Managing Population and Drought Risks using Many-Objective Water Portfolio Planning under Uncertainty

Joseph R. Kasprzyk and Patrick M. Reed

Civil and Environmental Engineering

The Pennsylvania State University

jrk124@psu.edu, preed@engr.psu.edu

Brian R. Kirsch and Gregory W. Characklis

Environmental Sciences and Engineering

University of North Carolina Chapel Hill

2010 Technology Management Policy Graduate Consortium

Cambridge, England June 2010

Collaborators

Patrick M. Reed
Associate Professor
The Pennsylvania State University

Gregory W. Characklis
Associate Professor
University of North Carolina at Chapel Hill

Brian R. Kirsch
Graduate Student
University of North Carolina at Chapel Hill

For more about this study, please see:
Kasprzyk, J. R., et al. (2009). “Managing population and drought risks using many-objective water portfolio planning under uncertainty”, *Water Resour. Res.*, 45, W12401, doi:10.1029/2009WR008121.

National Science Foundation
WHERE DISCOVERIES BEGIN
NSF CAREER grant CBET 0640443

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

Threats to Urban Water Supply

- Population growth and supply variability threaten urban water supplies
  - IPCC recommends water markets and portfolio planning
- Water markets allocate water to its "highest value use" through transfers between regions or sectors
  - **Permanent rights**: traditional non-market supply (% of reservoir inflows)
  - **Spot leases**: immediate transfers of water, variable price
  - **Adaptive options contract**: reduces lease-price volatility (similar to European call stock option)

Research Motivation

- Our goal is to help water planners better understand how to use water markets and portfolio planning
- This study contributes the first **many-objective tradeoff analysis** of water portfolio planning
- Challenges
  - Need portfolio planning strategies that are **flexible** and **robust to change** (pop. growth, land use change)
  - Need to more accurately capture **severe risk aversion** in water supply planning problems

Introduction: Multi-Objective Optimization

- Two Objective Example:
  - Dominance
  - Non-dominance
  - Pareto Set
- Tradeoffs or Conflicts:
  - Small increases in "Cost" initially result in big "Error" decreases (blue arrows)
  - Further decreases in "Error" require big increases in "Cost" (red arrows)

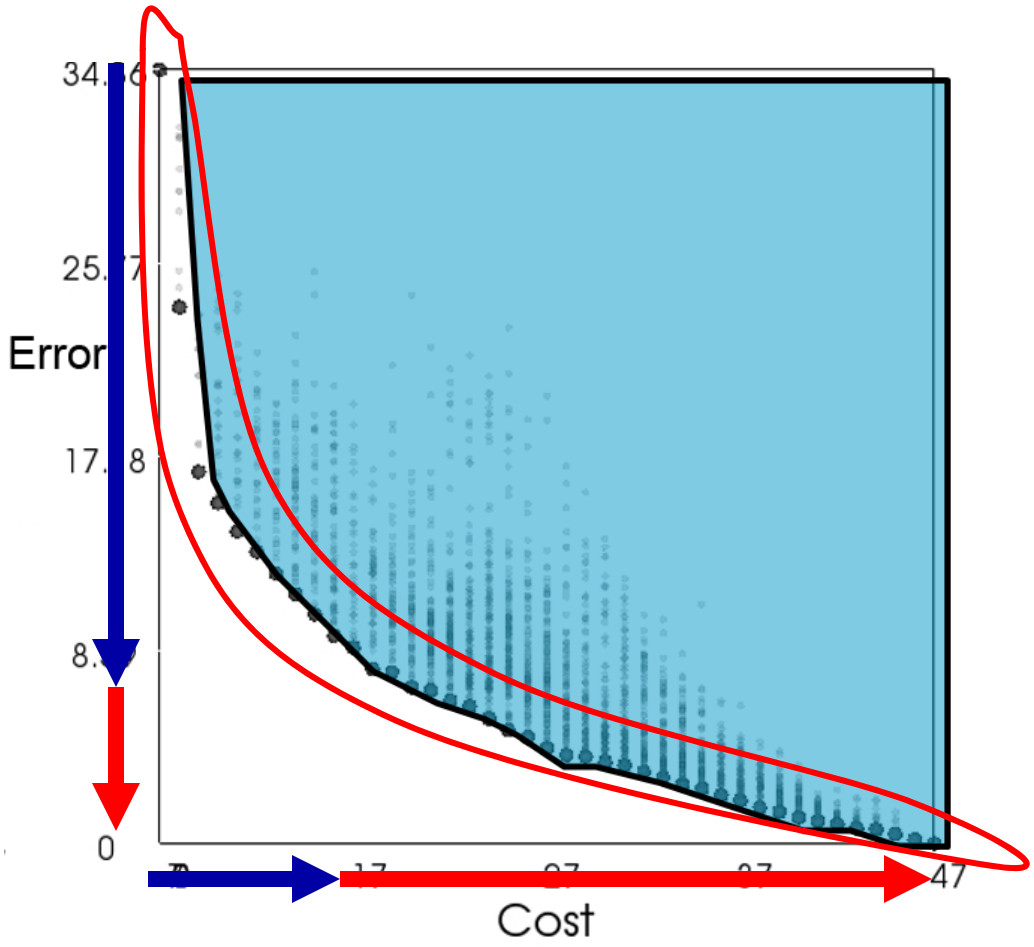


Figure adapted from J. Kollat 2007

Case Study: Lower Rio Grande Valley, Texas USA

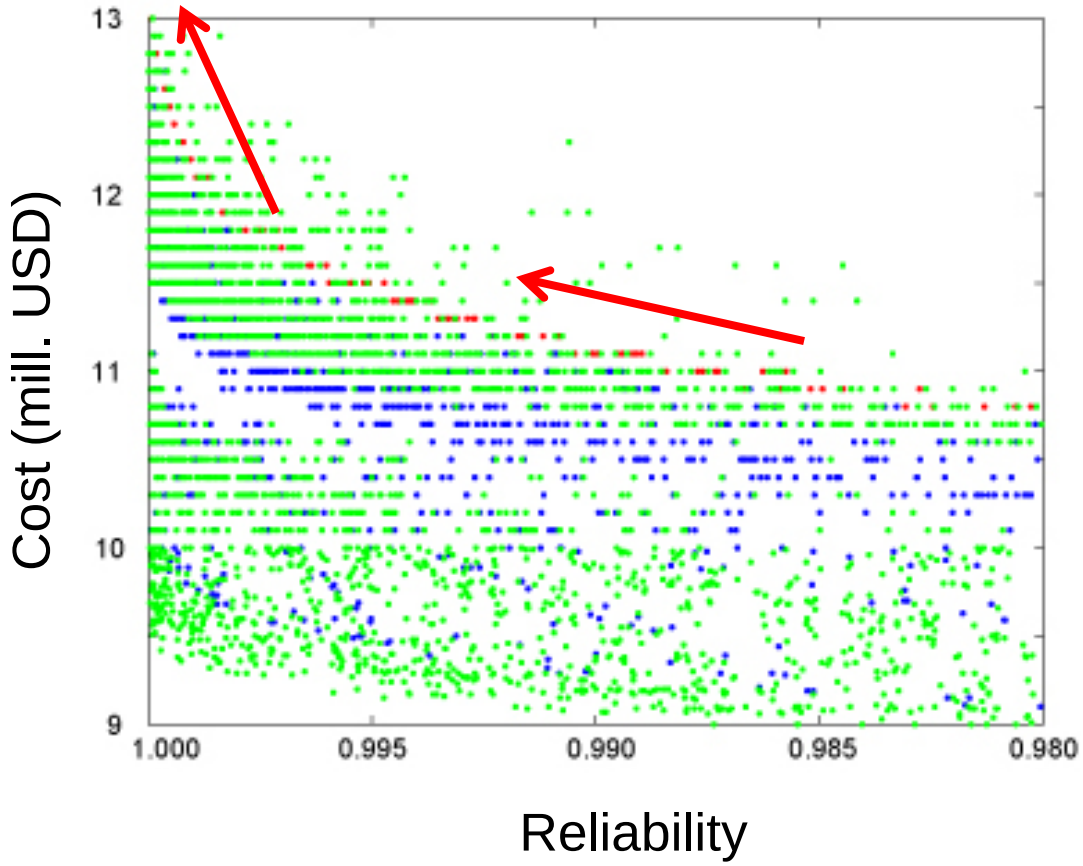
- Active water market, 85% water use for irrigation
- Research question
  - Is it possible to increase reliability and decrease water supply surpluses, while also lowering cost?
- Monte Carlo simulation model
  - Supply decisions for a single city
  - Anticipatory **risk-based rules** for options and leases
  - Monte Carlo simulation of hydrology, demands, lease pricing
  - 10-year planning horizon
- Find nondominated solutions for up to six planning objectives using Multiobjective Evolutionary Algorithms (MOEAs)

Analysis of Added Supply Instruments

Case	Decisions	Objectives	Constraints
A: Rights Only	•Permanent Rights Volume	•Cost •Reliability •Surplus Water	•Reliability > 98%
B: Rights and Options	•Options Contract •Planning Thresholds: Options	•Cost Variability •Dropped Transfers	•Cost Variability < 1.1
C: Rights, Options, Leases	•Planning Thresholds: Options and Leases	•Number of Leases	
D: Critical Constraint			•No Critical Failures

Results: Cost / Reliability Tradeoffs

- Case A :
  - Limited flexibility
  - Increasing marginal cost of reliability (red arrows)
- Case B:
  - Cost Savings
  - Dampened marginal cost
- Case C:
  - Adding leases provides a large number of alternatives.
  - Greatest cost savings **at each level** of reliability

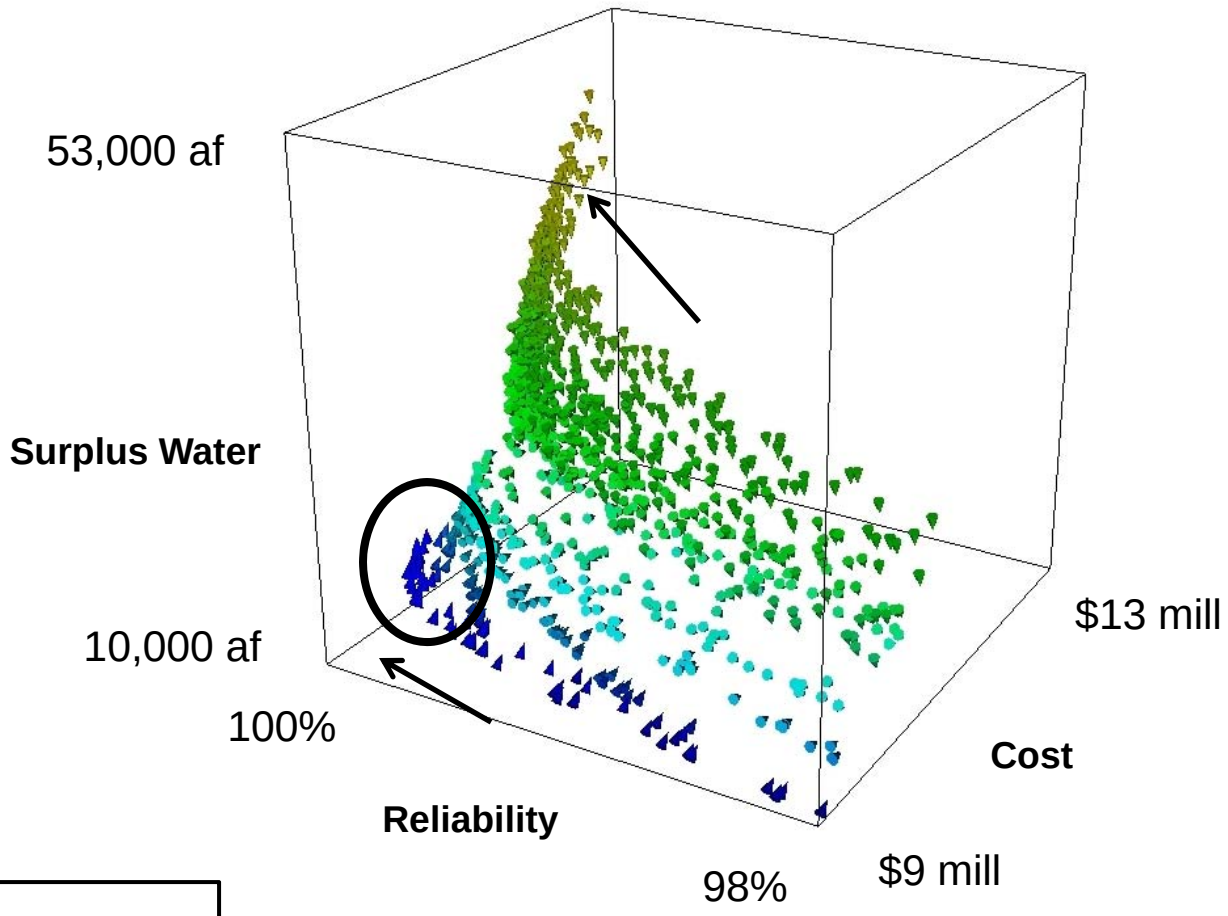


However … Traditional visualization is limited. Additional objectives? How do supply instruments affect performance?

Results: Case B

Rights - Options

- Highly reliable solutions:
  - Lower permanent rights cost (changing **color**)
  - Decreased surplus water
  - Lower marginal cost
- Highlighted portfolios have increasing volumes of exercised options (**orientation** pointing up).



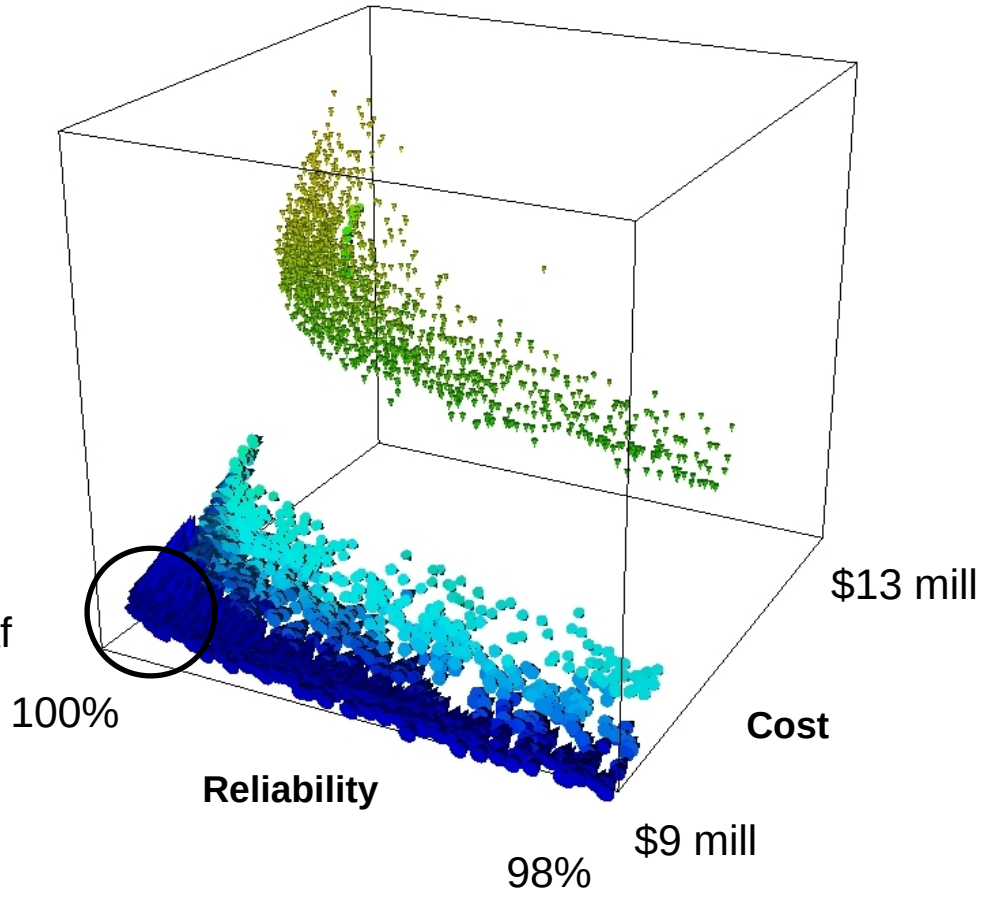
Color: Perm. Rights (x1000 af)
30 **60**

Orientation: Vol. Exercised Opt. (x 100,000 af)
0 ***Down to Up*** **160**

Legend

Results: Case C

- Complex surface with discontinuities
  - Distinct portfolio strategies (high rights, low rights)
  - Monthly flexibility of options vs. discrete rights/options
- High reliability, low surplus solutions **blend** both leases and options



Color: Perm. Rights (x1000 af) **30** — **60**	**Orientation:** Vol. Exercised Opt. (x 100,000 af) **0** ▼ ***Down to Up*** ▲ **160**
Size: Vol. Leases (x 1000 af) **0** — **25**	▲ ***Small to Large*** ▲

Legend

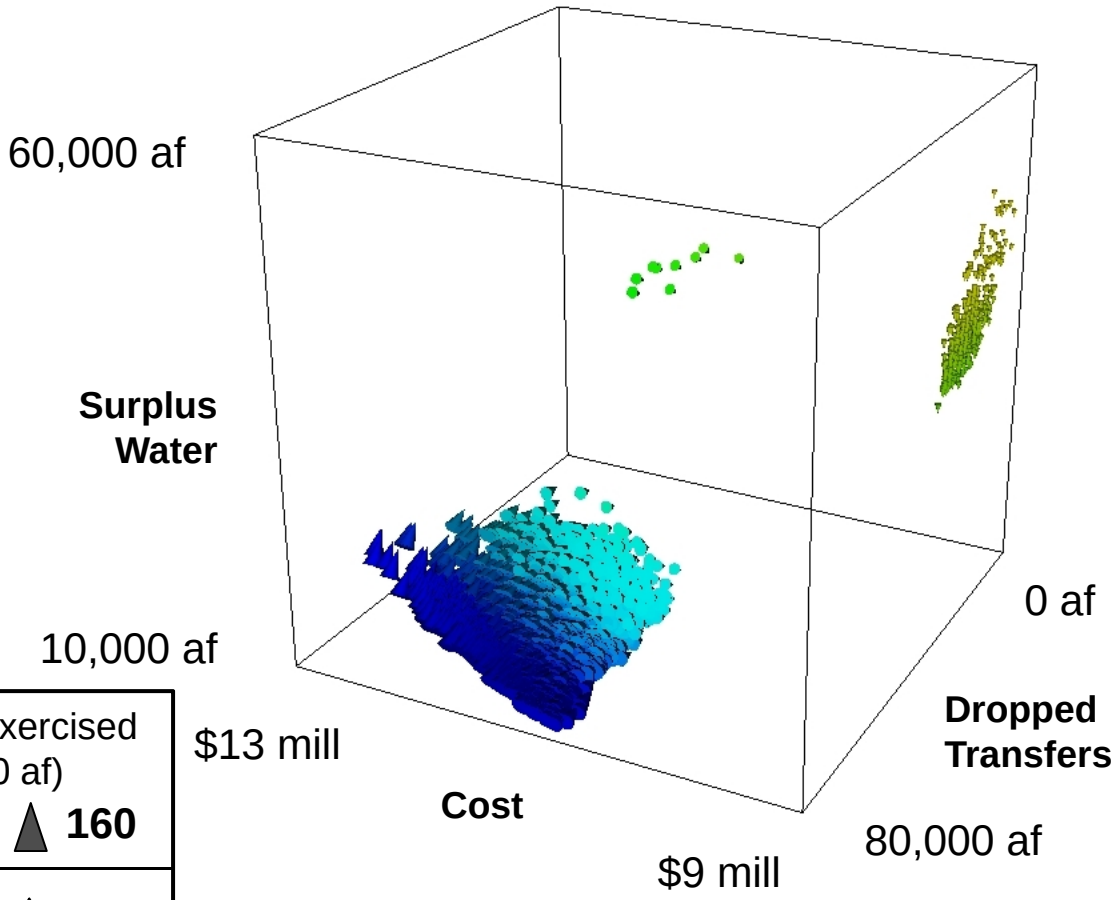
Lessons from Cases A - C

- We found **distinct portfolio types** and surprising objective interactions
  - Flexibility was critical to preventing failures (highest-performing alternatives mixed all supply instruments)
  - The analysis promoted a better understanding of planning rules and objective interactions
- Can we modify our formulation to more accurately capture **risk-aversion** and **rigorously test** the results?

Case D Constraint: **No month** in any realization has Supply < 60% of Demand.

Results: Case D

- Islands of feasible solutions
  - Only reliability > 99.5% (some failures in A – C were critical)
  - Long-term risks difficult to identify
  - Are optimal solutions "standing on a needle"?
- Diverse range of portfolios
  - Higher dropped transfers for options/leases portfolios
  - Perm. Rights portfolios: high cost, surplus



Color: Perm. Rights (x1000 af)
30 **60**

Orientation: Vol. Exercised Opt. (x 100,000 af)
0 ***Down to Up*** **160**

Size: Vol. Leases (x 1000 af)
Small to Large
0 **25**

Legend

Drought Scenario

Test solutions in a single-year:

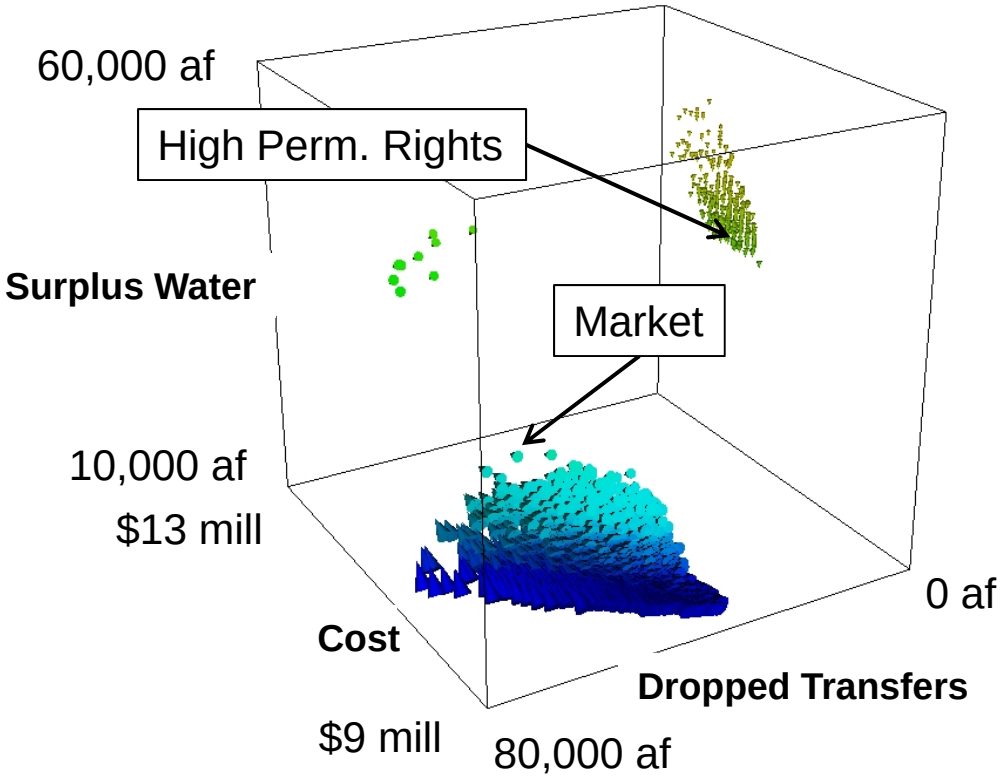
Highest projected monthly demand

Driest year on record

How will the selected solutions perform in this extreme scenario?

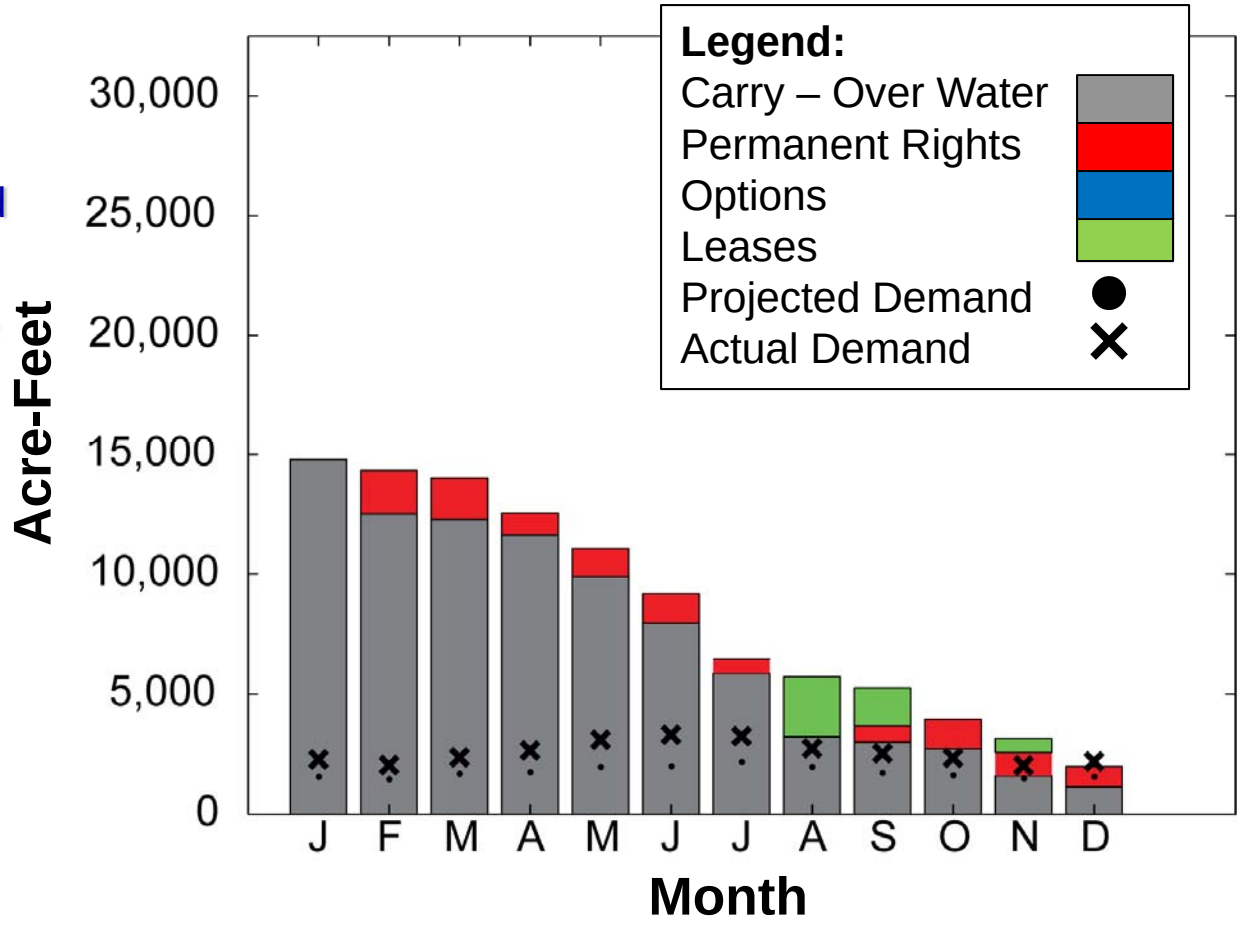
Drought Scenario

- Solution 1: High Permanent Rights
  - $11.5 mil., 49k af rights, 600 af dropped transfers
  - Number of leases – 0.5
- Solution 2: More Market Use
  - $11.0 mil, 40k af rights, 54k af dropped transfers
  - Number of leases – 1.1



Solution 1 (Permanent Rights Dominate)

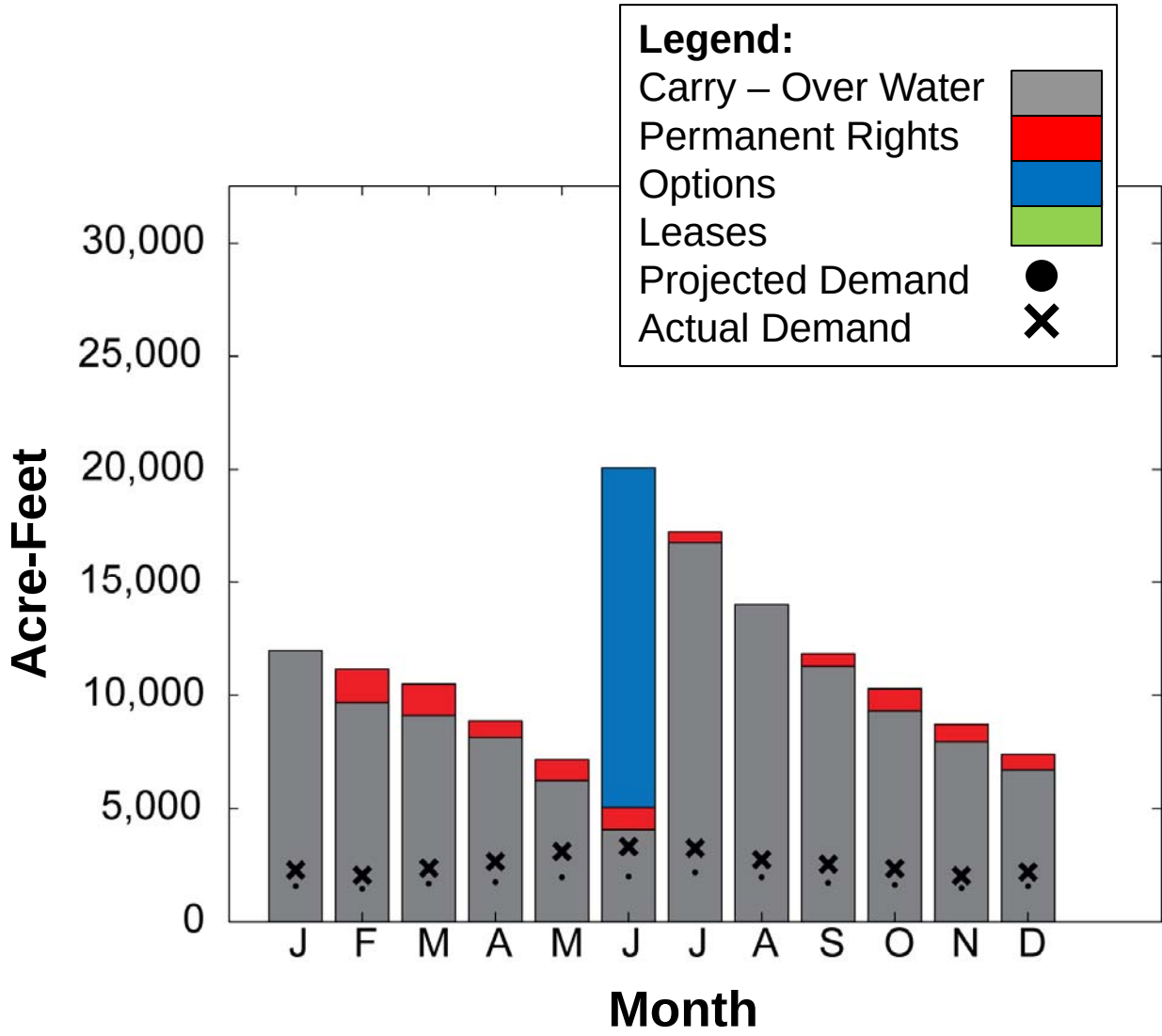
- Effect of surplus water
  - Carry-over supply decreases with low inflow (drought) and high demand
  - Minor failure in December
- Drought year caused city to rely on leases (much more than in 10-year scenario)
  - Low inflows and high demands are unexpected
  - Lease acquisitions not sufficient to avoid December failure



Solution 1 (10-year): Cost $11.5 mil, Surplus 37k af, Dropped Transfers 598 af, Leases 0.5
Solution 2 (10-year): Cost $11.0 mil, Surplus 21k af, Dropped Tranfsers 54k af, Leases 1.1

Solution 2 (Market)

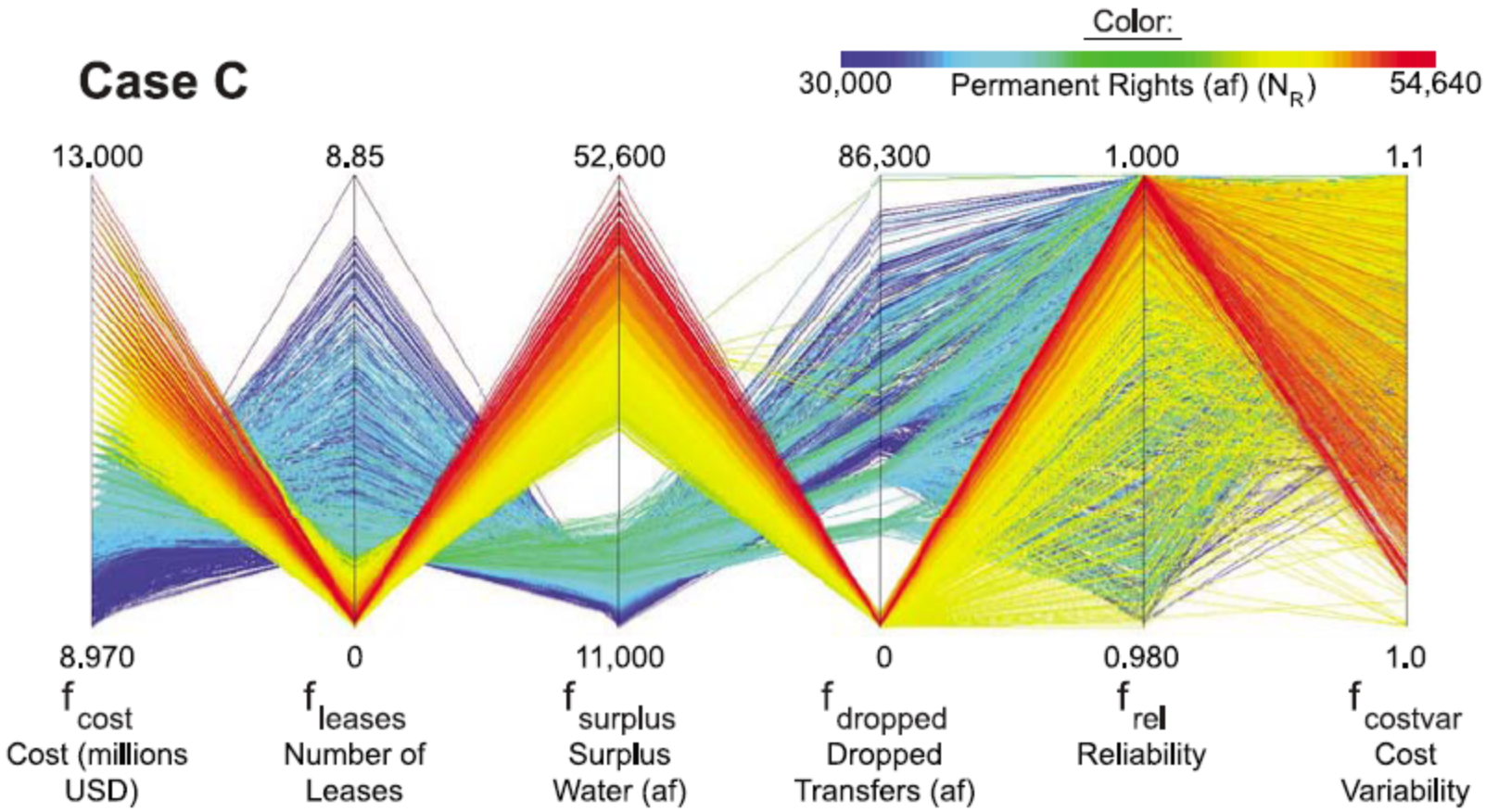
- Effective combination of rights and options
  - More conservative options contract
  - Exercised options provide large supply, but city still ends year with less water than in Jan.
- Demonstrating distinct portfolio types
  - Interaction between rights, options, leases
  - Finding portfolios that are adaptive under drought conditions



Solution 1 (10-year): Cost $11.5 mil, Surplus 37k af, Dropped Transfers 598 af, Leases 0.5
Solution 2 (10-year): Cost $11.0 mil, Surplus 21k af, Dropped Tranfsers 54k af, Leases 1.1

Conclusions

- A many-objective analysis with evolving problem formulations showed **distinct portfolio types** and **tradeoffs** between planning objectives
- A drought analysis exhibited that **risk aversion** and **uncertainties** represent mathematical challenges, aided by optimization, visualization, and solution exploration
- The approach used in this work has potential for **confronting cognitive challenges** for decision making under uncertainty, facilitating discovery and negotiation



Thank You! Questions?

E-mail: jrk301@psu.edu
Site: http://water.psu.edu/reed/home.htm