Managing Conflicting Water Resource Goals and Uncertainties in a Multi-Reservoir System

Lin Guo

PhD Candidate
School of Industrial and Systems Engineering
University of Oklahoma
E-mail: lin.guo@ou.edu

Co-Advisors:
Professor Janet K. Allen
School of Industrial and Systems Engineering
Professor Farrokh Mistree
School of Aerospace and Mechanical Engineering

April 4th, 2018

Content

Dam-Network Planning (1/2)

Network – 38 dams (nodes), streams (arcs), plan the flows to meet requirements

Goals – supplying appropriate amount of water to multiple user-groups (fish, people)

Decisions – water flow plans, model improvement

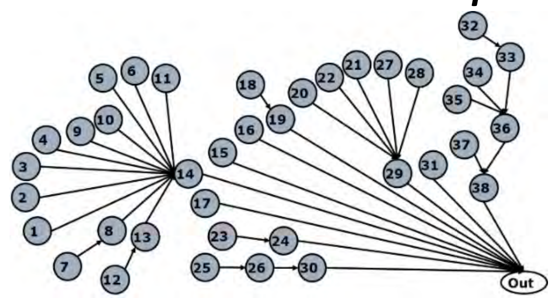
Uncertainties – variation in inflows (precipitation, tributary)

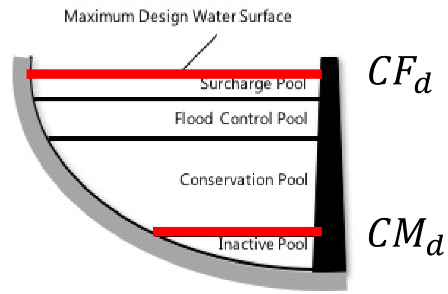
Hypothesis – by exploring the solution space and improving the model, we can make water flow plans that are relatively insensitive to uncertainties.

Dam-Network Planning (2/2)

- Introduction of the data we use

The structure the network: the ***upstream dams*** and ***downstream dams*** of each dam





The physical ***upper and lower bound*** of water storage of each reservoir $CM_d \le S_d^t \le CF_d$

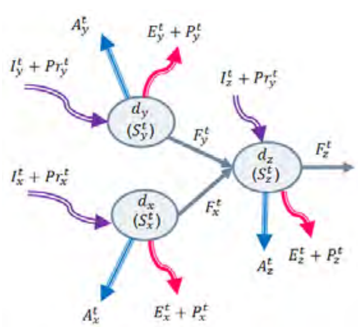
The upper and lower bound of predicted precipitation and tributary $I_d^t + Pr_d^t$

The target volume of water storage in the reservoirs ST_d^t

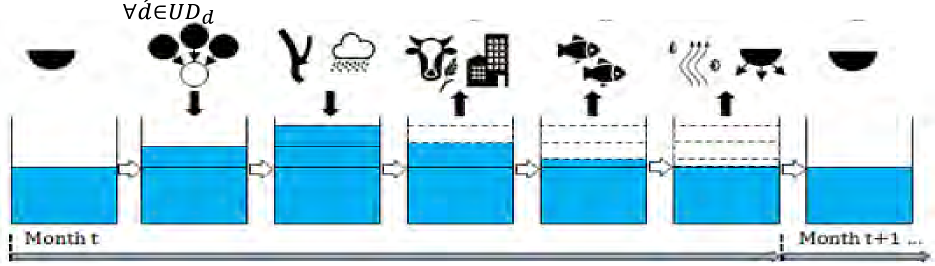
The target volume of water released to downstream dams of each dam FT_d^t

The target volume of water released for municipal and agricultural AT_d^t

The evaporation and seepage loss $E_d^t + P_d^t$



$$S_d^t + \sum_{\forall \acute{d} \in UD_d} F_{\acute{d}}^t + (I_d^t + Pr_d^t) - A_d^t \quad - F_d^t \quad - (E_d^t - P_d^t) = S_d^{t+1}$$

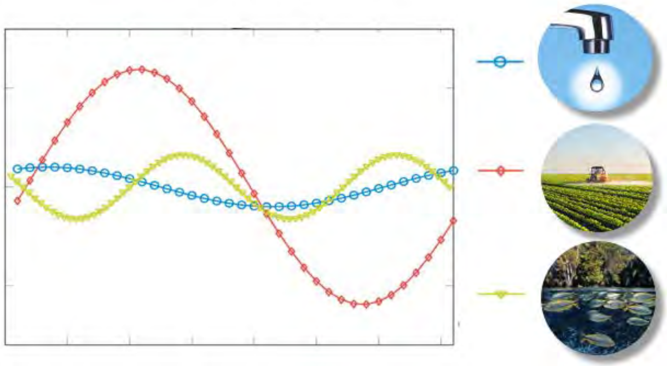


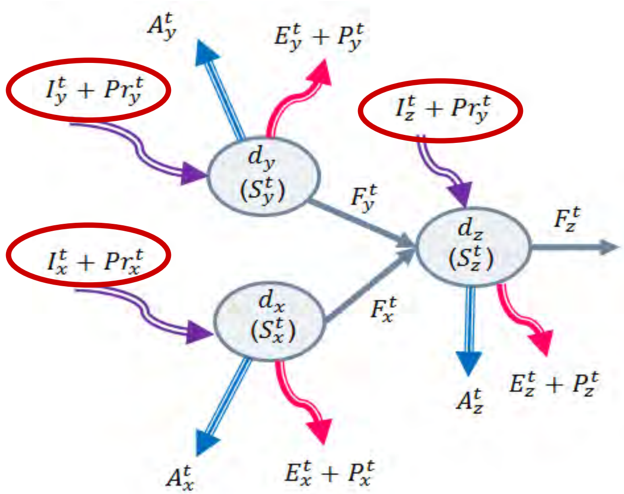
1 Problem Description | 2 Frame of Reference and Proposed Method | 3 Model Formulation | 4 Post-Solution Analysis | 5 Closure

Uncertainty in the Problem

Inflow

Outflow





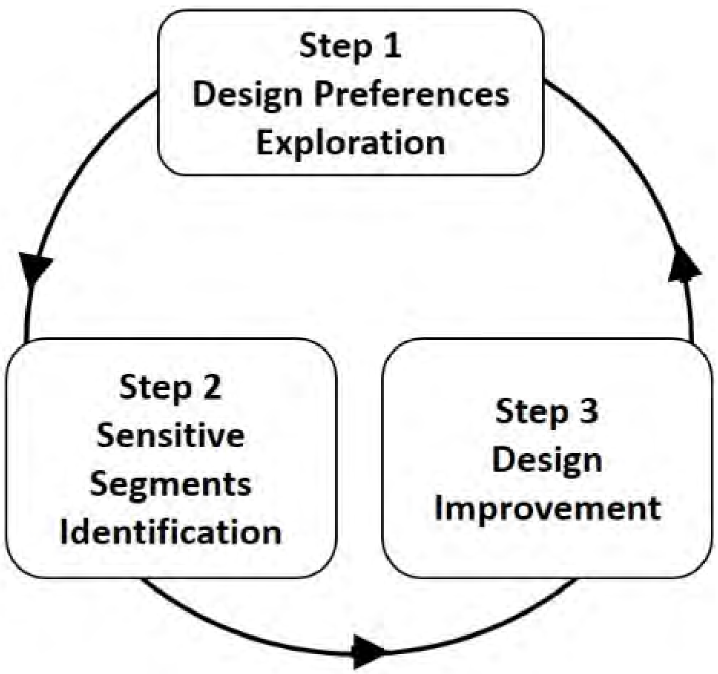
Literature Review and Gap Analysis (1/2)

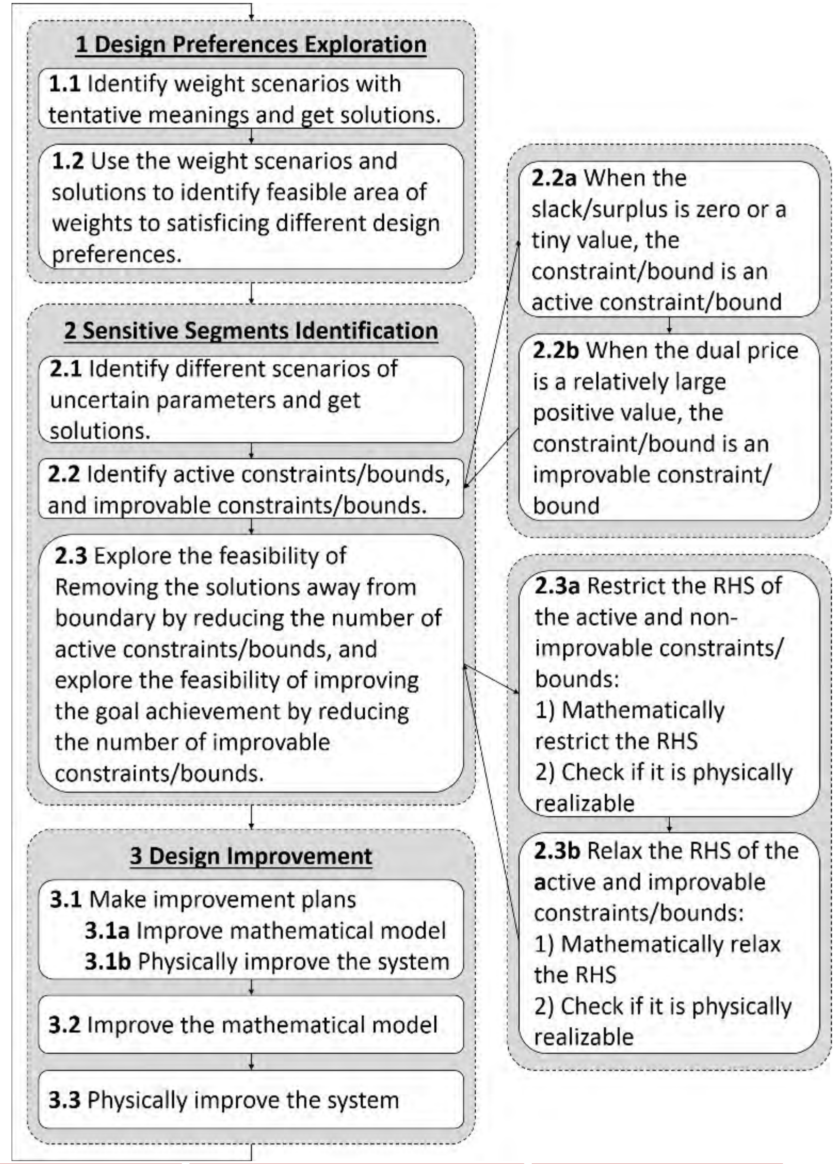
Methods in literature	Gaps and Limitations	Requirements of filling in the gaps	Proposed Methods and how do they meet the requirements
Deterministic Linear Programming (LP)	Cannot manage nonlinearity, nonconvexity, discontinuity, or variations in parameters	Form the problem more accurately, and capture the nonlinear, nonconvex, and discontinuous feature, and manage the critical variations in parameters	CDSP – use cDSP to formulate a problem accurately. The problem can be formulated as a nonlinear problem with continuous, binary and integer variables. Nonconvex problem can be converted into convex problem using the formulation rules
Mixed-Integer LP (MILP)	Computational dense	Approximate the problem to reduce the computational density, while maintain appropriate fidelity	ALP – approximate the problem using ALP, through linearizing the nonlinear constraints and goals
Stochastic LP (SLP)	Have ssumptions of the distribution of stochastic variables may be wrong	Manage the parameters with uncertainties without any assumptions of distribution of the parameters	ESS – explore the solution space in different design scenarios incorporating uncertainties. Identify a solution space that is relatively insensitive to the uncertainties
Chance-Constraint LP (CCLP)	Can decrease frequency of system failure but cannot guarantee severity of each system failure	Decrease the frequency and severity of systems failures by manage the optimality and feasibility simultaneously	Primal-dual interior method – the optimality and feasibility can be managed simultaneously using the primal-dual interior method.
Network Flow Programming (NFP)	Cannot evaluate the structure of the network and output improvement suggestion	Provide water flow plans, by analyzing the plans, we can evaluate the network structure and know how we can improve it	ESS – by exploring the solution space, we can pinpoint the segments in the dam-network that are with limited capacity, or sensitive to uncertainties, and know how we can make a change
Interior Point (IP)	only works efficient when the problem is a large-scale one, and is hard to be implemented.	IP can be used as a supplemental algorithm of Simplex algorithm when the problem is a large one	Implement IP in solving cDSP when the problem is large. Since in this General Exam, the problem is not a large-scale one, we do not do this right now. It can be in the future work.

Literature Review and Gap Analysis (2/2)

Methods in literature	Gaps and Limitations	Requirements of filling in the gaps	Proposed Methods and how do they meet the requirements
Nonlinear Programming (NLP)	Not computational efficiency for engineering design purpose in the long-term view	Form the problem accurately with nonlinear feature. Approximate the problem to reduce computational density	CDSP and ALP – we can use cDSP to formulate a problem accurately, and approximate the problem using ALP, through linearizing the nonlinear constraints and goals
Dynamic Programming (DP)	Curse of dimensionality	A method that is not sensitive to dimensionality, which means the increasing in dimension does not significantly increase the computational complexity	Partition the large-scale, high- dimension problem, and solve each sub-problem using cDSP and ALP. Since the problem in this General Exam is not a large-acale, high-dimension one, the partition methods can be further studied in future work to deal with large, complex problems.
Goal Programming (GP)	Preemptive GP: a tiny drawback of a primary goal hinders a huge improvement of a secondary goal. Weight GP: the difficulty in finding the appropriate value and evaluating the rationality of the weights of the goals.	Realize reasonable tradeoffs between fulfillments of different goals.	CDSP and ESS – cDSP is a construct within the framework of GP. In the process of ESS, we do weight sensitivity analysis hence we can get the knowledge of "how much weight should we assign to each goal to get certain achievements of the goals"

Proposed Method (1/2)





Proposed Method (2/2)

a. Identify n scenarios of parameters with uncertainties – ISs.

b. Use the latest model to identify the feasible area of weights, and identify m weight scenarios within the feasible area of weights that represent different design preferences – WSs.

c. Plug n ISs and m WSs into the latest model to get x solutions.

d. Use the x solutions to identify sensitive segments (active constraints/bounds and improvable constraints/bounds) in the model

  if no sensitive segments

    Go to i.

  else

    Continue with e.

e. For each active and non-improvable constraint/bound

  Explore the feasibility of restricting their RHS

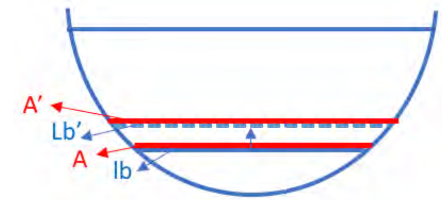
f. For each active and improvable constraint/bound

  Explore the feasibility of relaxing their RHS

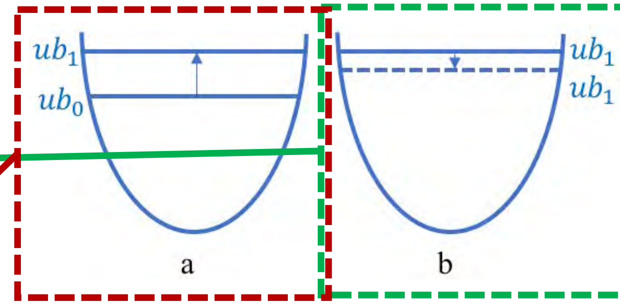
g. Make model improvement plans based on the conclusion in e and f.

h. Improve the model based on the improvement plans in g and go to b.

i. The latest model is relatively insensitive to uncertainties and has no potential to achieve a better solution. **End** the iteration.



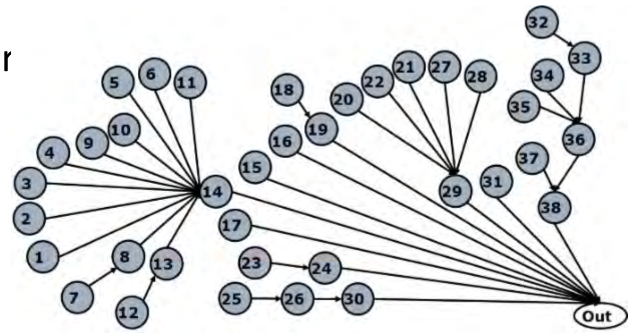
Bring the Solution Away from the Boundary by Restricting the RHS



Adding Buffer to Bring the Solution Away from the Boundary

Formulation of the Model (1/3)

- Definition and assumptions of the structure of the networ
  - No barriers between dams
  - Infrastructures are in good condition
  - Do not consider cost



- Goals we manage
  - Ecological benefits in the reservoirs ST_d^t
  - Ecological benefits in the streams between reservoirs FT_d^t
  - Societal benefits in the human society of the Red River basin AT_d^t
- Quantification and evaluation of the achievement of the goals
  - Minimizing the square of the difference between water supply and water demand target

$$\sum(S_d^t - ST_d^t)^2$$
$$\sum(F_d^t - \boldsymbol{FT}_d^t)^2$$
$$\sum(A_d^t - AT_d^t)^2$$

- Actions that the decision maker can take
  - Water flow plans
  - Model improvement – Right-hand-side (RHS) values of constraints and bounds

Formulation of the Model (2/3)

- Decision variables and parameters

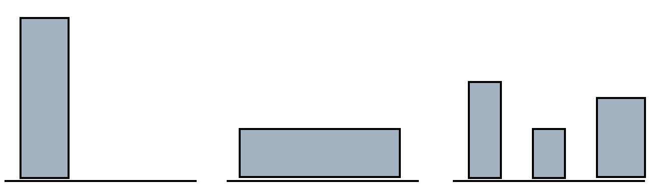
Data	Water storage volume in the reservoirs	Water release volume to the downstream reservoirs	Water release volume to people	Precipitation and tributary	Evaporation and seepage
1. If it is critical to system performance?	*	*	*	*	
2. If it can be determined by the decision maker?	*	*	*		
Category of the data	Decision variables	Decision variables	Decision variables	Parameters with uncertainties	Parameters with fixed value

- Robustness of the solutions

ability of not causing serious discrepancies between water supply and water demand

$$\sum(S_d^t - ST_d^t)^2$$
$$\sum(F_d^t - \boldsymbol{FT}_d^t)^2$$
$$\sum(A_d^t - AT_d^t)^2$$

Target values



Formulation of the Model (3/3)

Given

System parameters

$D = \{d\} = \{1, 2, \ldots, 14\}$ (P1)
//The set of 14 dams (reservoirs)

$T = \{t\} = \{1,2,3\}$ (P2)
//Planning period – twelve months

$UD_d = \{\acute{d}\}$ (P3)
//The set of upstream dams (reservoirs) Detail information is in Table 1

ST_d^t (P4)
//Target of water storage volume for Reservoir d at the beginning of Month t

FT_d^t (P5)
//Target of water release volume to downstream for fish for Dam d in Month t

AT_d^t (P6)
//Target of water release volume for agriculture and municipal use for Dam d in Month t

$(E_d^t + P_d^t)$ (P7)
//Natural loss (evaporation and seepage) of Reservoir d in Month t

CF_d (P8)
//Flood capacity of Reservoir d

CM_d (P9)
//Minimum storage volume of Reservoir d

$(I_d^t + Pr_d^t)$ (P10)
//Anticipated natural inflow (tributary inflow and precipitation) for Reservoir d

w_i, where $i = 1,2,3$ (P11)
//Weight of Goal i

Find

System variables

S_d^t (X1)
//The volume of water stored in Reservoir d at the beginning of Month t

A_d^t (X2)
//The volume of water released from Dam d to agricultural and municipal use in Month t

F_d^t (X3)
//The volume of water released from Dam d to downstream for fish in Month t

Deviation variables

d_i^+, d_i^-, where $i = 1,2,3$ (D)
Over-achievement and underachievement of Goal i

Satisfy

System constraints

$S_d^t + \sum_{\forall \acute{d} \in UD_d} F_{\acute{d}}^t + I_d^t + Pr_d^t - F_d^t - A_d^t - E_d^t - P_d^t = S_d^{t+1}$, where $t = 1,2,3$ (C1)

System goals

$$\sum_{d \in D}\sum_{t \in T}\left(1 - \frac{S_d^t}{ST_d^t}\right)^2 + \sum_{d \in D}\left(1 - \frac{S_d^4}{ST_d^4}\right)^2 + d_1^- - d_1^+ = 0 \quad \text{(G1)}$$

//Goal 1 – Reservoir: reach the target of water storage in each reservoir in the beginning of each month, and in the end of the last month.

$$\sum_{d \in D}\sum_{t \in T}\left(1 - \frac{A_d^t}{AT_d^t}\right)^2 + d_2^- - d_2^+ = 0 \quad \text{(G2)}$$

//Goal 2 – People: reach the target of water released to people of each dam in each month.

$$\sum_{d \in D}\sum_{t \in T}\left(1 - \frac{F_d^t}{FT_d^t}\right)^2 + d_3^- - d_3^+ = 0 \quad \text{(G3)}$$

//Goal 3 – Fish: reach the target of water released to wild fish of each dam in each month.

Bounds

$S_d^t \leq CF_d$ (B1)
$S_d^t \geq CM_d$ (B2)
$F_d^t \geq 0$ (B3)
$A_d^t \geq 0$ (B4)
//Bounds of system variables

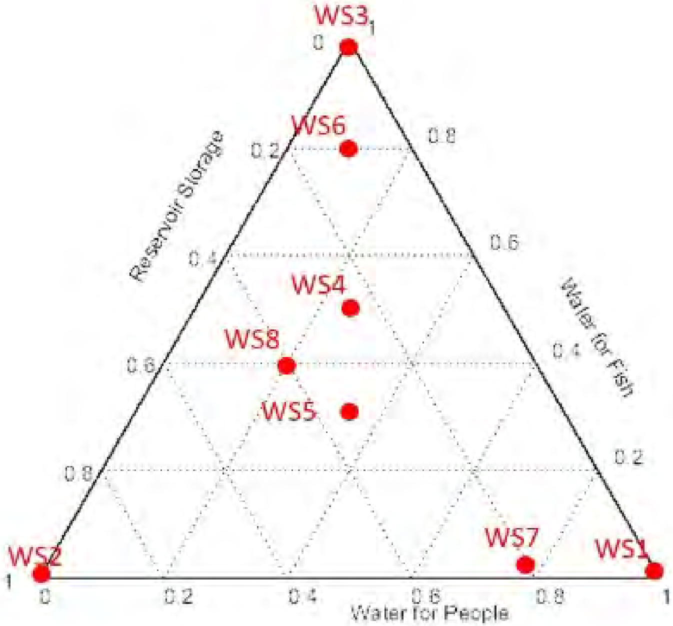
$d_i^- \geq 0, d_i^+ = 0, d_i^- \cdot d_i^+ = 0$, where $i = 1,2,3$ (DB)
//Bounds of deviation variables

Minimize

The deviation function

$z = \sum_{i=1}^{3} w_i \cdot d_i^-$, where $0 \leq w_i \leq 1$, and $\sum_{i=1}^{3} w_i = 1$ (Z)
//The weighted sum of deviation variables

Results (1/2)



Weight Scenarios (WS) Identification

Meaning of the Weight Scenarios (WS)

Meaning of the Weight Scenarios (WS)

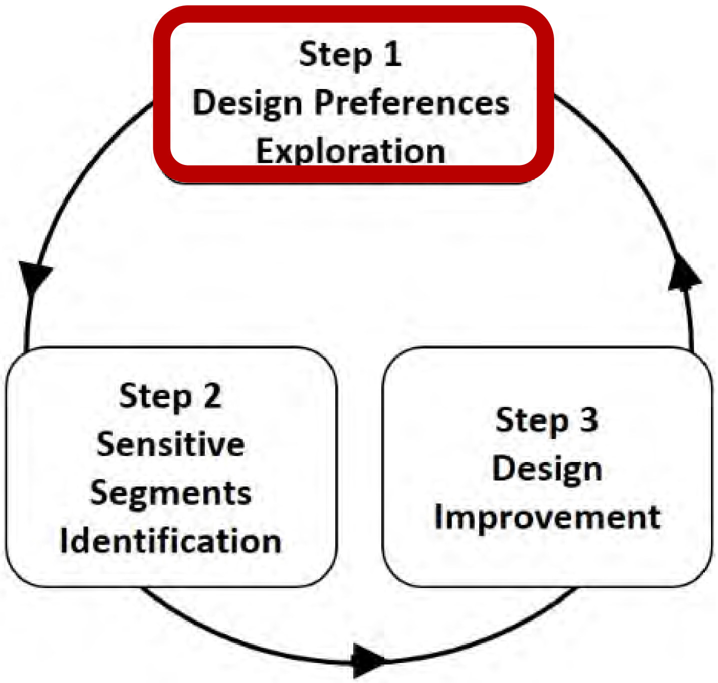
WS	w1	w2	w3	Tentative physical meaning
1	0	1	0	People is the only important goal
2	1	0	0	Reservoir is the only important goal
3	0	0	1	Fish is the only important goal
4	0.25	0.25	0.5	Reservoir and people have equal importance whereas fish is much more important than the former two.
5	0.33	0.33	0.33	All three goals are equally important
6	0.1	0.1	0.8	Reservoir and people are not the priority whereas fish is much more important than the former two.
7	0.2	0.79	0.01	People is the most important, followed by reservoir, whereas fish is much less important than the former two[1].
8	0.4	0.2	0.4	Reservoir and fish have equal importance whereas people are less important than the former two.

Results (2/2)

Results of the 34 Weight Scenarios (WSs) from the Original Model

	Weights			Goals			
WS	W1	W2	W3	G1	G2	G3	Total
1	0.33	0.33	0.33	0.23	0.53	0.31	0.44
2	1	0	0	0.00	2.00	2.00	0.05
3	0	1	0	1.00	0.00	2.00	0.00
4	0	0	1	1.00	2.00	0.00	0.00
5	0.8	0.1	0.1	0.16	0.73	0.62	0.43
6	0.1	0.8	0.1	0.24	0.10	1.60	0.29
7	0.1	0.1	0.8	0.31	1.06	0.02	0.19
8	0.6	0.2	0.2	0.20	0.56	0.37	0.45
9	0.2	0.6	0.2	0.23	0.27	0.77	0.42
10	0.2	0.2	0.6	0.26	0.83	0.09	0.33
11	0.5	0.25	0.25	0.21	0.54	0.34	0.45
12	0.25	0.5	0.25	0.23	0.37	0.54	0.44
13	0.25	0.25	0.5	0.25	0.72	0.15	0.39
14	0.4	0.3	0.3	0.22	0.53	0.31	0.45
15	0.3	0.4	0.3	0.23	0.46	0.38	0.45
16	0.3	0.3	0.4	0.23	0.60	0.24	0.43
17	0.2	0.4	0.4	0.24	0.53	0.29	0.43
18	0.4	0.2	0.4	0.23	0.71	0.18	0.41
19	0.4	0.4	0.2	0.22	0.37	0.56	0.45
20	0	0.5	0.5	0.26	0.56	0.25	0.41
21	0.5	0	0.5	0.07	2.00	0.00	0.10
22	0.5	0.5	0	0.10	0.02	2.00	0.13
23	0.5	0.33	0.17	0.21	0.38	0.58	0.45
24	0.17	0.5	0.33	0.24	0.43	0.42	0.44
25	0.33	0.17	0.5	0.24	0.82	0.11	0.37
26	0.67	0.33	0	0.09	0.05	2.00	0.17
27	0	0.67	0.33	0.24	0.37	0.53	0.42
28	0.33	0	0.67	0.08	2.00	0.00	0.06
29	0.56	0.33	0.11	0.20	0.30	0.86	0.44
30	0.11	0.56	0.33	0.24	0.41	0.45	0.44
31	0.33	0.11	0.56	0.24	0.98	0.07	0.32
32	0.22	0.33	0.44	0.24	0.61	0.22	0.41
33	0.44	0.22	0.33	0.22	0.64	0.24	0.43
34	0.33	0.44	0.22	0.22	0.37	0.55	0.44

Design Preference Exploration



Design Preference Exploration (1st iteration)

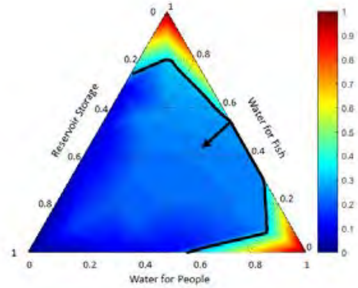


Figure 8 Feasible Solution Space of Goal 1 – Reservoir

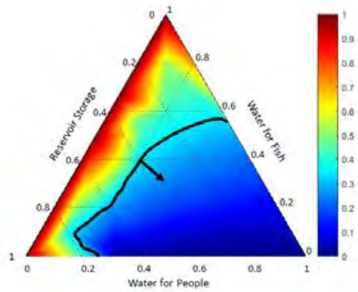


Figure 9 Feasible Solution Space of Goal 2 – People

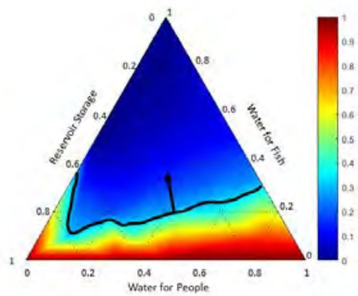


Figure 10 Feasible Solution Space of Goal 3 – Fish

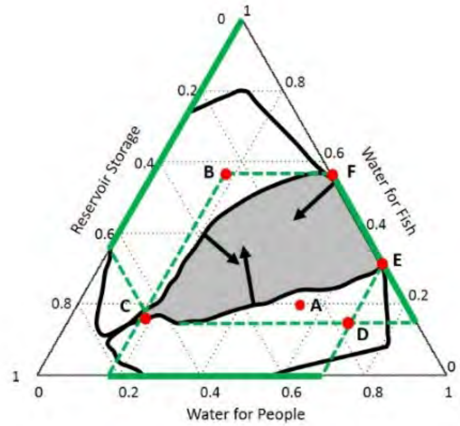


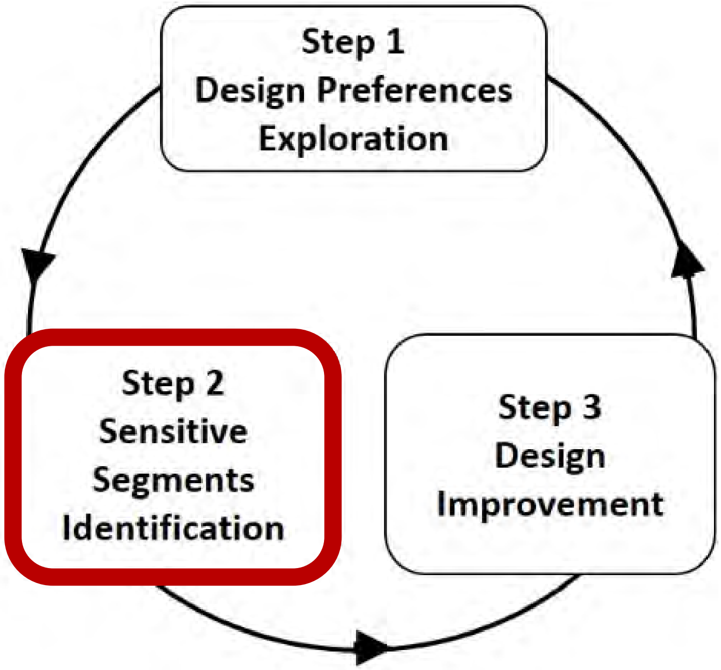
Figure 11 *Satisficing* Area for Three Goals

Table 5 Range of Weights of the Satisficing Space

Weight	Range
w1	0 – 0.65
w2	0.18 – 0.7
w3	0.15 – 0.56

1 Problem Description | 2 Frame of Reference and Proposed Method | 3 Model Formulation | 4 Post-Solution Analysis | 5 Closure

Sensitive Segments Identification



Sensitive Segments Identification (1st iteration)

Table 6 Inflow Scenarios

#	Inflow scenarios	The percentage of the inflow as the forecast value in each month		
		M1	M2	M3
1	No Rain	0%	0%	0%
2	Extremely Dry	20%	20%	20%
3	Dry	60%	60%	60%
4	Normal	100%	100%	100%
5	Rainy	150%	150%	150%
6	Extremely Rainy	200%	200%	200%
7	Flood	400%	400%	400%
8	Rain Unevenly I	0%	200%	100%
9	Rain Unevenly II	400%	0%	0%
10	Rain Unevenly III	400%	0%	400%

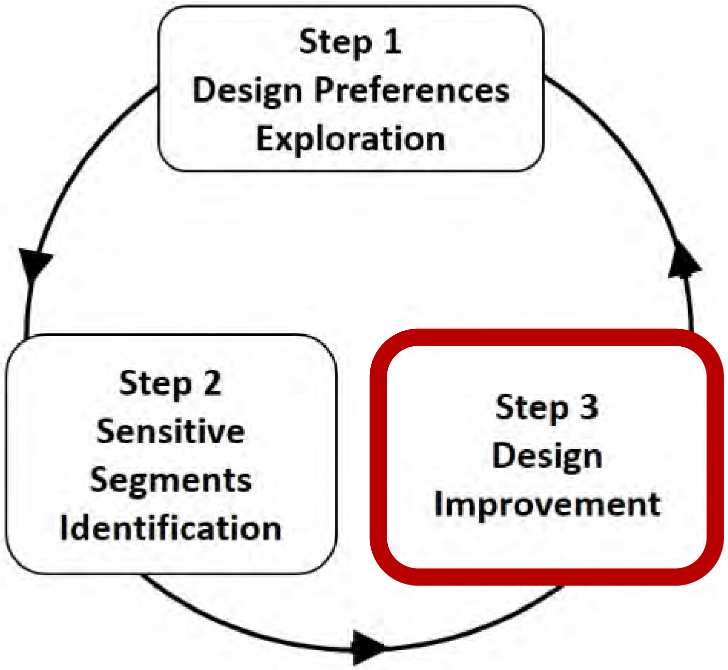
Table 7 Active Bounds in Each IS and WS

Active Bounds	Inflow Scenarios	Weight Scenarios	Physical meaning of the bounds
S7M2L	1 – 10	All except 2, 4	The lower bound of storage volume in Reservoir 7 in Month 2 is relatively high
S7M4L	1 – 10	All except 3	The lower bound of storage volume in Reservoir 7 in Month 4 is relatively high
S6M3U	7	All except 2, 3, 4	The upper bound of storage volume in Reservoir 6 in Month 3 is relatively low
S6M4U	7	All except 2, 3, 4	The upper bound of storage volume in Reservoir 6 in Month 4 is relatively low

Table 8 Improvable Bounds in each IS and WS

Improvable bounds	Inflow Scenarios	Weight Scenarios	Physical meaning of the constraints or bounds
S6M3U	1 – 10	1, 3, 26 – 28	The upper bound of storage volume in Reservoir 6 in Month 3 is relatively low
S6M4U	1 – 10	1, 26, 28	The upper bound of storage volume in Reservoir 6 in Month 4 is relatively low

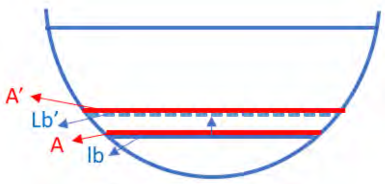
Design Improvement



Design Improvement (1st iteration)

Table 9 suggestions of model improvement

#	Improvement	Constraints or Bounds functions change, i=1,2,3
1	Raise the lower bound of storage volume in Reservoir 7 by 1%	S7Mi>=40900 ⇨ S7Mi>=40900*1.01
2	Raise the upper bound of storage volume in Reservoir 6 by 1%	S6M2<=74799 ⇨ S6M2<=74799*1.01



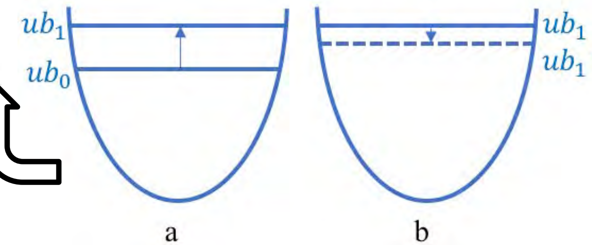


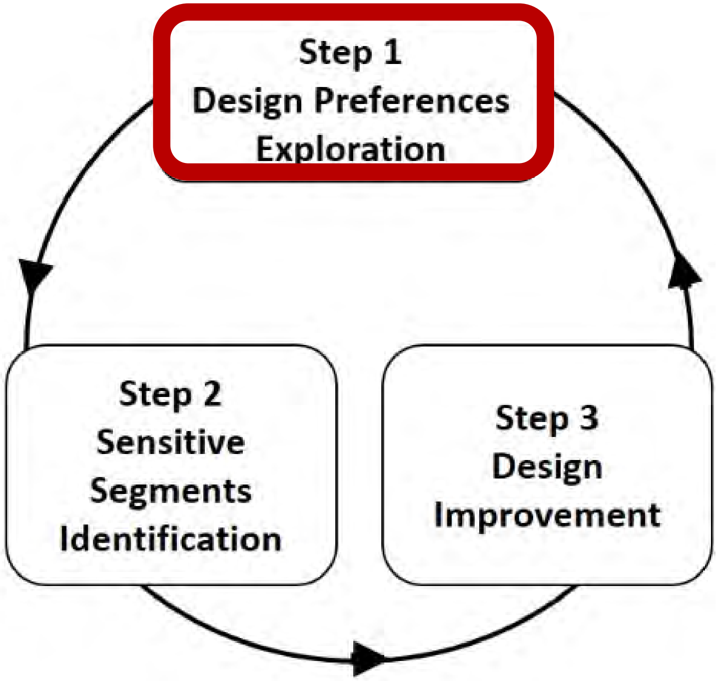
Table 7 Active Bounds in Each IS and WS

Active Bounds	Inflow Scenarios	Weight Scenarios	Physical meaning of the bounds
S7M2L	1 – 10	All except 2, 4	The lower bound of storage volume in Reservoir 7 in Month 2 is relatively high
S7M4L	1 – 10	All except 3	The lower bound of storage volume in Reservoir 7 in Month 4 is relatively high
S6M3U	7	All except 2, 3, 4	The upper bound of storage volume in Reservoir 6 in Month 3 is relatively low
S6M4U	7	All except 2, 3, 4	The upper bound of storage volume in Reservoir 6 in Month 4 is relatively low

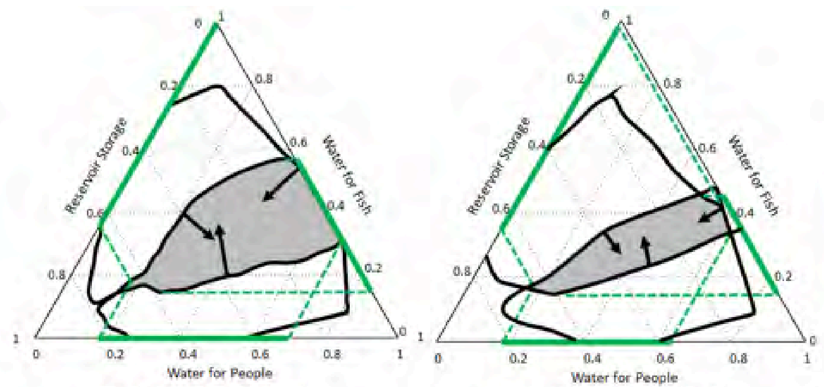
Table 8 Improvable Bounds in each IS and WS

Improvable bounds	Inflow Scenarios	Weight Scenarios	Physical meaning of the constraints or bounds
S6M3U	1 – 10	1, 3, 26 – 28	The upper bound of storage volume in Reservoir 6 in Month 3 is relatively low
S6M4U	1 – 10	1, 26, 28	The upper bound of storage volume in Reservoir 6 in Month 4 is relatively low

Design Preference Exploration



Design Preference Exploration (2nd iteration)

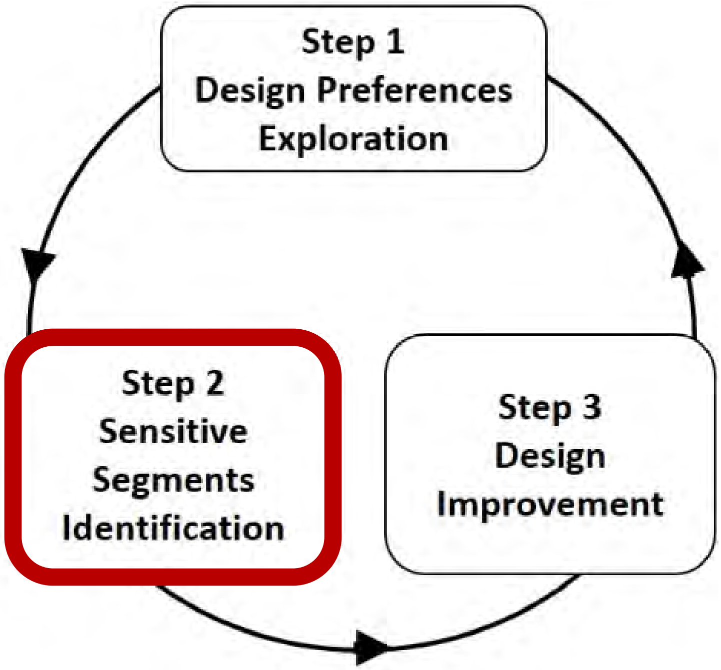


Original Model
w1: 0 – 0.65
w2: 0.18 – 0.7
w3: 0.15 – 0.56
(1)

Improved Model
w1: 0.2 – 0.65
w2: 0.18 – 0.62
w3: 0.15 – 0.45
(2)

Figure 15 The Satisficing Area of the Weights of the Original Model (1) and the Improved Model (2)

Sensitive Segments Identification



Sensitive Segments Identification (2nd iteration)

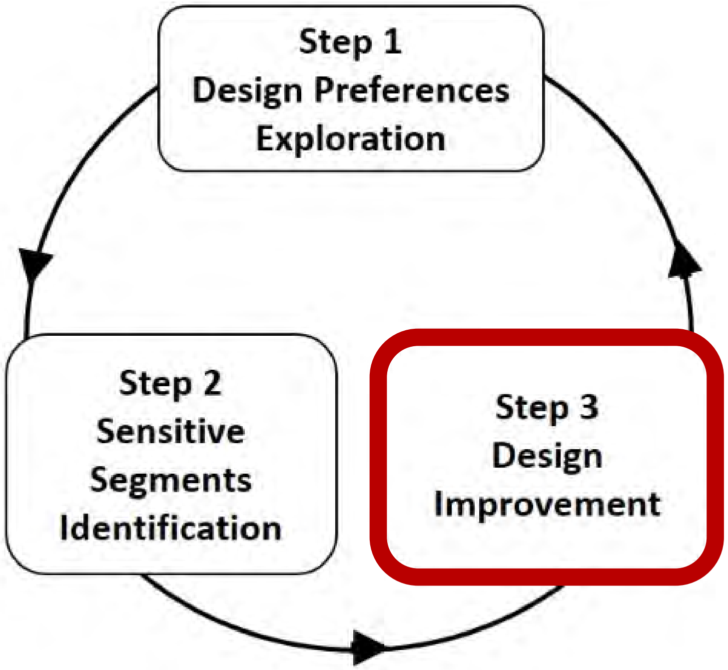
Table 6 Inflow Scenarios

#	Inflow scenarios	The percentage of the inflow as the forecast value in each month		
		M1	M2	M3
1	No Rain	0%	0%	0%
2	Extremely Dry	20%	20%	20%
3	Dry	60%	60%	60%
4	Normal	100%	100%	100%
5	Rainy	150%	150%	150%
6	Extremely Rainy	200%	200%	200%
7	Flood	400%	400%	400%
8	Rain Unevenly I	0%	200%	100%
9	Rain Unevenly II	400%	0%	0%
10	Rain Unevenly III	400%	0%	400%

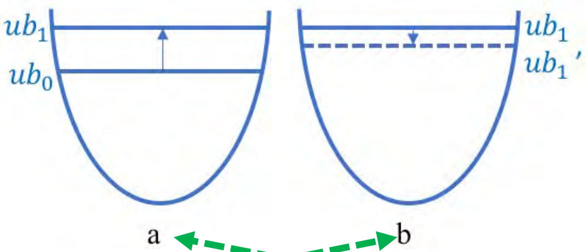
Active Bounds	Physical meaning of the bounds	Further improvement Suggestions
S7M3L	The lower bound of storage volume in Reservoir 7 in Month 3 is relatively high	Raise the lower bound of storage volume in Reservoir 7 by 1%

Improvable Bounds	Physical meaning of the constraints or bounds	Further improvement Suggestions
S4M1	The storage volume in Reservoir 4 in the beginning of Month 1 is relatively low	Raise the lower bound of storage volume in Reservoir 4 by 1%

Design Improvement



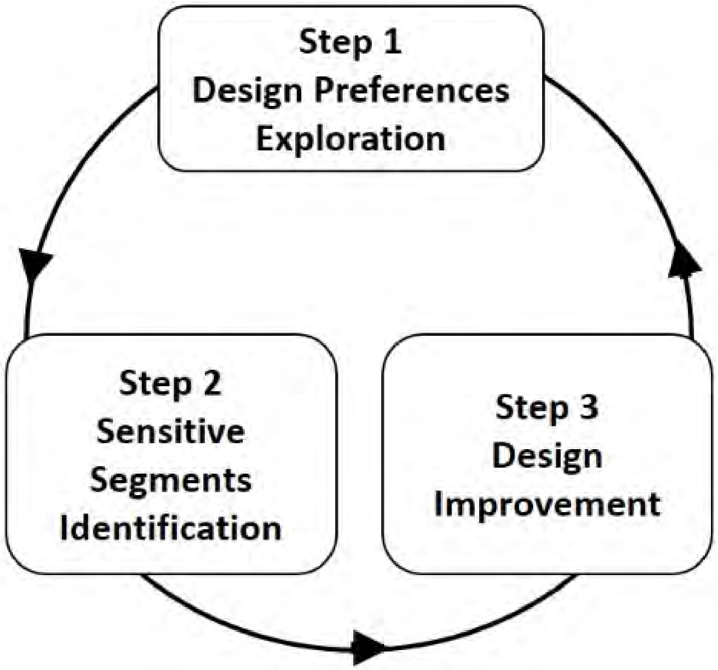
Design Improvement (2nd iteration)



Active Bounds	Physical meaning of the bounds	Further improvement Suggestions
S7M3L	The lower bound of storage volume in Reservoir 7 in Month 3 is relatively high	Raise the lower bound of storage volume in Reservoir 7 by 1%

Improvable Bounds	Physical meaning of the constraints or bounds	Further improvement Suggestions
S4M1	The storage volume in Reservoir 4 in the beginning of Month 1 is relatively low	Raise the lower bound of storage volume in Reservoir 4 by 1%

Design Improvement Validation



With continuous improvement, which is going through the three steps for many several iterations, we finally get a model with <u>no sensitive segments</u>, which means all the solutions are not at or close to the boundary, and we have <u>no potential to further improve</u> the achievement of the goals.

Closure

- Explore the solution space using three steps
- Identify feasible area of weights and provide their physical meanings
- Use inflow scenarios considering different weather and climate conditions to identify sensitive segments
- Improving the design by bring the solutions away from the boundary and relaxing the constraints to better achieve the goals
- With satisficing solutions, we reduce the frequency and severity of discrepancies between water supply and water demand and hence reduce the flood and drought risk
- Future work:
  - more functionalities (hydropower, industry water demand),
  - more types of uncertainties (fluctuation in user demand),
  - self-learning algorithms to improve design automatically, etc.