Optimization of conjunctive water supply and reuse systems with distributed treatment for high-growth water-scarce regions

University of Arizona

July 17, 2013

Participants & Partners

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Chris Choi (Ag and Bio – U. of Wisc.)

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- *Moved on to other endeavors
- Also, we have had several undergrauate students.

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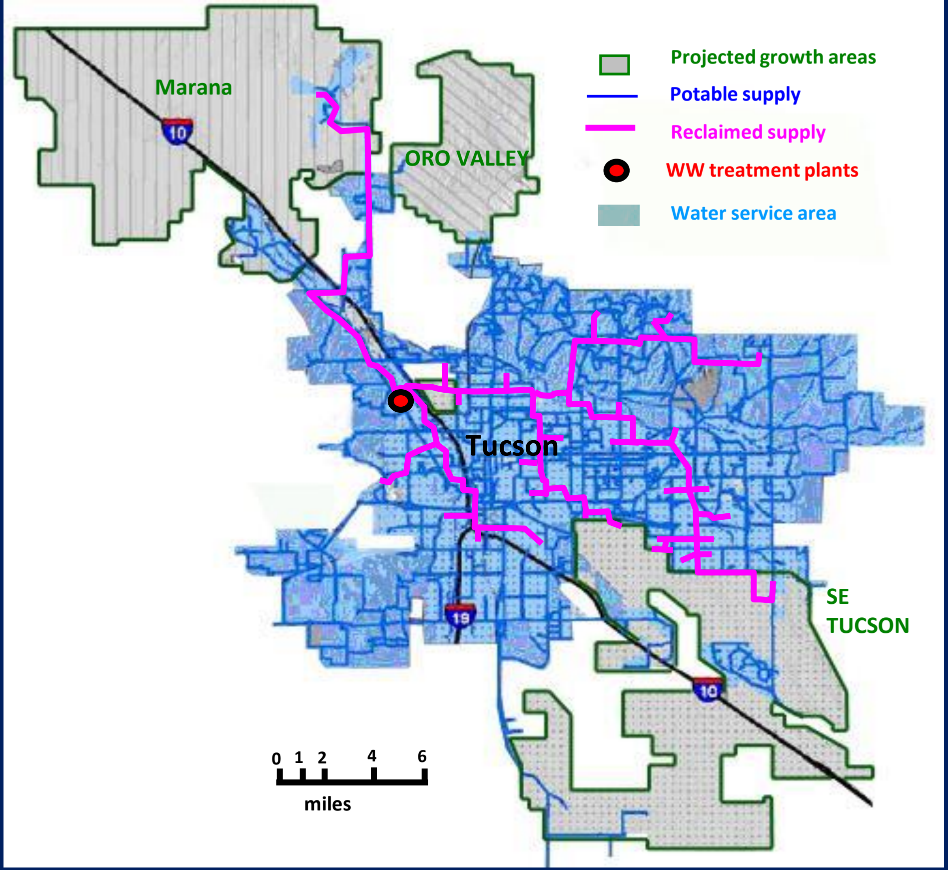
Partners

GLOBAL WATER
RELIABLE · RENEWABLE · REUSABLE

Pima County
Department of
Wastewater Management

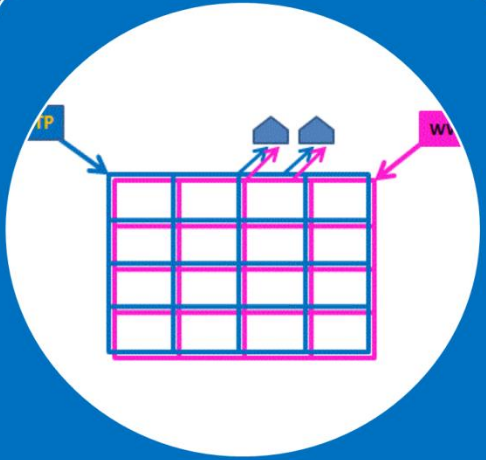
TUCSON
WATER



Three Planning/Design Scales

Water Resource Supply System

Regional Water & Wastewater System



Local Dual Distribution System

Identify mass balances at watershed level

(Active Management Area - large scale water resource system)

Identify infrastructure components, capacities, locations

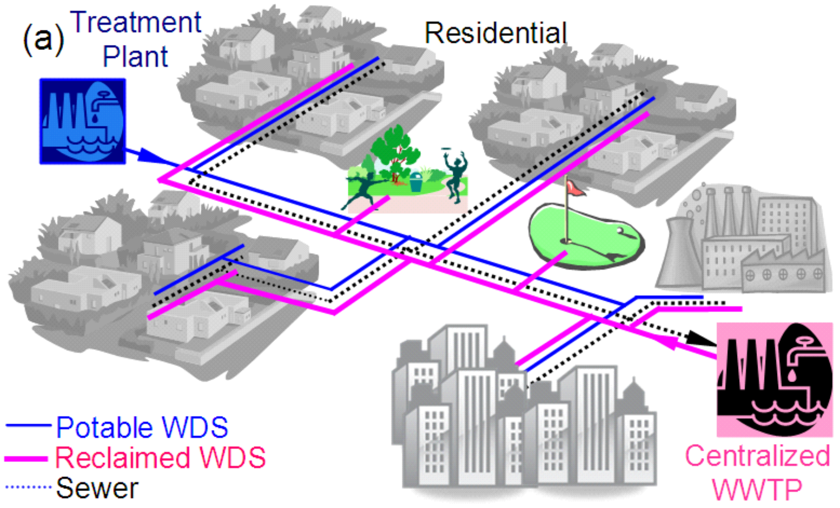
(City-wide regional scale major infrastructure system)

Design detailed distribution System

(Local household scale water distribution system)

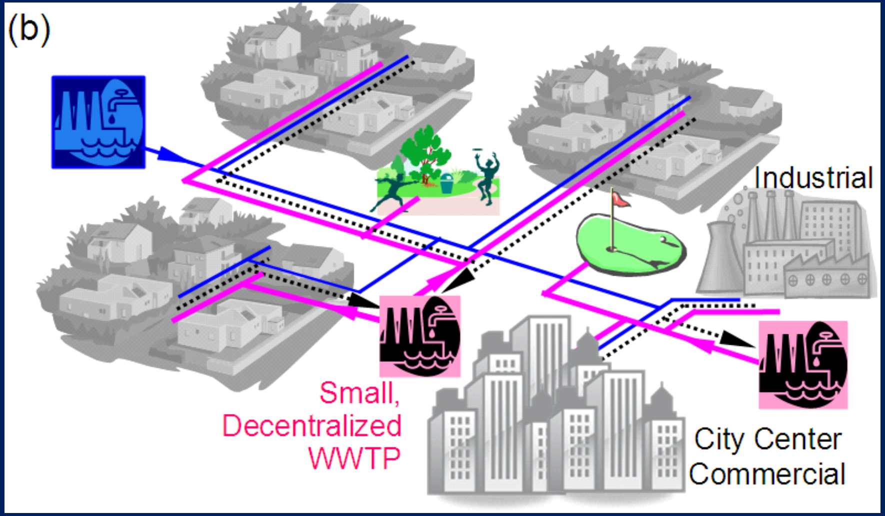
Is water reclamation the next bucket?

NAE grand challenge: "Combined neighborhood" of urban water and wastewater systems



Decentralized/satellite treatment -

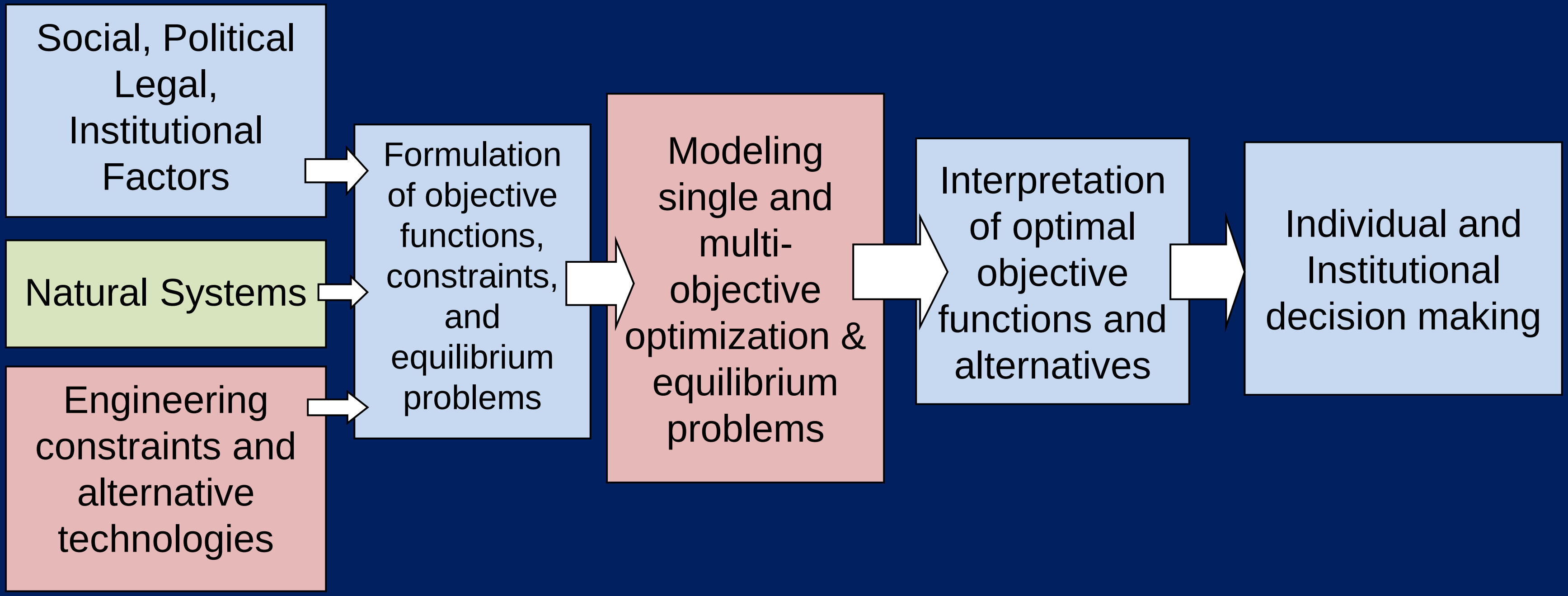
Where and how to treat?



Dual distribution systems -

How to distribute and for what uses?

Infrastructure Planning



Social, Political Legal, Institutional Factors

Natural Systems

Engineering constraints and alternative technologies

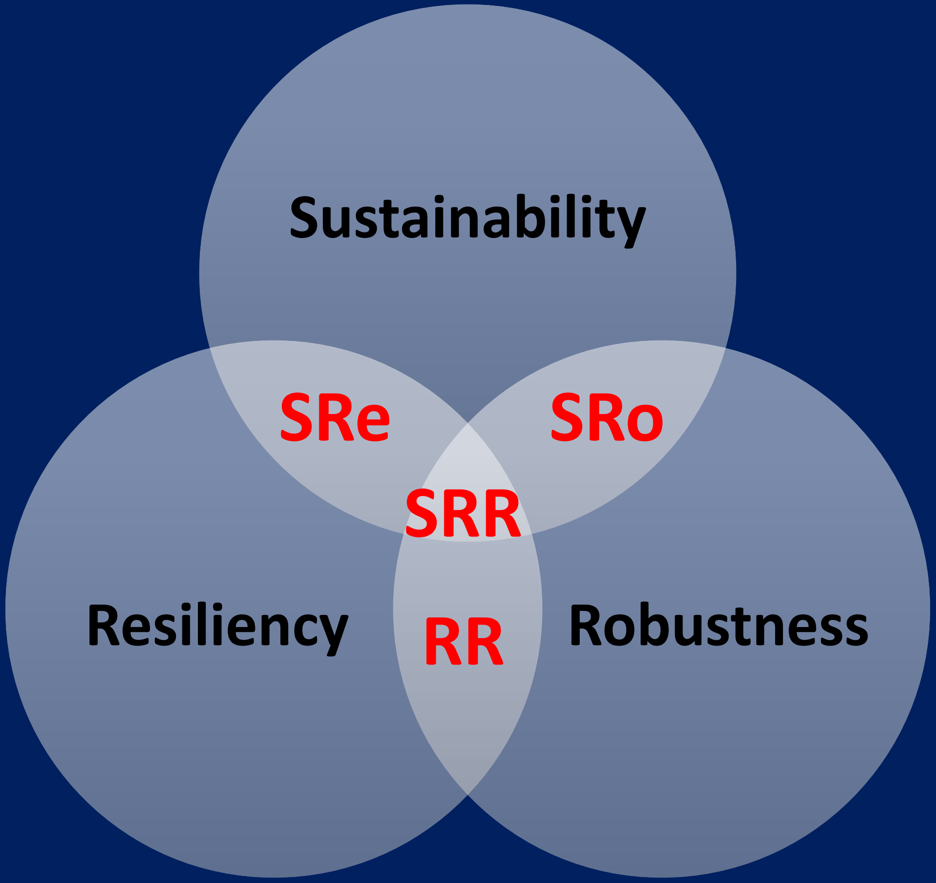
Formulation of objective functions, constraints, and equilibrium problems

Modeling single and multi-objective optimization & equilibrium problems

Interpretation of optimal objective functions and alternatives

Individual and Institutional decision making

Planning/Design Objectives


Sustainability

SRe

SRo

SRR

Resiliency

RR

Robustness

Can we design a fully integrated complex system?

Can decision makers understand the process and be capable of making informed judgments?

SRR for W/WW System

- (Infrastructure) Sustainability
  - Design and operate system with least impact in terms of TBL costs
    - ✓ Economic cost
    - ✓ Environmental cost (GHG)
    - ✓ Social and Institutional cost
- Resilience
  - System adaptation and recovery when a failure occurs
- Robustness
  - Consistent functionality under external forces
  - Evolve over time as supply and demand develop

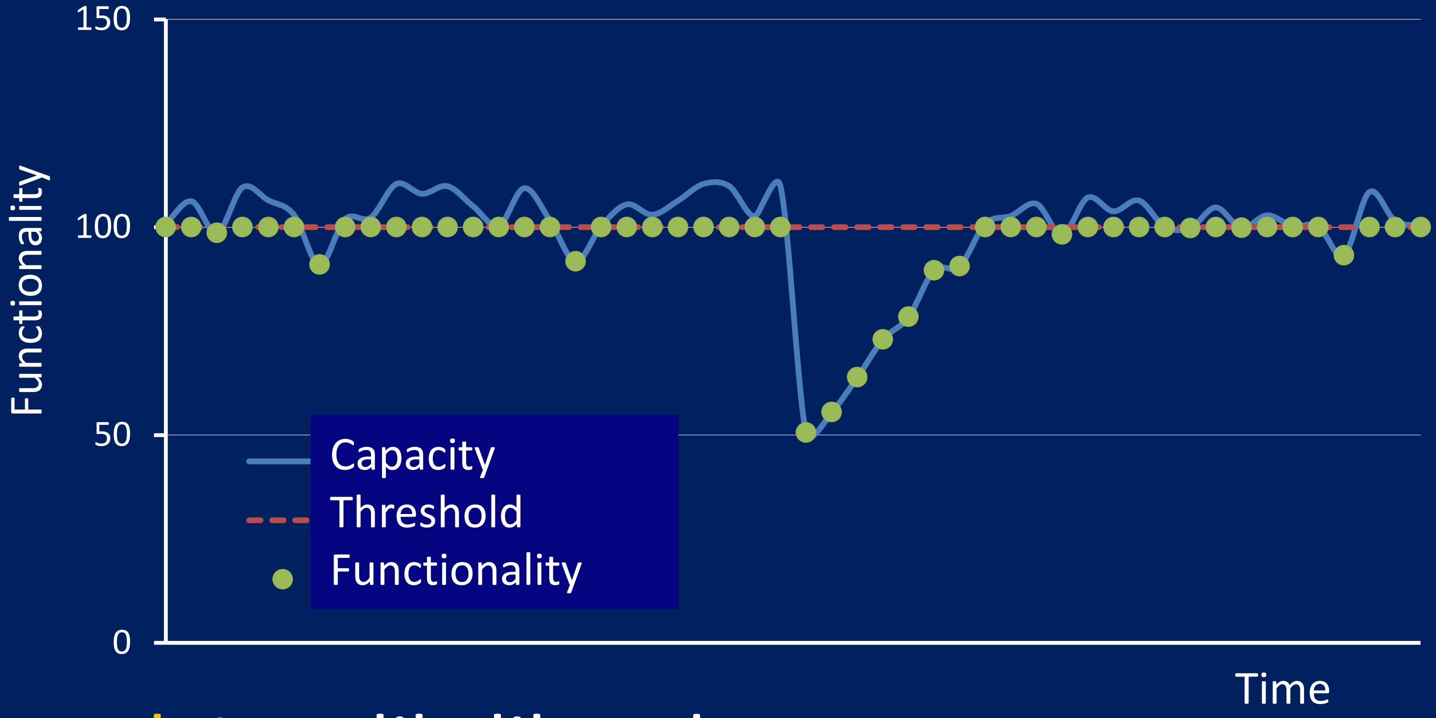
Robustness

The robustness of a system to a given class of disturbances is defined as the ability to maintain its function when it is subject to a set of disturbances of this class

Resilience

Infrastructure resilience is the ability to gracefully degrade and subsequently recover from a potentially catastrophic disturbance that is internal or external in origin

General and Specified Resilience

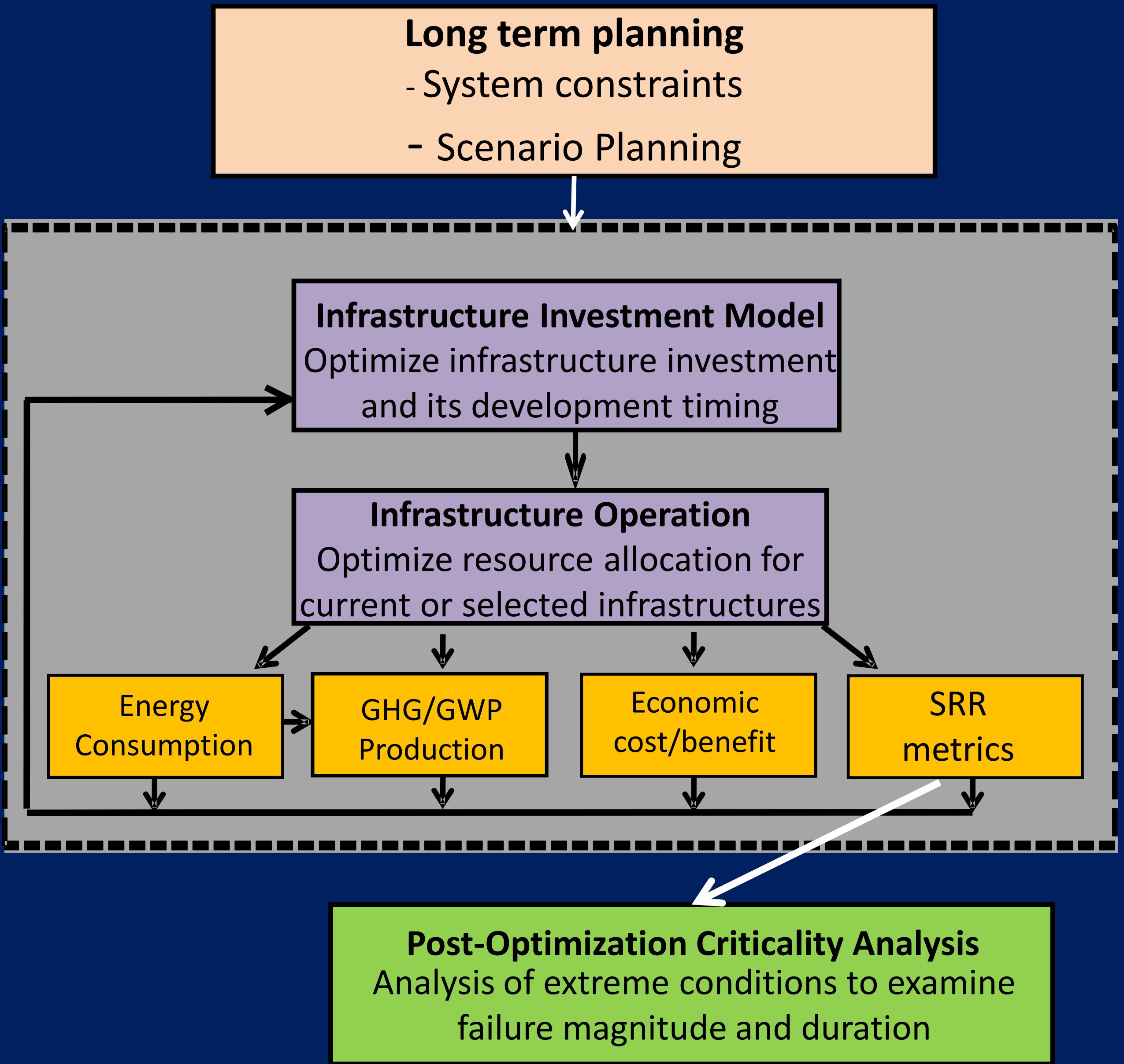


General: Low likelihood severe events

Specified: Higher frequency, less severe failure events

Scholz (2011) – Risk analysis literature

SRR Design/Planning Framework



Long term planning
- System constraints
- Scenario Planning

Infrastructure Investment Model
Optimize infrastructure investment and its development timing

Infrastructure Operation
Optimize resource allocation for current or selected infrastructures

Energy Consumption

GHG/GWP Production

Economic cost/benefit

SRR metrics

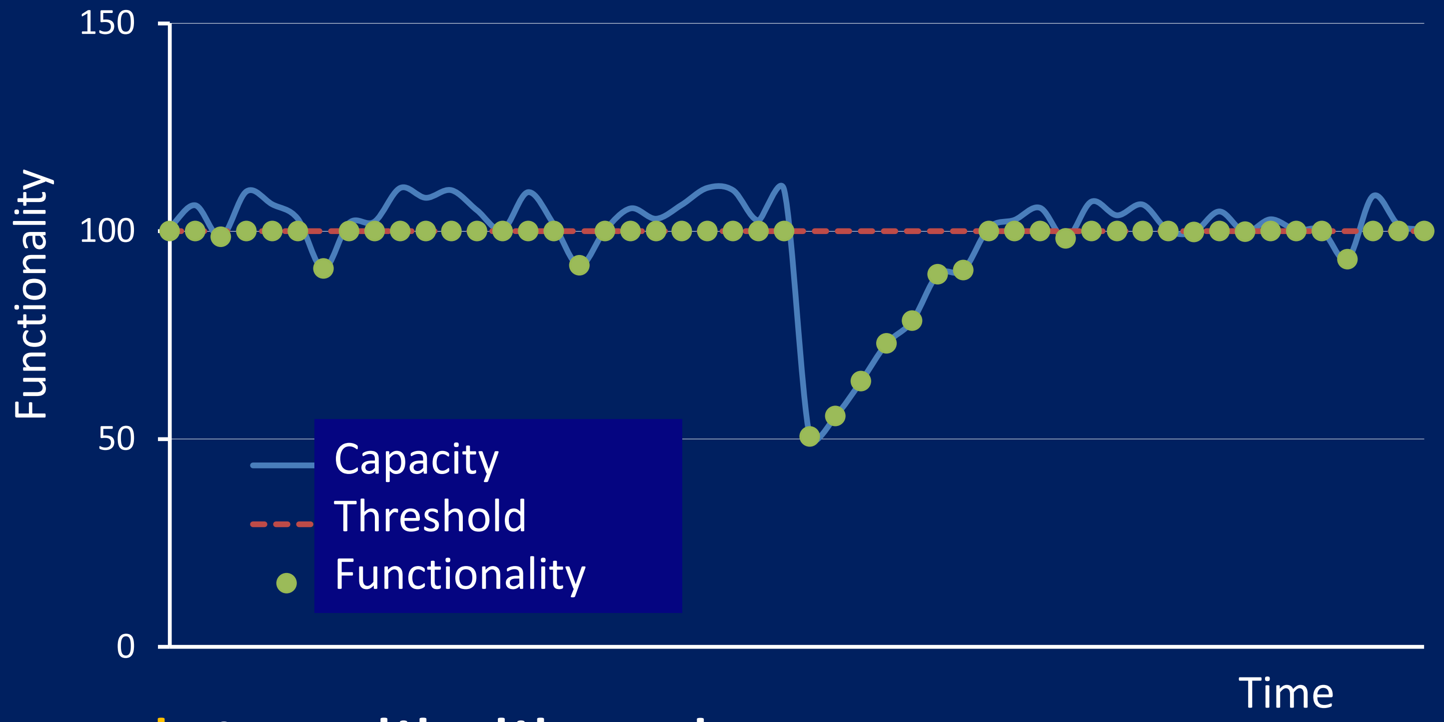
Post-Optimization Criticality Analysis
Analysis of extreme conditions to examine failure magnitude and duration

Robust Design or Operation for a set of disturbances/alternative futures

- Operation – range of conditions under which a fixed infrastructure system will perform acceptably
- Design – range of alternative futures that can be adapted to with minimal regret costs

Resilience analysis – Range of extreme conditions (beyond operation /design set) that is examined to determine the degree and duration of failure

General and Specified Resilience



General: Low likelihood severe events

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Scholz (2011) – Risk analysis literature

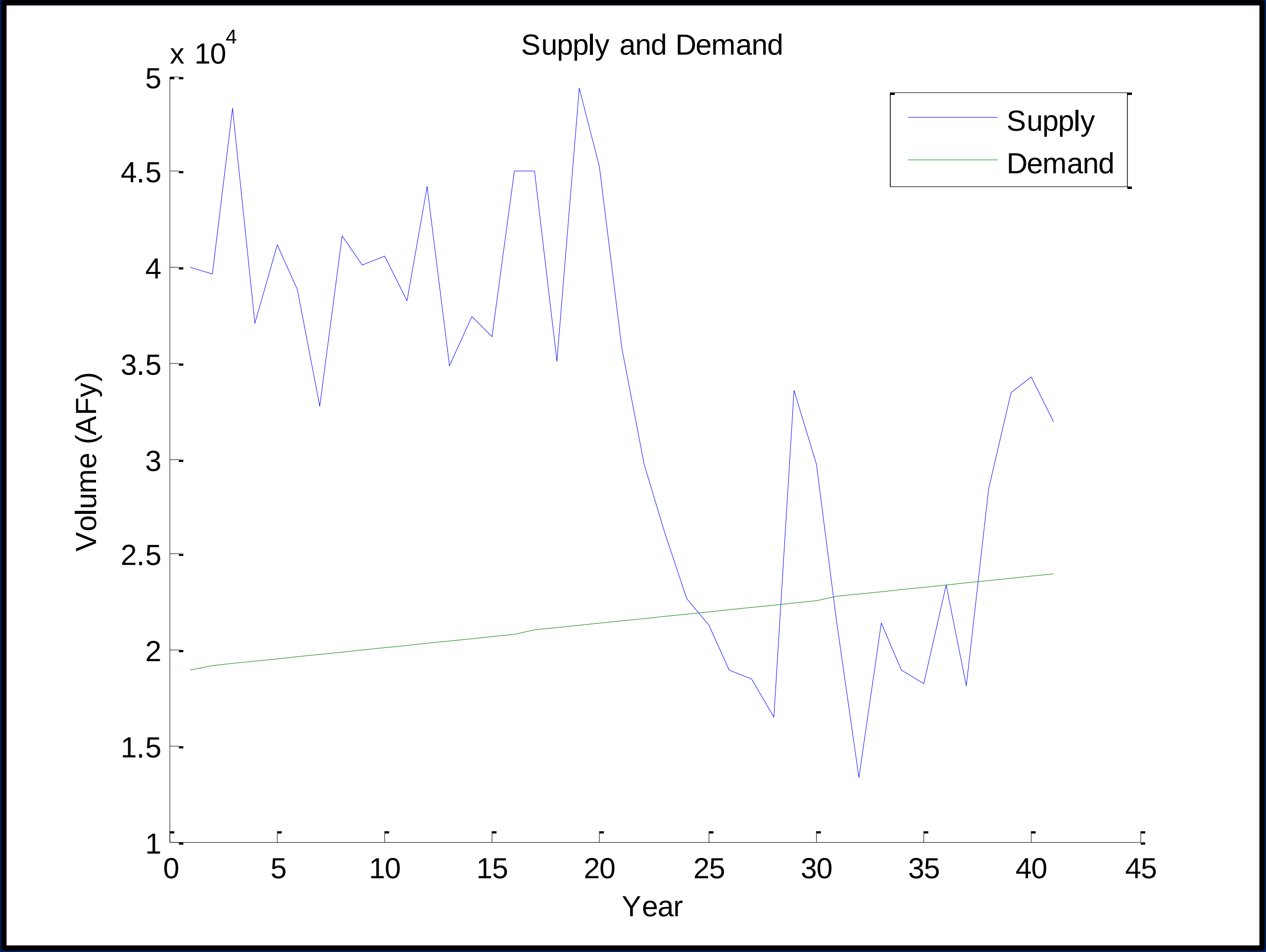
	Study Period	
	User	**Source**
Functionality	$\frac{S_t}{D_t}$	$\frac{W_t}{R_t}$
Robustness		
Availability	$\frac{\sum_{t=T_0}^{T} Y_t}{T - T_0 + 1} = \frac{MTBF}{MTBF + MTTR}$	
Reliability	$e^{-\lambda L}, \qquad \lambda = 1/MTBF$	
Sustainability		
Sustainability	$\frac{\sum_{t=T_0}^{T} S_{i,t}}{\sum_{t=T_0}^{T} D_{i,t}}$	$\frac{X_{j,t}}{W_{ij,t}}$

Resilience	
Max Event Volumetric Severity	$\max_{T_0<t<T} 1-\frac{\int_{t_{f,0}}^{t_f}[1-f(t)]dt}{(t_f-t_{f,0})}$
Volumetric Severity	$1-\frac{\int_{T_0}^{T}[1-f(t)]dt}{(T-T_0)}$
Severity	$\min_{T_0\leq t\leq T}[f]$
Repair Rate	$\mu=\frac{1}{MTTR}$
Maintainability	$1-e^{-\mu L}$

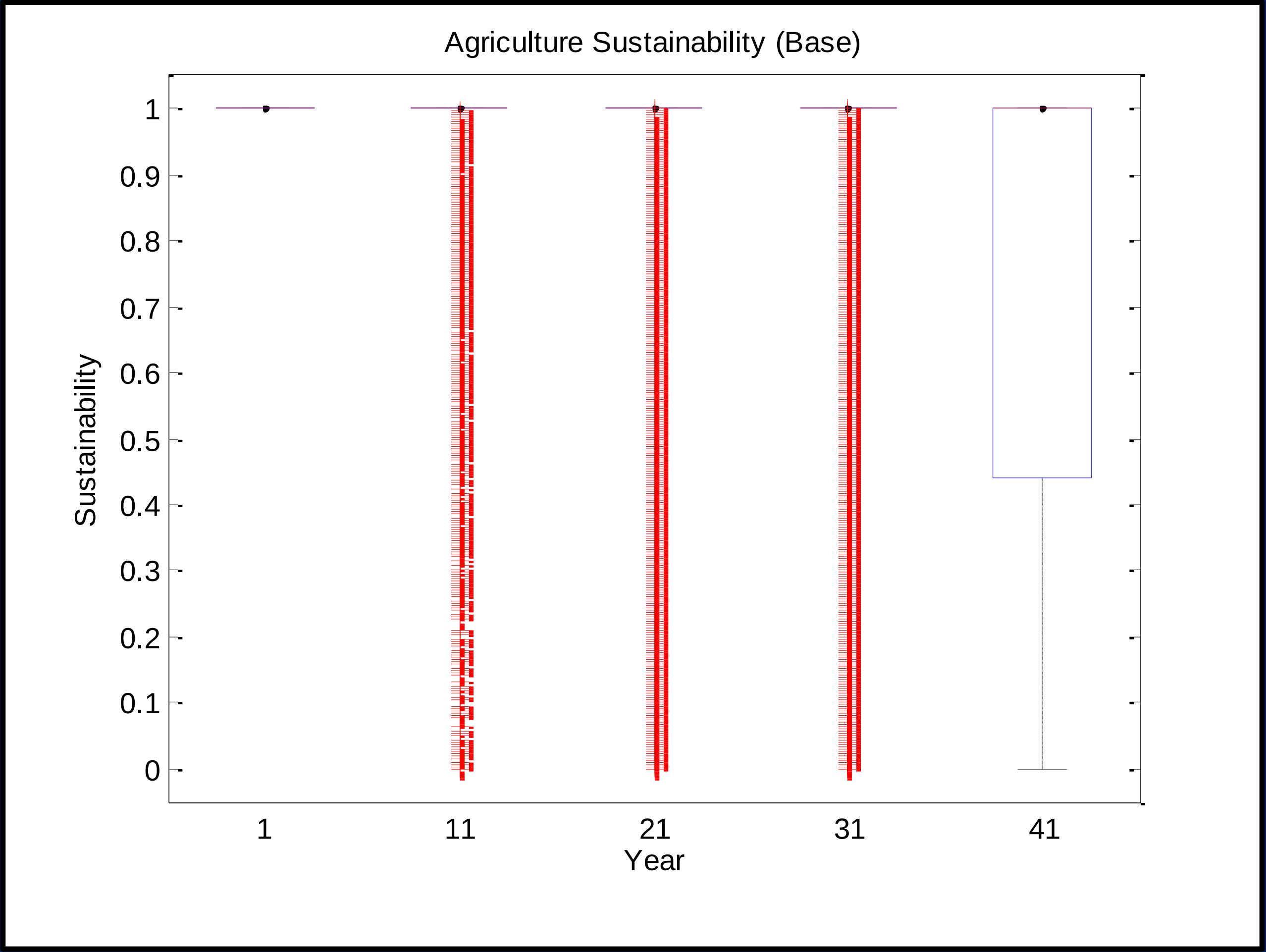
Reservoir Supplied Community Characteristics

- Demand
    - Municipal demand 11,000 AFy increasing by 125 Afy per yr
    - Agriculture demand 6,000 AFy
    - Downstream demand 2,000 AFy
- Supply
- Avg. inflow - 20,000 AFy
- Stand. Dev. – 6,000 AFy
- Reservoir capacity - 20,000 AF
- Reclaimed water
    - BASE case (2,000 AFy for downstream environmental demand)
    - RW case (4,000 AFy)

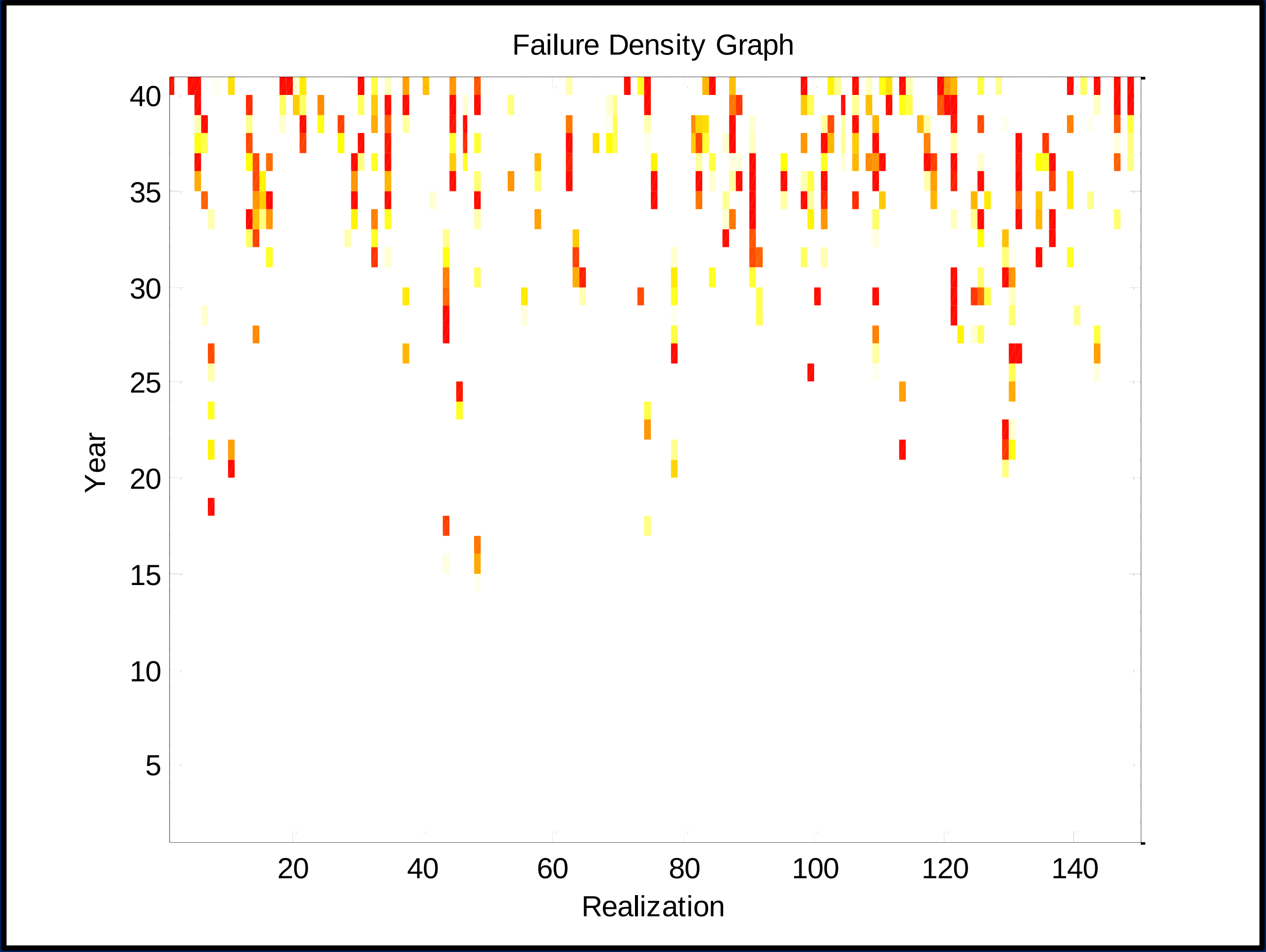
Typical flow sequences – base case



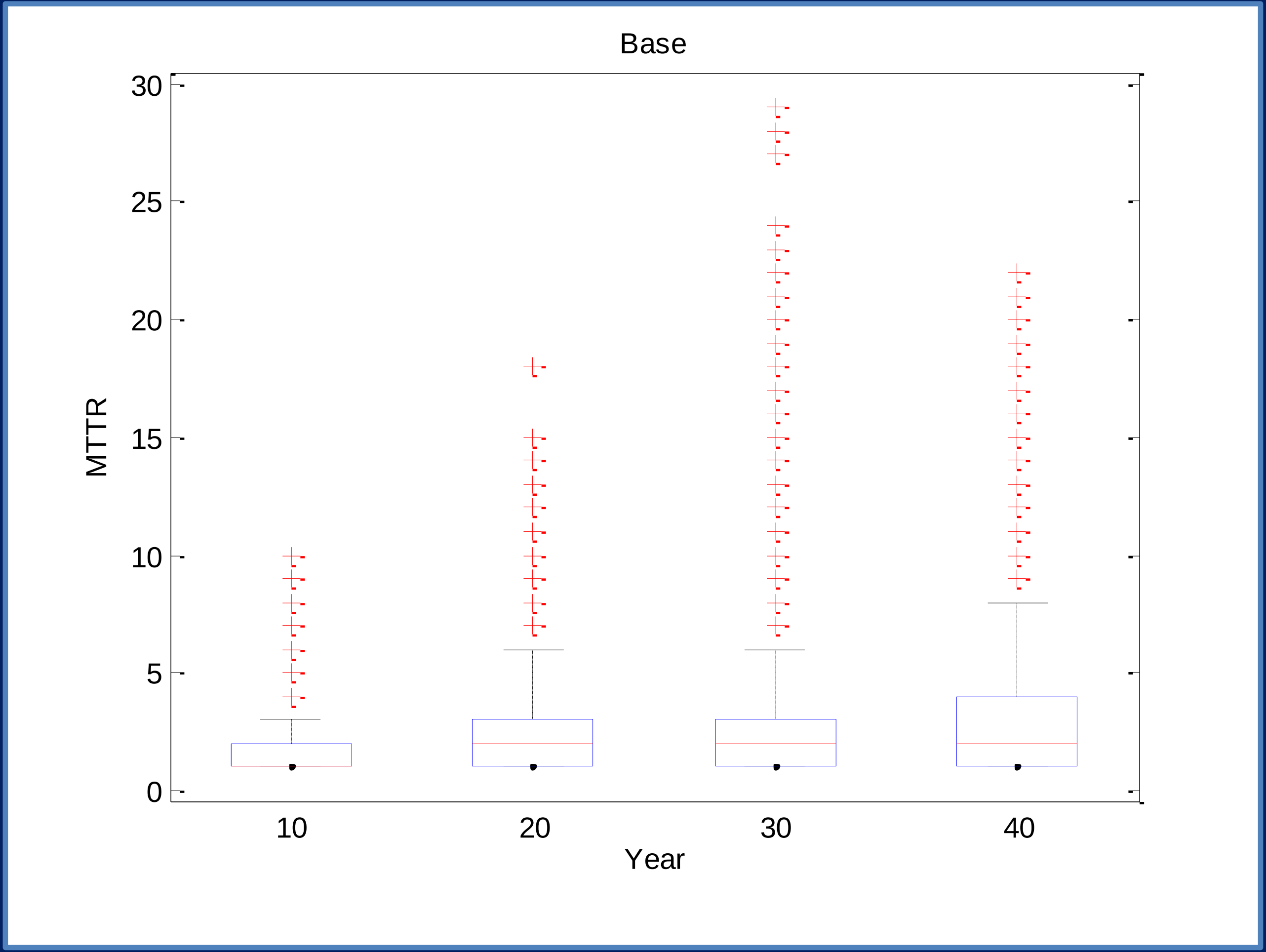
Change in sustainability over time



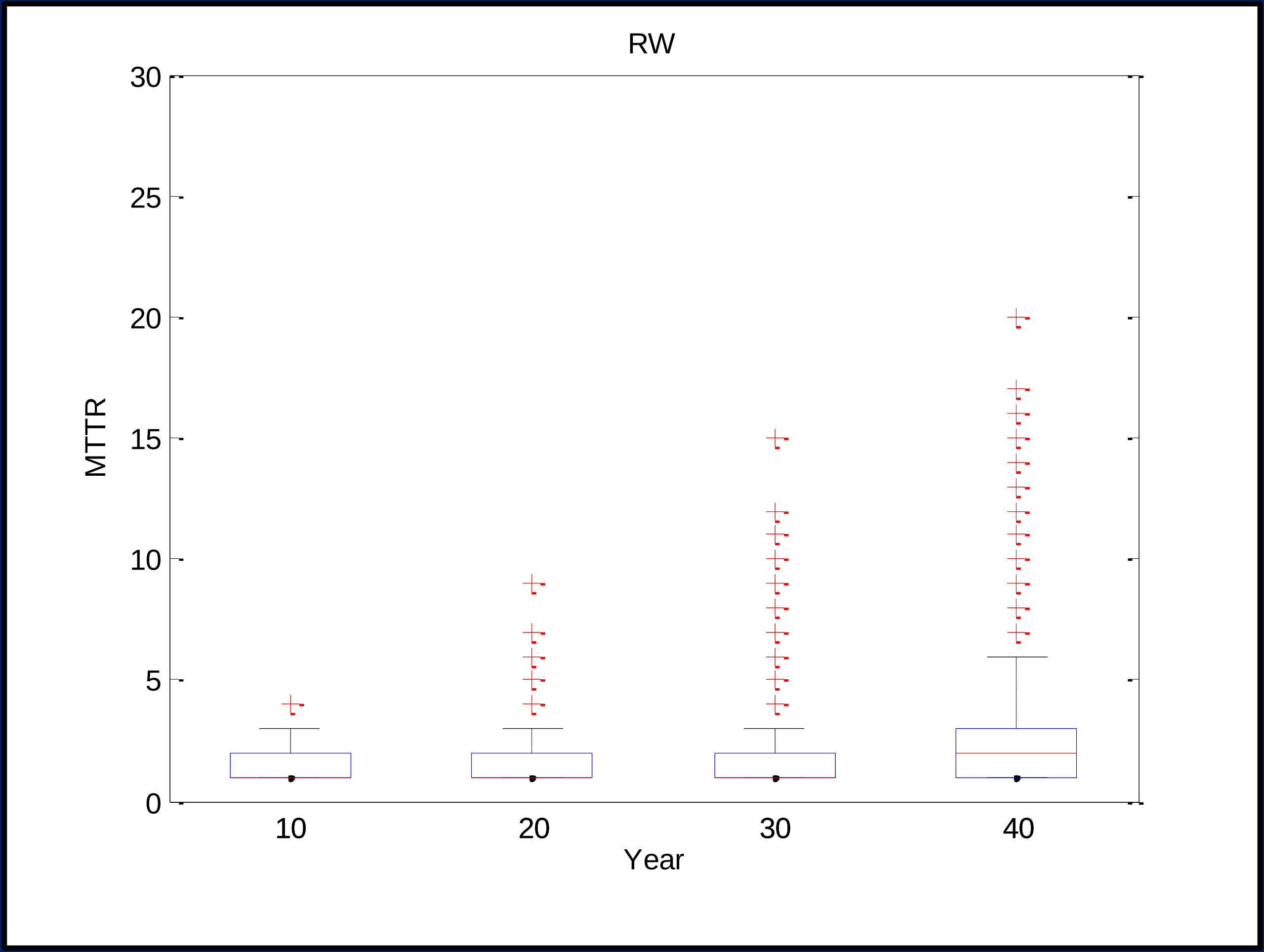
Severity for Multiple Realizations



MTTR Base Case



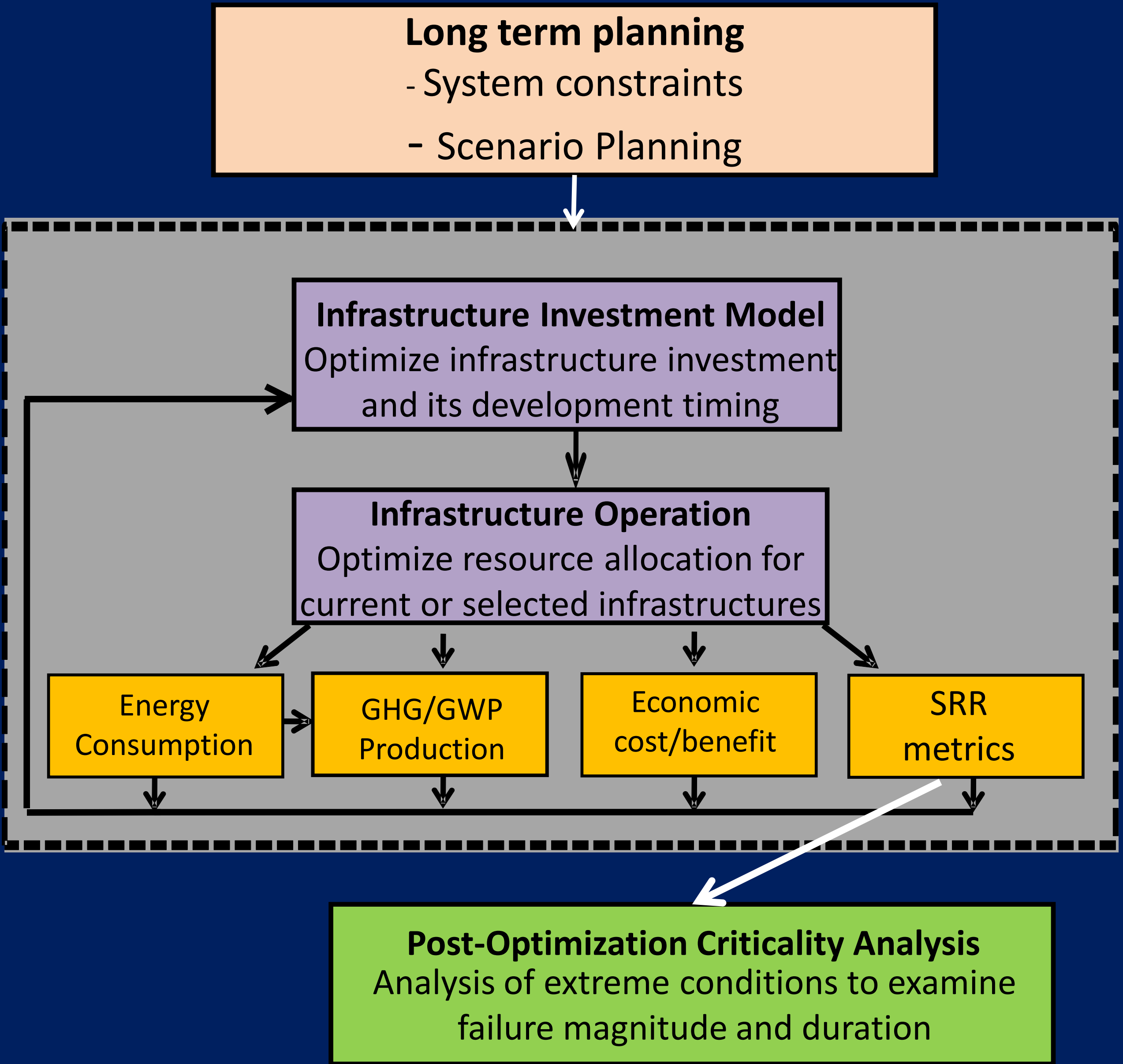
MTTR – With Reclaimed Water Facility



Adaptability/Evolvability

- Systems are not static
- Infrastructure systems adapt:
  - To applied stresses change operations or usage patterns
  - To failure conditions in responding to failure through resource allocation and speed of response
- Systems evolve over time:
  - To user demands
  - To availability of supplies

SRR Design/Planning Framework



Long term planning
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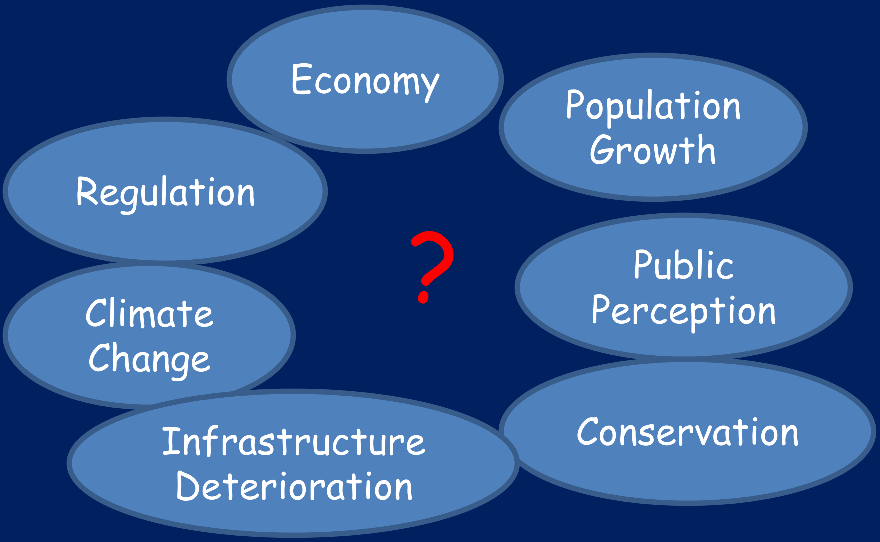
Scenario-based Robust Optimization of Regional W/WW Infrastructure

- **Regret costs**
  - Cost of having imperfect information about the future
  - Total of *overpayment* and *supplementary* costs
    - ✓ ***Overpayment cost***: when initially a larger system is constructed than is necessary
    - ✓ ***Supplementary cost***: explicit cost of expanding initially undersized system

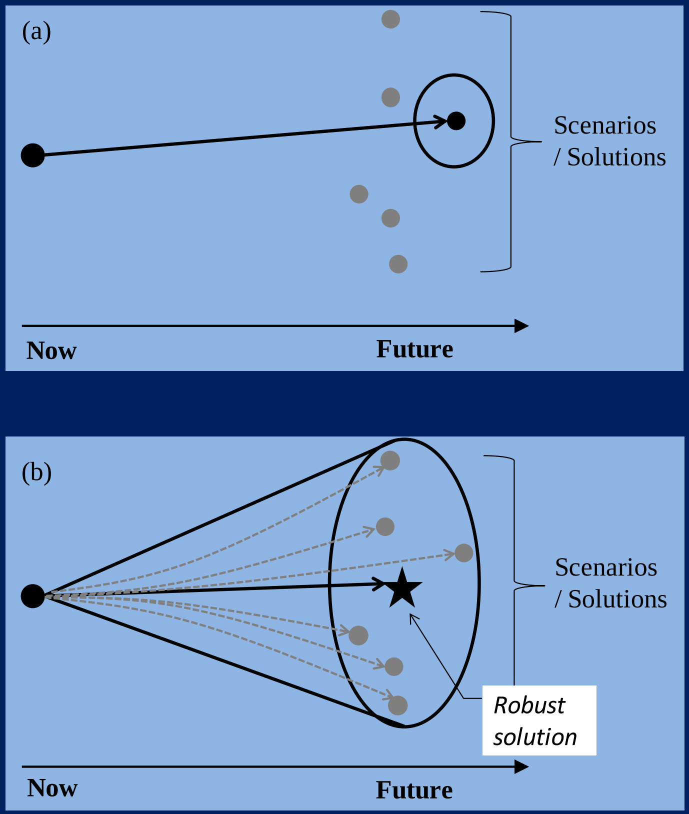
- **Scenario-based Multiple Objective Robust Optimization (SMORO)**
  - For the purpose of minimizing regret costs over multiple scenarios
  - Two objectives are imposed
    - ✓ Objective 1 - minimize the expected cost
    - ✓ Objective 2 - minimize the cost variance across scenarios

Scenario Planning

Uncertainty/Scenario



Scenario Planning



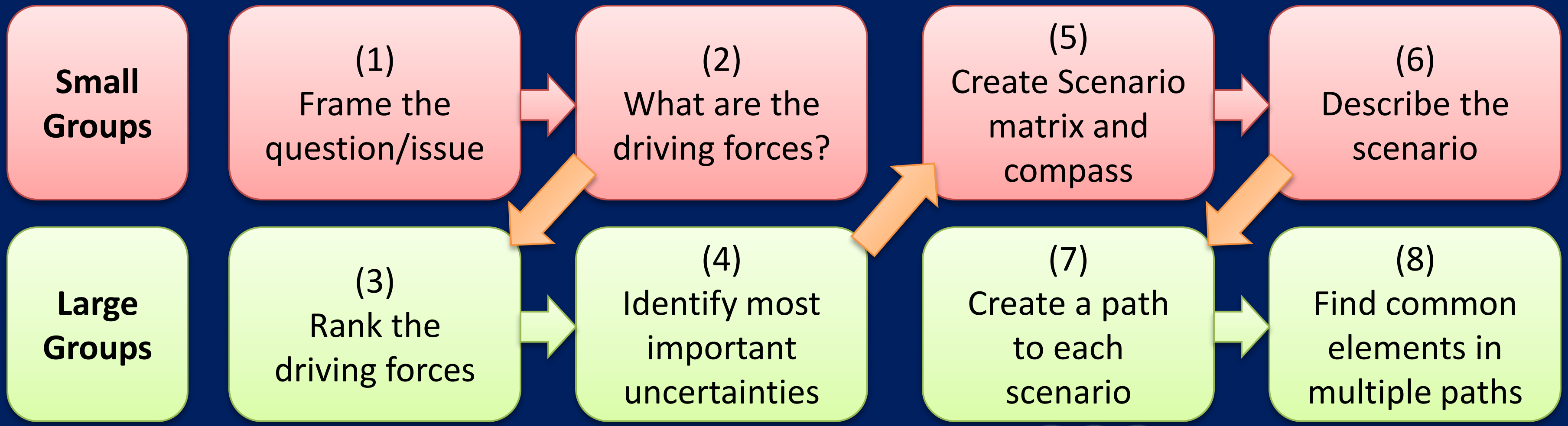
Scenario Planning

- Best fits to dynamic planning environments
- Consider uncertainties and unknowns – particularly non-quantifiable and highly variable
- Maximize flexibility and minimize regret costs
- Maximize system adaptability to change

→ **PLANNING ROBUSTNESS**

- Needs to be revised to reflect time varying uncertainties

Scenario Planning Process *(The Art of the Long View: Planning for the Future in an Uncertain World , Peter Schwartz)*



Small Groups

(1)
Frame the question/issue

(2)
What are the driving forces?

(5)
Create Scenario matrix and compass

(6)
Describe the scenario

Large Groups

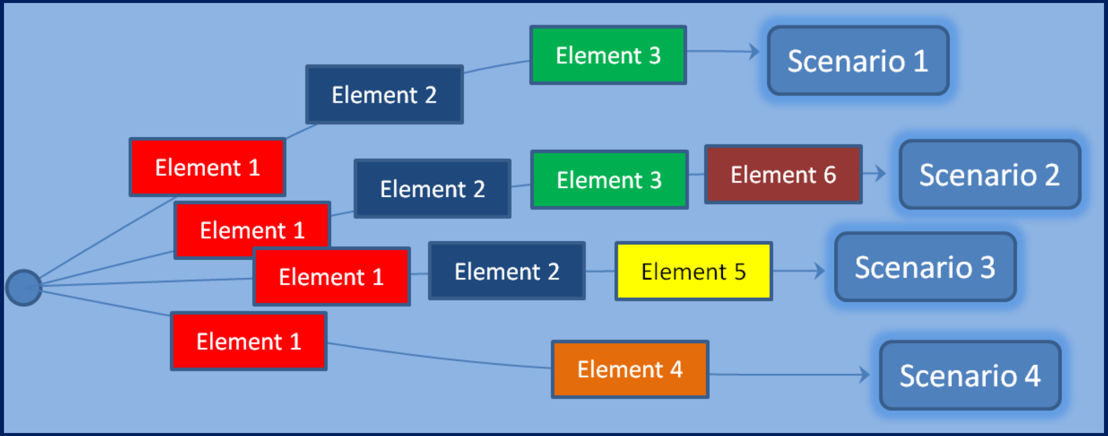
(3)
Rank the driving forces

(4)
Identify most important uncertainties

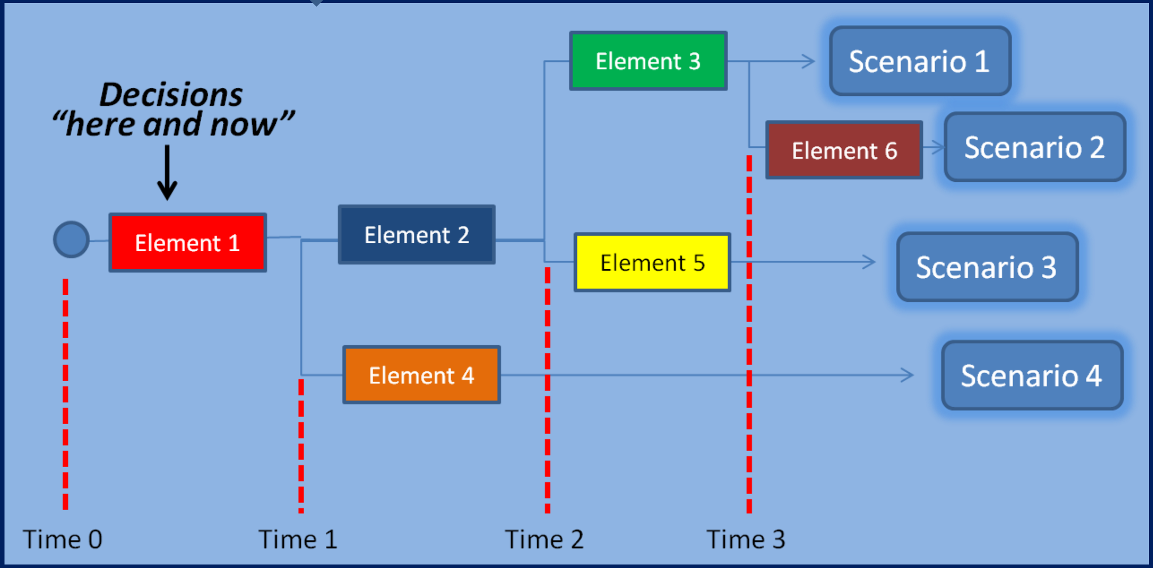
(7)
Create a path to each scenario

(8)
Find common elements in multiple paths

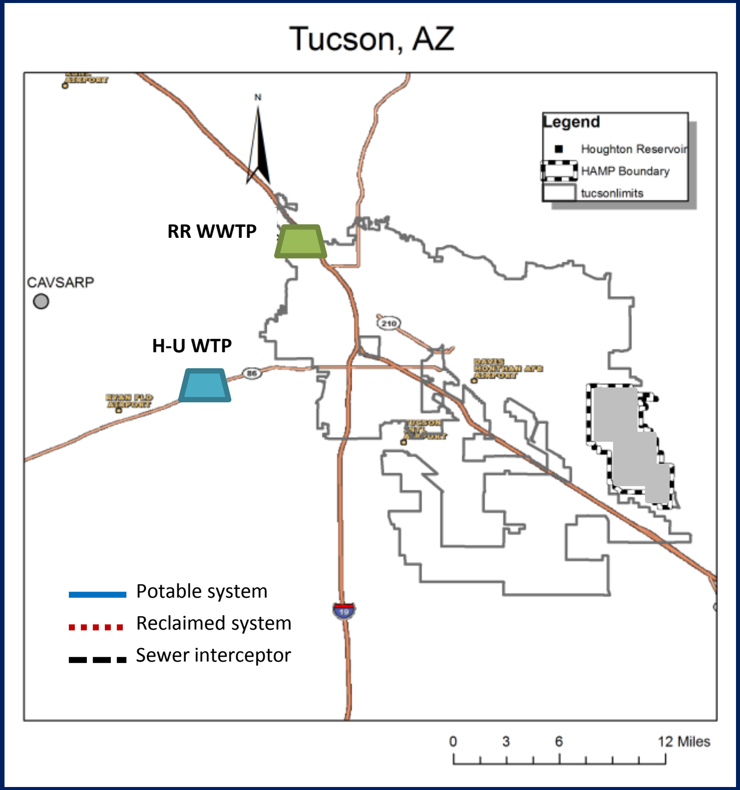
Scenario Planning

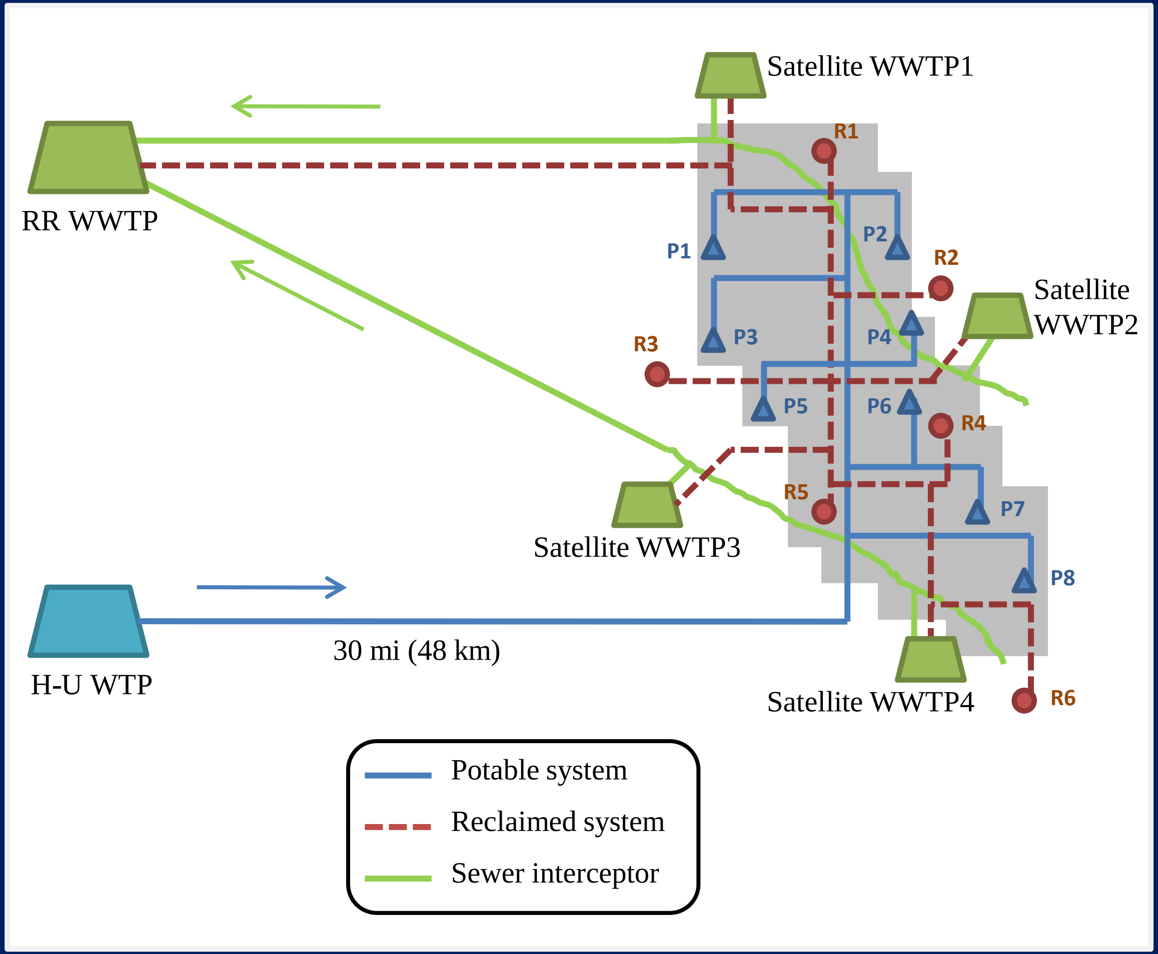


Find common elements



HAMP Area Application





Methodology

- Optimization Algorithm – Genetic algorithm
- Decisions
  - Potable transmission pipe sizes
  - Reclaimed transmission pipe sizes
  - Satellite WWTPs capacities (1 MGD increment)
  - Centralized WWTP expansion capacity (5 MGD increment)
  - Recharge/recovery facility capacity
- Construction and O&M costs (w/ 3% discount rate)

Design Steps

Step 0
Developing Scenarios

Step I
Solve a set of single scenario problems

Multi-period single-scenario optimization (MPSSO) model

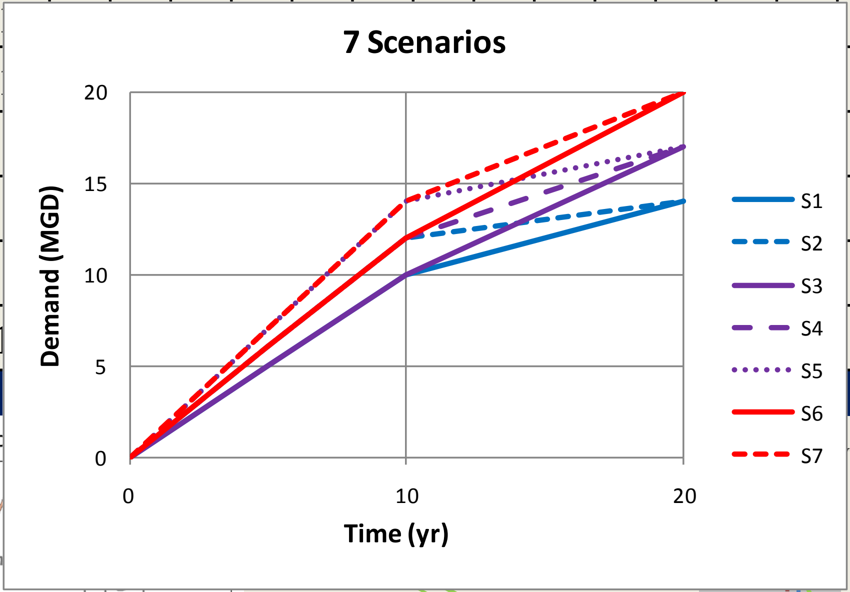
Step II
Identify common elements

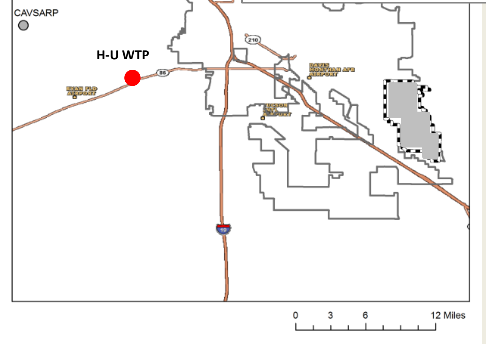
Step III
Determine optimal compromise solution

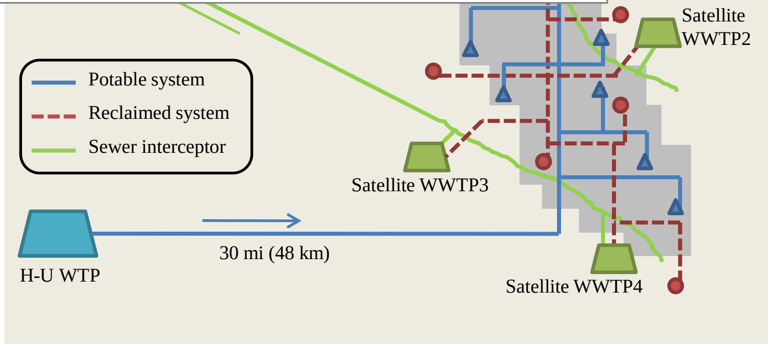
Multi-period multi-scenario optimization (MPMSO) model

Scenario-based Robust Optimization of Regional W/WW Infrastructure

Scenario	Low Growth Scenario						Medium Growth Scenario									High Growth Scenario					
	S1			S2			S3			S4			S5			S6			S7		
Year	5															5	10	20	5	10	20
Total demand	5															6	12	20	7	14	20
RW demand	1															1	2	4	1	3	4
PW demand	4															5	10	16	6	11	16
WW produced	3															4	8	13	5	9	13
Prob. of scenario																1/7			1/7		

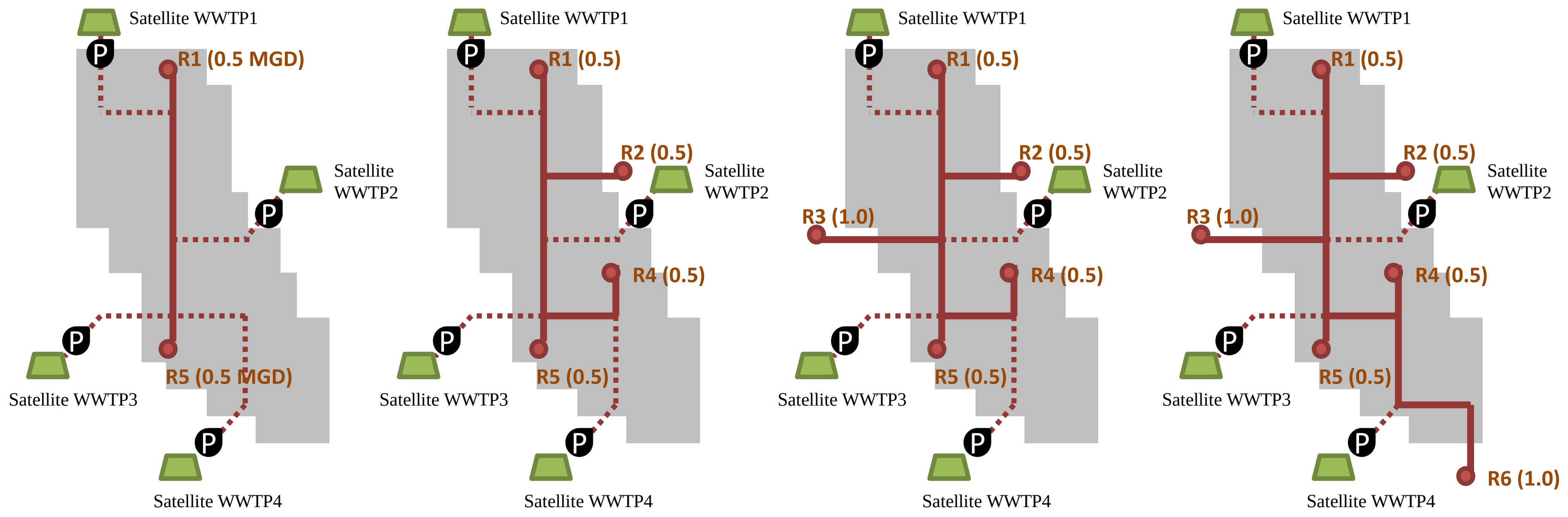






Community growth projection

- Reclaimed system (park, school & golf course) - based on development plan, nodal Q fixed



1 MGD **2 MGD** **3 MGD** **4 MGD**

R1, R4, R5 – Park & School
R2 – Rocking K
R3 – Rita Ranch
R6 – Del Lago

Full development →

Design Steps

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Solve a set of single scenario problems

Step II
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Step III
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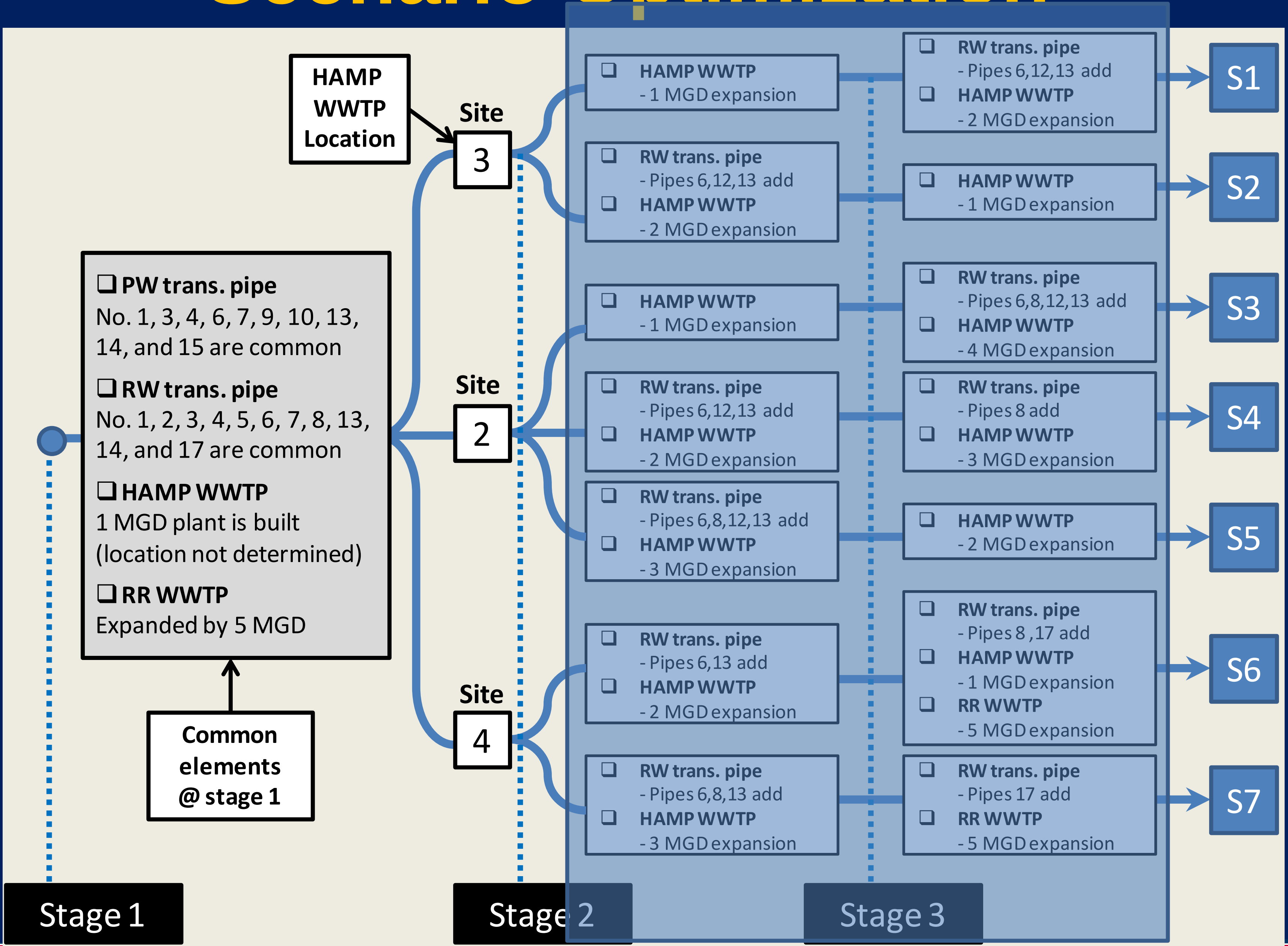
Multi-period single-scenario optimization (MPSSO) model

Multi-period multi-scenario optimization (MPMSO) model

Scenario Optimization



HAMP WWTP Location

☐ **PW trans. pipe**
No. 1, 3, 4, 6, 7, 9, 10, 13, 14, and 15 are common

☐ **RW trans. pipe**
No. 1, 2, 3, 4, 5, 6, 7, 8, 13, 14, and 17 are common

☐ **HAMP WWTP**
1 MGD plant is built (location not determined)

☐ **RR WWTP**
Expanded by 5 MGD

Common elements @ stage 1

Site 3

- ☐ HAMP WWTP - 1 MGD expansion
  - ☐ RW trans. pipe - Pipes 6,12,13 add; ☐ HAMP WWTP - 2 MGD expansion → S1
- ☐ RW trans. pipe - Pipes 6,12,13 add; ☐ HAMP WWTP - 2 MGD expansion
  - ☐ HAMP WWTP - 1 MGD expansion → S2

Site 2

- ☐ HAMP WWTP - 1 MGD expansion
  - ☐ RW trans. pipe - Pipes 6,8,12,13 add; ☐ HAMP WWTP - 4 MGD expansion → S3
- ☐ RW trans. pipe - Pipes 6,12,13 add; ☐ HAMP WWTP - 2 MGD expansion
  - ☐ RW trans. pipe - Pipes 8 add; ☐ HAMP WWTP - 3 MGD expansion → S4
- ☐ RW trans. pipe - Pipes 6,8,12,13 add; ☐ HAMP WWTP - 3 MGD expansion
  - ☐ HAMP WWTP - 2 MGD expansion → S5

Site 4

- ☐ RW trans. pipe - Pipes 6,13 add; ☐ HAMP WWTP - 2 MGD expansion
  - ☐ RW trans. pipe - Pipes 8 ,17 add; ☐ HAMP WWTP - 1 MGD expansion; ☐ RR WWTP - 5 MGD expansion → S6
- ☐ RW trans. pipe - Pipes 6,8,13 add; ☐ HAMP WWTP - 3 MGD expansion
  - ☐ RW trans. pipe - Pipes 17 add; ☐ RR WWTP - 5 MGD expansion → S7

Stage 1

Stage 2

Stage 3

Design Steps

Step 0
Developing Scenarios

Step I
Solve a set of single scenario problems

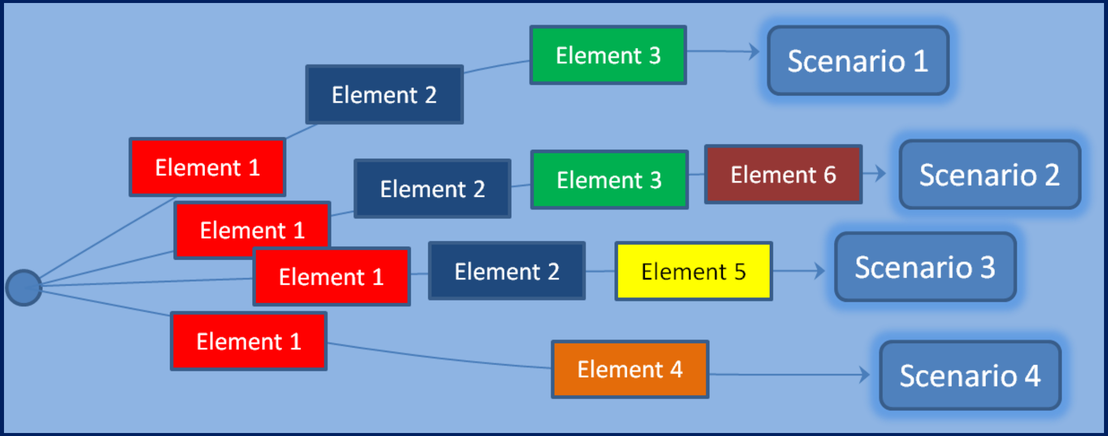
Multi-period single-scenario optimization (MPSSO) model

Step II
Identify common elements

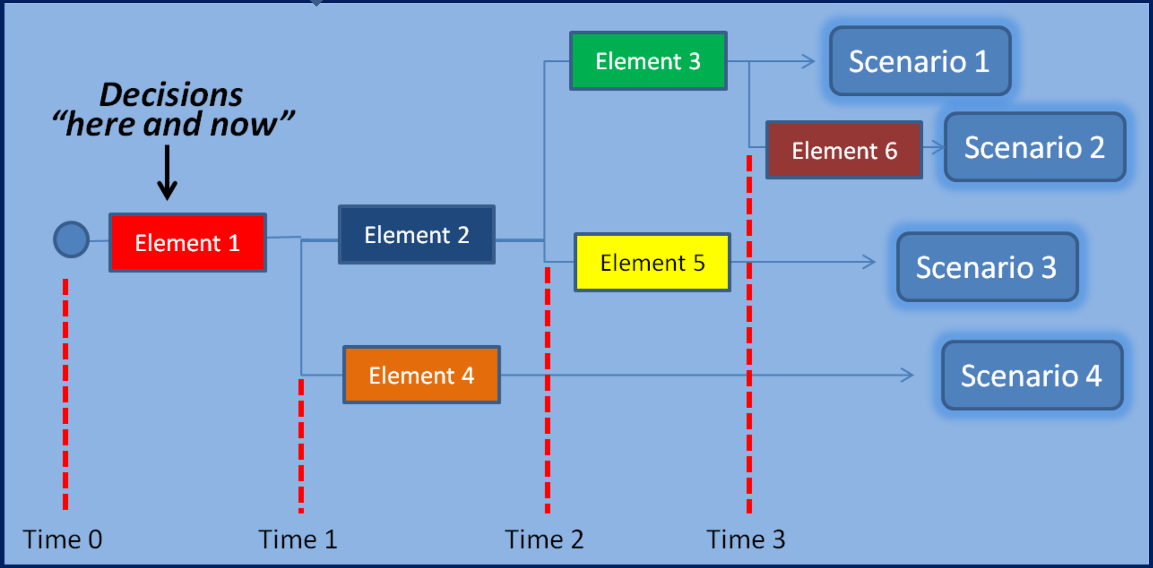
Step III
Determine optimal compromise solution

Multi-period multi-scenario optimization (MPMSO) model

Scenario Planning

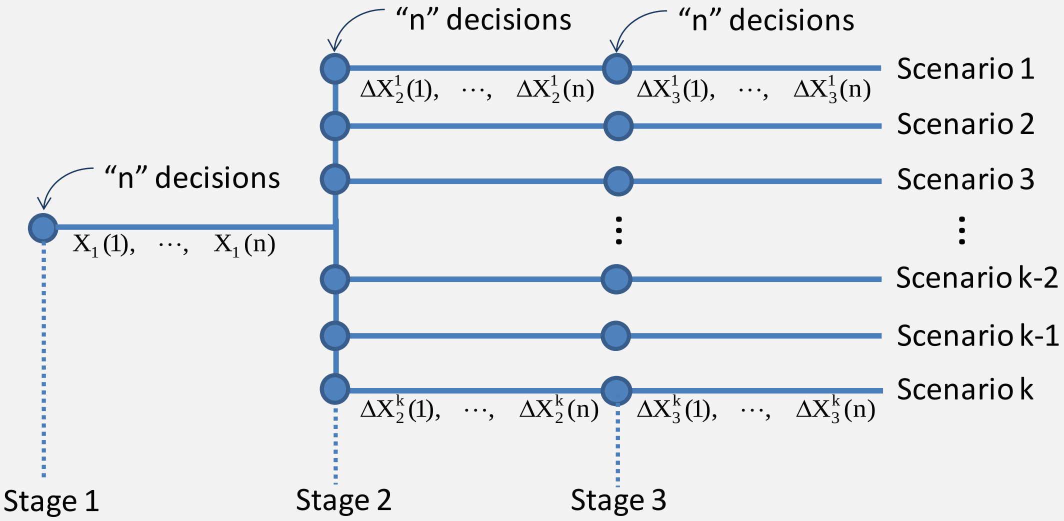


Find common elements


Decisions
“here and now”

Multi-Period Multi-Scenario Optimization - MPMSO

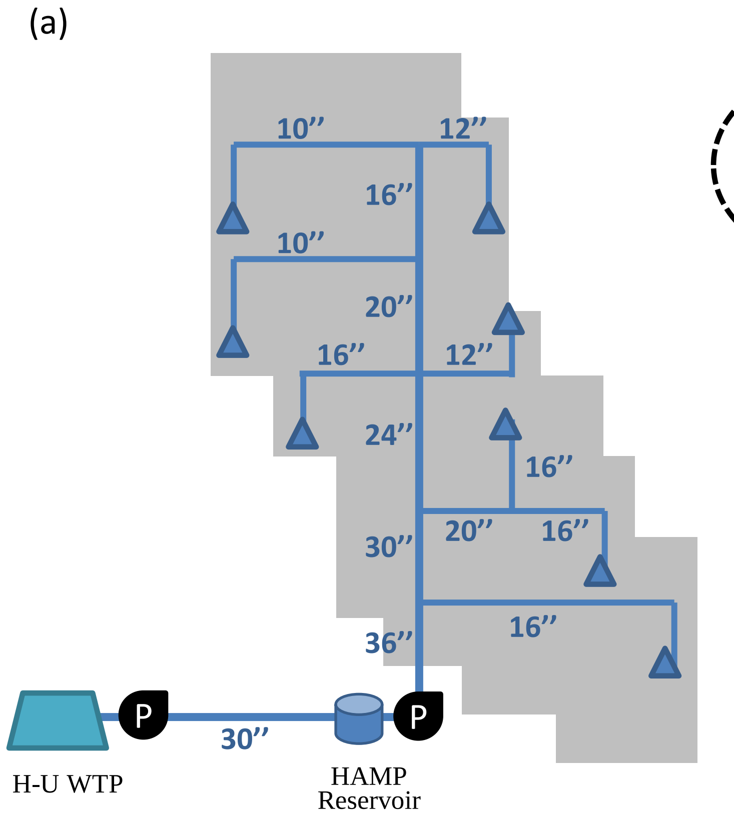
- Original problem has **510** (=225+285) DVs
- By adopting common solutions obtained from MPMSO, no. of DVs drops to **89** (=5+84) (83%↓)



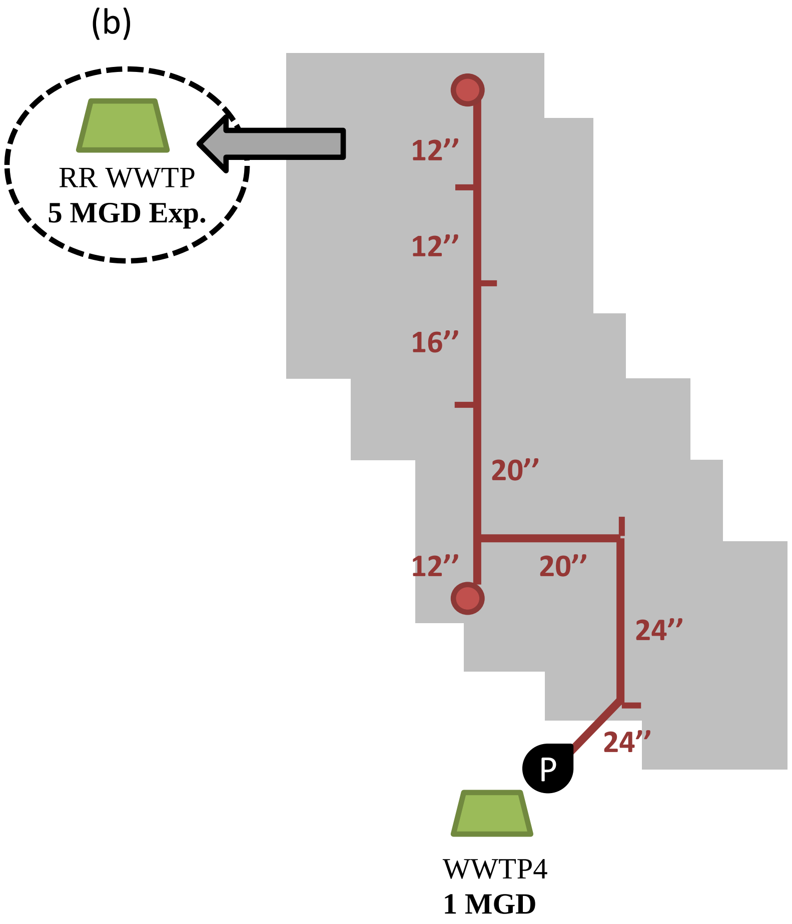
Total number of decisions = n + k*(s-1)*n

where n = number of decisions at each stage
k = number of scenarios addressed
s = number of planning stages

Optimal system design at stage 1



Potable System



Reclaimed System

Optimal Costs by Scenario
Expected cost = $329.5 M

Cost in $M	S1	S2	S3	S4	S5	S6	S7
Scenario-optimal cost	285.1	293.6	321.0	332.1	340.7	363.0	371.1
Actual cost	285.7	294.1	323.9	333.2	341.9	363.1	371.2
Regret cost*	0.62	0.53	2.86	1.14	1.16	0.12	0.14

Repeat over time!

At time 0

Element

Element

Element

Element

Element

Element

Scenario 1

Scenario 2

Scenario 3

Scenario 4

Time 0 Time 1 Time 2 Time 3

At time 1

Element

Element

Element

Element

Element

Scenario 1

Scenario 2

Scenario 3

Time 0 Time 1 Time 2 Time 3

At time 2

Element

Element

Element

Element

Scenario 1

Scenario 2

Time 0 Time 1 Time 2 Time 3

At time 3

Element

Element

Element

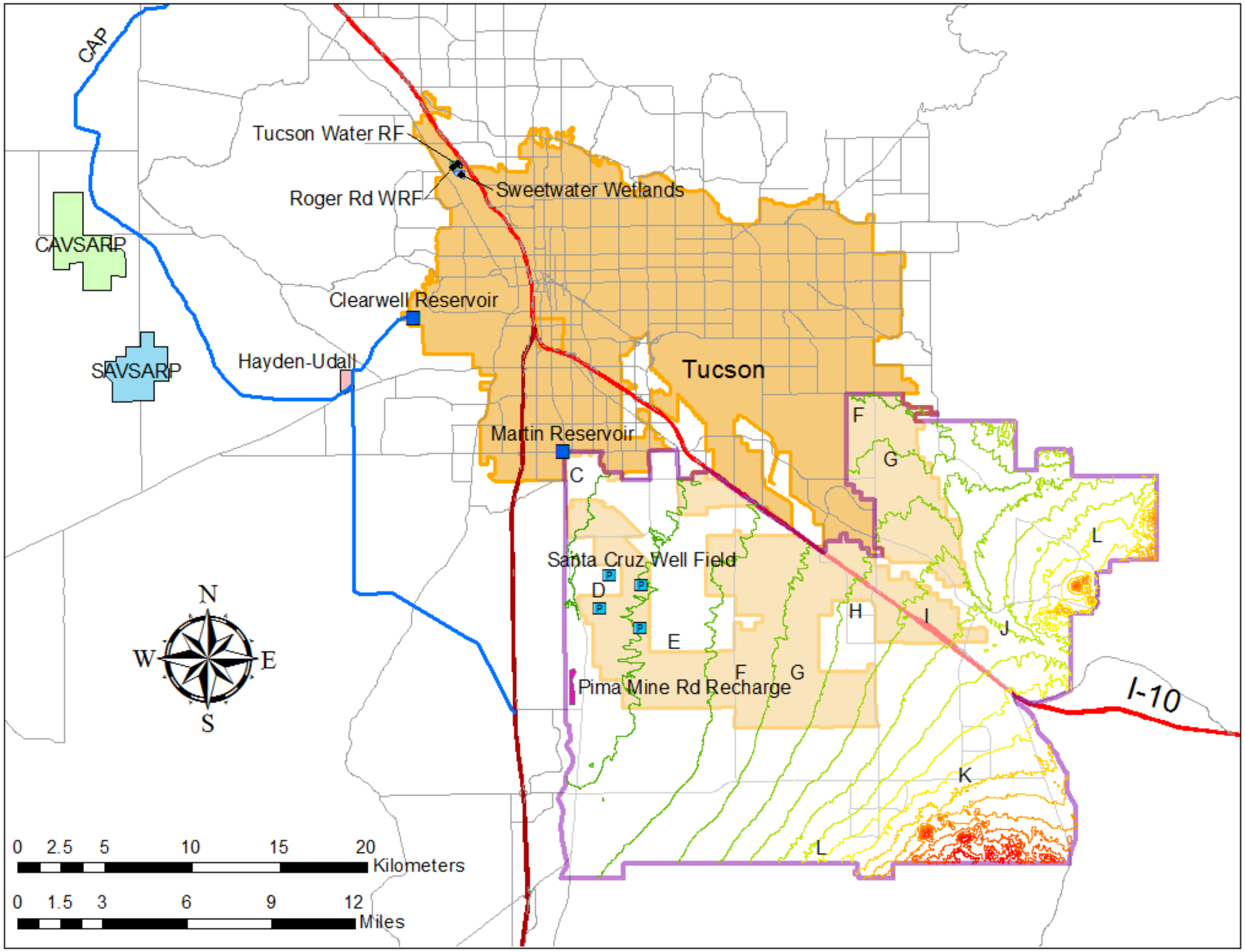
Element

Scenario 1

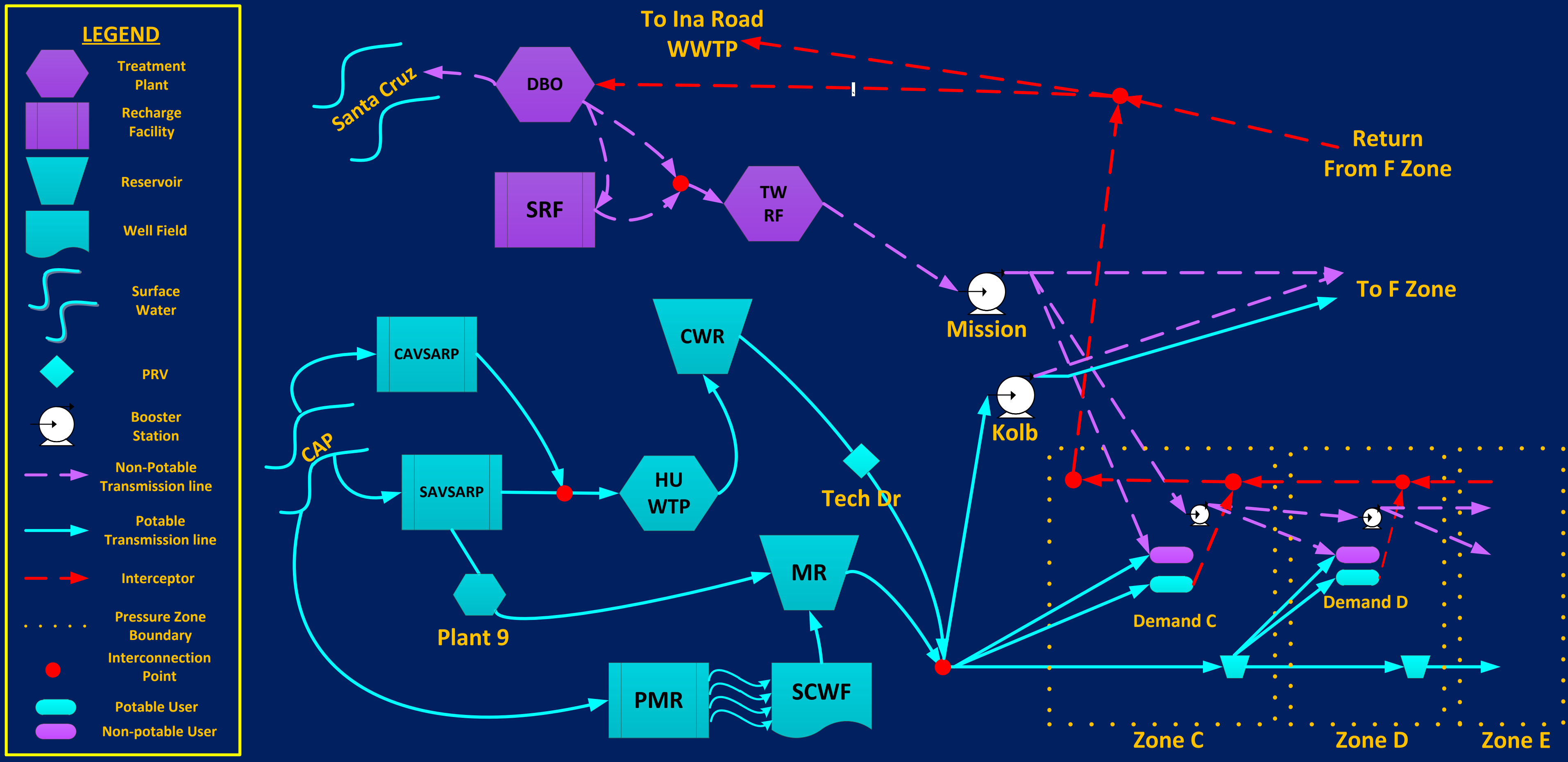
Vulnerability Assessment

- Criticality analysis
- Fail one or more components and examine impact on resilience measure
  - Deficit in ability to deliver water
- Function of
  - Decentralized facility locations
  - Time (increasing demand with constant supply)

Tucson Region

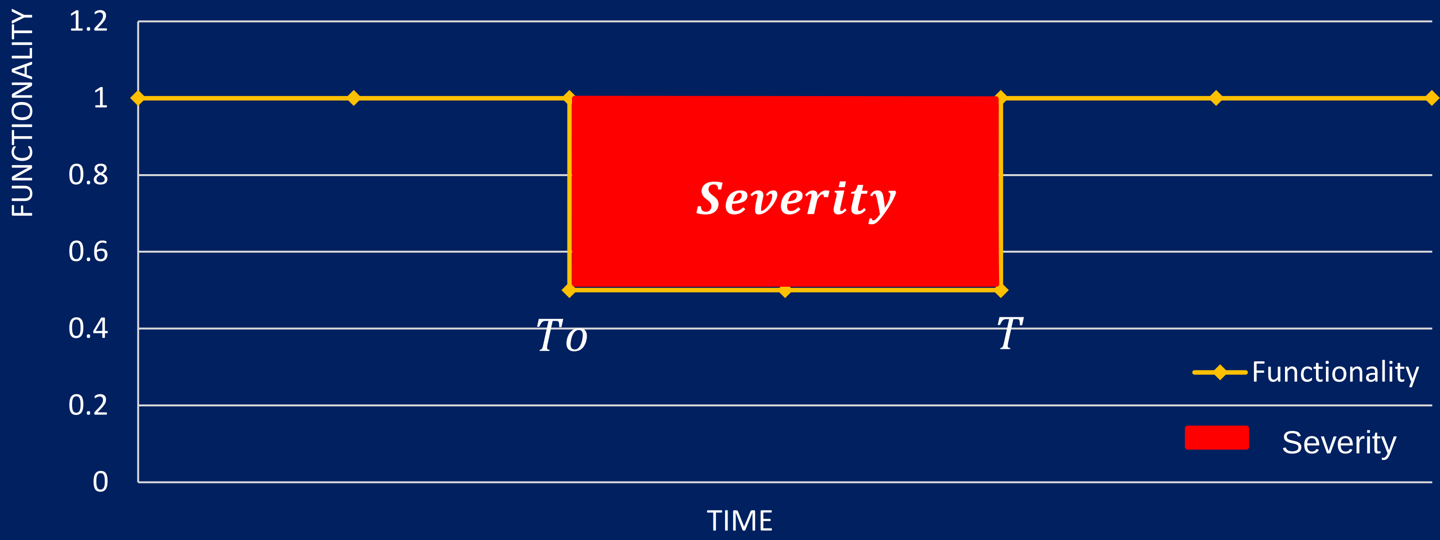


Flow Schematic



Core Model

- Network flow model with losses
  - Optimize the flow distribution on a monthly time step minimizing overall distribution and treatment costs
    - WT, WWT, and energy costs
  - Subject to constraints/variable bounds



- $f_P(t) = \frac{S_P}{D_P}$
- $f_{NP}(t) = \frac{S_{NP}}{D_{NP}}$
- $Severity_P = \frac{\int_{T_0}^{T}[1-f_P(t)]dt}{(T-T_0)}$
- $Severity_{NP} = \frac{\int_{T_0}^{T}[1-f_{NP}(t)]dt}{(T-T_0)}$

$f_P =$ functionality (potable water)

$f_{NP} =$functionality (non-potable water)

$S_P =$ supplied potable wataer

$D_P =$ demand of potable water

$S_{NP} =$ supplied non−potable water

$D_{NP} =$ demand of non−potable water

$T - T_0 =$failure duration=1 month

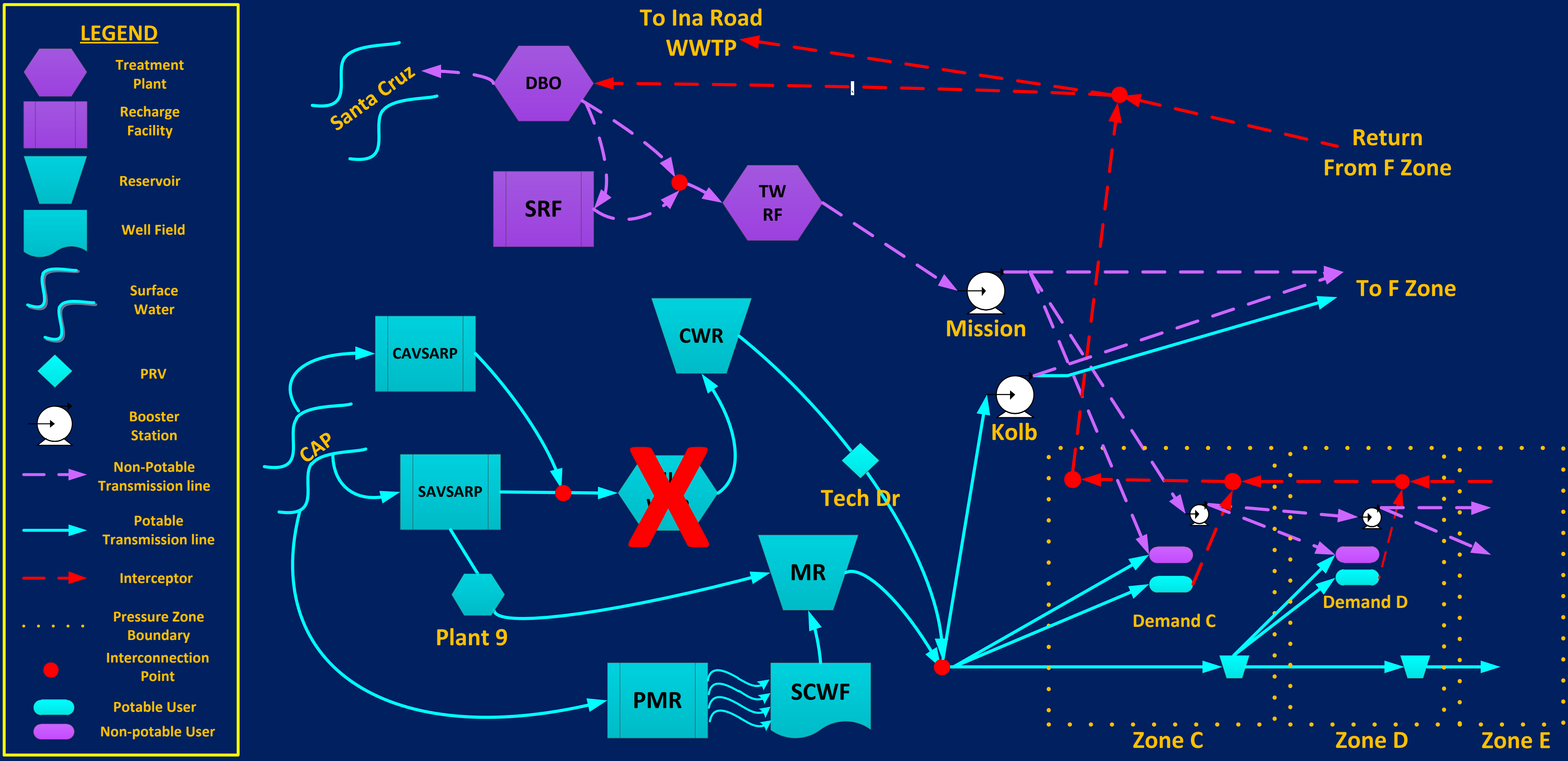
$0 \leq f_P(t) \leq 1$

$0 \leq f_{NP}(t) \leq 1$

$0 \leq Severity_P \leq 1$

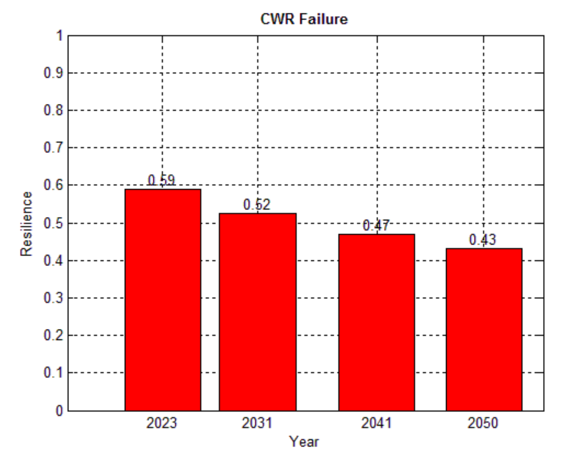
$0 \leq Severity_{NP} \leq 1$

Failure Scenario 7



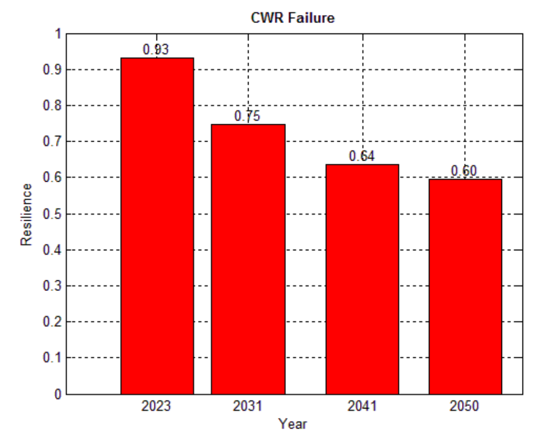
- Hayden-Udall Water Treatment Plant (HUWTP) failure
- $Severity_P$= 0.69; $Severity_{NP}$= 0.81

RWSS Resilience (Potable Demand)



No SP and IPR

Zone FS



Zone GS

Zone HS

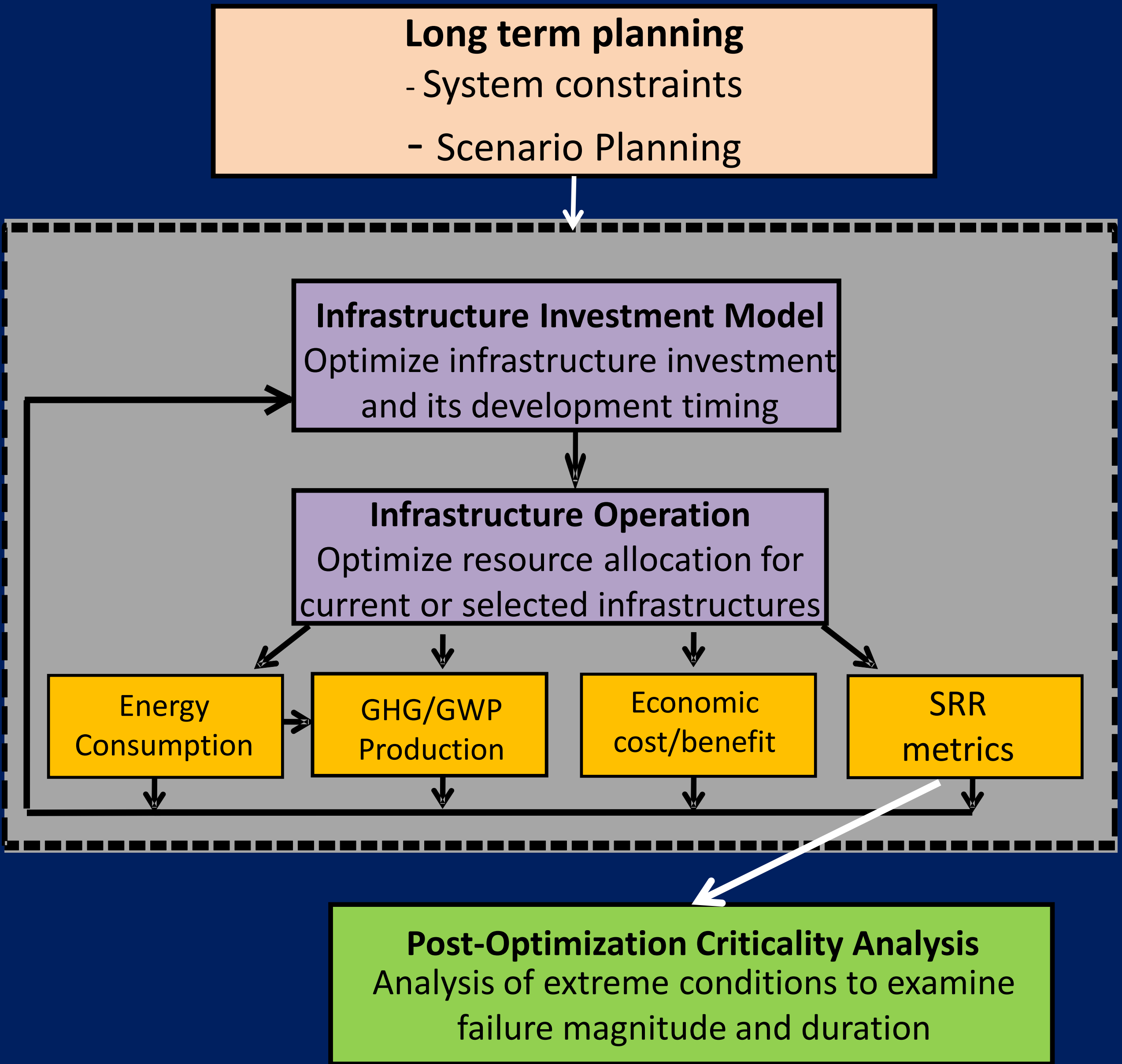
Failure Mode Effects and Criticality Analysis (FMECA)

- Develop means to identify critical elements
- Risk analysis
- Risk Priority Number = Severity x Occurrence

Result of risk assessment with the base RWSS

Failure mode	Failure severity		Severity scale value		Occurrence scale value	RPN	
	P	NP	P	NP		P	NP
1	0.77	0.37	8	3	2	16	6
2	0.57	0.43	5	4	2	10	8
3	0.57	0.43	5	4	2	10	8
4	0.38	0.26	3	2	3	9	6
5	0.31	0.26	3	2	3	9	6

SRR Design/Planning Framework



Long term planning
- System constraints
- Scenario Planning

Infrastructure Investment Model
Optimize infrastructure investment and its development timing

Infrastructure Operation
Optimize resource allocation for current or selected infrastructures

Energy Consumption

GHG/GWP Production

Economic cost/benefit

SRR metrics

Post-Optimization Criticality Analysis
Analysis of extreme conditions to examine failure magnitude and duration

Robust Design or Operation for a set of disturbances/alternative futures
- Operation – range of conditions under which a fixed infrastructure system will perform acceptably
- Design – range of alternative futures that can be adapted to with minimal regret costs

Resilience analysis – Range of extreme conditions (beyond operation /design set) that is examined to determine the degree and duration of failure