Challenges in Assessing , Predicting, and Managing Water Resources Systems

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Snowmass Impacts Session

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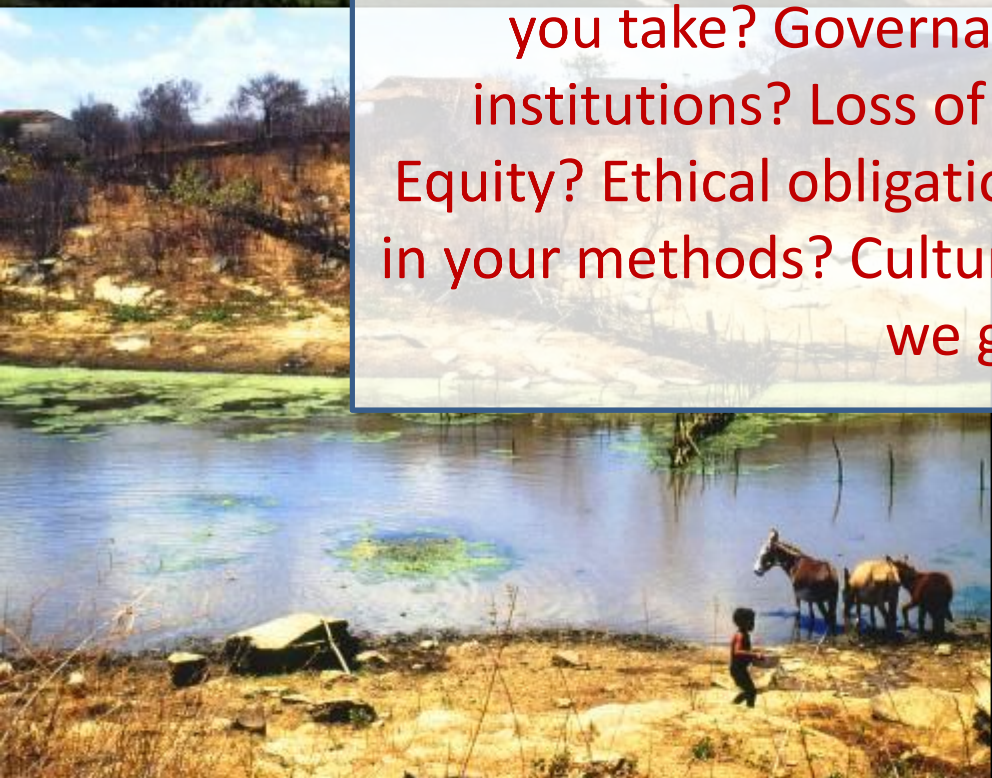
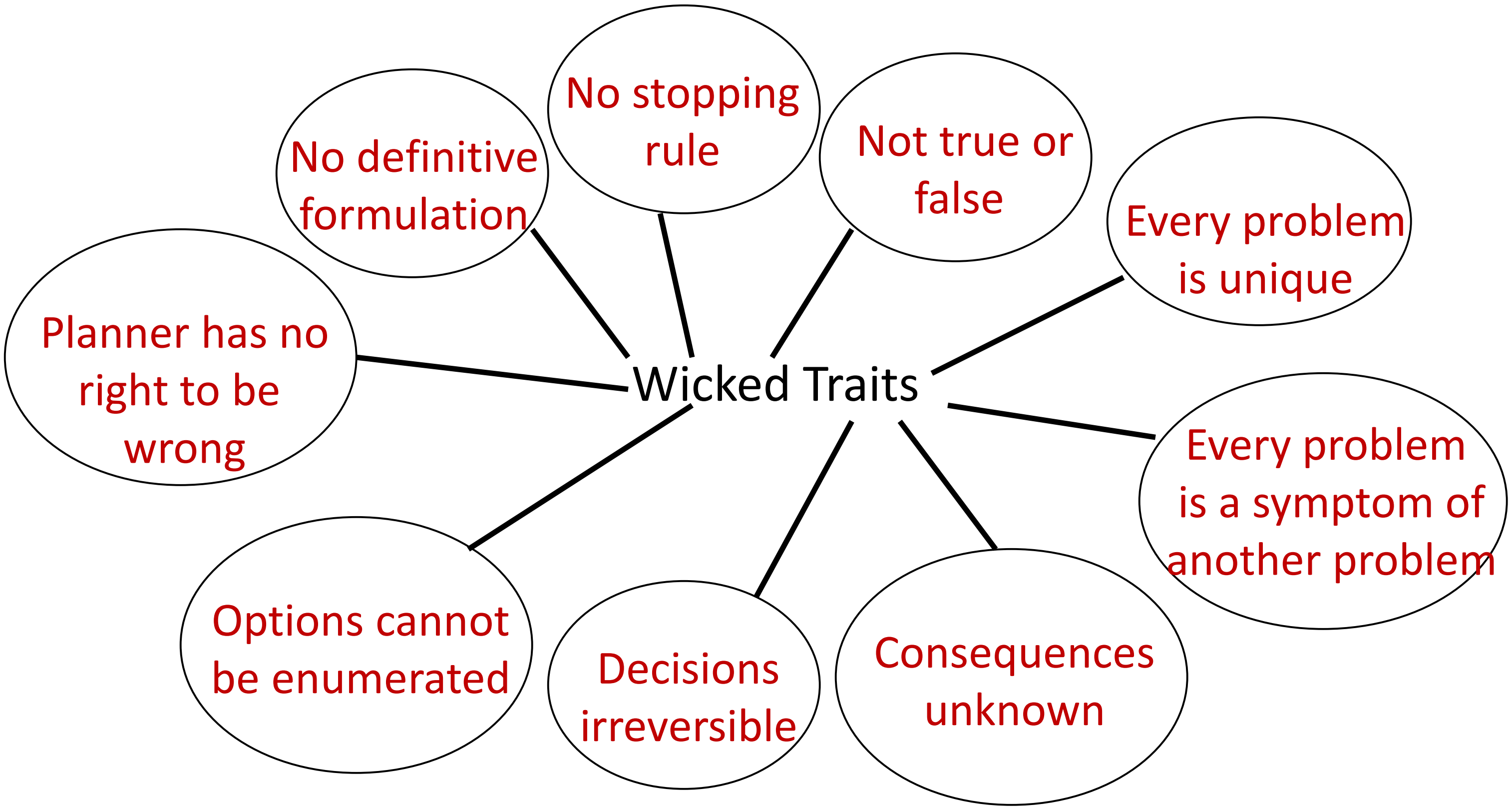
Ok, so what do you mean by impacts? Who are your stakeholders? Decision makers? Objectives? Constraints? Potential to do harm with modeling assumptions? What actions can you take? Governance issues? Stable institutions? Loss of human life matter? Equity? Ethical obligations? Tacit assumptions in your methods? Cultural bias? and on and on we go…




So let's start with a well regarded criticism model-based policy planning



Rittel & Webber, 1973 "Dilemmas in Planning", Policy Sciences

So defining "wicked water problems" is *The Problem*

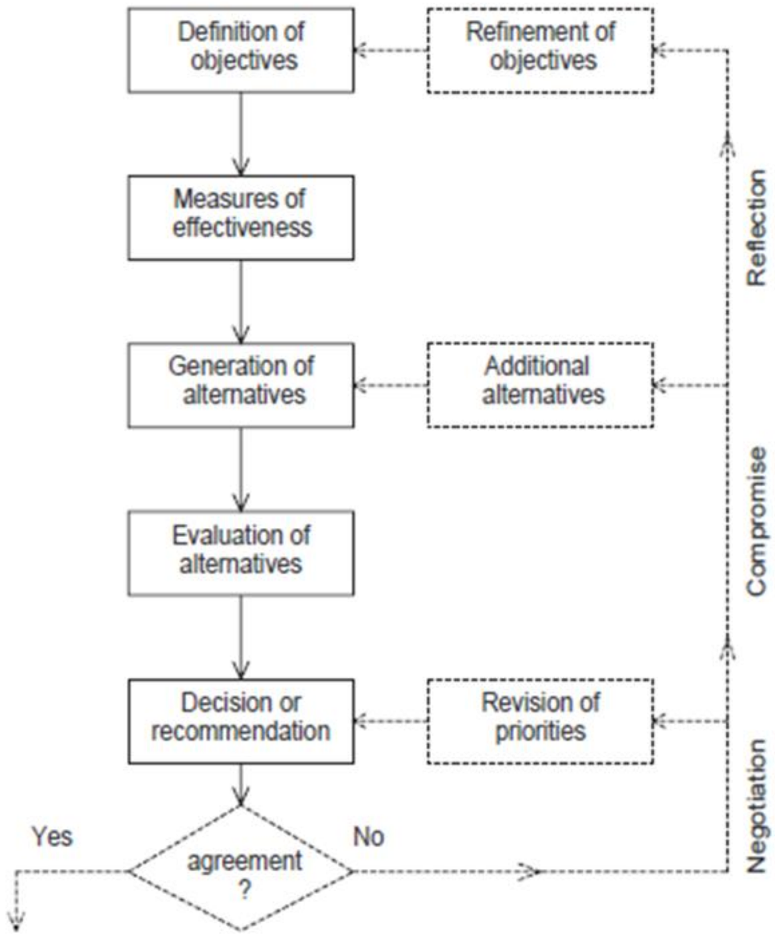
Maass et al 1962

(1) Identify suite of objectives
(2) Translate objectives into design criteria
(3) Identify "optimal" designs
(4) Evaluate the consequences of the designs

"For many water-resource activities in this country, for example, the design criterion (as set forth in the Flood Control Act of 1936) …is so imprecise that it encourages engineers to design river systems for maximum physical outputs and confine economic considerations solely to cost minimization."

Calling for consideration of both economic & engineered performance objectives. First detailed motivation for multiobjective design.

"Prescriptive Multi-objective Decision Support"

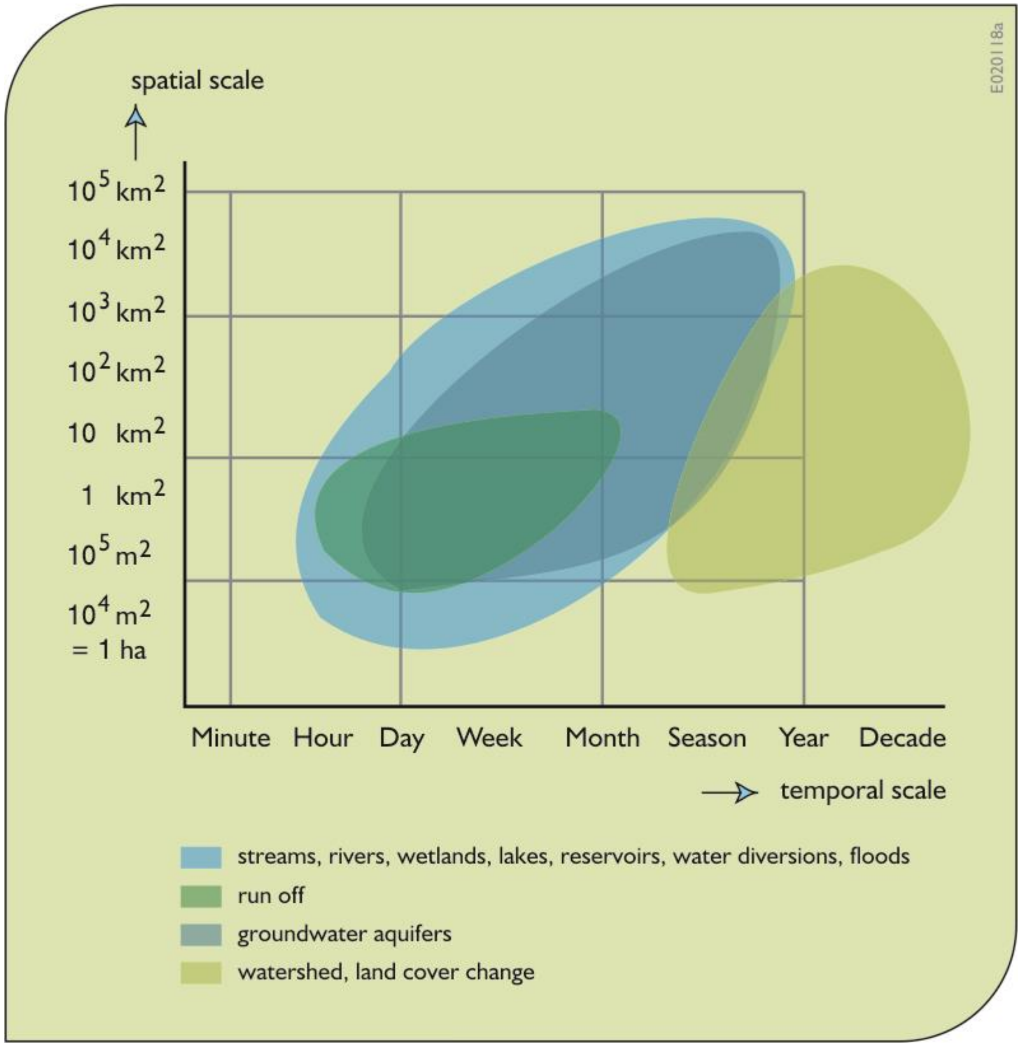


Bruen (2008) "Systems Analysis – a new paradigm and decision support tools for the water framework directive." HESS vol. 12

> The ultimate point of disagreement … was the role of policy analysts: to simply *make the relevant tradeoffs known* to policymakers … or, to *make normative recommendations*…

— Banzhaf (2009), on the 1960's debate between the Harvard Water Program and Resources for the Future (RFF)

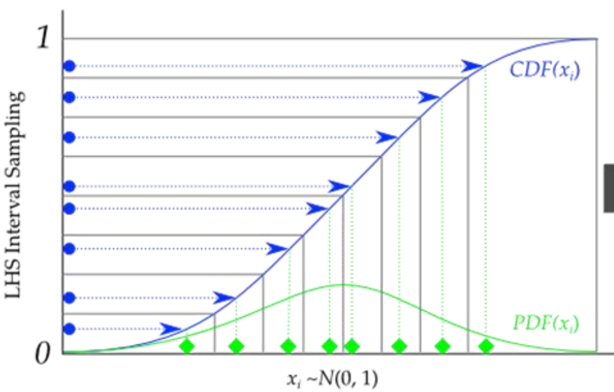
Space & time Scales are critical to properly posing problems

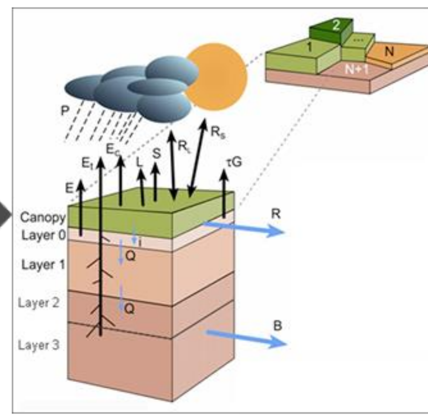


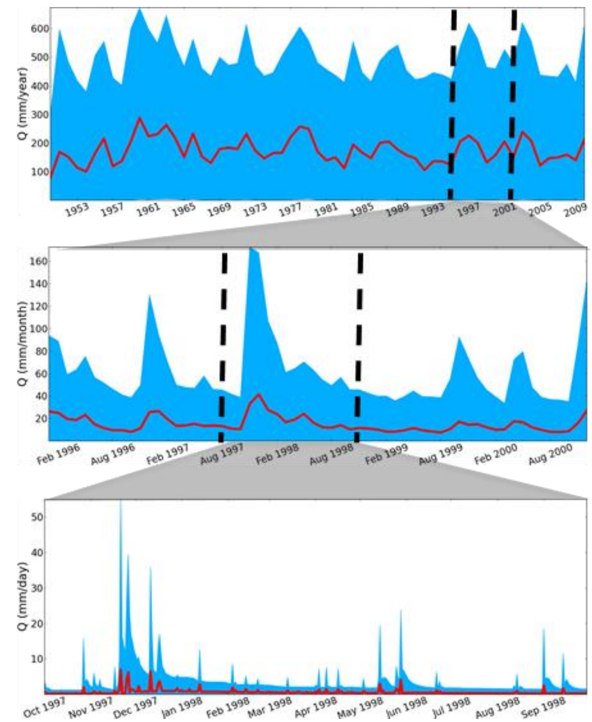
Loucks, D. P. and E. van Beek (2005). Water Resources Systems Planning and Management United Nations Educational, Scientific and Cultural Organization.

Uncertainty & Observation Limits Change Over Space and Time Scales!!

- Let's play with a 10,000 LHS 1-degree VIC Monte Carlo for the globe (~300 years of computation & 1.5 petabytes of output)

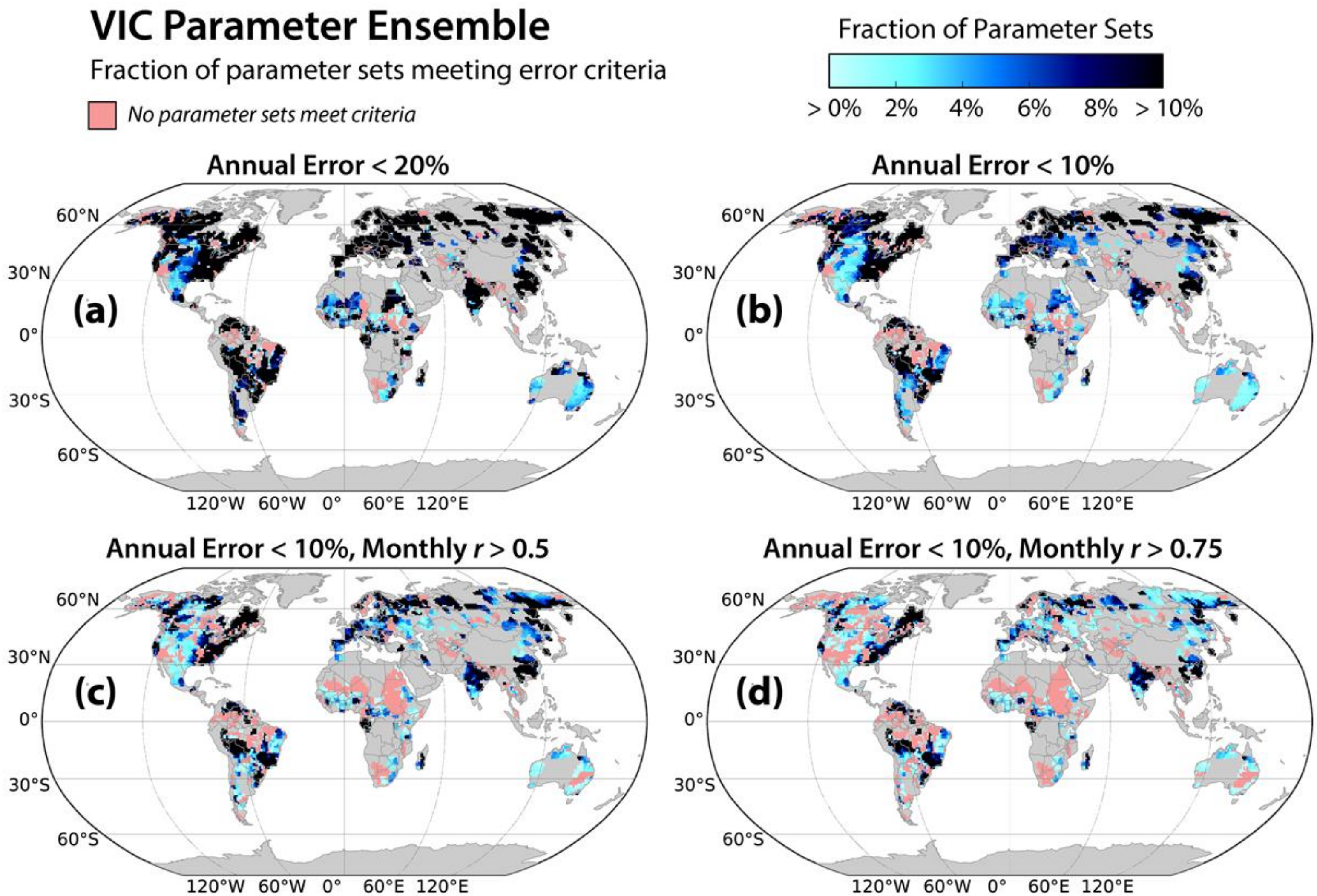






Chaney, Herman, Reed, and Wood, (In-Prep)

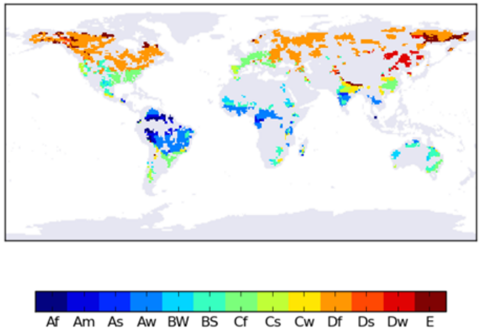
GRDC Observations Limited in Value & Coverage When Assessing Uncertain Hydrologic Extremes

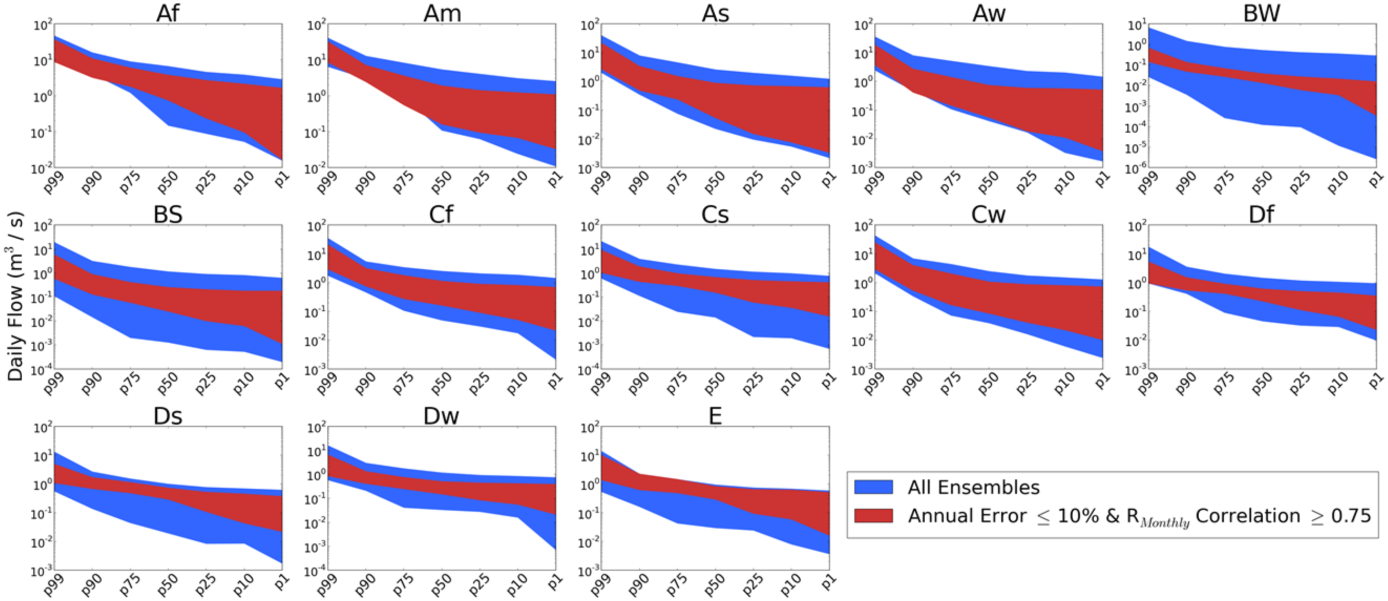


GRDC observations may not help reduce uncertainty in floods & droughts in a lot of places

Flow Duration Curve: Climate

- Spread in the flow duration curve (Daily)
- Large differences between climates

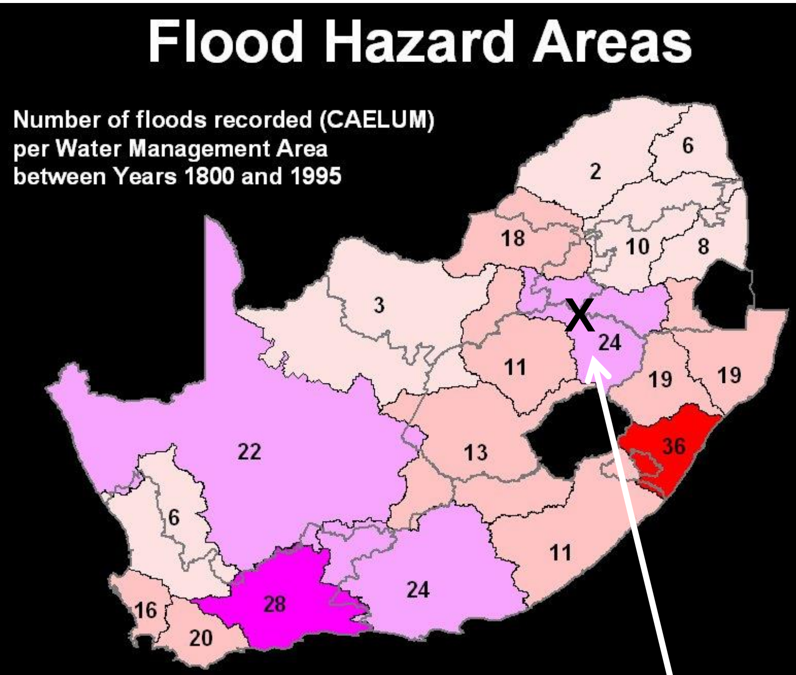




By the way, the observations themselves are bit uncertain when they exist…

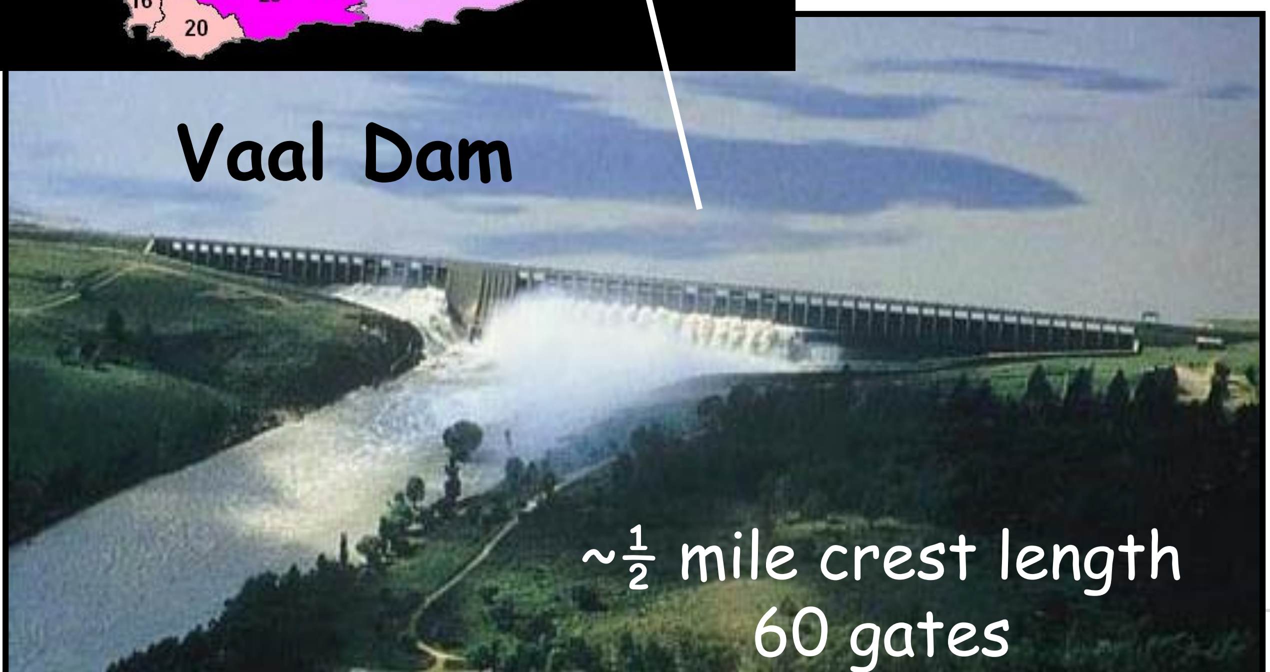
Courtesy of K. van Werkhoven

Some fun with the trivial notion of mass balance



- ✓ 56 km from Johannesburg
- ✓ Highly developed downstream

- ✓ Ensure safety of the structures
- ✓ Minimization of damages downstream
- ✓ Ensuring the dams are 100% full after event



Capacity

100%
"Full" Storage = 2603 mil m^3

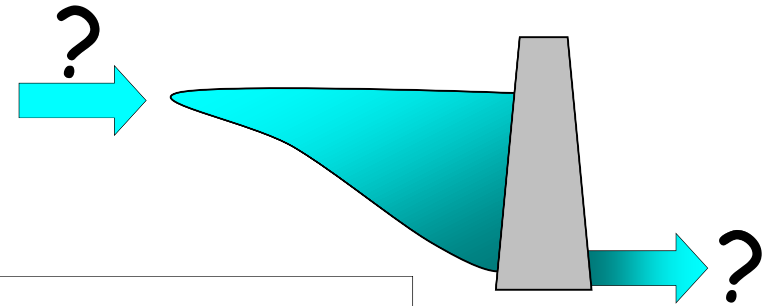
+26%
Additional Flood Absorption
Capacity = 677 mil m^3

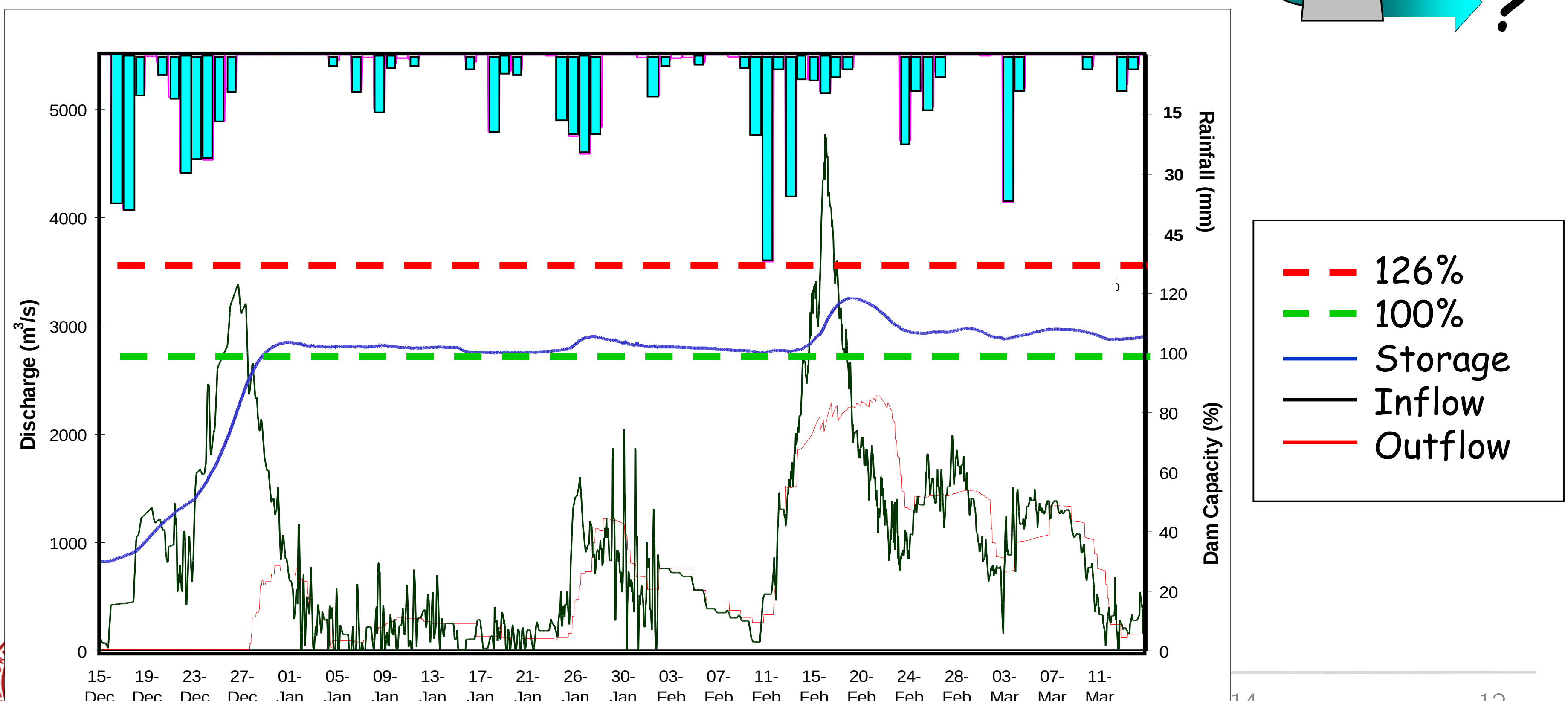
Courtesy of K. van Werkhoven

It's awesome to be lucky in the absence of river forecasting institutions?

February 1996

- ✓ Highest inflow ever recorded at 4800 cms
- ✓ **Already at full capacity**
- ✓ Maximum release 2300 cms
- ✓ Storage peaked at 118.5%





Ok, let's ask a few IAM relevant questions after our mass balance toy problem.

Can IAMs capture major extremes and potential major infrastructure failures that are likely to become more common and dominate impacts?

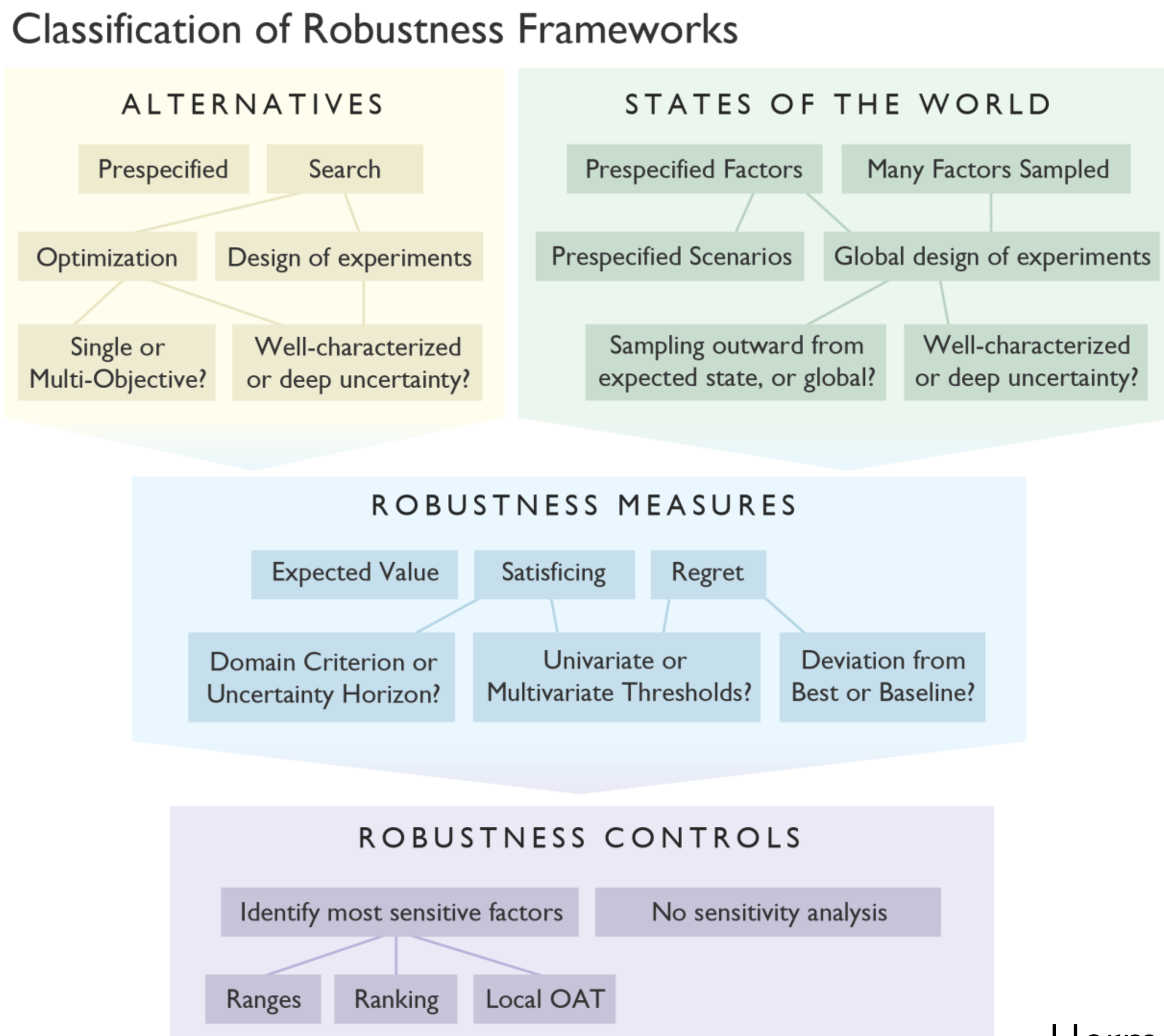
Is it appropriate to evaluate actual climate change impacts including loss of life using deterministic scenario driven frameworks?

Do IAMs need to deal with the fact that the structure of our "water balance" is changing with an endogenous dependence on human actions?

Do IAMs have/need observations for evolving global depletion rates of aquifers, water quality concerns, failures in allocative institutions, locally evolving & competing multi-sector demands, changing infrastructures, financial risks, etc.?

What are the appropriate roles of normative economics? Tacit assumptions? Who is represented in measures of efficiency & equity? Whose impacted negatively by those measures? Willingness to support ex post monitoring/analysis? Culpable for unintended consequences for poor predictions for real systems?

These types of questions are motivating a shift in water resources planning towards "robustness"



Herman et al. (In-Prep)

Multi-objective Decision Support under Deep Uncertainty

1. Defining stakeholders' decisions and objectives
2. Optimization and preference elicitation
3. Are these solutions robust to uncertainty?
4. Which uncertainties cause critical failures?
5. Balancing robustness across stakeholders

Overview of ‘Research Triangle’ Water Utilities: North Carolina, USA

- Transition from water abundance to scarcity
- Storage/demand ratios allow intra-regional transfers

Planning through 2025—new reservoir capacity is expensive and raises environmental concerns.

The utilities seek cooperative agreements to use existing infrastructure more efficiently.

Utilities' options for cooperative agreements

Usage Restrictions: Conserve water, lose revenue

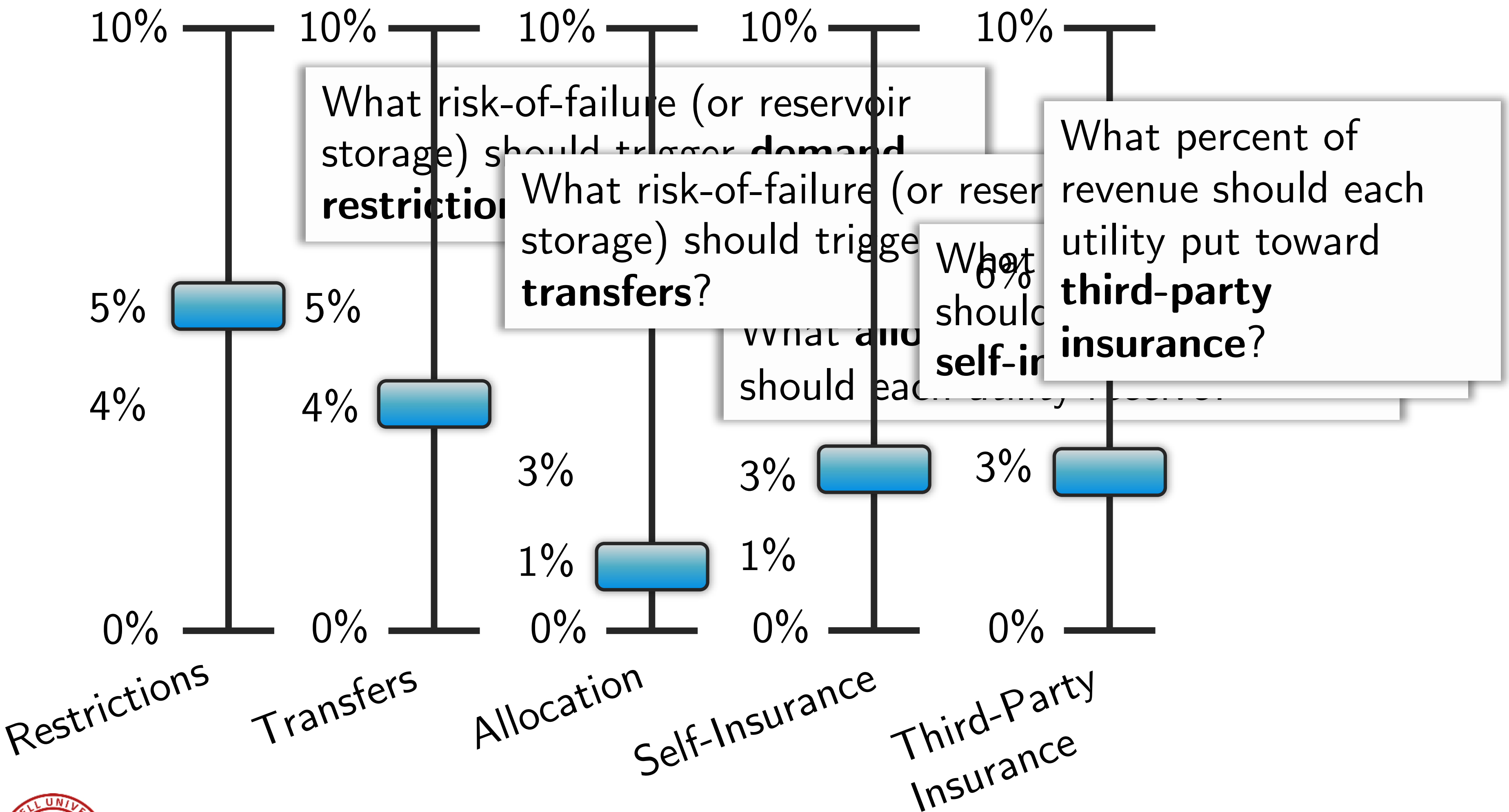
Water Transfers: Maintain reliability without restrictions

Financial instruments: Insure against lost revenue due to restrictions and transfers

→ Self-Insurance and Third-Party Insurance

(Zeff and Characklis, WRR 2013)

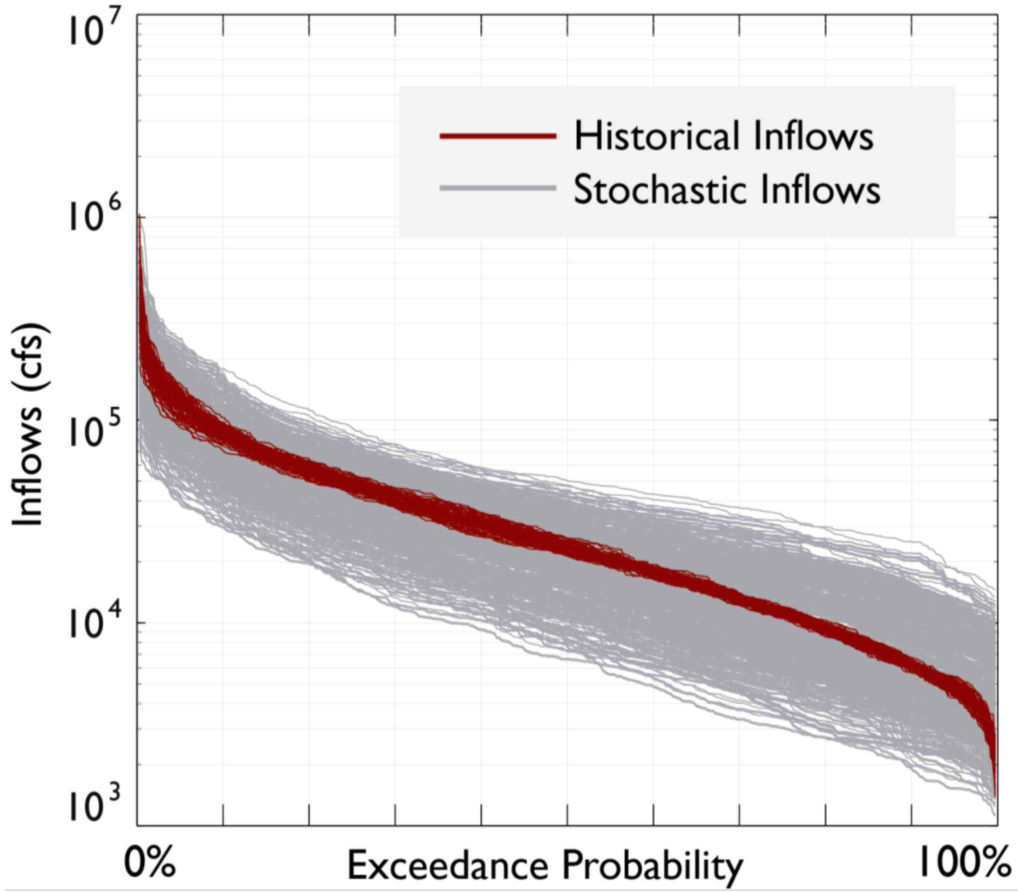
The utilities have defined five decision variables



Future reservoir inflows are uncertain!

Model includes an ensemble of future inflows generated from historical data

Force solutions to perform well across a broader range of hydrologic conditions



Four objectives defined by the utilities

Reliability (Max): # years where reservoir storage > 20%

Restriction Frequency (Min):

years with drought conservation measures enacted

Average Financial Losses (Min):

Revenue reductions + costs due to drought management

Worst-Case Financial Losses (Min):

Financial losses in the 1% worst scenario

The worst-performing utility is optimized such that others will perform as well or better.

What formulation meets stakeholder requirements? A constructive approach

> Constructive *decision aiding*:
> – Iterative learning process
> – Stakeholder feedback
> – Multiple formulations posed

— Tsoukias (2008), From decision theory to decision aiding methodology

1. Restrictions only (status quo)
2. Restrictions + Transfers
3. Restrictions + Transfers + Self-insurance
4. Restrictions + Transfers + Self-insurance + Third-party Insurance

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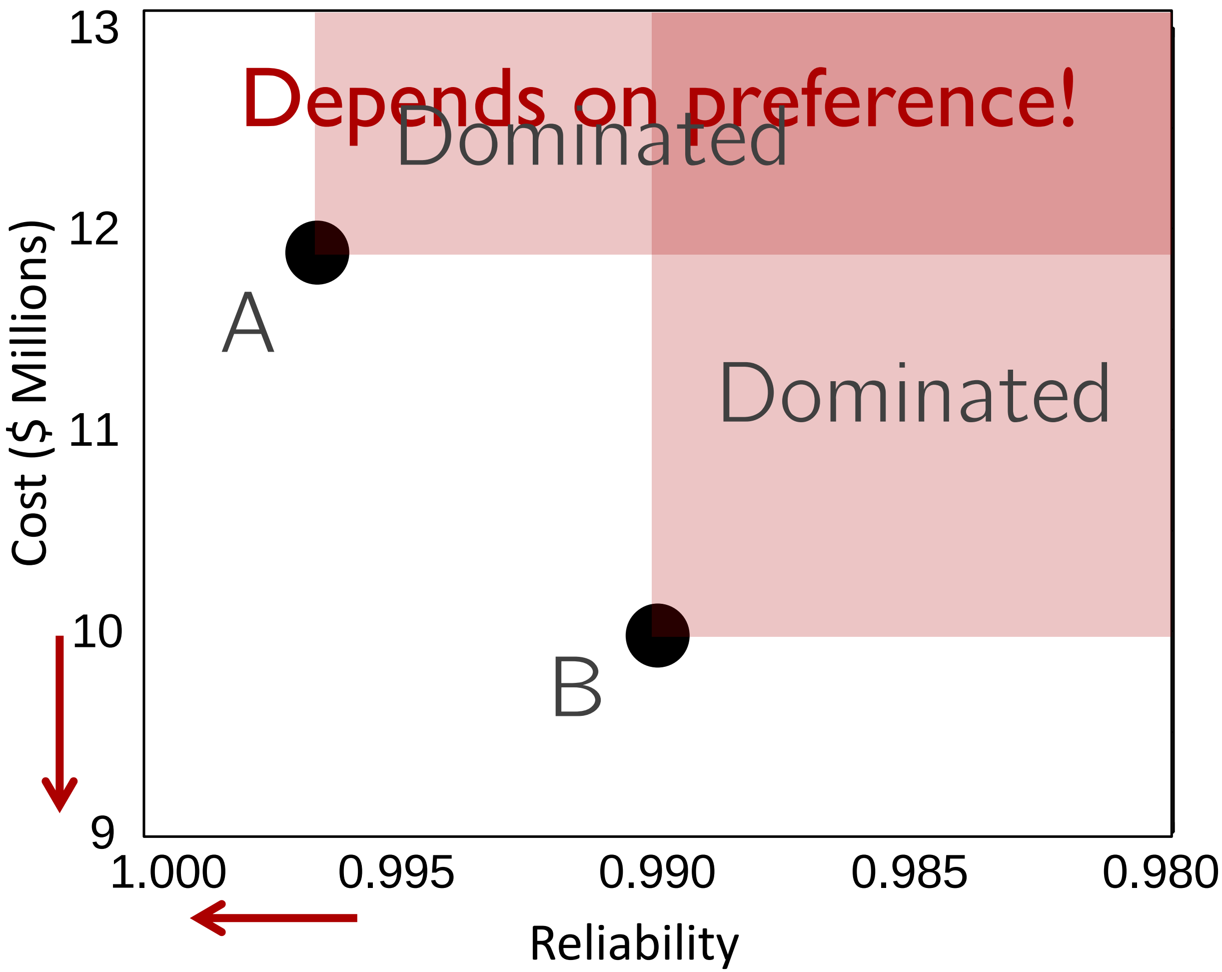
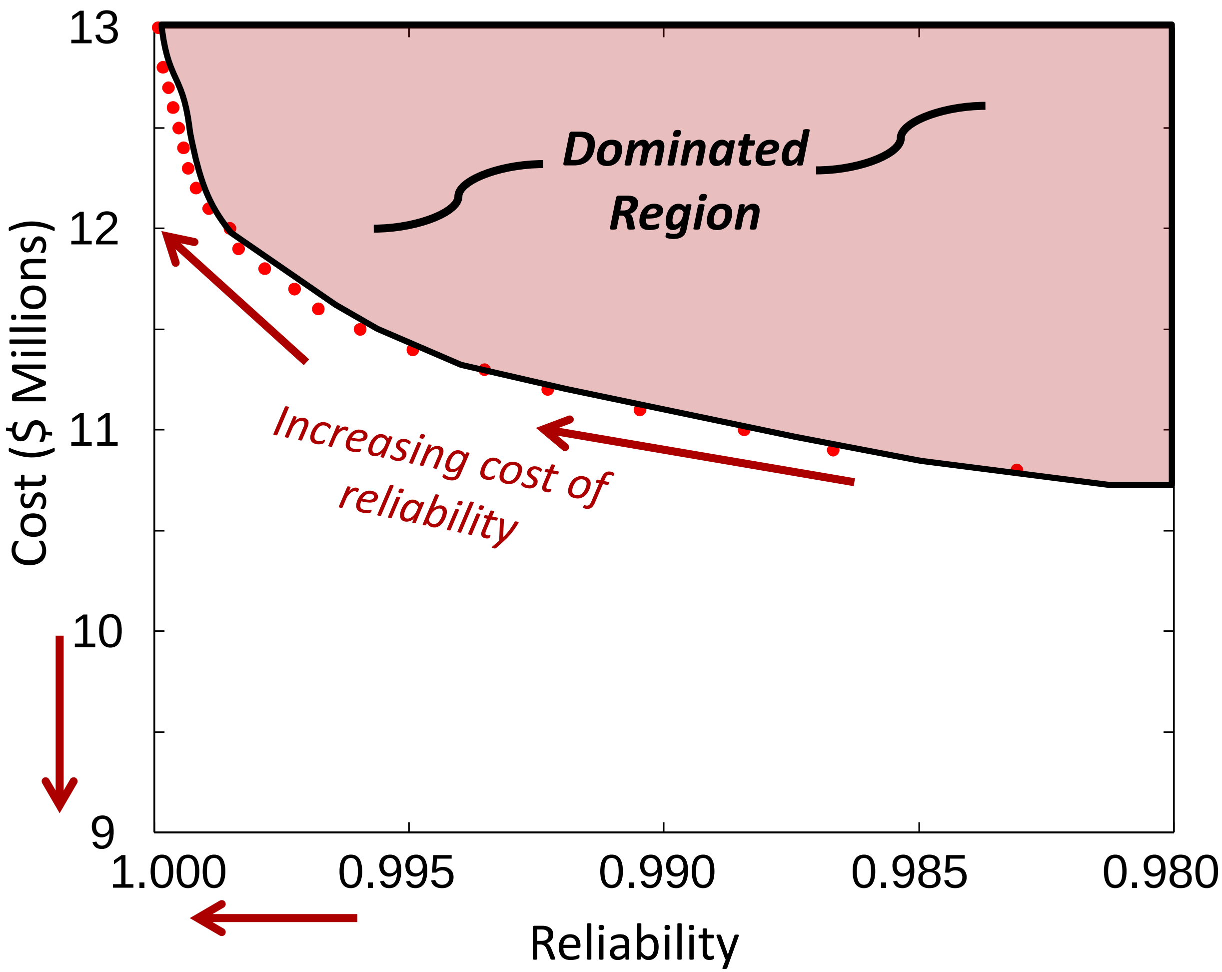
Multi-objective: which solution is better?



Kasprzyk et al. 2009

Looking for non-dominated solutions (tradeoff)



Kasprzyk et al. 2009

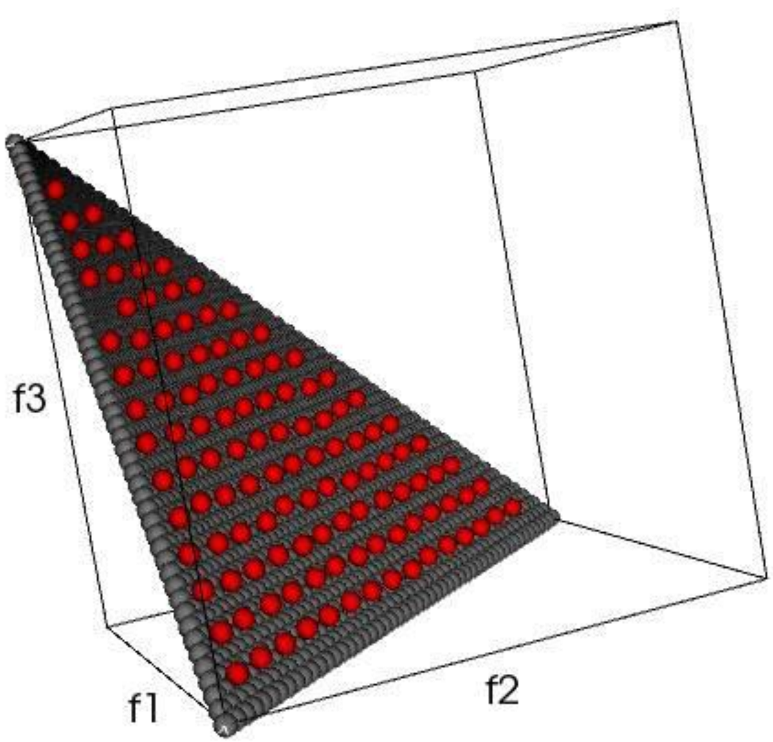
Multi-Objective Evolutionary Optimization

Heuristic method: flexibility for stochastic problems with unknown gradients

Search balances convergence and diversity

Multi-Objective Evolutionary Optimization

Three-objective Test Problem



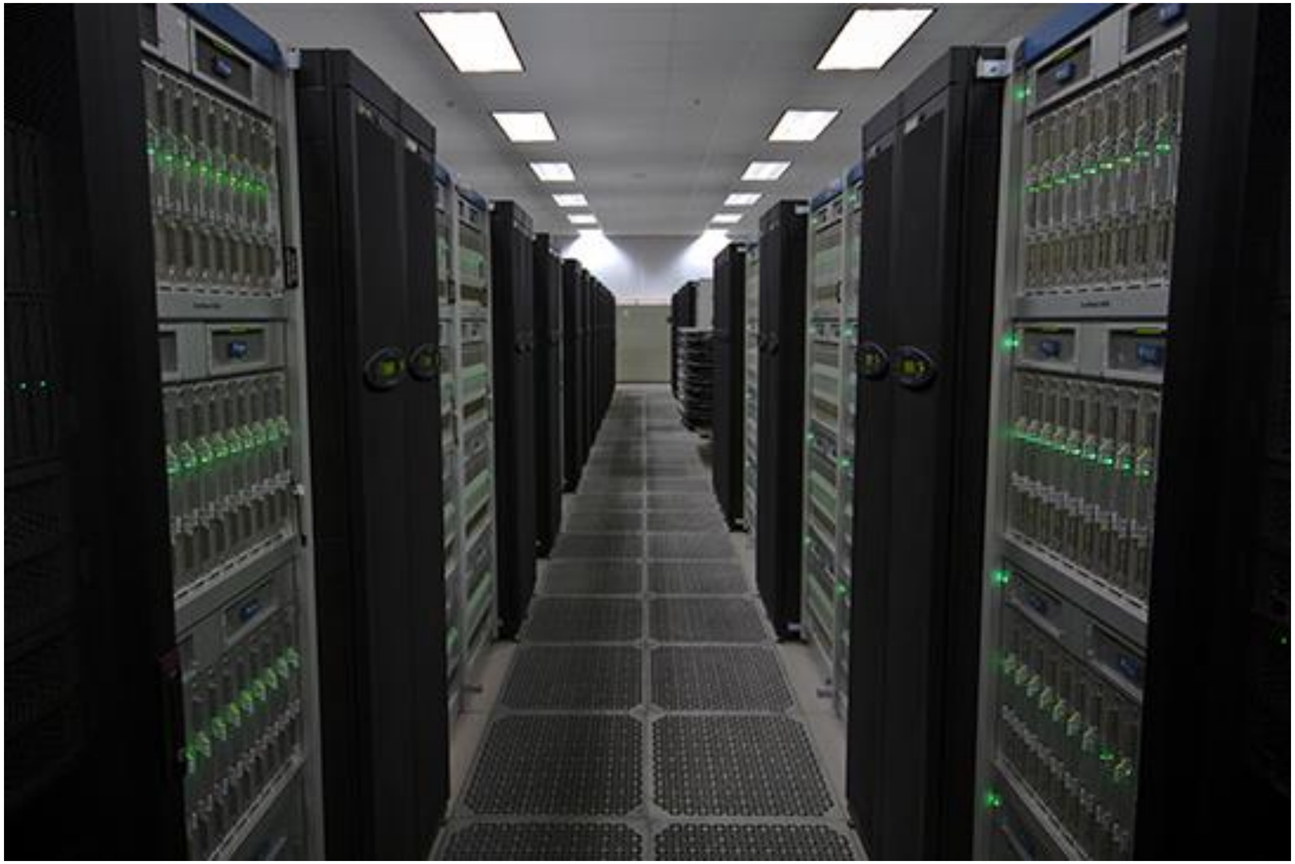
Heuristic method: flexibility for stochastic problems with unknown gradients

Search balances convergence and diversity

Borg MOEA: efficient, reliable performance for water portfolio planning

Reed, P.M., D. Hadka, J.D. Herman, J.R. Kasprzyk, and J.B. Kollat. 2013. Evolutionary Multiobjective Optimization in Water Resources: The Past, Present, and Future. *Advances in Water Resources*, 51, 438–456. [Invited Submission for 35th Anniversary Issue].

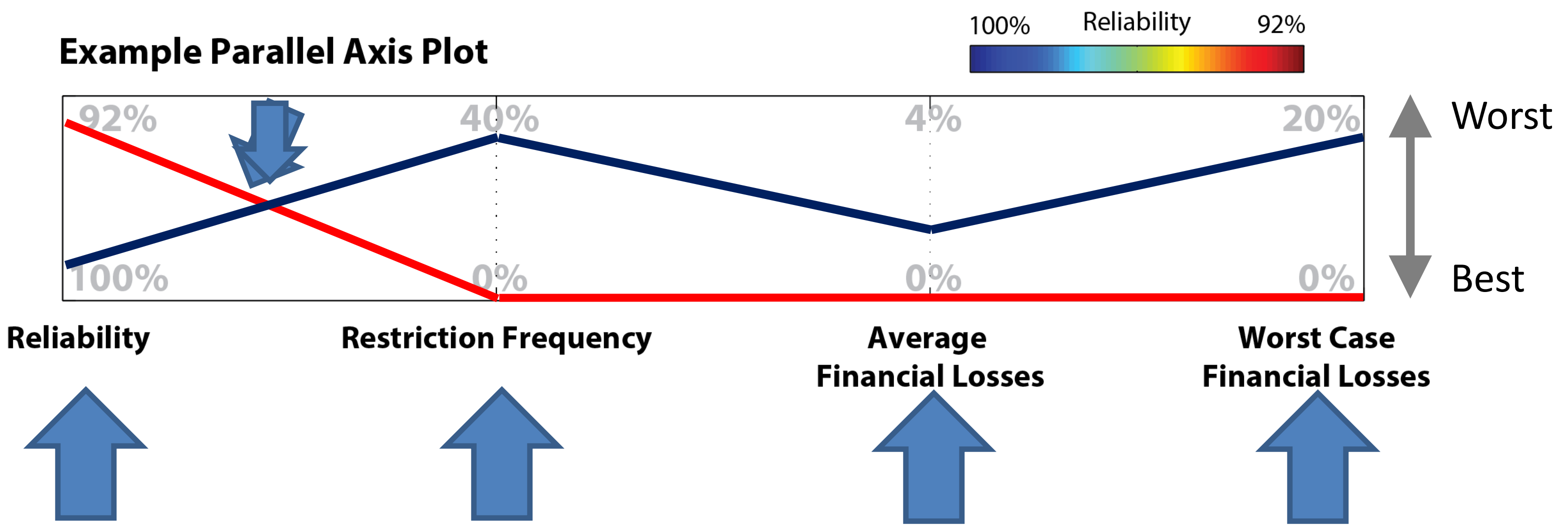
High-Performance Computing (HPC) lets us answer questions in minutes instead of days



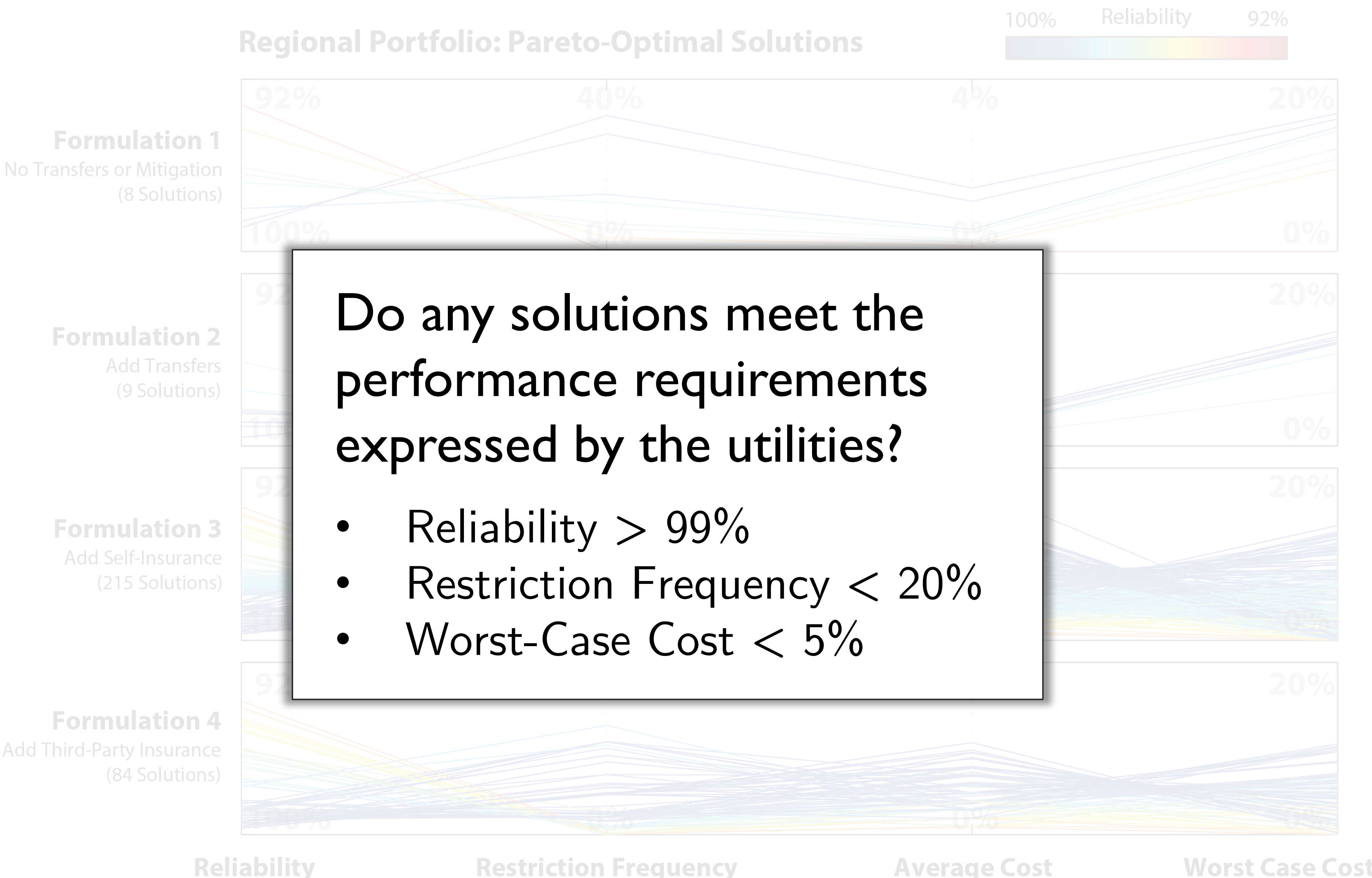
TACC Stampede Cluster

XSEDE
Extreme Science and Engineering Discovery Environment

Parallel axis plots help stakeholders visualize tradeoffs between conflicting objectives



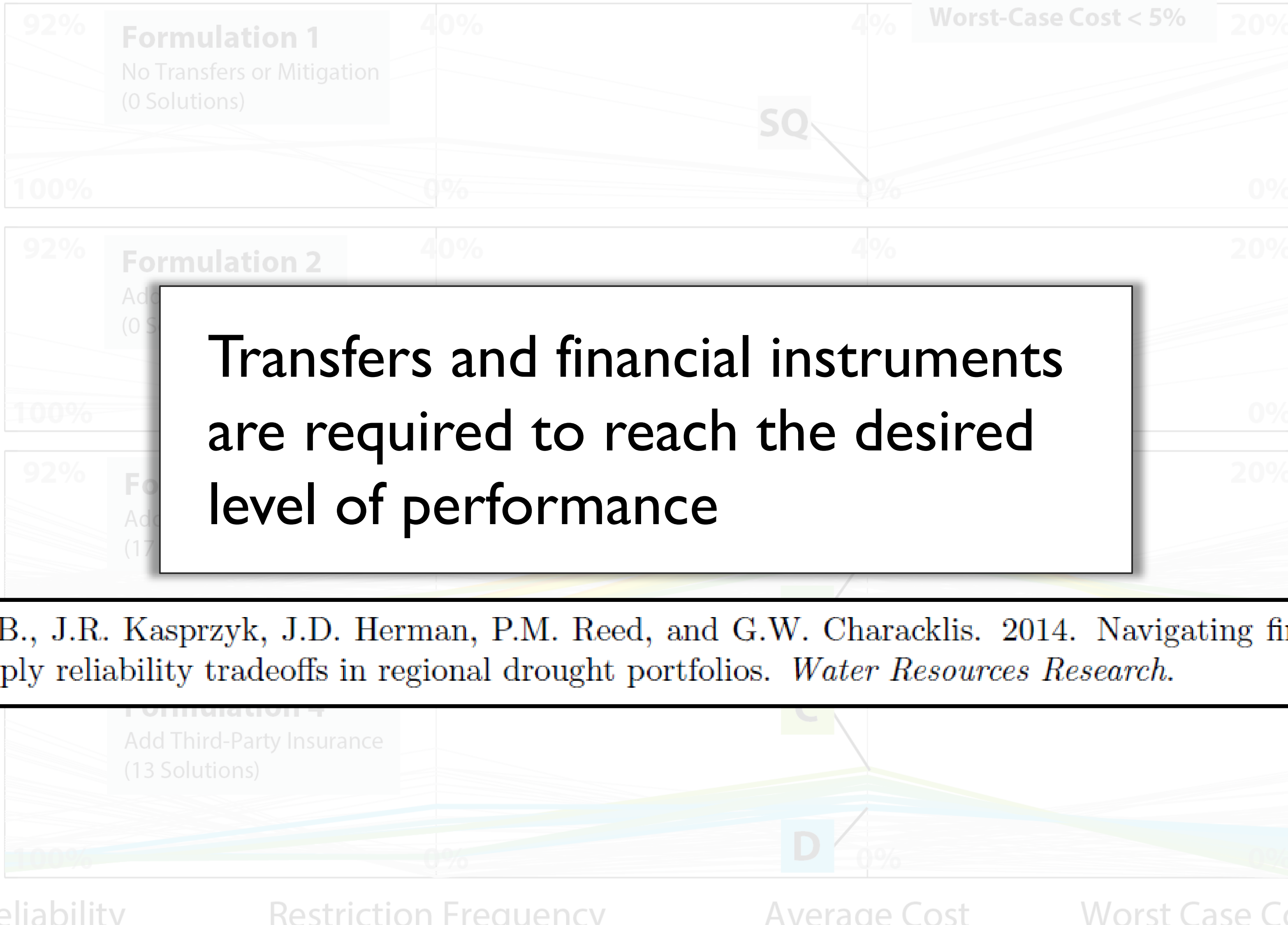
- Each line represents one solution
- X-Axis shows the four objectives to be optimized
- Y-Axis shows the objective value (performance)
- Crossing lines indicate tradeoffs



Do any solutions meet the performance requirements expressed by the utilities?

- Reliability > 99%
- Restriction Frequency < 20%
- Worst-Case Cost < 5%

Multi-Objective Optimization: High Reliability Solutions



Transfers and financial instruments are required to reach the desired level of performance

Zeff, H.B., J.R. Kasprzyk, J.D. Herman, P.M. Reed, and G.W. Characklis. 2014. Navigating financial and supply reliability tradeoffs in regional drought portfolios. *Water Resources Research*.

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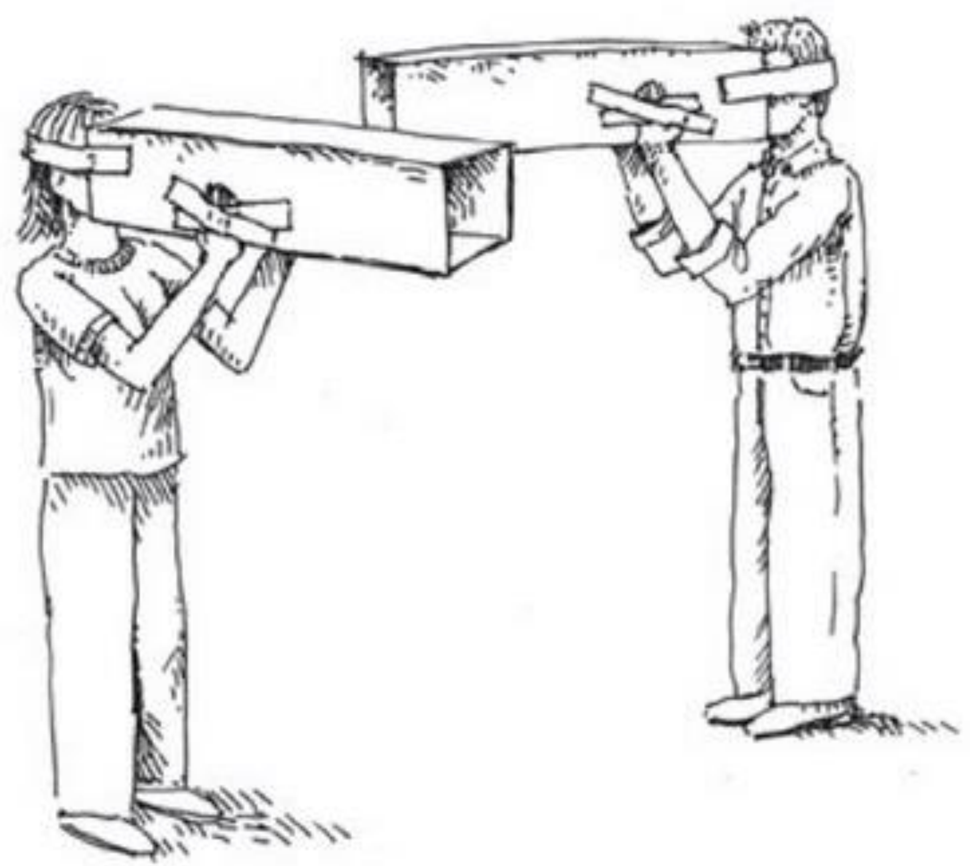
Optimizing to a single Monte Carlo future: what if we're wrong?

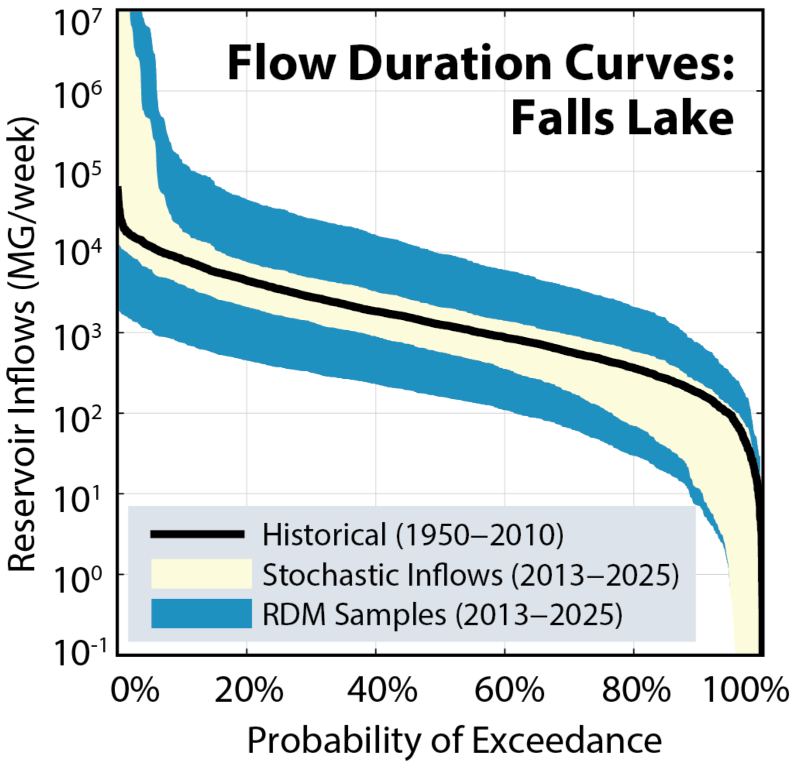


http://www.hockscqc.com/articles/tunnelvision/tunnel-vision.jpg

> Shift from asking the *prediction question* –
> ‘how likely is this scenario?’
> to asking the *decision impact question* –
> ‘how likely would this scenario need to be to affect one’s choice of strategy?’

— Bryant and Lempert (2010)

Construct alternative states of the world from a set of uncertainties, including inflow and demand multipliers



11 other uncertainties including demand seasonality, reservoir evaporation, transfer prices, etc.

Comparing alternatives under deep uncertainty

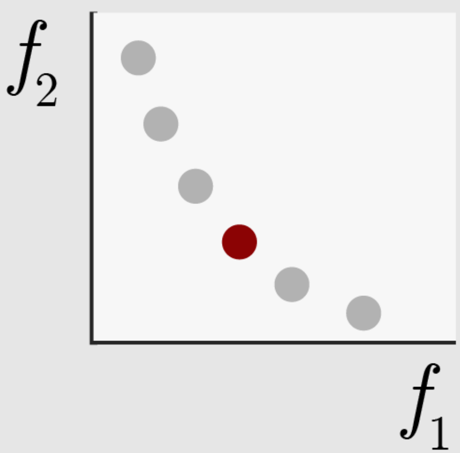
Robustness: The number of sampled states of the world in which a solution satisfies the elicited performance requirements

- Seeking "satisficing rather than optimality" (Lempert 2002 PNAS)
- Satisficing concept dates to Simon (1959 Am. Econ. Rev.)

Re-evaluate projected "optimal" solutions in uncertain states of the world

Many-Objective Robust Decision Making (MORDM)

Near-optimal solutions in expected future



MORDM: Kasprzyk et al. 2013 *Env. Mod. Soft.*

Individual Solution Robustness across Sampled States of the World

Fraction of states of the world in which solutions satisfy the conditions:
Reliability > 99%
Restriction Frequency < 20%
Worst-Case Costs < 5%

Our projected "optimal" solutions are not robust and may cause tension between stakeholders

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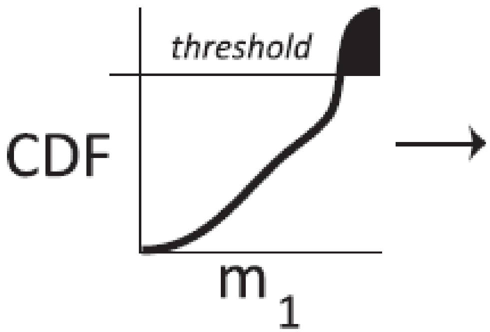
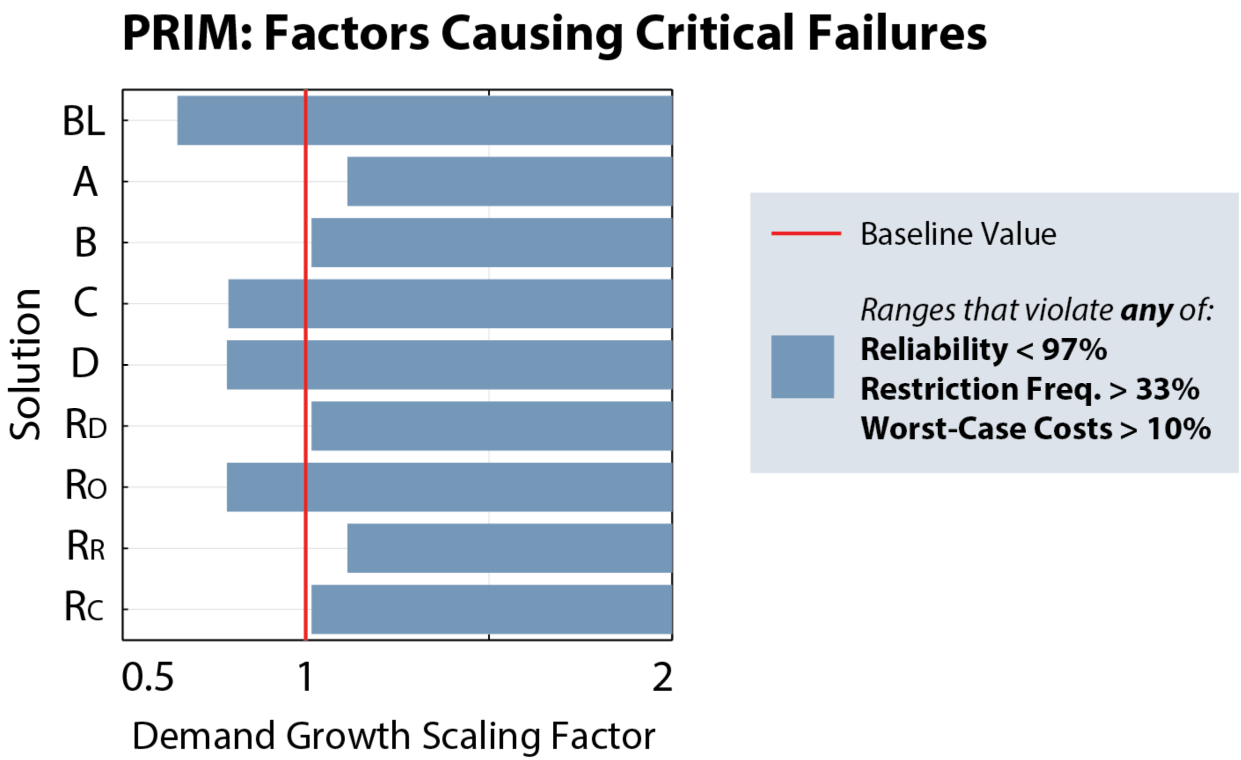
Global sensitivity analysis: Patient Rule Induction Method (PRIM)



Step 1: Set percentile performance threshold using one or more measures, (m)

Kasprzyk et al. 2013 *Env. Mod. Soft.*

The rate of demand growth is the factor most likely to violate the utilities' failure thresholds



Other factors such as climate, seasonal demand patterns, etc. not found to be influential

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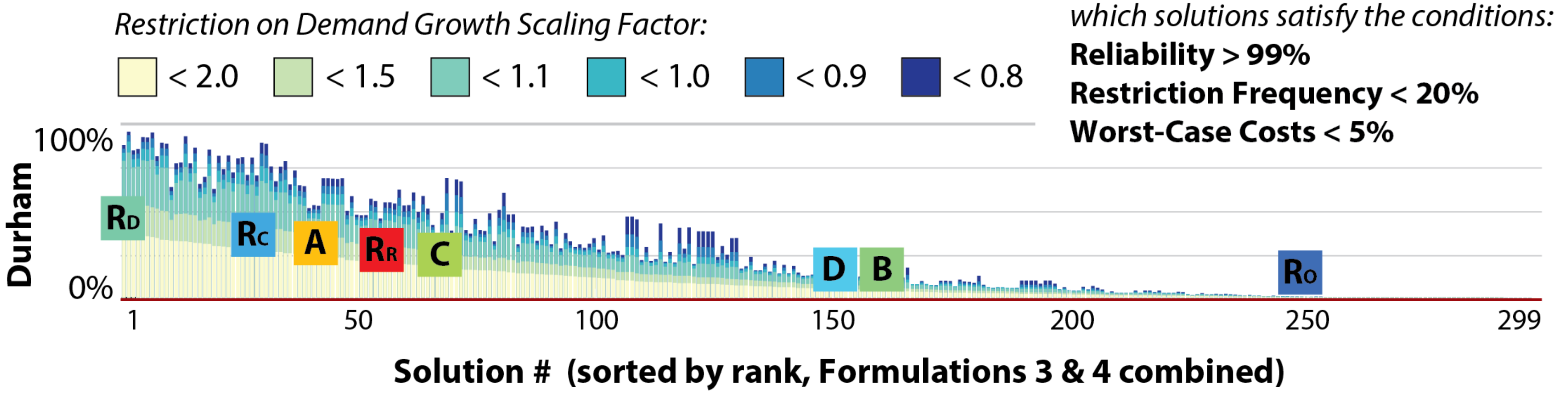
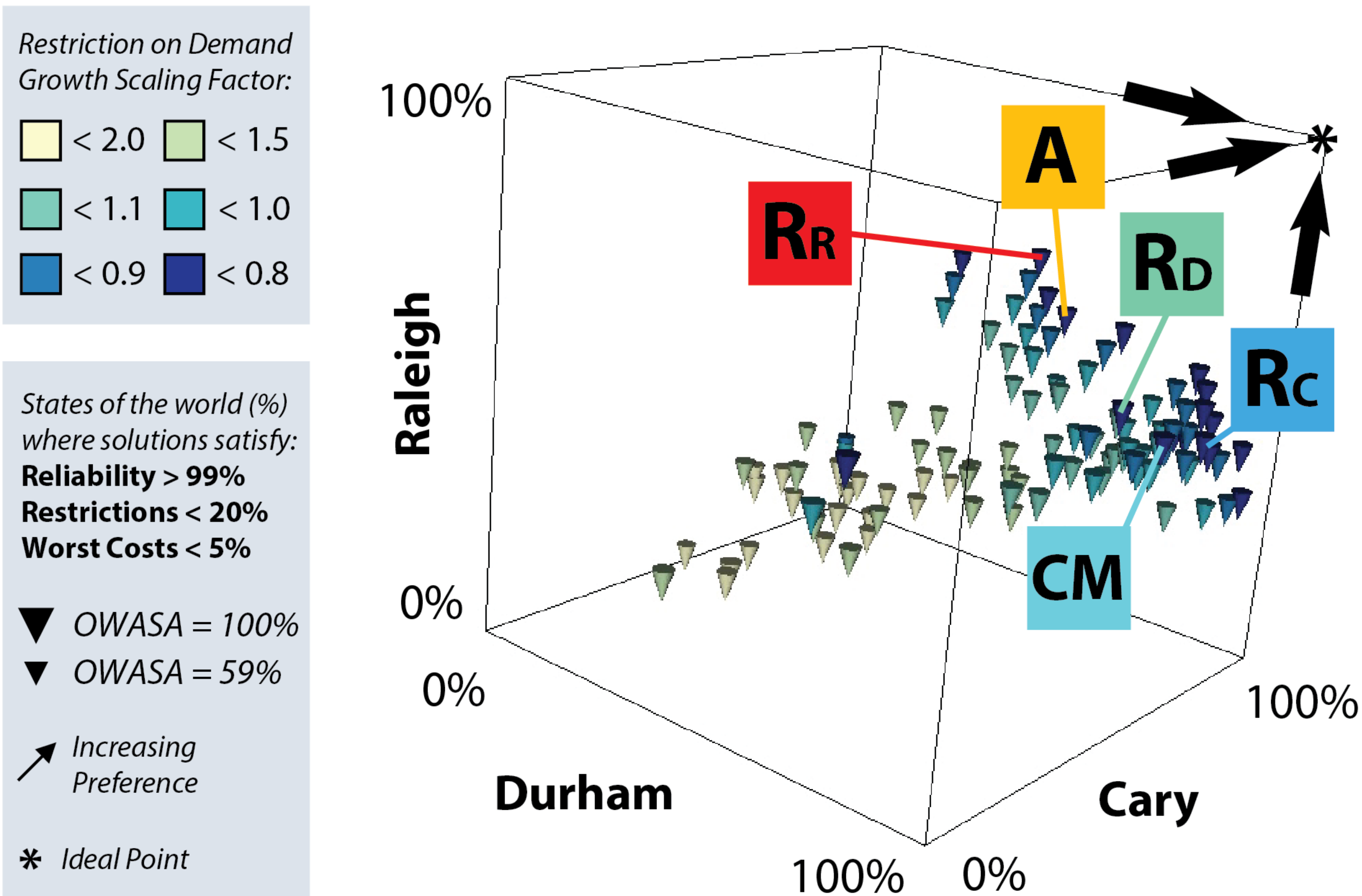
Robustness after Demand Growth Mitigation



Robustness tradeoffs between stakeholders suggest a compromise solution (CM)



Key Points Highlighted for IAM Discussion

Water is a "wicked problem" with a long history of impacts assessments that should not be ignored.

"Change" is the operative word and climate may not be the headline issue in every future decade.

Predictions under change pose some serious questions about our current knowledge & modeling of these systems.

Uncertainty/risk are critical drivers. Deep uncertainty is a current major focus.

Observations & information systems matter!! Including them in policy analysis makes the "math" pretty difficult though.

Governance, institutions, incentives, evolving demands…not a bad idea to carefully understand the validity of your modeling assumptions.