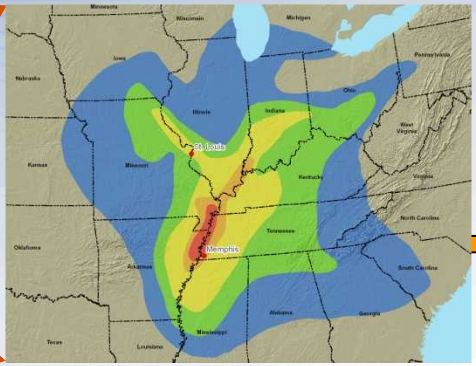
# Disaster Planning: understanding and quantifying infrastructure impacts and adaptation to improve risk management

## Example – Earthquake impacts on Transportation Fuels

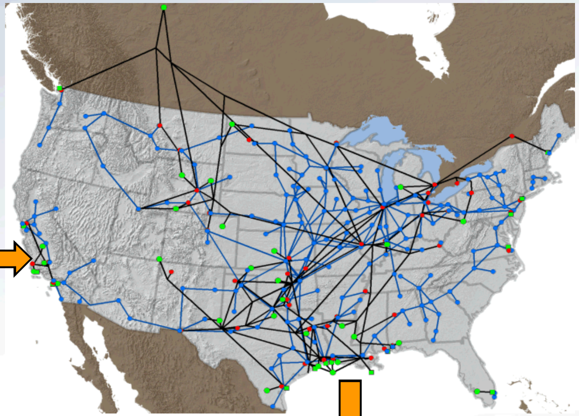


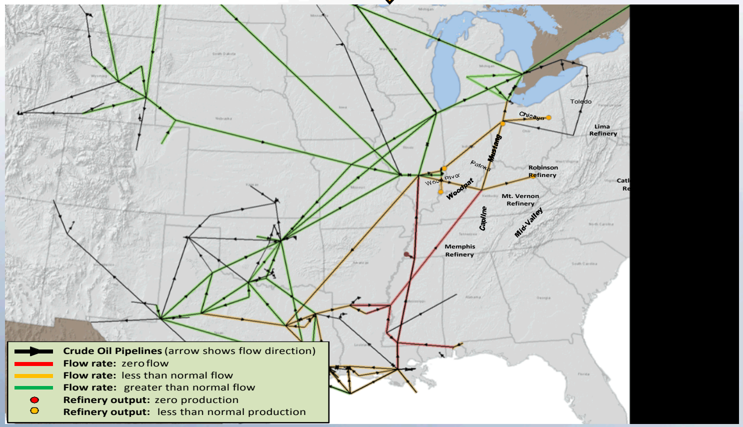

Petroleum Pipelines concentrated in central portion of US



Scenario Earthquake – Ground Motion

National Fuels Network Model (with crude oil production and import points, refineries and refined product terminals)





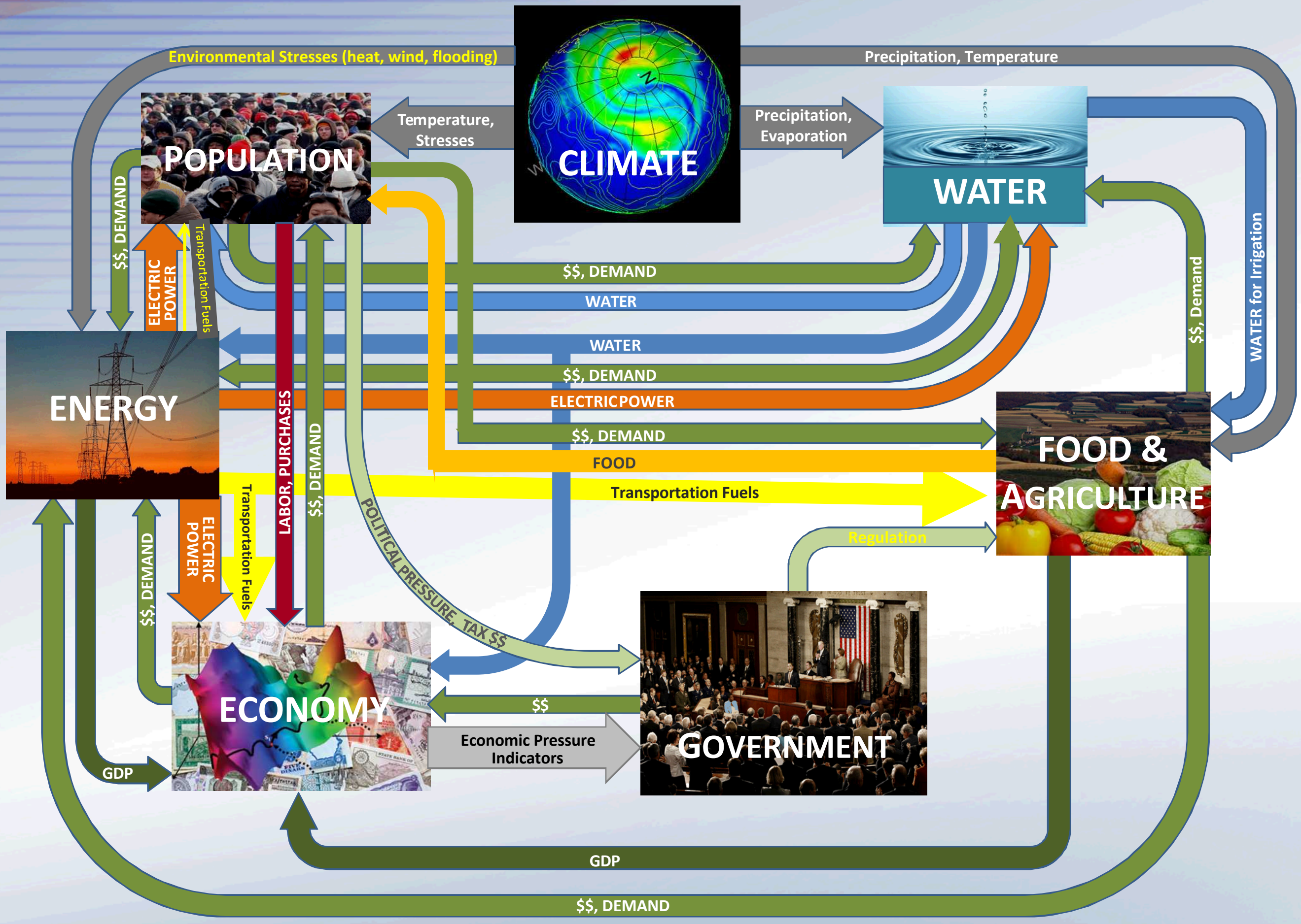

Changes in Fuel Production and Flows

For more information see the following website:
http://www.sandia.gov/casos
Or contact Tom Corbet (tfcorbe@sandia.gov)

# Adaptation to Climate Change Impacts

Goal: Identify key uncertainties and dynamics in order to design and develop a CASoS engineering approach for reducing climate risks

Method: risk analysis approach that accounts for the full range of potential outcomes by explicitly including uncertainty, design validation strategy and identify modeling needs. Interacting nation state transaction modeling

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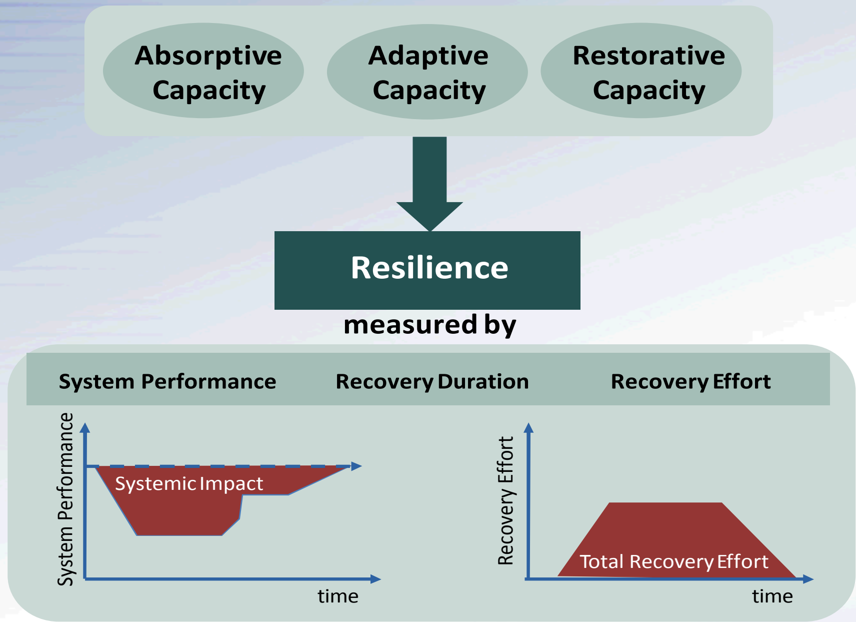
# Infrastructure Resilience

**Sandia's resilience assessment framework is especially effective at providing comprehensive assessments because of its flexibility and explicit evaluation of resources, recovery costs, and feedback loops between recovery activities and system performance.**




**For more details see:**


Vugrin, E. D., D. E. Warren, M. A. Ehlen, and R. C. Camphouse (2010a), "A Framework for Assessing the Resilience of Infrastructure and Economic Systems," in *Sustainable and Resilient Critical Infrastructure Systems: Simulation, Modeling, and Intelligent Engineering*, K. Gopalakrishnan and S. Peeta, eds., Springer-Verlag, Inc., 2010.

Vugrin, E. D., M. A. Turnquist, N. Brown, and D. E. Warren (2010b), "Measurement and Optimization of Critical Infrastructure Resilience," presentation to the 4th Annual Meeting of the Security and Risk Management Association, Arlington, VA, October 5-5, 2010. (Journal paper in preparation)

Vugrin, E.D., and R. C. Camphouse (2011), "Infrastructure resilience assessment through control design," *International Journal of Critical Infrastructures*, 7(3), pp. 243-260.

Vugrin, E. D., D. E. Warren, and M. A. Ehlen (2011), "A resilience assessment framework for infrastructure and economic systems: Quantitative and qualitative resilience analysis of petrochemical supply chains to a hurricane," *Process Safety Progress*, 30, pp. 280–290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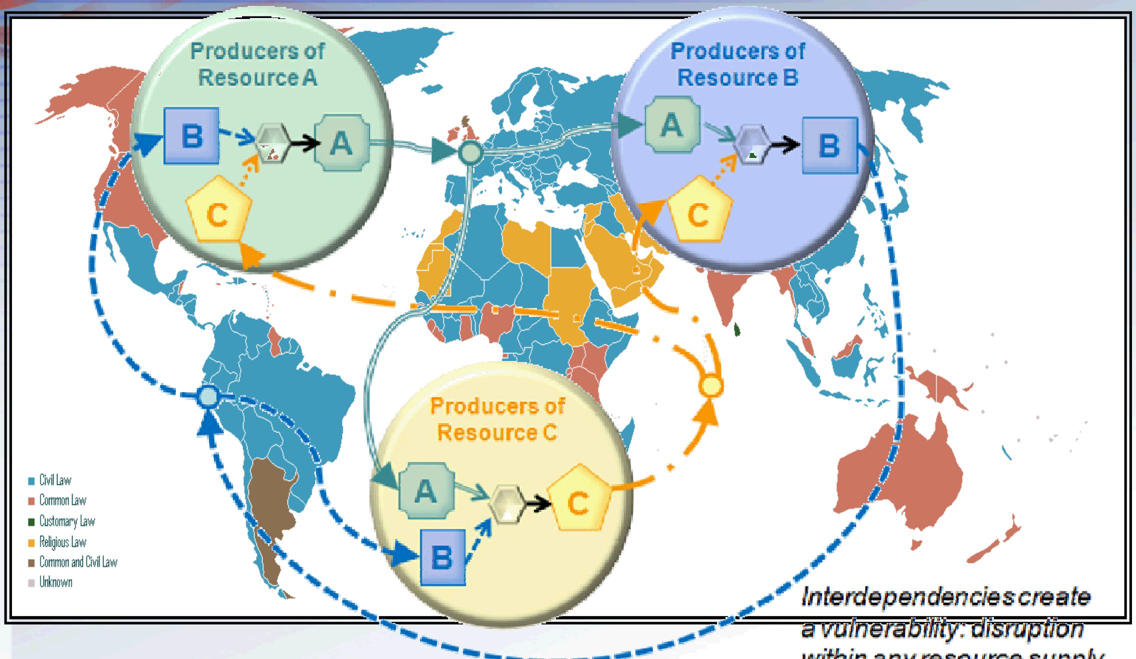
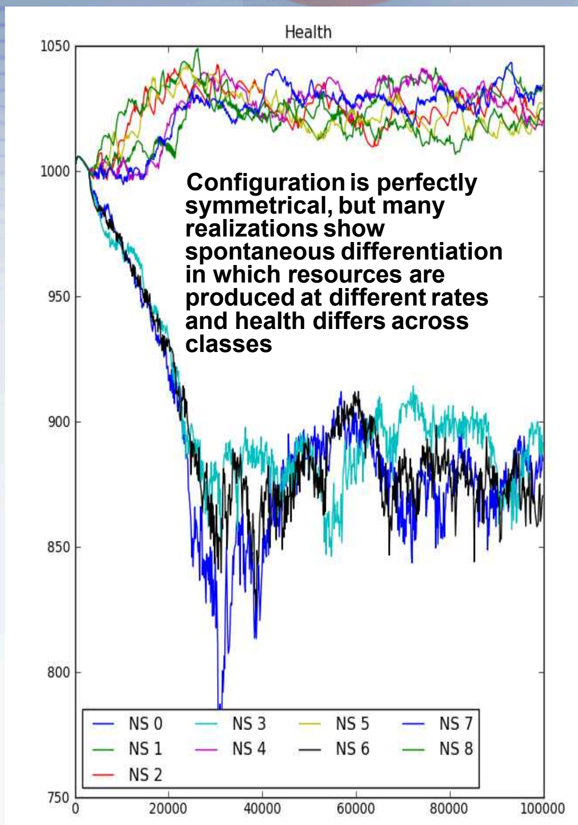
# Global Security Focus

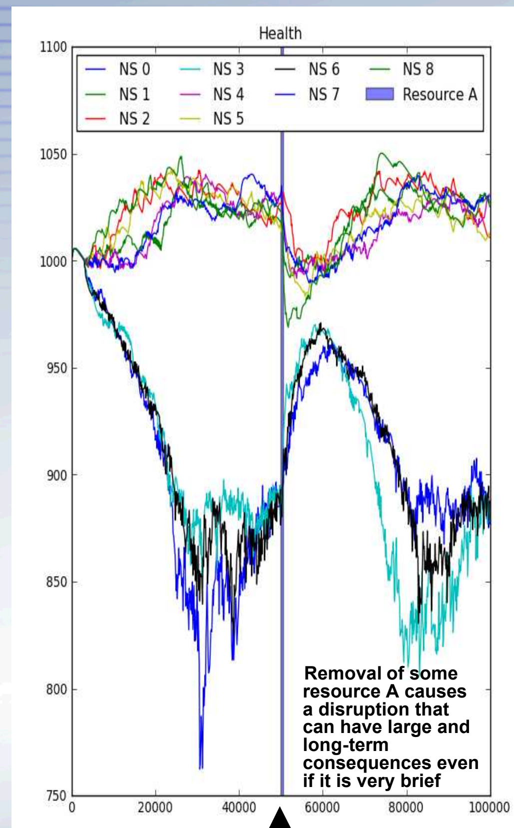


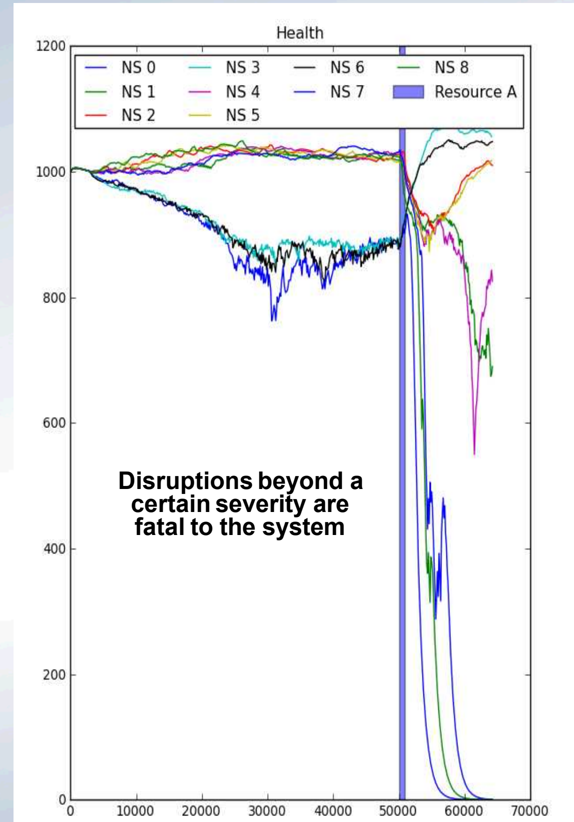

*Interdependencies create a vulnerability: disruption within any resource supply network can cascade to others.*

- Global socio-economic interdependent CASoS
- System Stability in context Perturbations and Stressors (e.g., climate)
- Design policy that enhances system resilience

# Example Results: Entity and Global Health in context of finite energy shocks




**Small Shock**

**Large Shock**

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# Modeling and Analysis of Infrastructure Dependencies

- **Purpose of the analysis will determine modeling needs/fit**
  - Time frame of concern
  - Capacity to absorb/respond/adapt/restore/recover = Resilience
  - Risk management
    - Threat management (security)
    - Consequence management (design for n-1 failures; design for resilience to specified threats; plan for restoration/recovery)
  - Risk mitigation
- **Experiment on models**
- **Engineer solutions for complex adaptive systems and dynamic conditions**