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Engineering Infrastructure for Resilience and Growth

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Infrastructures as Complex Adaptive Systems (CAS)

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- A CAS is a system in which the structure modifies to enable success in its environment (Johnson et al. 2012)
  - structure and behavior are products of all the perturbations the system has experienced and modifications it has implemented.
  - certain structural characteristics emerge, hierarchical and modular, with simple rules for interaction among the elements
- Infrastructures involve multiple interacting CAS or Complex Adaptive Systems of Systems (CASoS)
- Successful adaptation to disruptions is a characteristic of resilience, but it can lead to highly optimized tolerance and robust-yet-fragile properties (Carlson and Doyle, 1999)

What is changing in the infrastructure environment?

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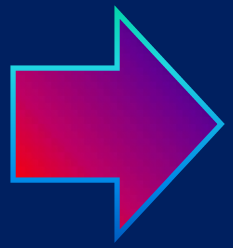
- Climate (temperature, precipitation)
- Population (growth, redistribution)
- Technology (transitional, transformational)
- Consumer Expectations (quality, reliability and/or cost of service)
- Economy



- Changes in infrastructure supply and demand (x, y, t)
  - Capacity to meet demand
  - Quality of service
  - Costs
- Changes in society
  - Productivity
  - Population health and wealth
- Changes in risks
  - Threats
  - Vulnerabilities
  - Consequences

Engineering Future Infrastructure

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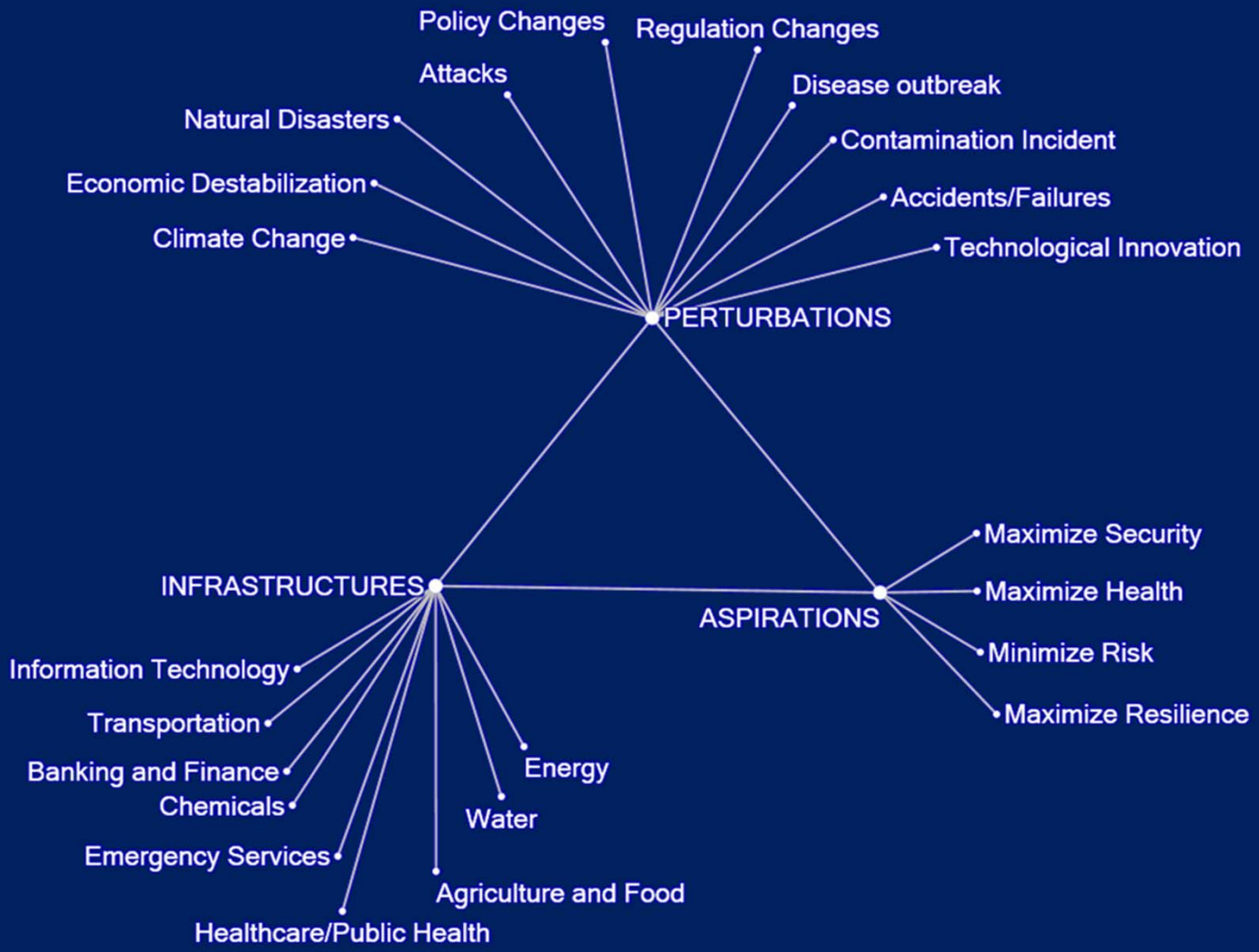

Modified from Brown et al., 2011

Engineering Infrastructure for Resilience to Climate Change

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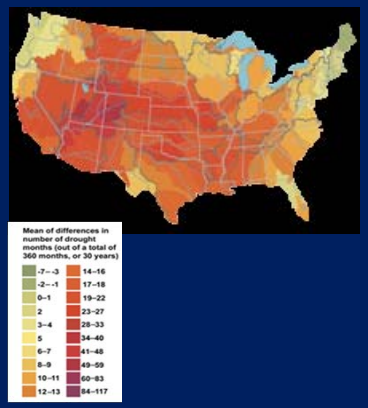
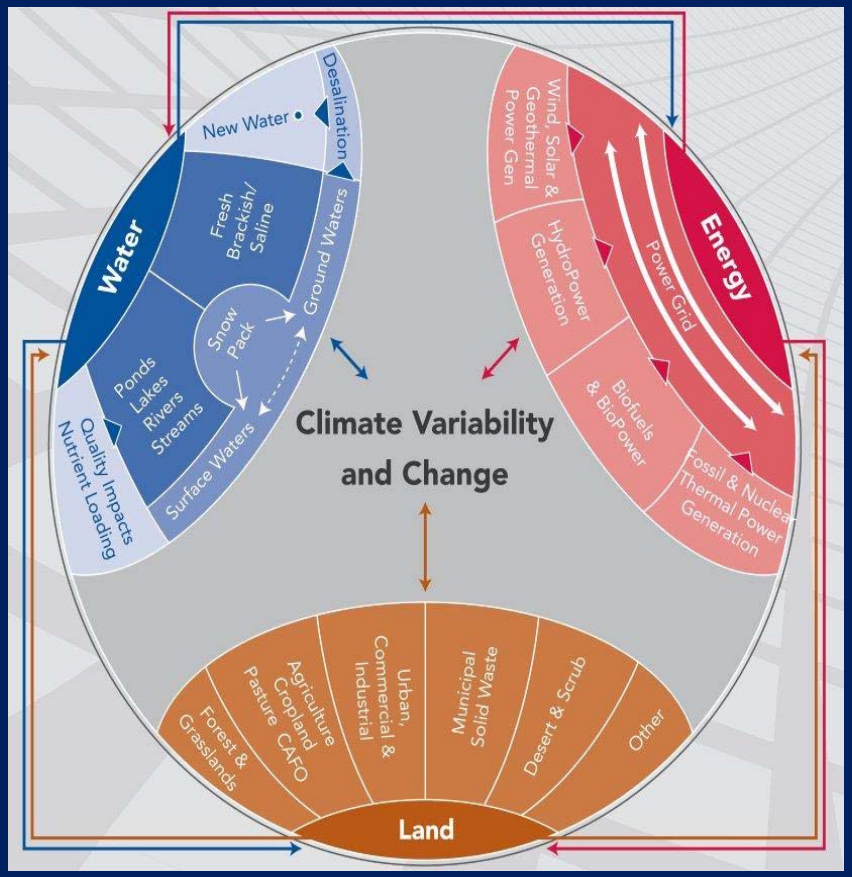
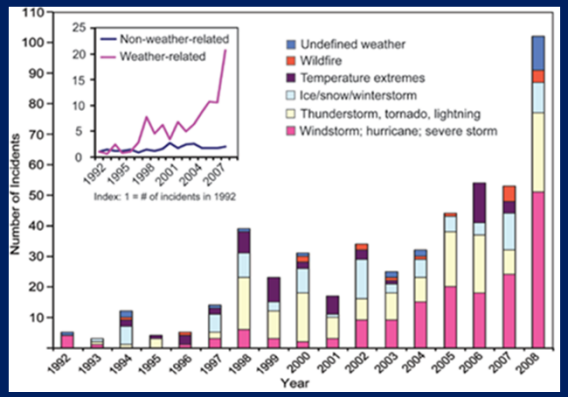
- Are there structural changes to national infrastructures that will keep them resilient to the combination of possible stresses that could occur over the next 10 - 100 years?

Changing Drought Frequency







Increasing Weather-Related Power Outages

What kinds of structural changes are possible?

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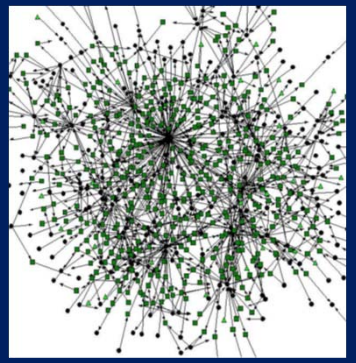
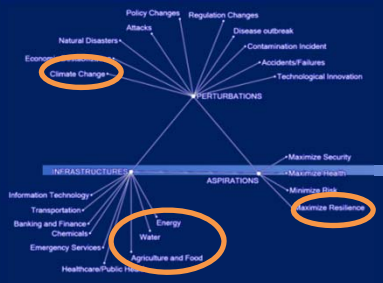
- Networks and Network Theory Insights
  - Greater connectivity makes networks more robust to random, node or link failures
  - Centralization allows greater control, creates potential single points of failure
  - Distribution decreases impact of directed attack; less control
- System Dynamics
  - Balancing loops to prevent death spirals



Climate change is not a random failure nor is it a directed attack; it is a long-term global change with large uncertainty in the impacts on regional and temporal climate variability and rates of change



Climate – Water – Energy- Food

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Climate

Rainfall/Runoff Watershed Modeling

Recharge

Runoff

Groundwater Modeling

River/Reservoir Routing

Available Water

Water Rights

Water Demand

Water Allocation

Damage

Consequence Analysis

Water Delivery

Environmental

Economic

Social

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Changes in Precipitation -Temporal and Spatial Scaling

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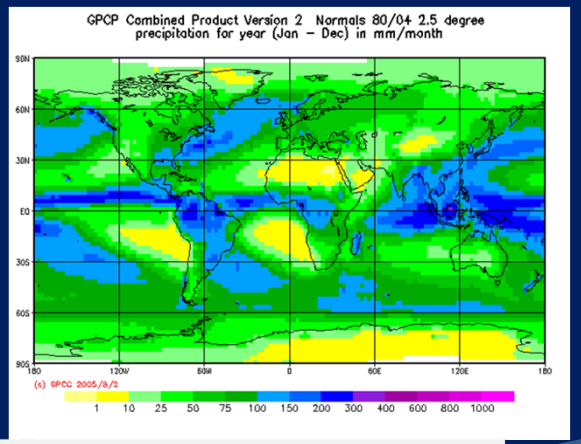
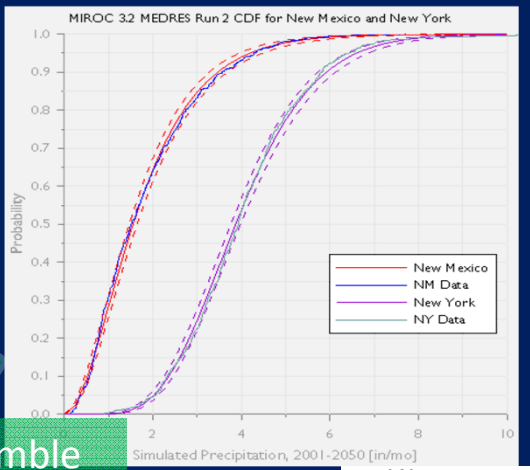
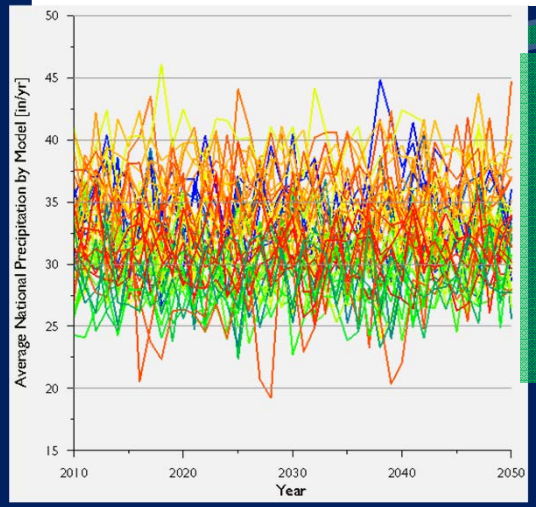
Projected changes in precipitation from global models with uncertainty

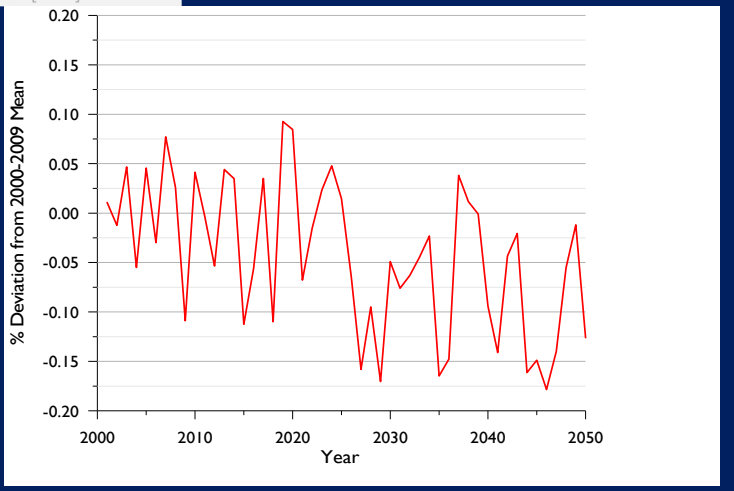




To create a model of regional precipitation that includes realistic variability (spatially and temporally)



IPCC Ensemble of 53 Climate model runs transformed to exceedance probability.



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Based on Backus et al., 2010 and 2012

Water Availability

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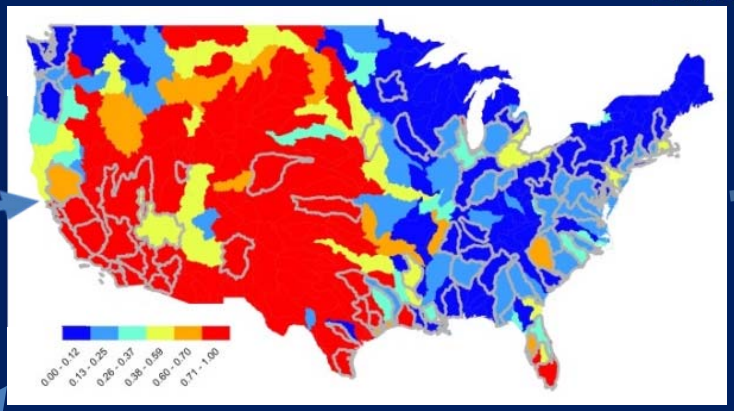
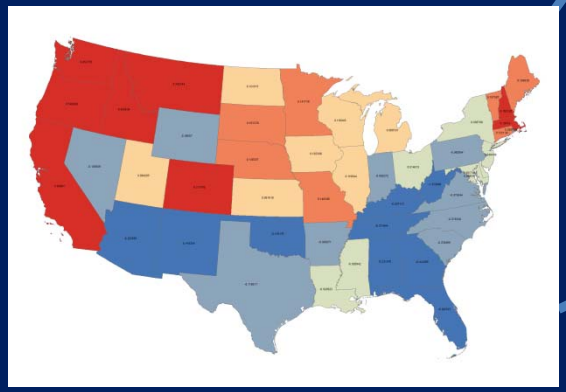
Physical boundaries for hydrology (watersheds) can be used to evaluate regional water supply

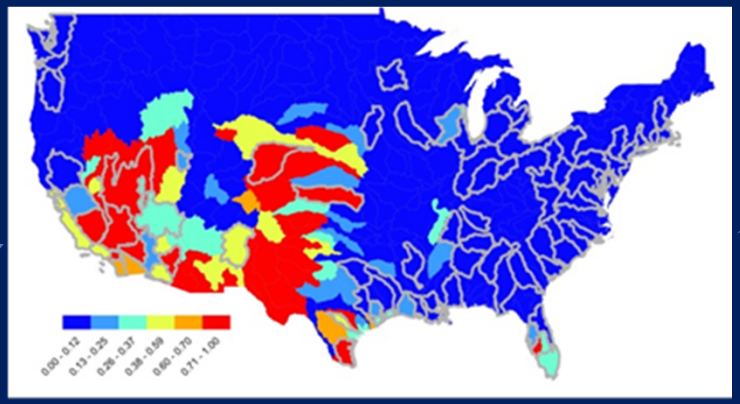


Projected minimum surface water availability by 2035 (summer demand adjusted for population growth : projected annual low flow conditions)

Projected Changes population changes and changes in economic activity impact water demand



Backus et al., 2010



Projected (sustainable) groundwater availability 2035 (pumping : recharge)

Tidwell, 2013

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Structural Characteristics of Regional Water Supply

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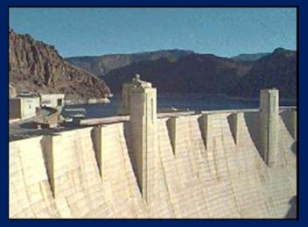
- Emerged/Evolving
  - Population centers developed near major surface water features
  - Population growth increases water demand and contamination; but provides economic power, growth and diversity
  - Risk management/Infrastructure development – water irrigation and distribution systems, allocation rules, flood control features (dams, levees); storage; treatment; use of groundwater; cross-basin water diversion projects; control systems
  - Technology and population growth drive expansion
- Mix of natural and engineered elements
  - Storage (reservoirs, aquifers, tanks) influences resilience to supply perturbations
    - Duration and magnitude dependent
    - Changes risks
  - Transportation networks (rivers, streams, pipes and pumps)
  - Water Treatment (filtration, chemical)
- Competing uses
  - Water for transportation (navigable locks and dams),



Reactive - Consequence Management

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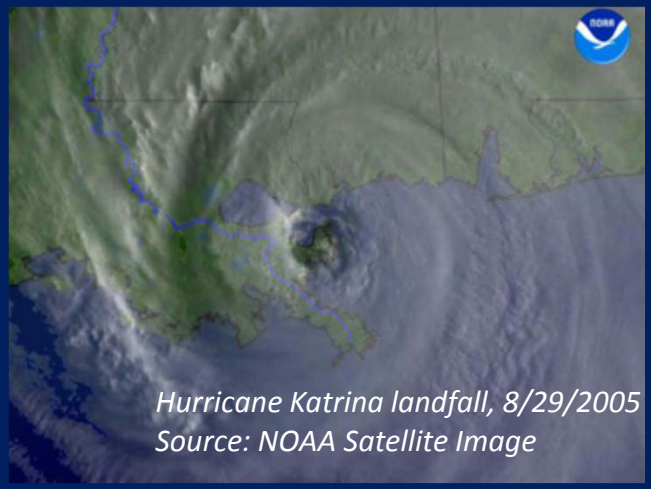
Aging – incremental upgrades to some; next generation equipment for others

Natural Disaster – population displaced; desire to restore natural barriers and increase engineered barriers (design basis) sea walls for surge, dams for flooding, underground power lines

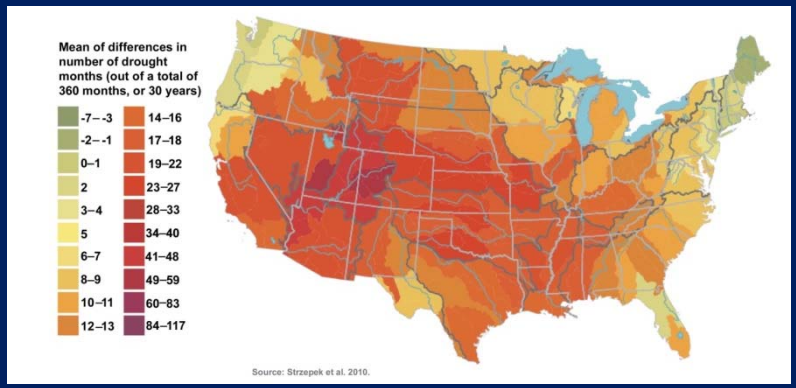
Drought – prioritizing urban water use (taking it from prior appropriations for irrigation/ranching)

Moving agriculture production

Gradual moving population out of floodplains



Hurricane Katrina landfall, 8/29/2005
Source: NOAA Satellite Image



Are there structural changes that could increase water supply resilience?

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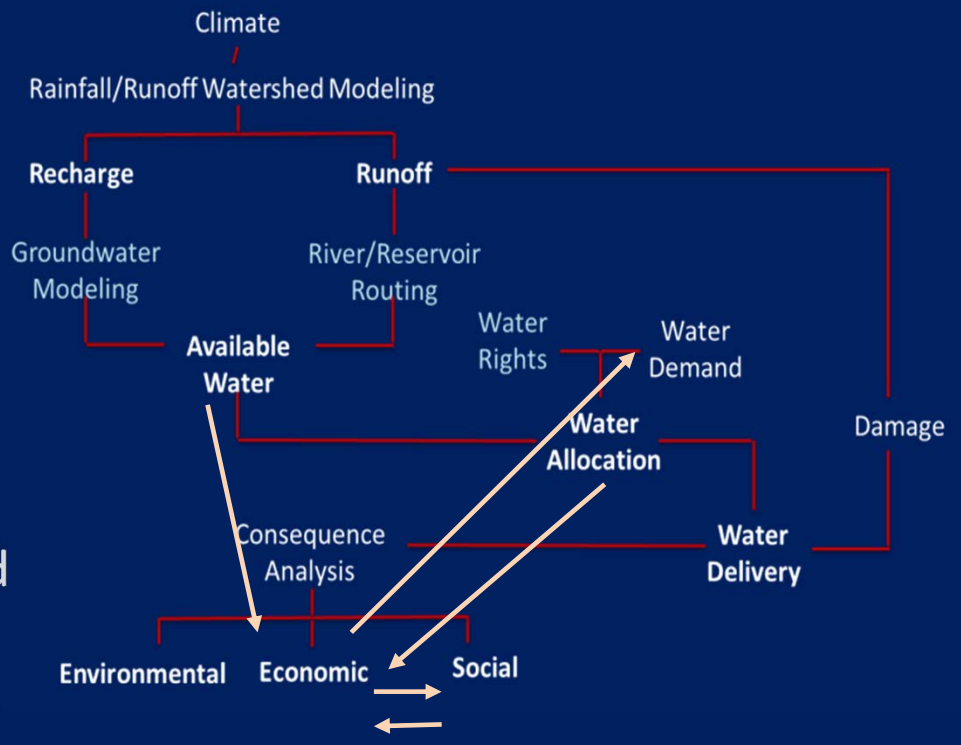
- Manage by emergence and control (Choi et al 2001)
  - Identify regional water policy strategies that are robust to uncertainty
  - Implement progressively and adjust
  - Incentives that allow creative/innovative solutions and recognition of viable solutions
  - Improve information for creating balancing loops



Understanding How Structure Influences Risks: requires dynamic or iterative solutions

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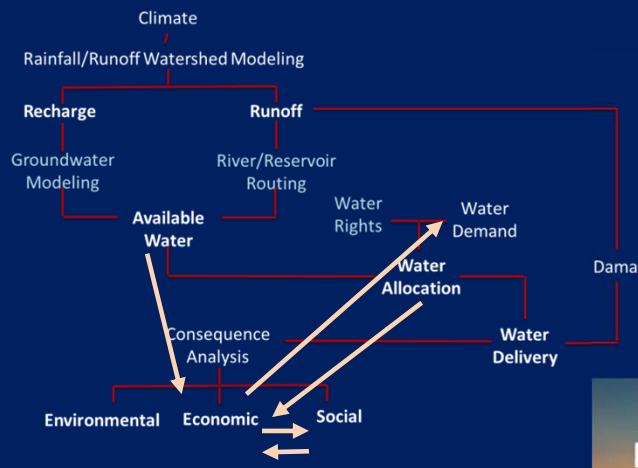
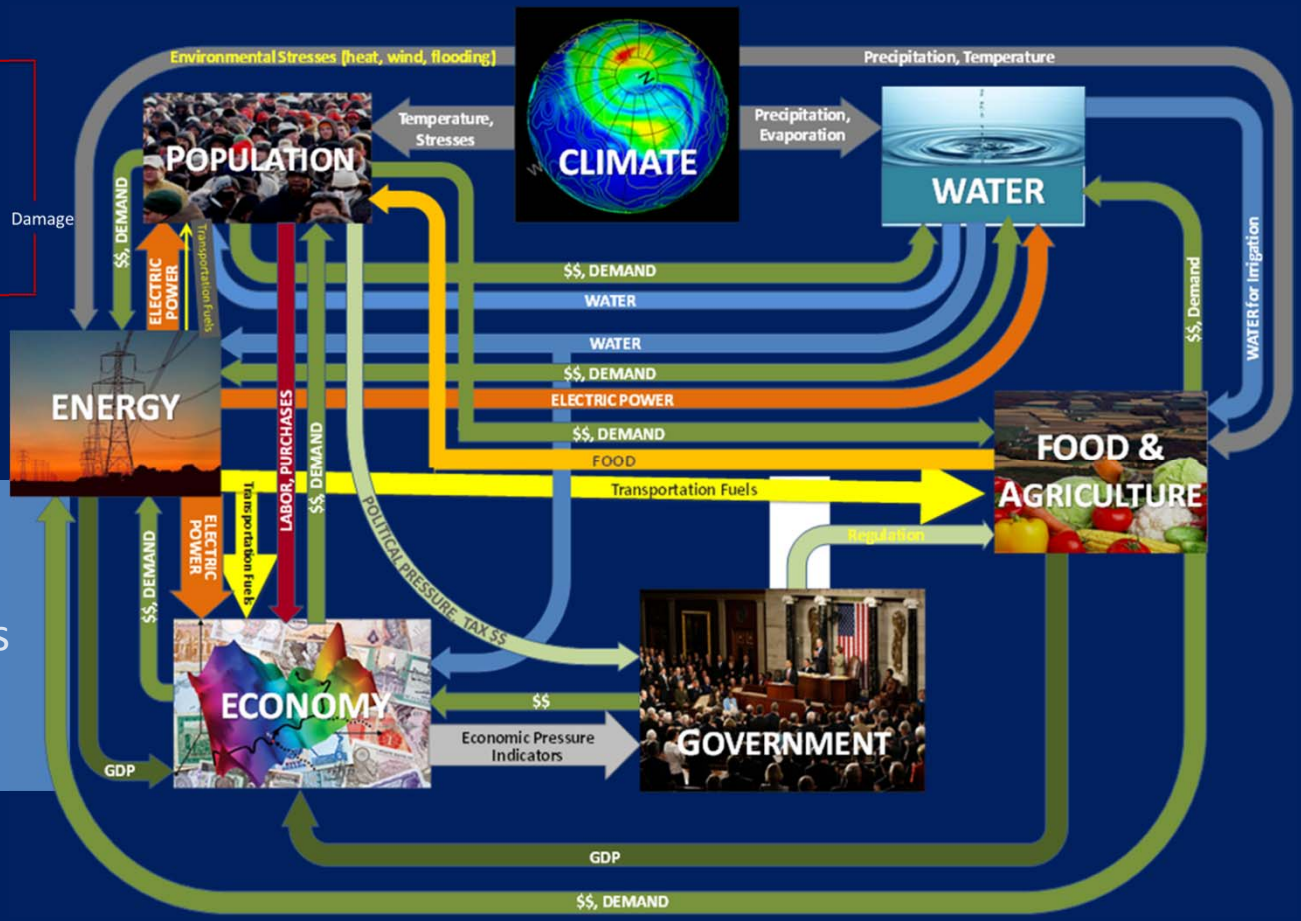


Going beyond water resilience - requires expanding the boundaries to global interdependencies



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What capabilities do we need in order to better design for resilience and growth?

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- Better understanding through modeling and analysis processes that account for the dynamics of human-technical-natural systems
  - Causal relationships
  - Condition dependent behavior
  - Resource constraints
  - Delays and the effects of delays on system viability and performance
  - Policy effects on dynamics
- Explicitly represent and account for uncertainties
- Explicitly represent and account for risk reduction strategies
- Comparative analysis to identify solutions that are robust to uncertainty
- Decision maker confidence in the analysis and ability to implement the engineered solution
- Evaluation and improvement