Engineering Infrastructure for Resilience and Growth

Theresa Brown
Sandia National Laboratories
ISNGI October 2013
Infrastructures as Complex Adaptive Systems (CAS)

- 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?

- 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

Modified from Brown et al., 2011
Engineering Infrastructure for Resilience to Climate Change

- 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?

- **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

Climate

/ \ Rainfall/Runoff Watershed Modeling

Recharge

Groundwater Modeling

Runoff

Available Water

Water Rights

Water Demand

Water Allocation

Water Delivery

Consequence Analysis

Environmental Economic Social

Damage
Changes in Precipitation - Temporal and Spatial Scaling

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.

Based on Backus et al., 2010 and 2012
Water Availability

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 in population changes and changes in economic activity impact water demand.

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

Backus et al., 2010

Tidwell, 2013
Structural Characteristics of Regional Water Supply

• 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

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
Are there structural changes that could increase water supply resilience?

- 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

Going beyond water resilience - requires expanding the boundaries to global interdependencies
What capabilities do we need in order to better design for resilience and growth?

- 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