



**Building Resilience to a Changing Climate:
A Technical Training in Water Sector
Utility Decision Support**

Methods for Decision Making Under Conditions of Deep Uncertainty

Robert Lempert, RAND

Water Planners Have Extensive Experience Managing Uncertainty

For instance, California's water system uses many options to manage large hydrologic variability, including:

- Safety factors (e.g. build more supply than projected demand)
- Operational rules (e.g. demand restriction schedule during droughts)
- Infrastructure with performance relatively insensitive to uncertainties (e.g. storage, demand reductions, conveyance)
- Diverse supply (e.g. surface water from three basins; local ground water, recycling rain water capture, desal, etc.)
- Adaptive decision strategies (e.g. regular plan updates, near-term actions designed to create future options)

So Why Introduce New Methods for Decision Making Under Conditions of Deep Uncertainty?

Today's challenges demand new approaches, because:

- The uncertainties are large, and will get even bigger over time
- Water systems face more constraints
- Increased demand for citizen engagement
- Better methods and tools for managing uncertainty have become available

DMDU Methods and Tools Can Help Water Managers Address Today's Uncertain Conditions

Our current and future climate is not the same as past climate, and no one is sure exactly how it has and will change

Some basic DMDU principles

1. Consider multiple futures, not one single future, in your planning. Choose these futures to stress test your organization
2. Seek robust plans that perform well over many futures, not optimal plans designed for a single, best-estimate future
3. Make your plans flexible and adaptive, which often makes them more robust

There are many ways, small and large, to fold these principles into your organization.

Outline

Introduction

Decision making under deep uncertainty (DMDU)

Example DMDU Application (RDM)

Other DMDU Approaches

Getting Started

What is a Good Decision?

**Seemingly reasonable decisions can turn out badly,
bad decisions can turn out well**

Good outcome \neq Good decision

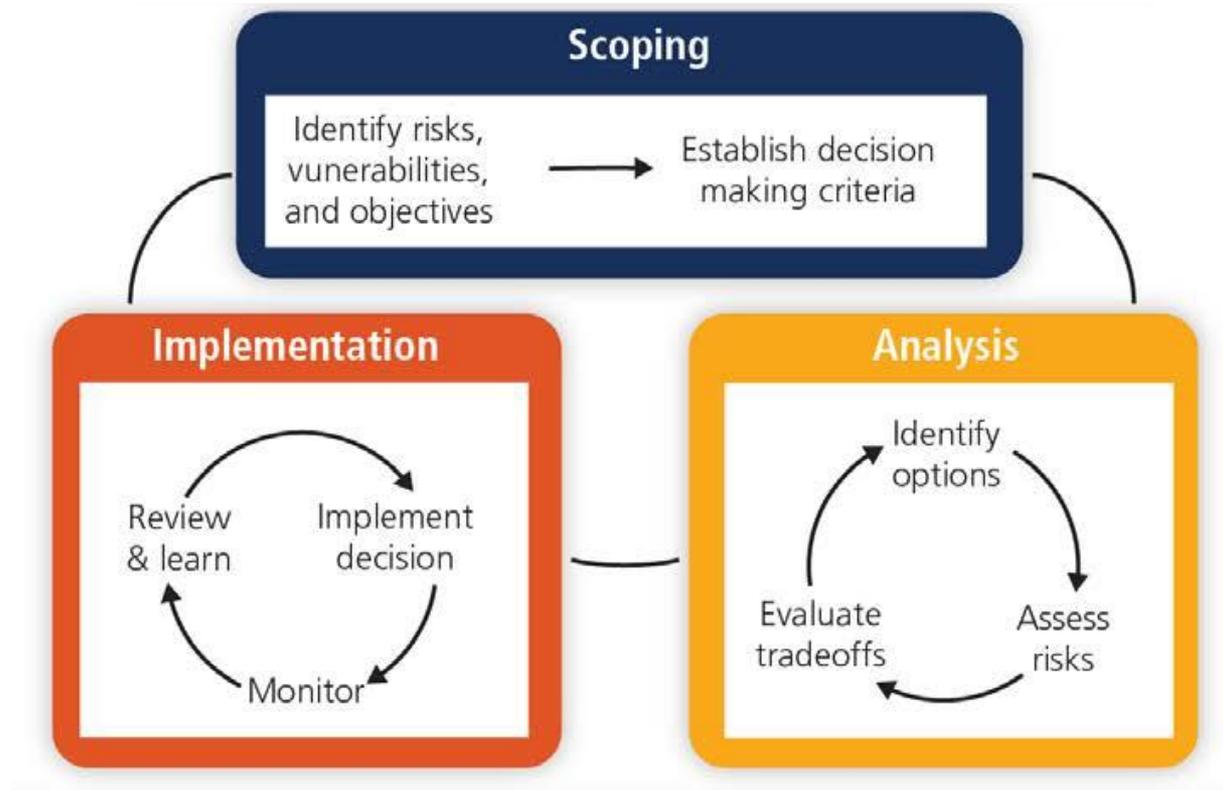
What is a Good Decision?

No universal criterion exists, but good decisions tend to emerge from processes in which people:

- Are explicit about their goals
- Consider a range of alternative options
- Consider tradeoffs
- Use best available science to understand the potential consequences of their actions
- Listen to others and contemplate decisions from a wide range of views and vantages
- Follow agreed-upon rules and norms that enhance the legitimacy of the process and its outcomes

Good Climate-Related Decisions Generally Require Iterative Risk Management

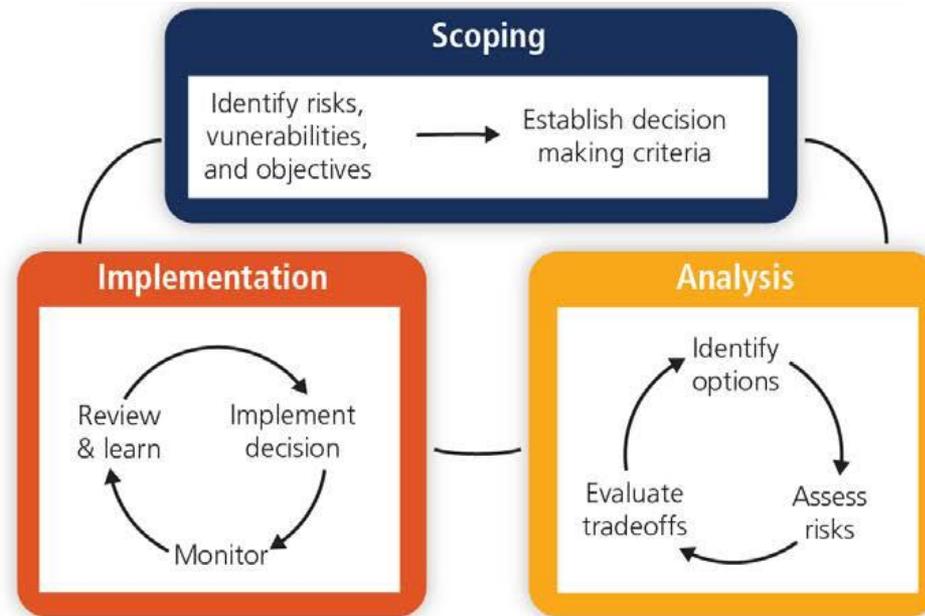
This is how the IPCC describes this very general process



The word “risk” is used here very broadly, as the potential for consequences when something we value is at stake and the outcome is uncertain

Our Four Adaptation Steps Are One Example of Iterative Risk Management

1. Understand

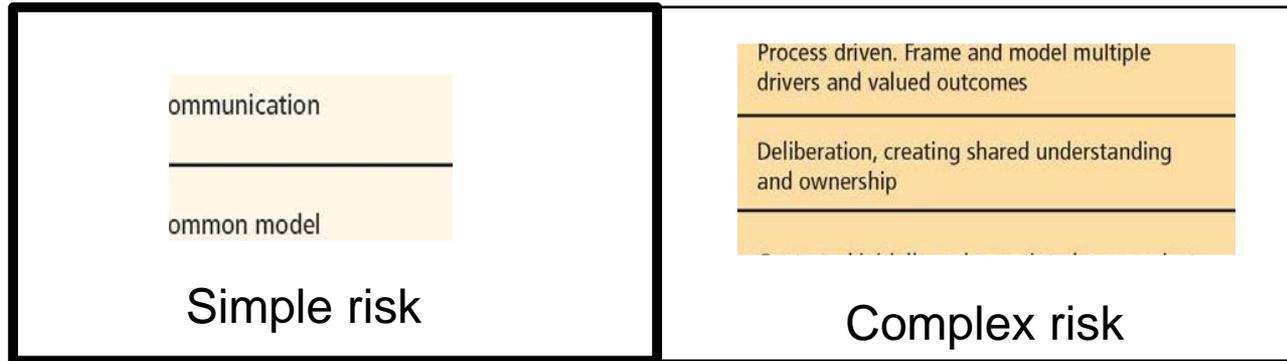


2. Assess
3. Plan

4. Implement

Crucial to Recognize Different Types of Risk

The IPCC considers simple and complex risk



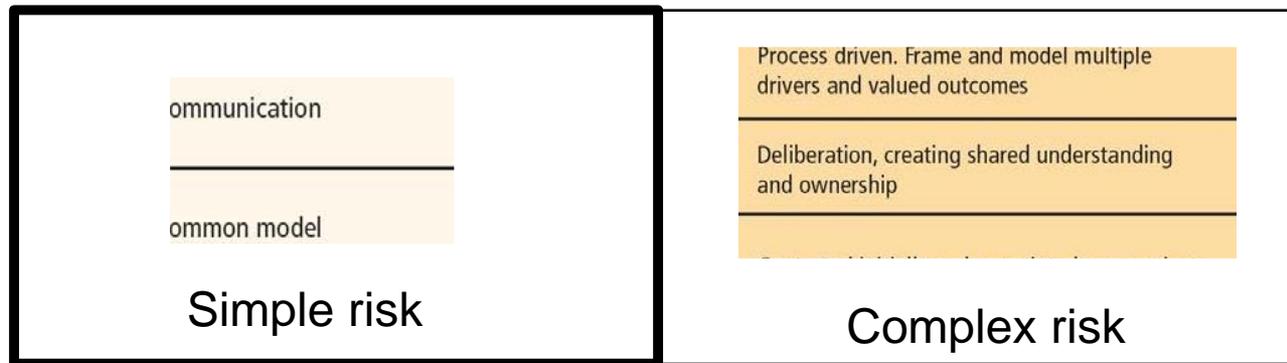
(Simple) risk = probability X consequence

Stakeholder strategy

Mental models

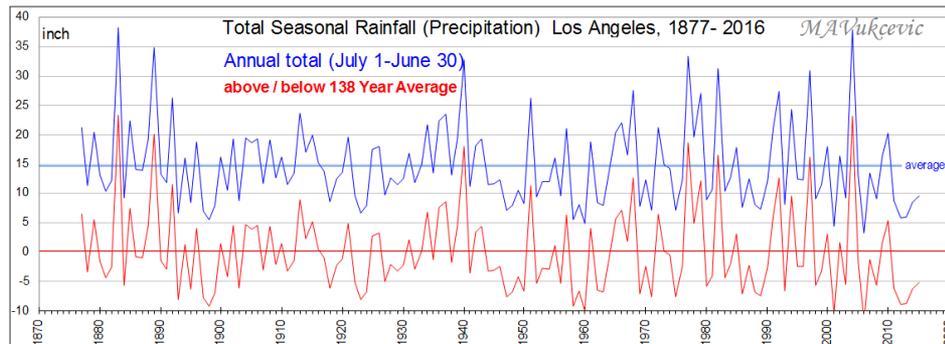
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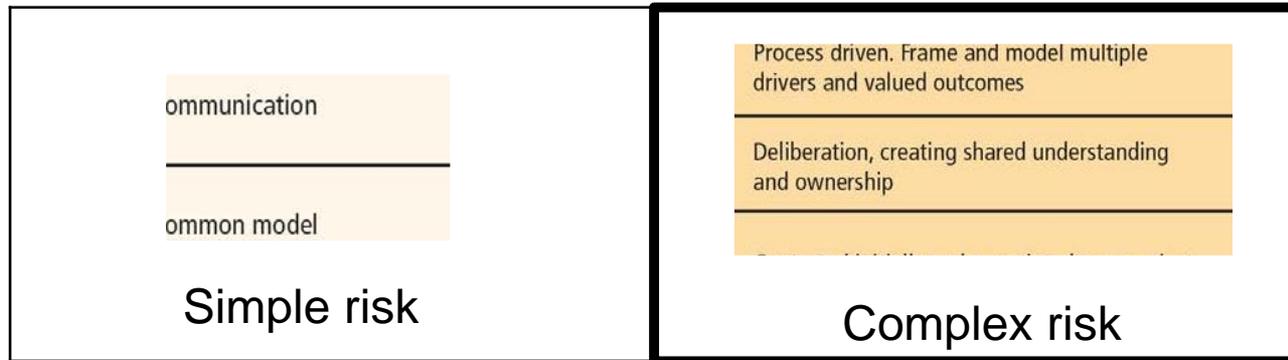
(Simple) risk = probability X consequence

For example, historic climate record have been used to approximate probability of future climate conditions

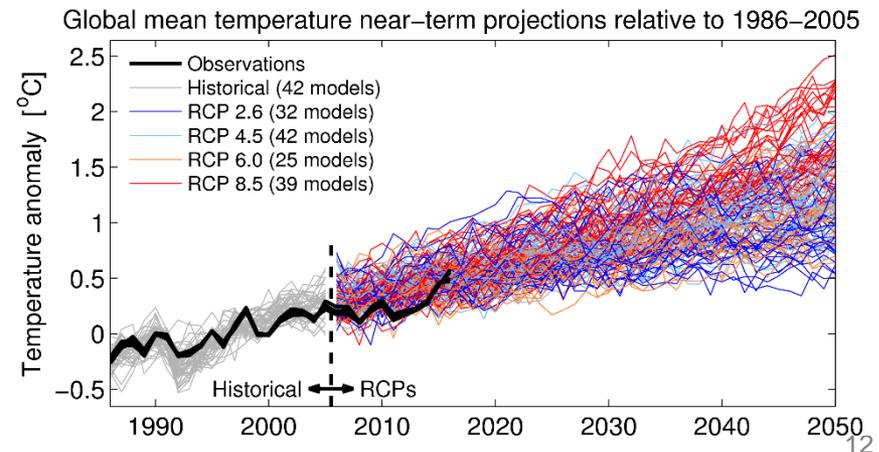


Crucial to Recognize Different Types of Risk

The IPCC considers simple and complex risk

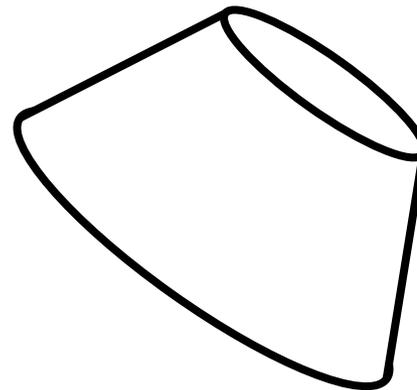
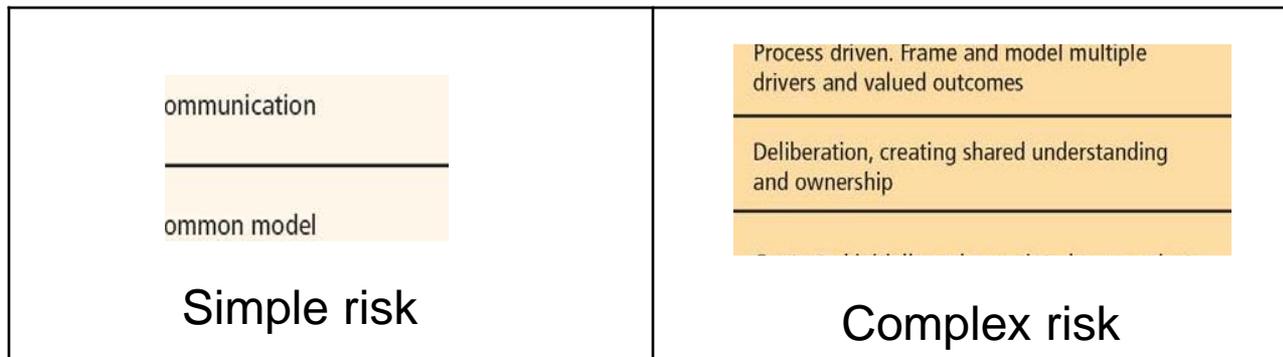


But future climate is a complex risk



Crucial to Recognize Different Types of Risk

The IPCC considers simple and complex risk



Deep uncertainty occurs when the parties to a decision do not know or do not agree on the likelihood of alternative futures or how actions are related to consequences

Traditional risk management works well when uncertainty is limited

“Agree on Assumptions”

What will future conditions be?



What is the best near-term decision?



How sensitive is the decision to the conditions?



These are sometimes called “optimization methods”

Traditional risk management works well when uncertainty is limited

“Agree on Assumptions”

What will future conditions be?



What is the best near-term decision?



How sensitive is the decision to the conditions?



But under conditions of deep uncertainty:

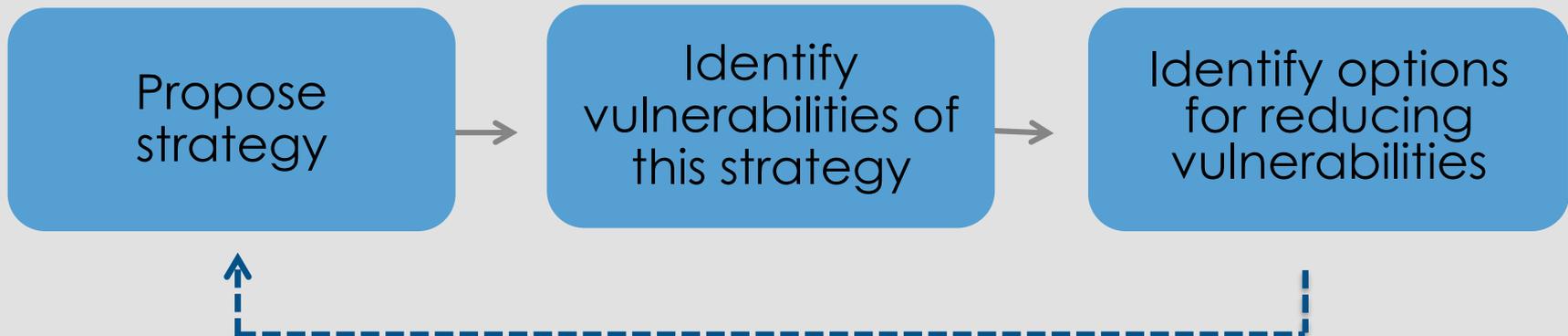
- Uncertainties are often **underestimated**
- Competing analyses can contribute to **gridlock**
- Misplaced concreteness can blind decision makers to **surprise**

Under deeply uncertain conditions, often useful to run the analysis “backwards”

“Agree on Assumptions”



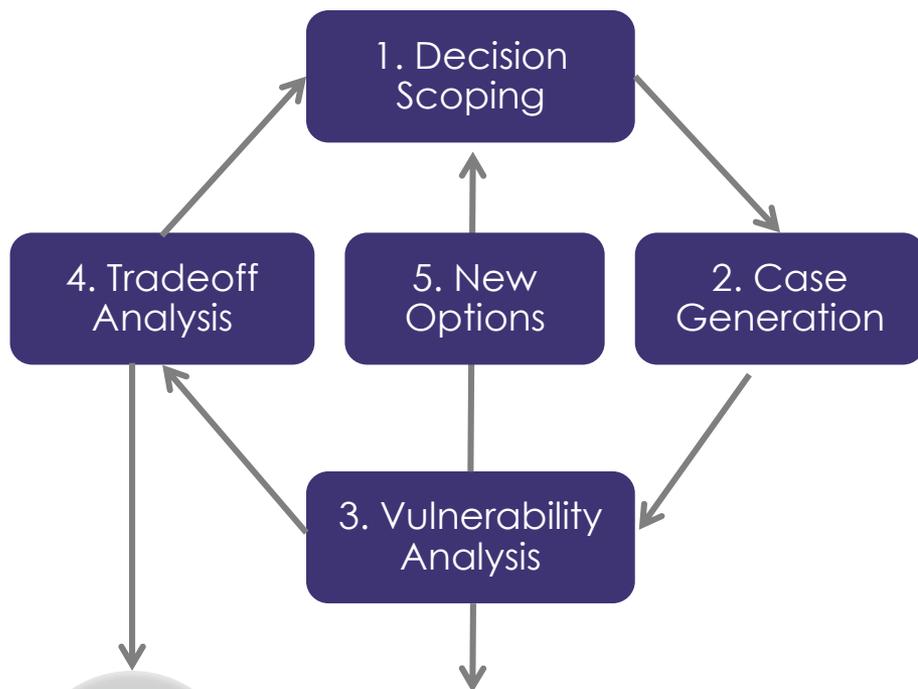
“Agree on Decisions”



Robust Decision Making (RDM) Implements an “Agree on Decisions” Approach

RDM is an iterative analytic process, often used in engagements with stakeholders, designed to support decision making under deep uncertainty

Process:

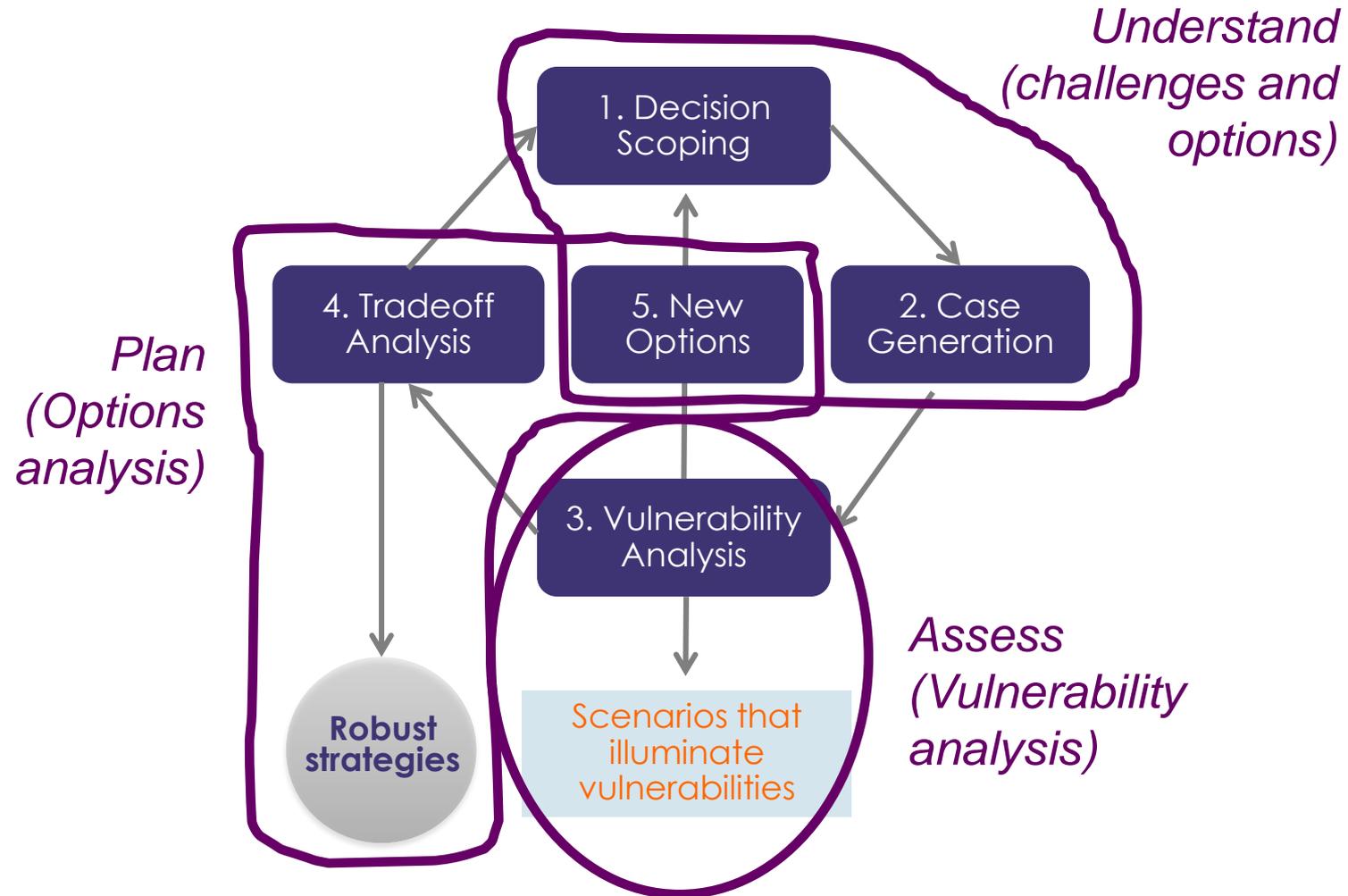


Outcomes:

Robust strategies

Scenarios that illuminate vulnerabilities

RDM Supports Our Adaptation Steps



What is a Robust Strategy?

A robust strategy is one that:

- Performs well over a wide range of plausible futures,
- Trades some optimal performance for less sensitivity to broken assumptions, or
- Keeps options open

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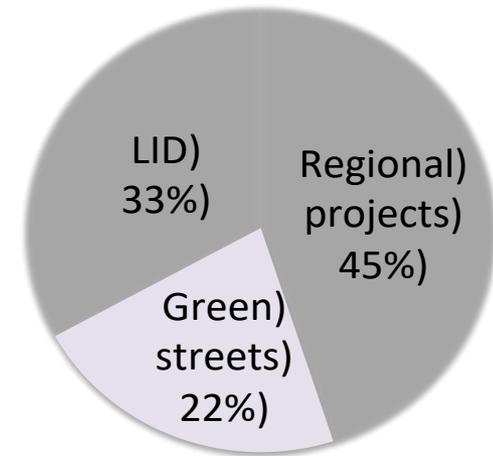
Getting Started

Can Los Angeles Meet Its Water Quality Goals In the Face of Climate Change?

New water quality implementation plans for the Los Angeles River* aim to meet federal standards by 2035



The Plan



Distribution of BMPs (best management practices)

* Our study focuses on Tujunga sub-watershed: 225 square miles (165 sq. miles Los Angeles National Forest + 60 sq. miles urbanized San Fernando Valley floor)

Decision Scoping: Work with decision makers and stakeholders to define key factors in analysis

Decision Scoping

Questions addressed this step include:

- What are our goals and what are options for achieving them?
- What are key factors important to our analysis?
- What tools, data, and models are available?

Decision Scoping: Work with decision makers and stakeholders to define key factors in analysis

Decision Scoping

Decision makers and stakeholders deliberate over issues of concern

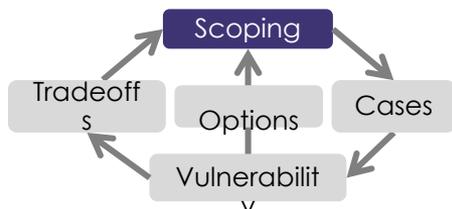


*Will our expensive new water quality investments still meet water quality standards in a changing climate?
If not, what can we do about it?*

List key factors in 'XLRM' Matrix

*Will our expensive new water quality investments still meet water quality standards in a changing climate?
If not, what can we do about it?*

Uncertainty Factors (X)	Policy Levers (L)
Relationships (R)	Performance Metrics (M)



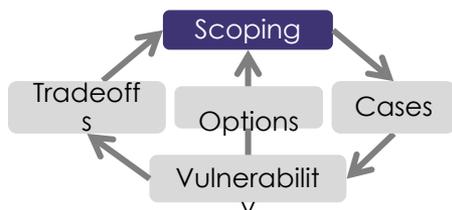
List key factors in 'XLRM' Matrix

*Will our expensive new water quality investments still meet water quality standards in a changing climate?
If not, what can we do about it?*

Uncertainty Factors (X)	Policy Levers (L)
What uncertain factors outside our control affect our ability to pursue our goals?	What actions might we take to pursue their goals?
Relationships (R)	Performance Metrics (M)
How might levers (L) and uncertainties (X) affect goals (M)?	What are we trying to achieve?

R

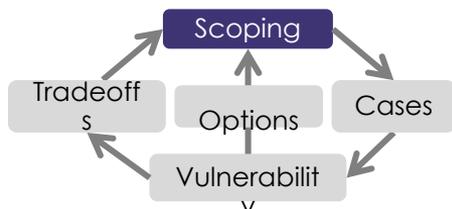
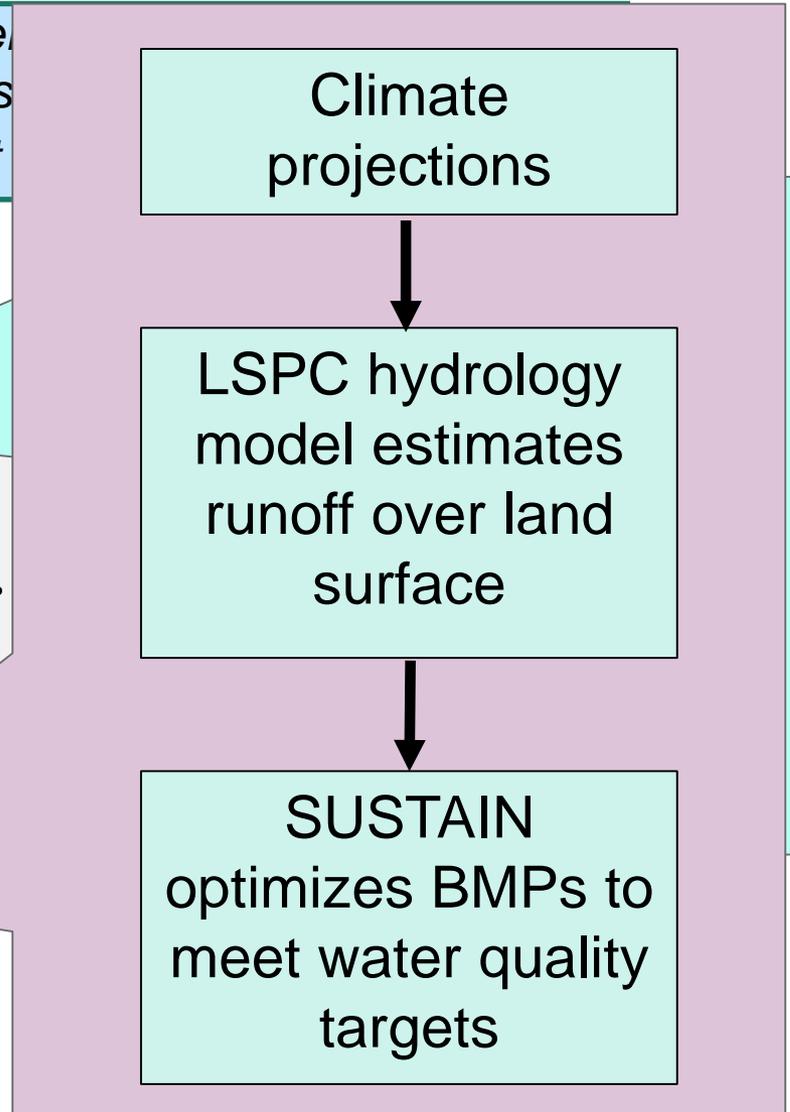
X, L \longrightarrow M



List key factors in 'XLRM' Matrix

*Will our expensive new water treatment plant meet water quality standards?
If not, what can we do about it?*

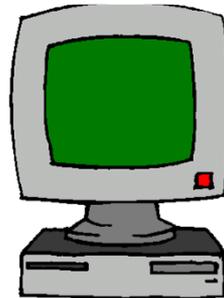
Uncertain Factors (X)
<ul style="list-style-type: none">• Future climate• Future land use
Relationships (models)
<ul style="list-style-type: none">• Simulation models used for regulatory assurance (SUSTAIN & LSPC)



Case Generation: Evaluate Strategy in Each of Many Plausible Futures

Simulating Futures

X	L
R	M

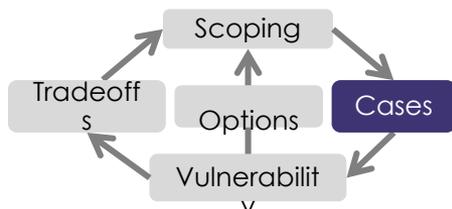
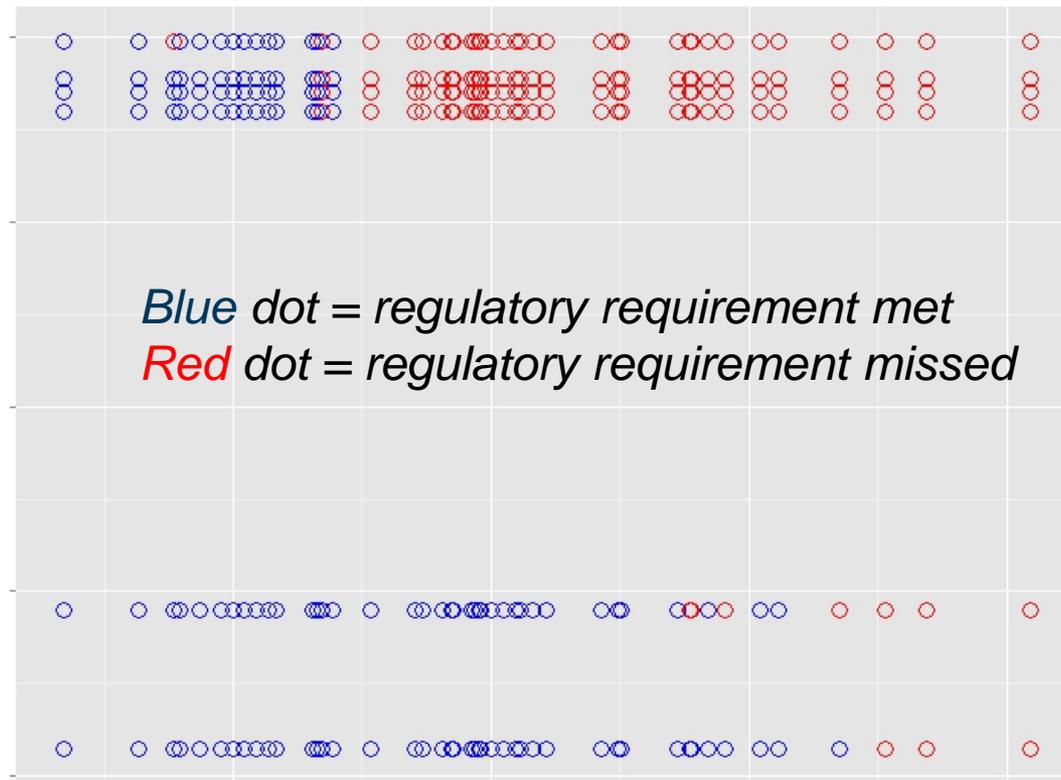


Case Generation

Large database of simulations model results (each element shows performance of a strategy in one future)

Case Generation: Evaluate Strategy in Each of Many Plausible Futures

- Stress test Tujung water quality implementation plan over 47 climate times 6 land use = 282 futures
- Each record in the database (a case) represents the performance of the plan in one future



Vulnerability Analysis: Use the Database of Cases to Identify Policy-Relevant Scenarios

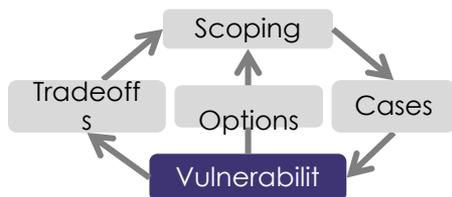
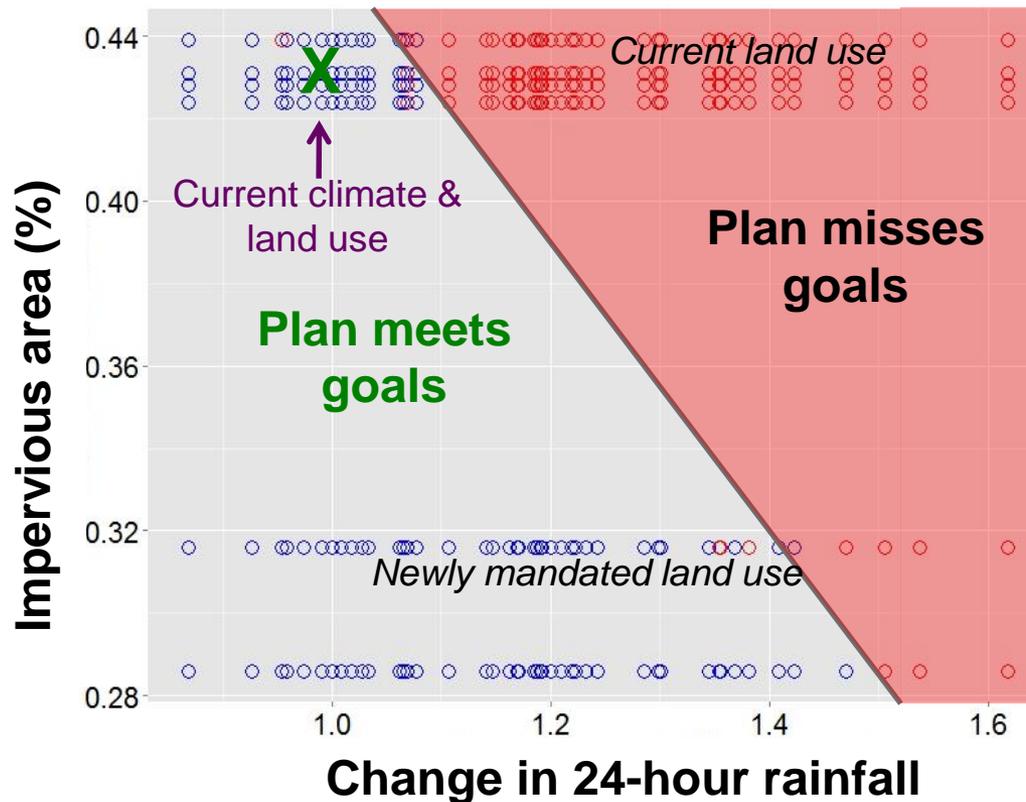
Questions addressed this step include:

- Under what conditions does our plan meet and miss our water quality goals?
- How can we best characterize those conditions with a small number of scenarios?
- Does the available scientific evidence suggest these scenarios are likely enough to justify looking for ways to manage these vulnerabilities?

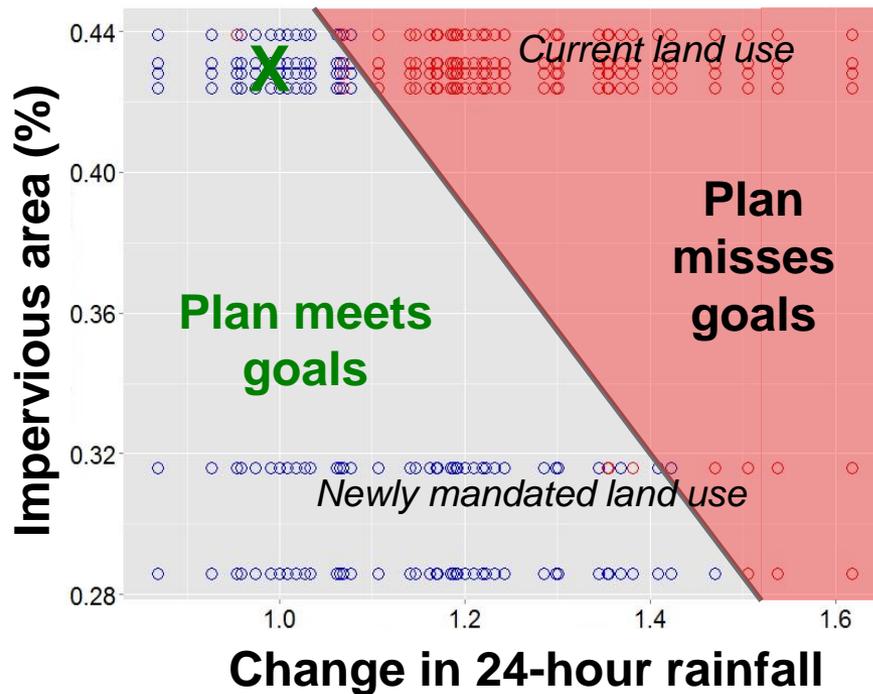
Vulnerability
Analysis

Vulnerability Analysis: Use the Database of Cases to Identify Policy-Relevant Scenarios

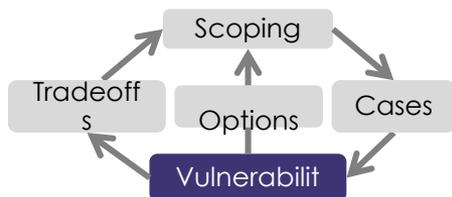
Answer these questions by applying statistical “scenario discovery” classification algorithms to the database of cases



Vulnerability Analysis: Use the Database of Cases to Identify Policy-Relevant Scenarios



- This chart shows a climate stress test
- Results can be interpreted as two scenarios
- Scenario driving forces depend both on climate and socio-economic uncertainties



Two General Ways to Evaluate Strategies' Success or Failure

1. Use standards of absolute performance, such as:
 - Benefit cost greater than 1
 - Regulatory requirements
 - Reliability requirement
2. Measure performance relative to other strategies, for instance using regret
 - A strategies' regret in any future is the difference between its performance and that of the optimal strategy in that future

Agencies are often required to meet performance standards

Measuring performance with regret can be useful when large uncertainties generate a very wide range of plausible outcomes

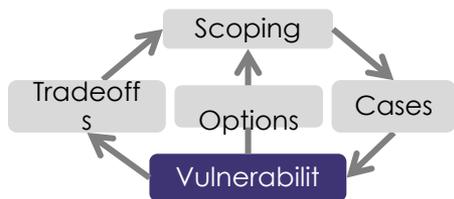
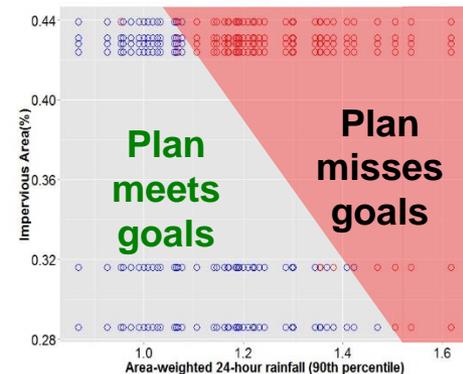
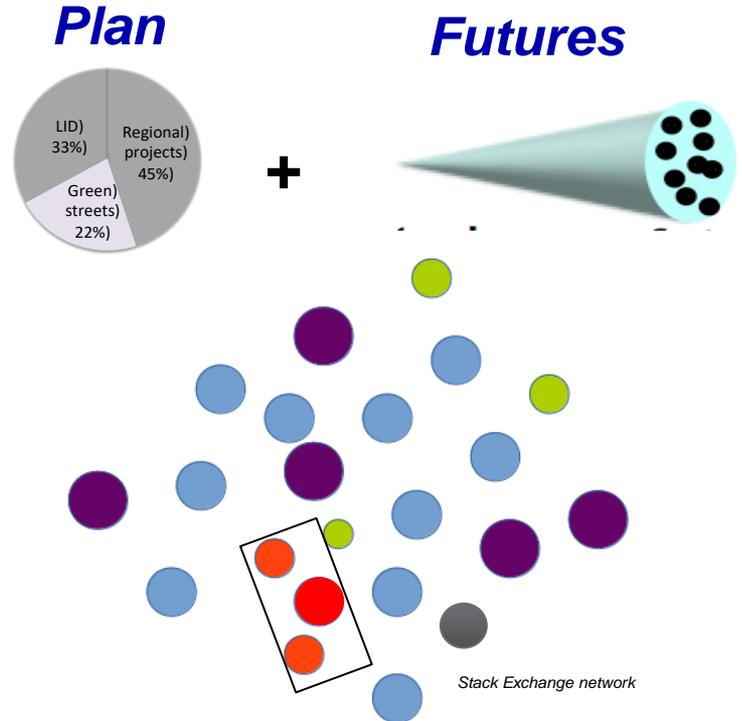
In RDM, Policy-Relevant Scenarios Emerge From Analysis

Run model to stress test proposed policy over many plausible futures

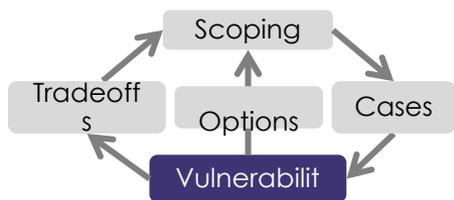
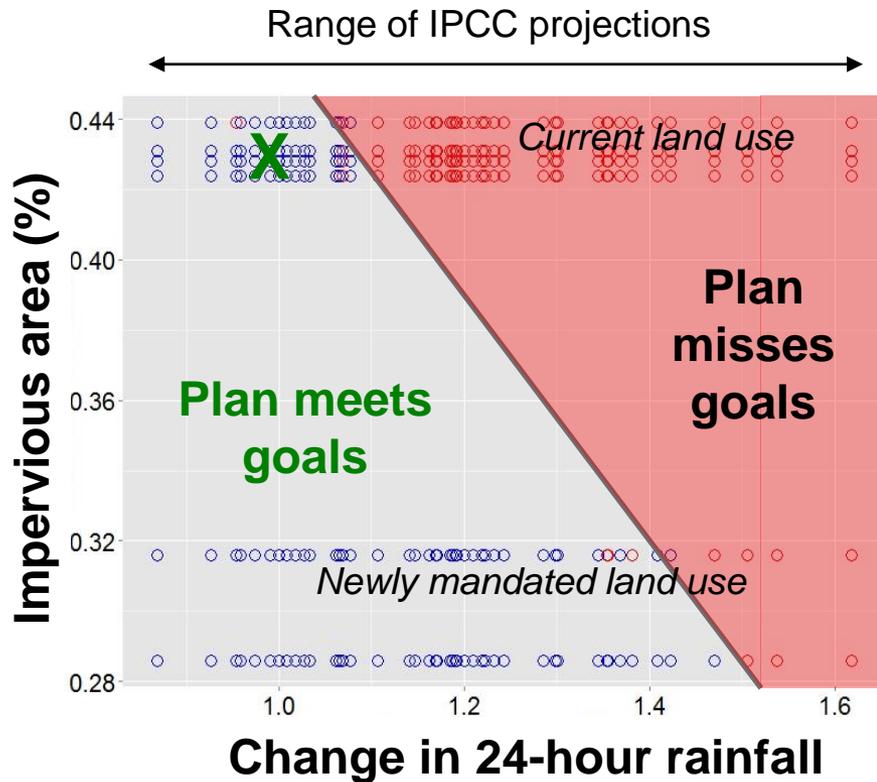
Generate large, multi-dimensional database

Scenario discovery algorithms find interpretable (low dimensional) clusters of policy-relevant cases

Display as policy-relevant scenarios

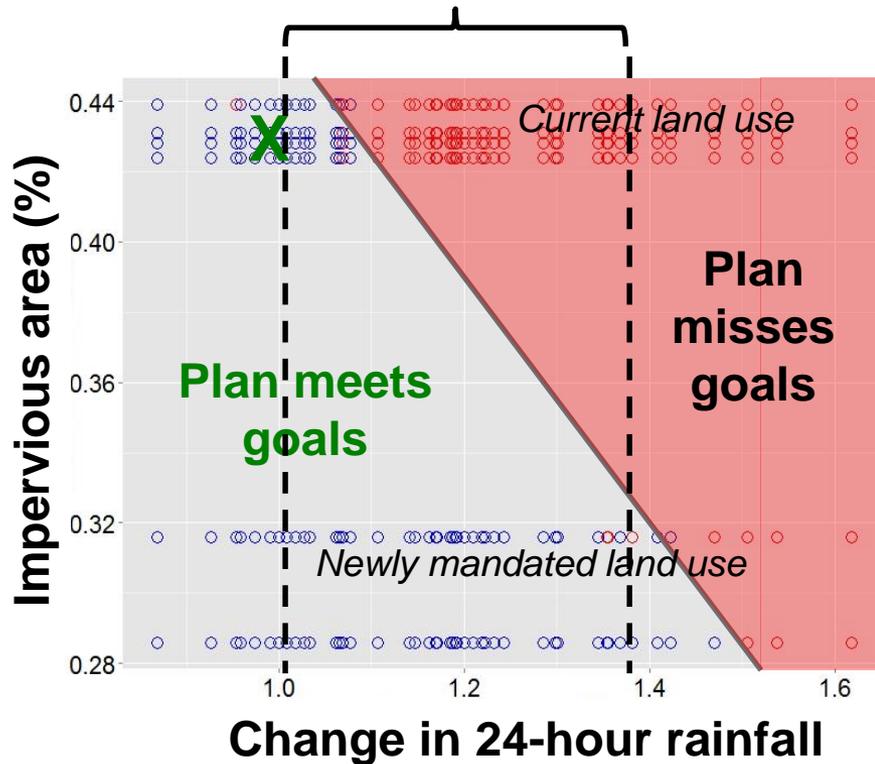


Compare Available Science to The “Plan Misses Goals” Scenario



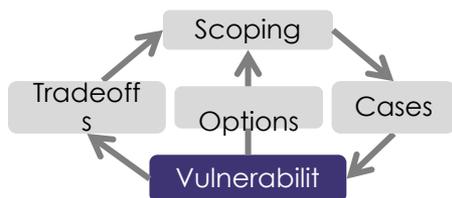
Compare Available Science to The “Plan Misses Goals” Scenario

Evidence from best study of local climate (Berg et al 2015)*



Bottom line:

- *We looked at two ways to estimate the probability of extreme precipitation events*
- *Both indicate Los Angeles' water quality implementation plan may not meet regulatory standards if the climate changes (or has changed)*



*Very high resolution (2 km) dynamic downscaling

New Options: Identify Potential Strategies for Reducing Vulnerabilities

New Options

Questions addressed this step include:

- How might we augment or modify our plan to reduce its vulnerabilities?
- Can we make the plan more flexible by monitoring and adjusting over time?
- Can we take action now to generate options we might want to use in the future?
- Are there no or low regret options that will work well over a wide range of futures?
- How might we combine several options into potentially robust strategies?

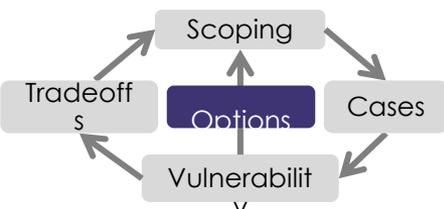
New Options: Identify Potential Strategies for Reducing Vulnerabilities

To identify such options:

- Return to options considered, but not included in your current plans
- Consider best practice elsewhere
- Solicit inputs from stakeholders and experts

To organize options into alternative strategies, use:

- Expert judgment
- Mix of optimization and qualitative methods
- Robust optimization methods



Study Used Expert Judgment and Simple Optimization to Identify an Adaptive Plan

An adaptive plan consists of near-term actions, signposts to monitor, and contingent actions if signposts are observed

Vulnerability analysis indicates current water quality plan will miss regulatory goals if:

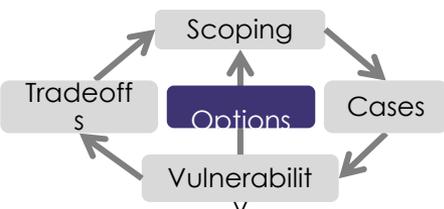
- City fails to implement new storm water master plan, and
- Frequency of large storms increases

Study identified such and adaptive plan to reduce this vulnerability



This adaptive plan represents a “low regret” strategy

* Used optimization to identify augmented plan



Tradeoff Analysis: Help Decisionmakers to Compare Tradeoff Among Strategies

Tradeoff Analysis

Questions addressed this step include:

- Are any strategies robust over all plausible futures?
- Do any strategies perform as well or better than all the other strategies over all plausible futures?
- If not, what are the key tradeoffs among the most robust options?

Note: RDM is designed to illuminate tradeoffs for people to evaluate, rather than dictate optimal solutions

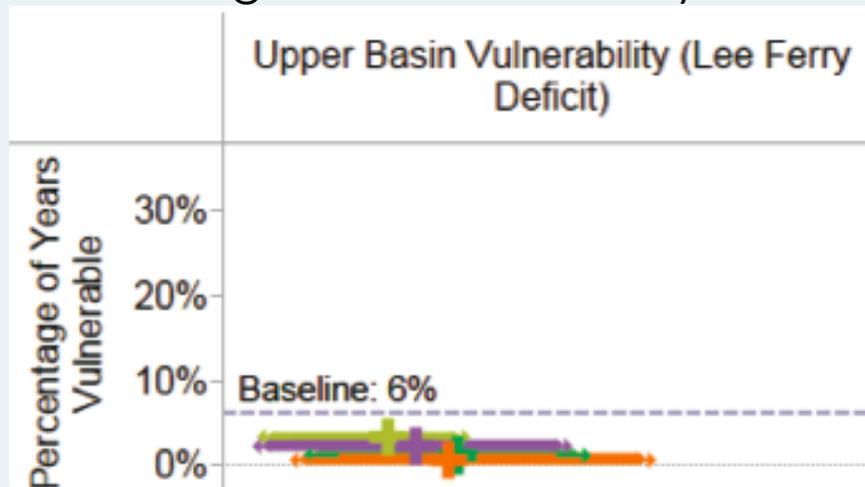
Reclamation Colorado Basin Study Considered Tradeoffs Among Robust Adaptive Strategies

Using expert judgment and multi-objective optimization tools, participants identified four potential portfolios of response options:

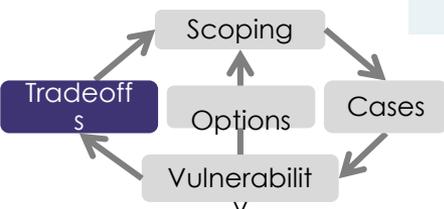
- A includes all options
- B focuses on options with high technical and implementation reliability
- C focuses on environmental options
- D focuses on those options common to B and C

These options offer tradeoffs among cost and reliability

Upper Basin
Reliability in
Declining
Supply
Scenario



Groves et. al. (2013)



Example of multi-objective (or multi-criteria) decision analysis

Multi-Objective Decision Analysis is a Wonky Term for Seeking to Recognize the Diversity of Human Interests

- Optimizing using a single measure of performance (e.g. benefit cost analysis) assumes that everyone has the same values
- But a diversity of priorities, goals, and values is a fundamental attribute of our world
 - Some see this as a feature, not a bug
- Quantitative analyses that inform a community's important decisions can usefully reflect this diversity of opinion
 - This is particularly true when supporting participatory processes

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Other DMDU Approaches

- Scenario Planning
- Decision scaling
- Adaptive pathways
- Multi-objective RDM (MORDM)

Getting Started

Humans Are Avid Scenario Builders

The ability to create and share scenarios represents a key difference between humans and other animals

Suddendorf (2013)

We:

Tell stories

Picture future situations

Imagine each other's experiences

Contemplate potential explanations

Plan how to teach

Reflect on moral dilemmas

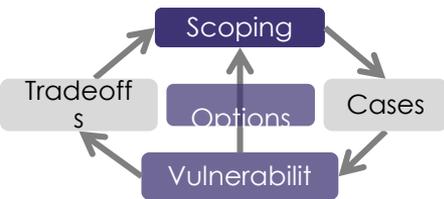
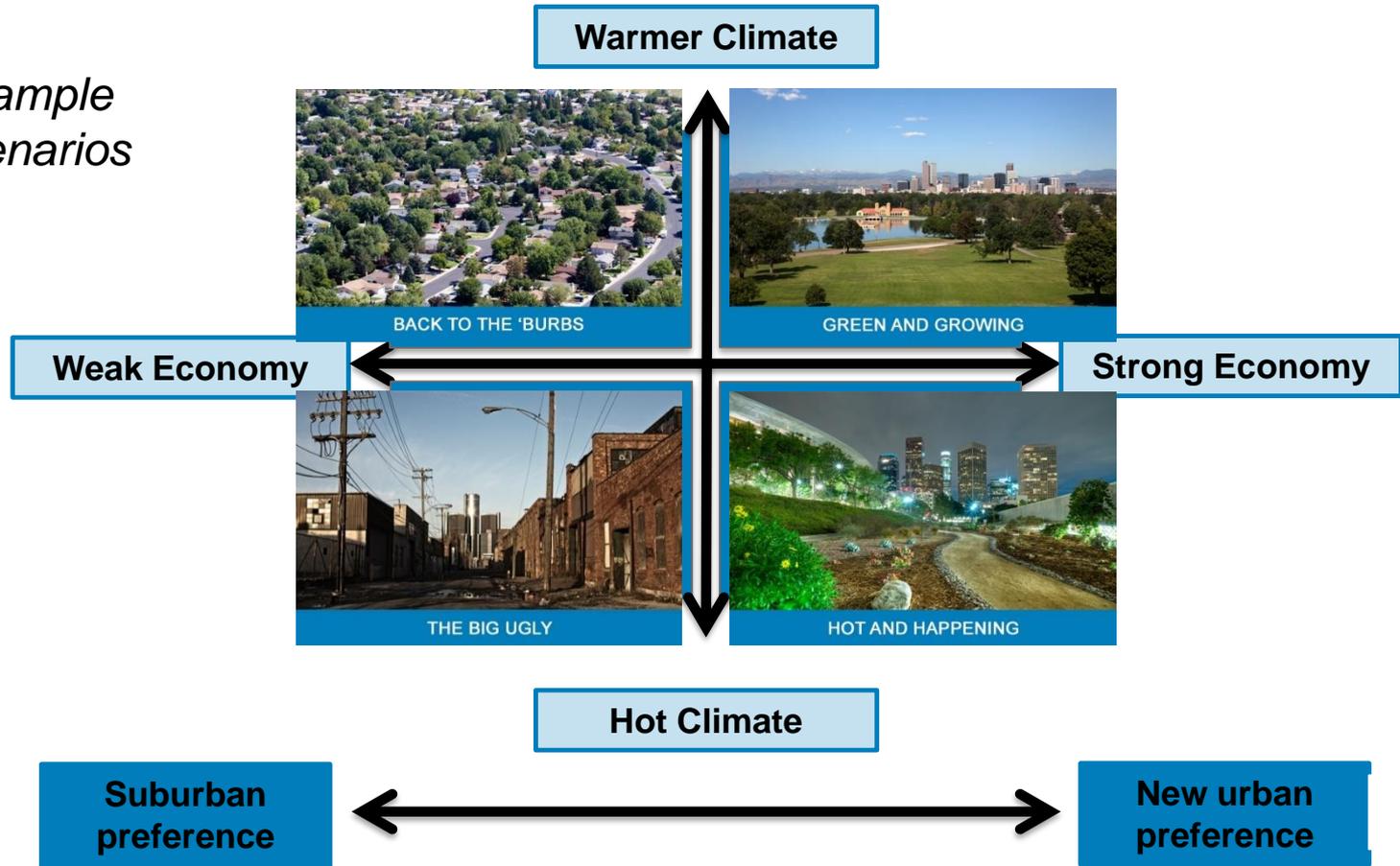


Scenarios are “focused descriptions of fundamentally different futures, often presented in a coherent script-like or narrative fashion”

Schoemaker (1993)

Scenario Planning Is a Qualitative DMDU Approach

Example scenarios

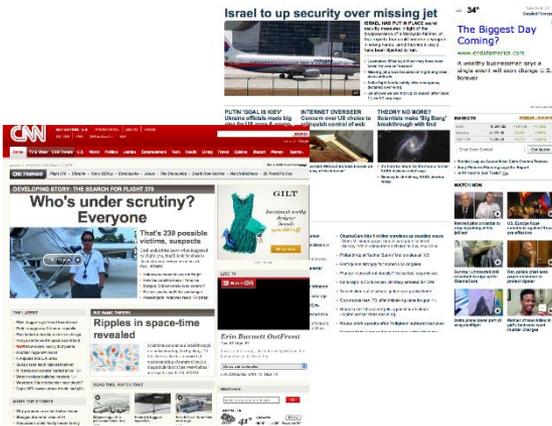


Scenarios Address Cognitive Barriers that Complicate Effective Decisions Under Uncertainty

Over-confidence



Uncertainty absorption

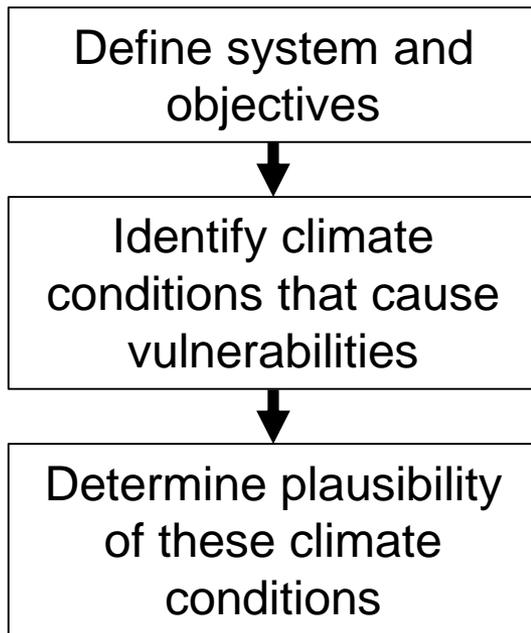


Strategic use of uncertainty

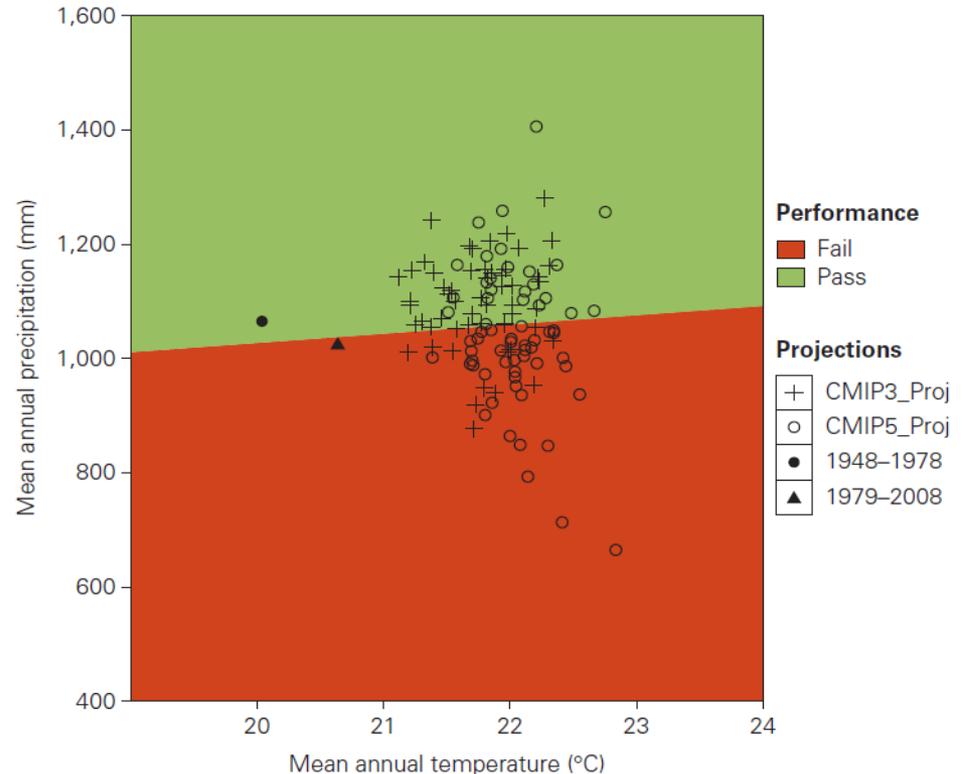


Decision Scaling Offers Simple Climate Stress Tests

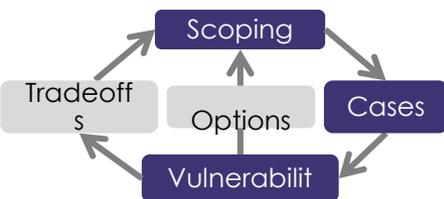
Process



This chart shows example results stress test

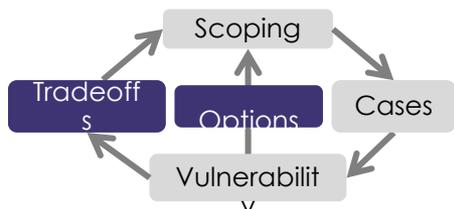
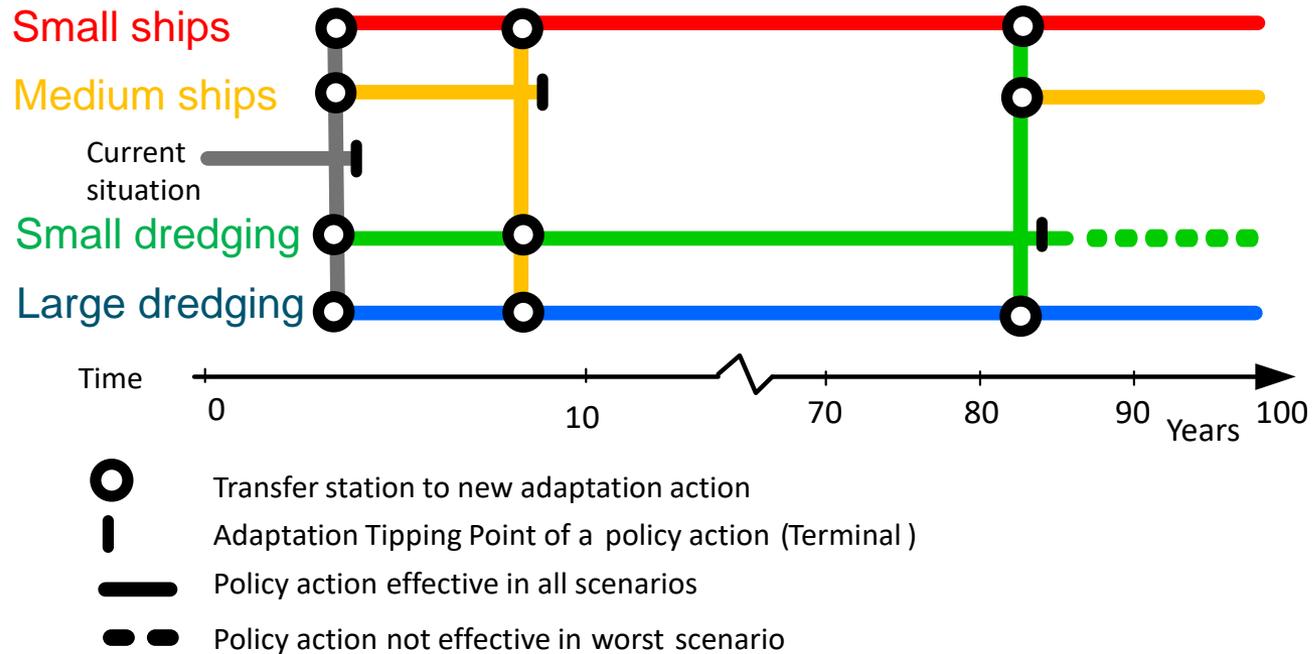


Decision scaling uses weather generators, which perturb observed weather in a location with climate trends (often ΔT and ΔP) to generate future climate time series.



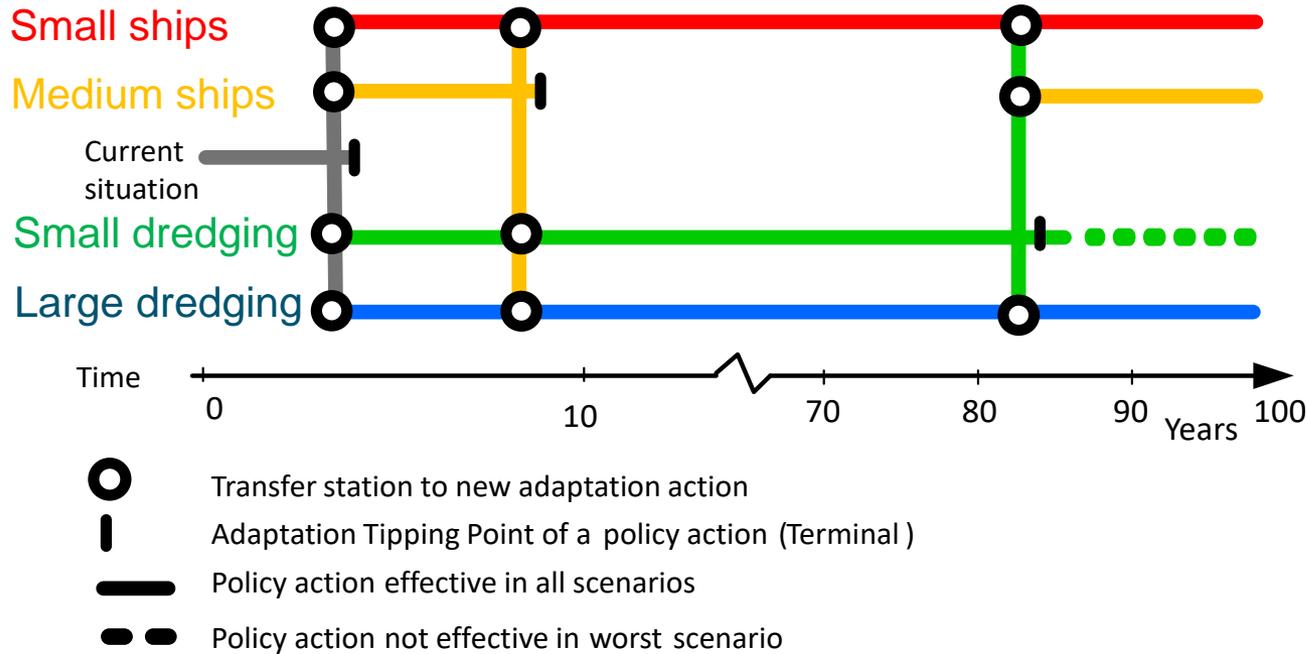
Dynamic Adaptive Pathways Identifies and Compares Robust and Flexible Strategies

Example: How to keep a river navigable in a changing environment that may result in lower water levels in the river?



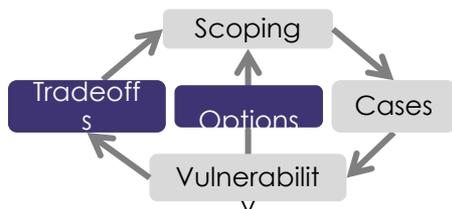
Dynamic Adaptive Pathways

Employs Multi-Objective Tradeoff Analysis

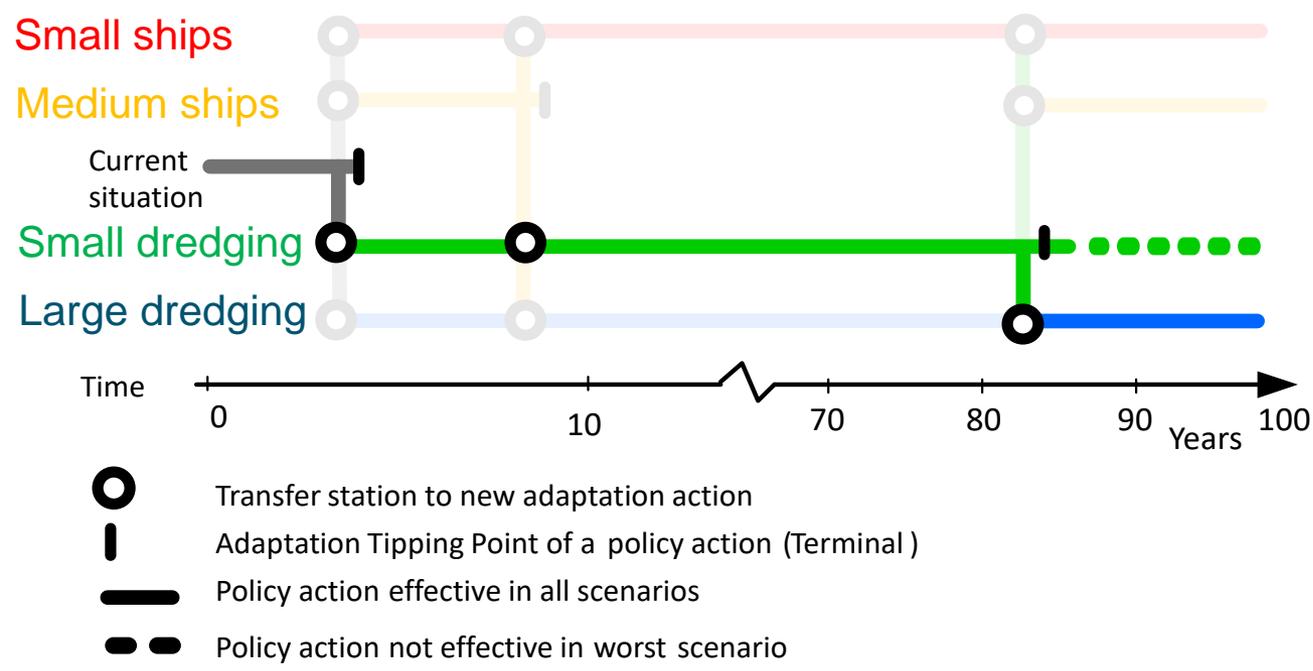


Multi-objective Scorecard for Pathways

Path actions	Costs	Target effects	Side effects
1 ○	+++	+	0
2 ○	+++++	0	0
3 ○	+++	0	0
4 ○	+++	0	0
5 ○	0	0	-
6 ○	++++	0	-
7 ○	+++	0	-
8 ○	+	+	- - -
9 ○	++	+	- - -



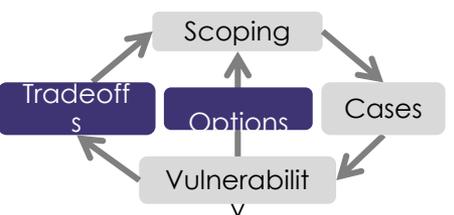
Dynamic Adaptive Pathways Employs Multi-Objective Tradeoff Analysis



Multi-objective Scorecard for Pathways

Path actions	Costs	Target effects	Side effects
1 ○	+++	+	0
2 ○●	+++++	0	0
3 ○●	+++	0	0
4 ○●	+++	0	0
5 ●	0	0	-
6 ●●	++++	0	-
7 ●●	+++	0	-
8 ●●	+	+	---
9 ●	++	+	---

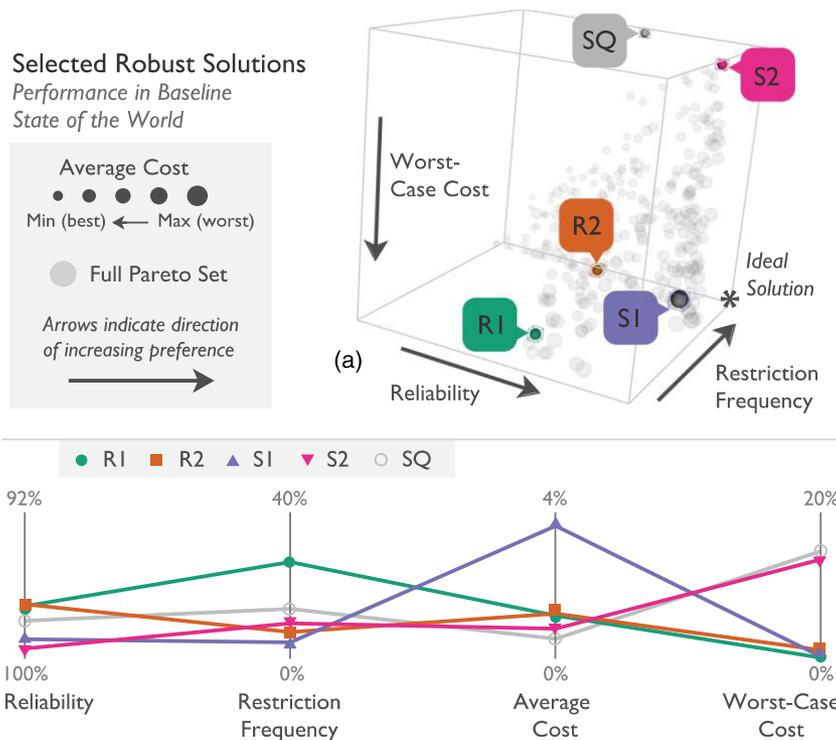
Adaptive Plan: small dredging and switch to large scale dredging. Implement corrective actions to mitigate negative side effects. Monitor river discharges and transport developments.



Multi-Objective Robust Decision Making (MORDM) Uses Evolutionary Solvers to Find Robust Strategies

MORDRM is the most general and comprehensive DMDU method, with the least “expert judgment” shortcuts

But its the most difficult to implement



For instance, MORDM has been used to integrate:

- Long-term infrastructure investments,
- Near-term operational strategies, and
- Medium term financial instruments

To address water agency's system and financial resilience

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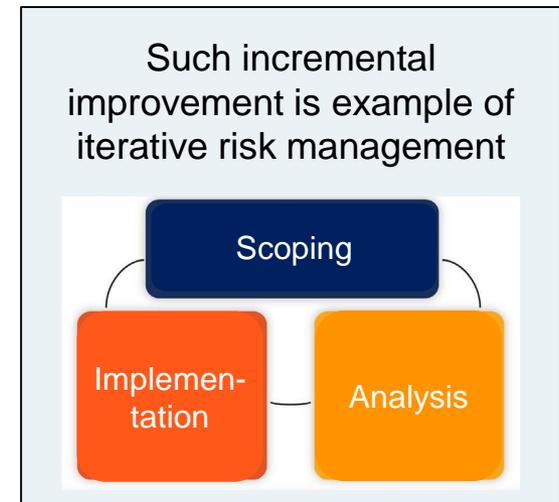
DMDU Is Part of “Mainstreaming” Climate Adaptation into Your Organization

Most important step is to get started

- Conduct a climate vulnerability analysis
- Use scenario planning
- Recruit a climate advisory panel

DMDU Is Part of “Mainstreaming” Climate Adaptation into Your Organization

- Adopt DMDU incrementally, augmenting each planning cycle
- One potential sequence
 1. Embrace concepts of multiple futures, robust and flexible strategies
 2. Employ qualitative methods and/or separate, piecework analyses
 3. Then begin running your system models over multiple futures to i) stress test plans and ii) identify and evaluate robust and flexible plans



Incremental Improvement Aided Because Most DMDU Methods are Similar

WUCA's case study new planning approaches embrace DMDU concepts

Qualitative or “piecemeal” analyses:

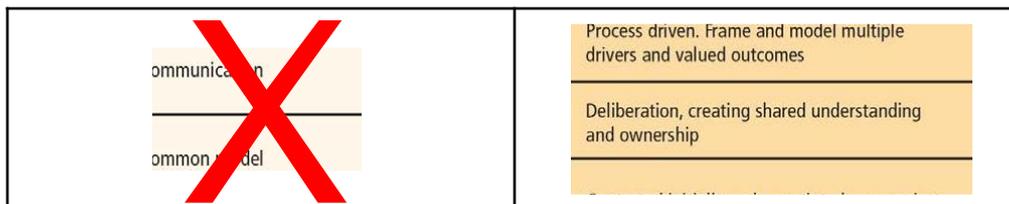
- Scenario planning
- Climate vulnerability assessments
- Plan for plausible ranges of extremes

Fully quantitative analyses:

- Decision scaling
- RDM
- Dynamic adaptive pathways
- Multi-objective RDM

Can start with any of these and move to the others

Different types of risk



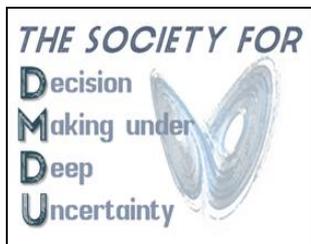
DMDU methods:

- Consider multiple futures
- Seek robust and flexible plans

Resources Becoming More Available to Help Implement DMDU Methods

There now exists:

- Open source software for implementing most DMDU methods
- Increasing numbers of case studies
- Many groups able to help

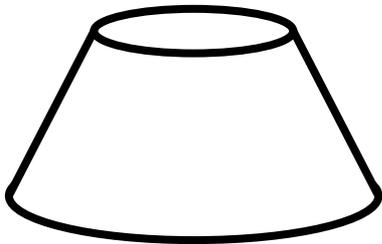


DMDU Methods and Tools Can Help Water Managers Address Today's Uncertain Conditions

Our current and future climate is not the same as past climate, and no one is sure exactly how it has and will change

Basic DMDU principles can help you meet this challenge

1. Consider multiple futures, not one single future, in your planning. Choose these futures to stress test your organization
2. Seek robust plans that perform well over many futures, not optimal plans designed for a single, best-estimate future
3. Make your plans flexible and adaptive, which often makes them more robust



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QUESTIONS???

Small Group Discussion Questions

1. What methods resonate with you and why?
2. What are your barriers to getting started?
3. What information do you need to overcome these barriers?