Uncertainty in Integrated Modeling for Decision Support: the Decision Center for a Desert City

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Background:

- NSF’s Decision Making Under Uncertainty (DMUU) Initiative
- Reframe climate change question to focus on decision making
- Create “what if” scenarios under conditions of policy change
- Boundary organization
Global Institute for Water Security

Water is life.
And water security - both quality and quantity - is one of the most critical issues facing our planet.
Today’s Presentation

- Integrated modeling for decision support
  - WaterSim 1.0-5.0
  - Process more than a product
- Approaches for dealing with uncertainty—sensitivity analysis, scenario planning, consultation and deliberation
- Research outputs
- Stakeholder engagement—what we learned from decision makers
**Box 2.1. Examples of Sources of Uncertainty**

**Problems with Data**
- Missing components or errors in the data
- “Noise” in the data associated with biased or incomplete observations
- Random sampling error and biases (nonrepresentativeness) in a sample

**Problems with Models**
- Known processes but unknown functional relationships or errors in the structure of the model
- Known structure but unknown or erroneous values of some important parameters
- Known historical data and model structure but reasons to believe that the parameters or model structure will change over time
- Uncertainty about the predictability (e.g., chaotic or stochastic behavior) of the system or effect
- Uncertainties introduced by approximation techniques used to solve a set of equations that characterize the model

**Other Sources of Uncertainty**
- Ambiguously defined concepts and terminology
- Inappropriate spatial or temporal units
- Inappropriateness or lack of confidence in underlying assumptions
- Uncertainty caused by projections of human behavior (e.g., future consumption patterns or technological change), which is distinct from uncertainty from “natural” sources (e.g., climate sensitivity, chaos)
Other Sources of Uncertainty

- Designation of endangered species
- Legal designations of Native American water rights
- Political forces
- Population and economic growth
- Enforcement of AZ Groundwater Management Act
- Decisions by neighboring communities
Uncertainties in human systems

Phoenix, Arizona Metropolitan Area House Prices

- Inflation-adjusted house prices
- Nominal house prices


Price: $0, $50,000, $100,000, $150,000, $200,000, $250,000, $300,000, $350,000
Uncertainties in human systems

Potash Prices

US$ per tonne

Spot Potash Prices (FOB Vancouver)

BPC announces 2011:Q4 price increases

Spot Prices
2008-09 US$633
2010 US$463
2011F US$463

US$490 (Sept)
Stationarity Assumption

Annual Flows on Salt/Verde River System

Infrastructure and Operations
Low-frequency variability and persistent periods of low flow

25-yr running means of reconstructed and observed annual flow of the Colorado River at Lees Ferry, expressed as percentage of the 1906-2004 observed mean (Meko et al. 2007).
Annual Flows on Saskatchewan River at AL/SK Border (1928-2000)

Source: Alberta Canada. Natural flow (apportionment on the SSR at the AB/SK border.)
“Stationarity is Dead”

Stationarity Is Dead: Whither Water Management?


Stationarity—the idea that natural systems fluctuate within an unchanging envelope of variability—is a foundational assumption that permeates training and practice in water-resource engineering. It implies that any variable (e.g., annual streamflow or annual flood peak) has a time-invariant (or 1-year periodic) probability density function (pdf), whose properties can be estimated from the instrumental record. Under stationarity, pdf estimation errors are acknowledged, but have been assumed to be reducible by additional observations, more efficient estimators, or regional or paleohydrologic data. The pdfs, in turn, are used to evaluate and manage risks to water supplies, waterworks, and floodplains; annual global investments in water infrastructure exceed US$500 billion.

The stationarity assumption has long been compromised by human disturbances in river basins. Flood risk, water supply, and water quality are affected by water infrastructure, channel modifications, drainage works, and land-use and land-use change. One other sometimes insidiously challenging stationarity has been externally forced, natural climate changes and low-frequency, internal variability (e.g., the Atlantic multidecadal oscillation) enhanced by the slow dynamics of the oceans and ice sheets (2, 3). Warmer boreal forests have tools to adjust their analyses for human disturbance within rivers, and this fact may be an important factor in the changing climate.

How did stationarity die? Stationarity is dead because substantial anthropogenic climate change is significantly altering the mean and extremes of precipitation, evapotranspiration, and rates of discharge of rivers (4, 5) (see figure, above). Warmer air temperature, which increases atmospheric moisture and water transport. This increases precipitation, and potentially flood risk, where prewarming atmospheric water vapor fluxes have increased (6). Rising sea level induces gradually heightened risk of contamination of coastal freshwater supplies. Glacial meltwater temporarily enhances water availability, but glacier and snowpack losses diminish natural seasonal and interannual storage (7).

Anthropogenic climate warming appears to be driving a poleward expansion of the subtropical dry zone (2), thereby reducing runoff in some regions. Together, uncertainties in the global and hemispheric temperature responses largely explain the picture of regional gains and losses of sustainable freshwater availability that has emerged from climate models (see figure, p. 274).

Why now? That anthropogenic climate change affects the water cycle (9) and water supply (10) is now well known. Nevertheless, sensible objections to discarding stationarity have been raised. First, hydrologic data have not demonstrably ended the envelope of natural variability and the effective range of operation of engineered infrastructure (11, 12). Accounting for the substantial uncertainties of climate parameters estimated from short records (13) effectively protected against small climate changes. Additionally, climate change projections were not considered reliable (12, 13).

Recent developments have led us to the opinion that the time has come to move beyond the water-and-soil approach. Projections of runoff change are moderated by the recent demonstrated predictive skill of climate models. The global pattern of observed annual streamflows is likely to have been driven by anthropogenic forcing and is consistent with modeled responses to climate forcing (15). Paleohydrologic studies suggest that small changes in summer climate might produce large changes in extremes (16), although attempts to detect recent change in global flood frequency have been equivocal (17). Regional changes in runoff during the midlands long-term impact of major infrastructure projects began early enough to be used to assess the range of regional changes (18). The region has relatively little information to inform the impacts of change.

Stationarity cannot be revived. Even with significant mitigation, continued warming is very likely, given the rate of emission of greenhouse gases (19) and the thermal inertia of the Earth system (20). A consequence. We need to find ways to identify sustainable probabilistic models of relevant environmental variables and to use these models to optimize water systems. The challenge is daunting. Patterns of change are complex, inaccuracies are large, and the knowledge base changes rapidly.

Under the national planning framework advanced by the Harvard Water Program (21, 22), the assumption of stationarity was...
Uncertainty is growing.
More knowledge, less certainty

Kevin Trenberth

Major efforts are underway to improve climate models both for the advancement of science and for the benefit of society. But early results could cause problems for the public understanding of climate change.

The climate models that comprise the Intergovernmental Panel on Climate Change (IPCC) don’t do predictions, or at least they haven’t up until now. Instead the scientists of the IPCC have, in the past, made projections of how the future climate would change for a range of what-if scenarios. But for its fifth assessment report, known as AR5 and due out in 2013, the UN panel plans to examine explicit predictions of climate change over the coming decades. In AR5’s Working Group I report, which focuses on the physical science of climate change, one chapter will be devoted to assessing the skill of climate predictions for timescales out to about 50 years. These climate forecasts, which should help guide decision makers on how to plan for and adapt to change, will no doubt receive much attention.

Another chapter will deal with longer-term projects, to 2100 and beyond, using a suite of global models. Many of these models will attempt new and better representations of important climate processes and their feedbacks — in other words, those mechanisms that can amplify or diminish the overall effect of increased radiative forcing. Including these elements will make the models into more realistic simulations of the climate system, but it will also introduce uncertainties. So here is my prediction: the uncertainty in AR5’s climate predictions and projections will be much greater than in previous IPCC reports, primarily because of the factors noted above. This could present a major problem for public understanding of climate change. It is not a reasonable expectation that as knowledge and understanding increase over time, uncertainty should decrease but while our knowledge of certain factors does increase, so does our understanding of factors we previously did not account for or even recognize.

Climate models project large decreases in permafrost by 2100. Some models used for the IPCC’s next assessment will relate important feedbacks associated with increased emissions of the greenhouse gases methane and carbon dioxide change adopted from ref. B.

Dramatic changes to agriculture

In previous IPCC assessments, changes in the atmospheric concentrations of greenhouse gases and aerosols over time were geared using ‘idealized’ emission scenarios, which are informed estimates of what might happen in the future under various sets of assumptions related to population, lifestyle, standard of living, carbon intensity and the like. Then the changes in future climate were simulated for each of these scenarios. The output of such modeling is usually referred to as a projection, rather than a prediction or a forecast. Unlike a weather prediction, the model in this case is not initialized with the current or past state of the climate system, as derived from observations. Instead, they begin with arbitrary climate conditions and examine only the change in pre-industrial levels, therefore removing any less that could be associated with variability to realistically simulate the current climate as a starting point. This technique works quite well for examining how the climate could respond to various emissions scenarios in the long term.

Climate models have, however, improved in the past few years, and society is now demanding ever more accurate information from climate scientists. Faced with having to adapt to a range of possible impacts, policy-makers, coastal planners, water resources managers and others are keen to know how the climate will change on timescales that influence decision-making. Because the amount of warming that will take place up to 2100 is largely dependent on greenhouse gases that have already been released into the atmosphere, it is theoretically possible to predict, with modest skill, how the climate will respond over this time period. In recent years, several modeling groups have published such predictions for the coming decades (Fig. 1). In weather prediction, and in this near-term form of climate projection, it is essential to start the model with the current state of the system. This is done by collecting observations of the atmosphere, oceans, land surface and soil moisture, vegetation state, sea ice and so forth, and assimilating these data into the model — which can be challenging, given model imperfections. Although important progress has been made in this area, the techniques are not yet fully established. In part because it takes at least a decade to verify a 10-year forecast, evaluating and optimizing the model will be a time-consuming process. The spread in model results is therefore bound to be large, and the uncertainties much larger than for the
Problems of “Deep Uncertainty”

- Parties cannot agree upon:
  - The fundamental driving forces that will shape the future and/or the models that describe them
  - The probability distributions used to represent uncertainty and key variables and parameters
  - How to value alternative outcomes (gains or losses?)
New Questions for Problems of Deep Uncertainty

- What kind of future do we want and what decisions do we need to make to get there?
- What is the range of how the future might look and how do we avoid regrettable outcomes?
- “What if-ing” What are the consequences of particular decisions in a complex system?
  - Inflection points
  - Critical feedbacks (water-energy nexus)
- What policies work best across a range of climate futures?
- What are the costs of delaying decisions?
- What are the tradeoffs between these costs and the risk of making expenditures that are not necessary?
WaterSim 4.0

Diagram of water simulation model:
- Historic Colorado flows
- Climate effects on Colorado
- Colorado inflow
- Colorado storage
- Colorado outflow to Phoenix Metro
- Historic Salt-Verde flows
- Climate effects on Salt-Verde
- Salt-Verde inflow
- Salt-Verde storage
- Salt-Verde outflow to Phoenix Metro
- Land use projections
- Population change
- Population estimates
- Retirement of agricultural land
- Acres of agriculture
- Commercial & other water demand
- Residential water demand
- Agricultural water demand
- Total unconstrained demand
- Surplus or deficit
- Desired supply from groundwater
- Actual supply from groundwater
- Protect GPCD or groundwater
- Demand that is fulfilled
- Groundwater change
- Groundwater supply
- Groundwater availability

Legend:
- Parameter (constant)
- Auxiliary
- Stock
- Flow from outside the model into a stock
Trace effects on WaterSim results
Trace Analysis--Colorado
WaterSim in Decision Theater
Implications of Climate on Watershed

2007 IPCC Fourth Assessment Report Results Applied to the Colorado Basin

Change in Colorado Runoff Under Model/Scenario Combinations

Number of combinations vs. % of historical runoff for different scenarios.

2007 IPCC Fourth Assessment Report Results Applied to the Salt/Verde Basin

Change in Salt/Verde Runoff Under Model/Scenario Combinations

Number of combinations vs. % of historical runoff for different scenarios.
Policy Tradeoffs

Policy start year: 2020

Total estimated gallons used per person per day under policy: 224

Indoors: 78
- toilet: 5.3 flushes, 3.9 gal/flush
- clothes washing: 0.4 loads, 42.1 gal/load
- showers: 0.8, 10.4 min, 1.7 gal/min
- baths: 0, 40 gal
- faucet: 6.7 min, 1.8 gal/min
- leaks: 3.8 drips/sec
- other domestic: 1.8 gal/day
- dish washing: 0.1 loads, 13.6 gal/load

Outdoors: 146
- Density of urban expansion
- Non-desert landscaping: 13%
- Pools: 13%
Critical Trade-off: Lifestyle and Sustainability

50% for outdoor use
Water use increases with urban densities.

$$y = -0.12583374 \ln(x) + 0.56909296$$
Sensitivity Analysis
Business as usual vs. slow growth, high density, desert landscaping, and no pools.
Robust Policy Decisions
Problems of Aggregation
### Scenario 1: Stationary climate conditions

<table>
<thead>
<tr>
<th>Period Range (Aggregate of 5 years)</th>
<th>Status Quo</th>
<th>Regional Cooperation (Optimization model)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Providers in Deficit</td>
<td>Total Deficit</td>
<td>Providers in Deficit</td>
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<tr>
<td>2006-10</td>
<td>2</td>
<td>79,944</td>
<td>0</td>
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<tr>
<td>2011-15</td>
<td>4</td>
<td>107,733</td>
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<tr>
<td>2016-20</td>
<td>4</td>
<td>116,046</td>
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<tr>
<td>2021-25</td>
<td>5</td>
<td>138,693</td>
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<tr>
<td>2026-30</td>
<td>7</td>
<td>165,685</td>
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### Scenario 2: Moderate reductions in current flows

<table>
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<th>Period Range (Aggregate of 5 years)</th>
<th>Status Quo</th>
<th>Regional Cooperation (Optimization model)</th>
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<tr>
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<td>Providers in Deficit</td>
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<td>Providers in Deficit</td>
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<td>2006-10</td>
<td>3</td>
<td>91,926</td>
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<tr>
<td>2011-15</td>
<td>4</td>
<td>129,854</td>
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</tr>
<tr>
<td>2016-20</td>
<td>4</td>
<td>303,257</td>
<td>0</td>
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<tr>
<td>2021-25</td>
<td>6</td>
<td>170,274</td>
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<tr>
<td>2026-30</td>
<td>7</td>
<td>231,815</td>
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</table>

### Scenario 3: Severe reductions in current flows

<table>
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<th>Period Range (Aggregate of 5 years)</th>
<th>Status Quo</th>
<th>Regional Cooperation (Optimization model)</th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Providers in Deficit</td>
<td>Total Deficit</td>
<td>Providers in Deficit</td>
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<tr>
<td>2006-10</td>
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<td>226,240</td>
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<tr>
<td>2011-15</td>
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<td>2016-20</td>
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<td>2021-25</td>
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<td>447,827</td>
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<tr>
<td>2026-30</td>
<td>8</td>
<td>493,701</td>
<td>2</td>
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</table>
Can we manipulate growth and consumption to reduce risk?

- Steer growth in favor of surplus districts
  - Who are the winners and losers?
  - What is the redistributed pattern of growth?
  - How many people need to be redistributed?

- Reduce consumption to retain growth pattern
  - Where? How severe?

- Trigger outmigration at low GPCD (<120 GPCD)
  - How much growth is redistributed under varying climate change conditions?
  - How soon do districts transition from growth to no-growth futures?
Uncertainty was described as ‘the nature of the beast,’ ‘always present,’ and ‘the whole reason we exist.’

Findings point to the challenges of meshing different knowledge systems for collaborative research and policy making.
Stakeholder Engagement — mind mapping
# Stakeholder Priorities for SRB

<table>
<thead>
<tr>
<th>Major Concerns</th>
<th>Priority</th>
</tr>
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<tbody>
<tr>
<td>Water Quality</td>
<td>3.41</td>
</tr>
<tr>
<td>Water Governance</td>
<td>3.62</td>
</tr>
<tr>
<td>Water Quantity</td>
<td>3.96</td>
</tr>
<tr>
<td>Land-use Management</td>
<td>4.07</td>
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<tr>
<td>Competing Demands</td>
<td>4.62</td>
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<tr>
<td>Drought</td>
<td>4.72</td>
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<tr>
<td>Long-term climate change</td>
<td>5.24</td>
</tr>
<tr>
<td>Flooding</td>
<td>6.26</td>
</tr>
</tbody>
</table>
Policy makers with more direct contacts with researchers are more likely to utilize research. Policy makers interacting more with other policy makers regarding research are also more likely to utilize it. This indicates the importance of policy makers’ in social networks and the importance of external reputation of boundary organizations for successful knowledge transfer.