A Computationally Efficient and Robust Approach for Multi-objective Operation of Multi-reservoir systems Subjected to Multiple Constraints

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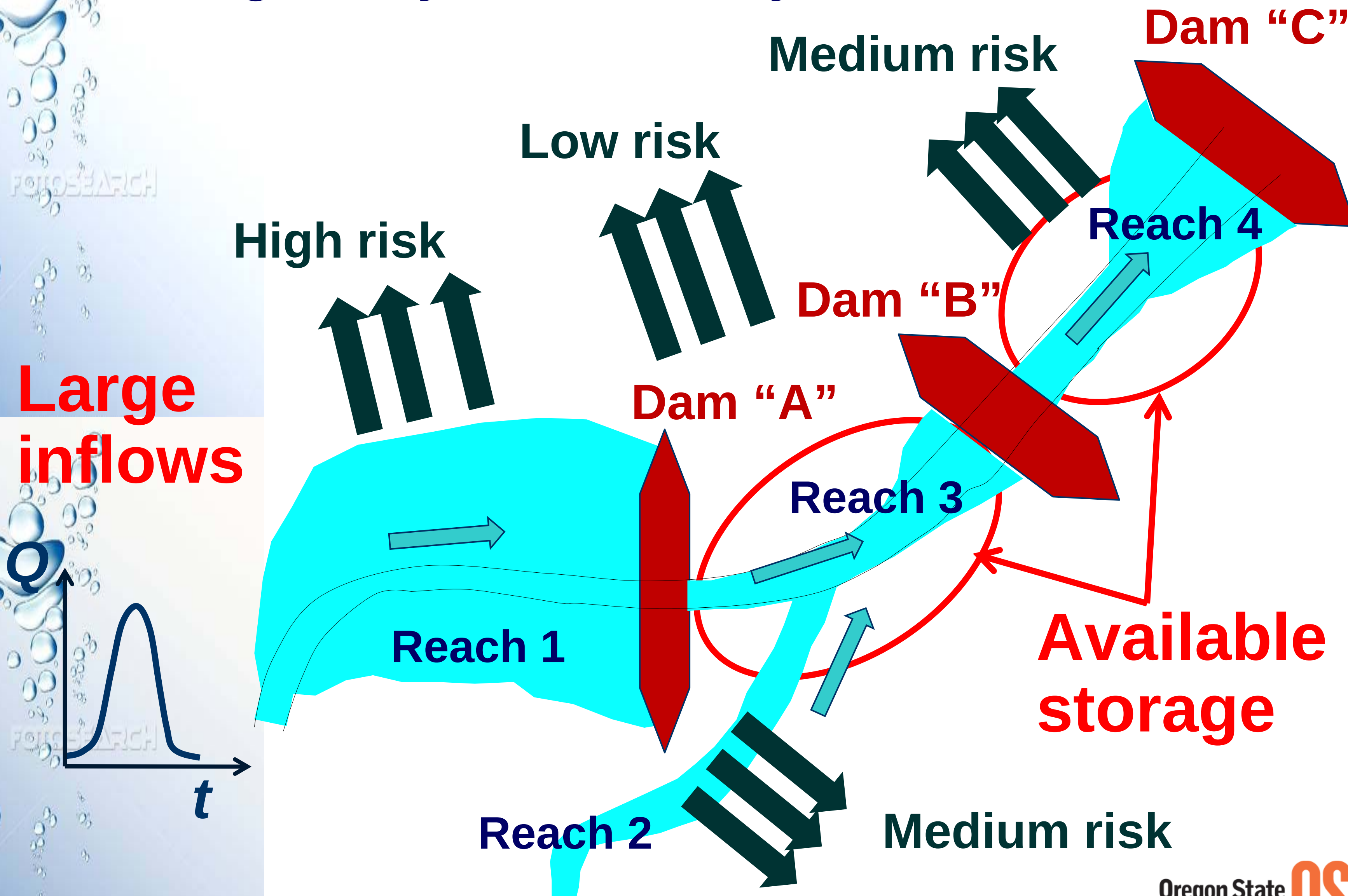
Presentation outline

- ✓ Need of real-time control and need of accounting for system flow dynamics
- ✓ Overview of proposed framework
- ✓ Applications
- ✓ Near-future work

Need of real-time control and need of accounting for system flow dynamics



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Why does current frameworks neglect system flow dynamics?

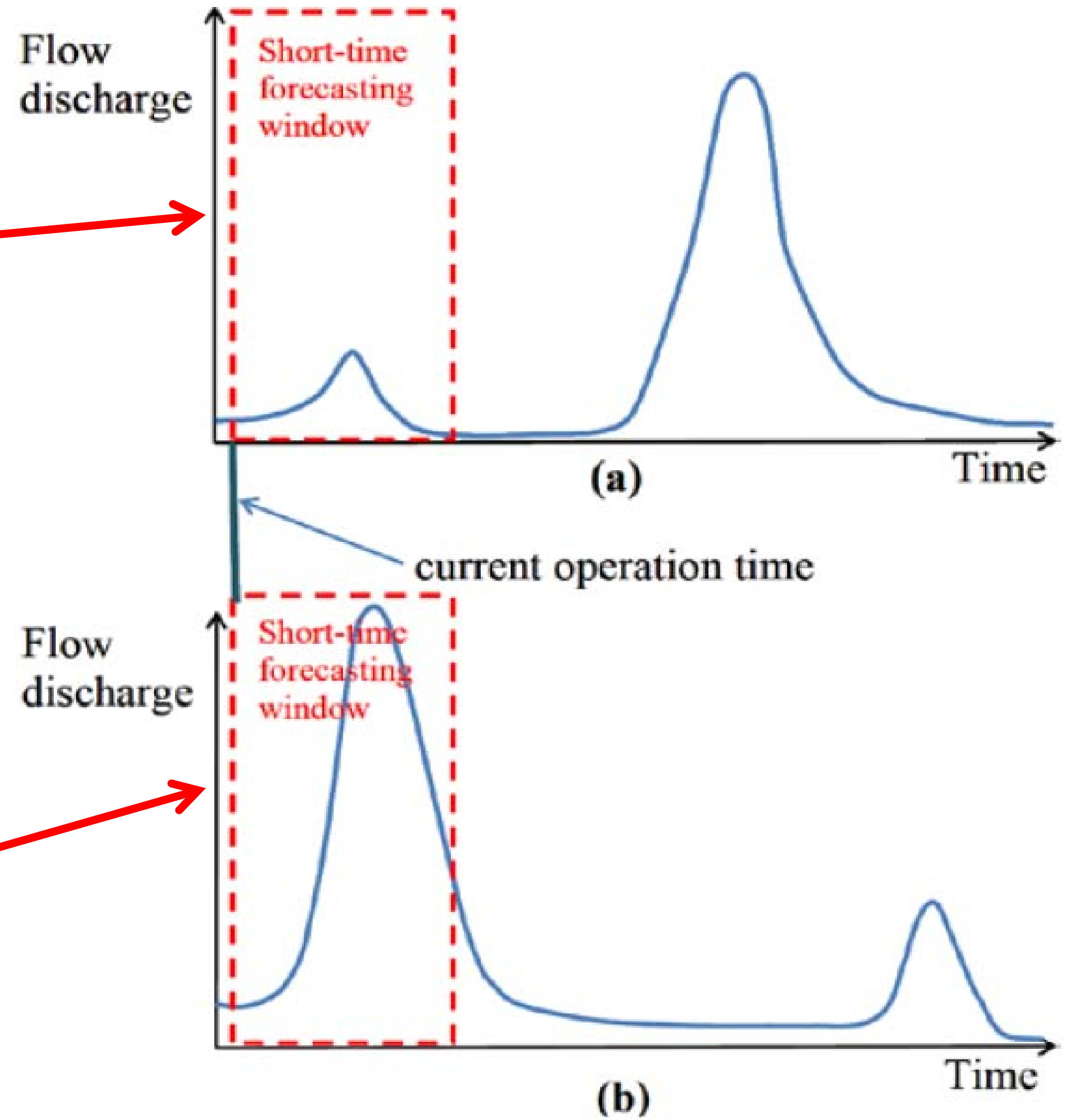
- ✓ Lack of robustness: Unsteady models typically have convergence and stability problems.

- ✓ Computational burden: A framework that combines simulation and optimization may require hundreds or even thousands of simulations for each operational decision.

Need of accounting for short- and long-term forecasting

May result in Flooding

May lead to an unnecessary release of a large volume of water. Conflict with long-term objectives



Proposed Framework (OSU Rivers)

- ✓The proposed framework couples a robust and numerically efficient hydraulic routing technique (simulation model) with a state-of-the-art Optimization technique (Genetic Algorithm) **(will add operation under uncertainty in the near-future)**

- ✓Provides a system analysis and a system control in real-time conditions.

Proposed Framework (Cont.)

Two sets of objectives: **Short-term and long-term (This may change depending on the user)**

Long term: Maximize benefits of irrigation, eco-hydrology, etc.

Constraints: Ecological flows, water rights, etc.

Short-term: Maximize hydropower production, Avoid flooding or in the worst case allow controlled flooding

$$\textbf{Minimize} \sum_{i=1}^{RR} (w_{L_i} FV_{L_i} + w_{R_i} FV_{R_i})$$

Proposed Framework (Cont.)

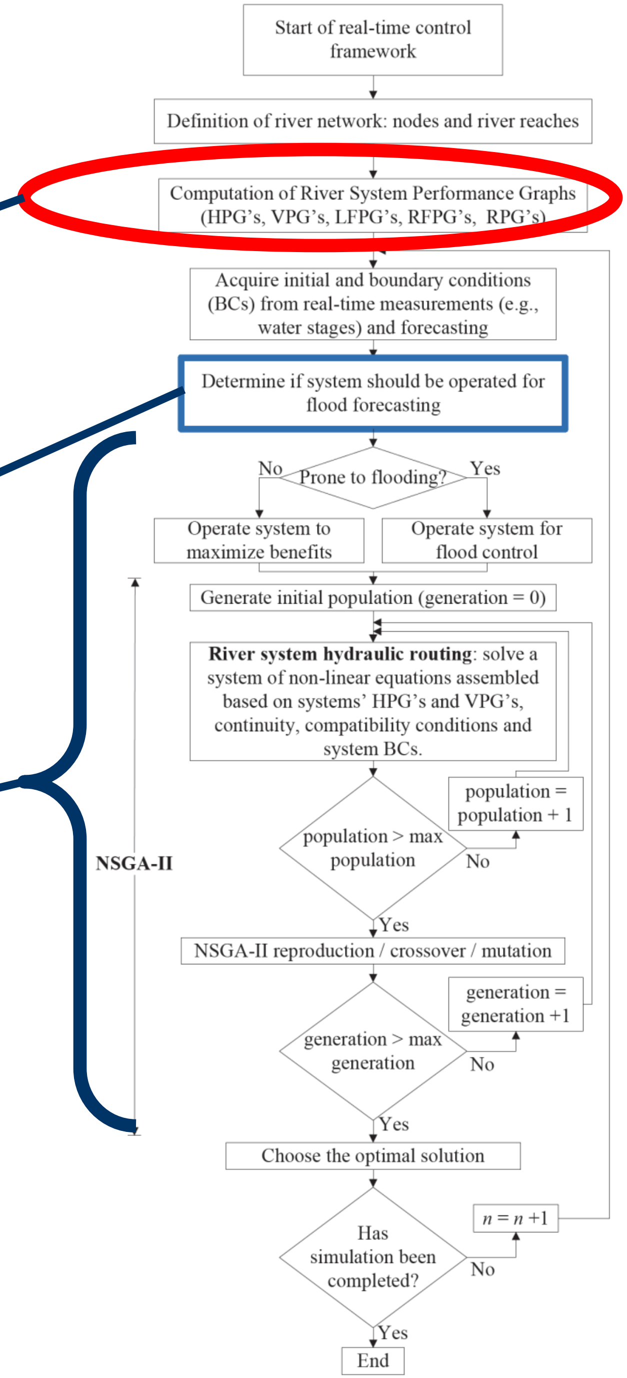
When capacity of river system is exceeded, the proposed framework allows controlled flooding based on a **hierarchy of risk areas (Urban areas have highest risk)**

Flow chart of Proposed Framework

Hydraulic routing for each reach (pre-computed)

Does system should be operated to fulfill short-term or long-term objectives?

Coupling of NSGA-II Genetic Algorithm with river system hydraulic routing. Will account for uncertainty.



Components of the proposed framework: River system flow routing

Navier Stokes equations:

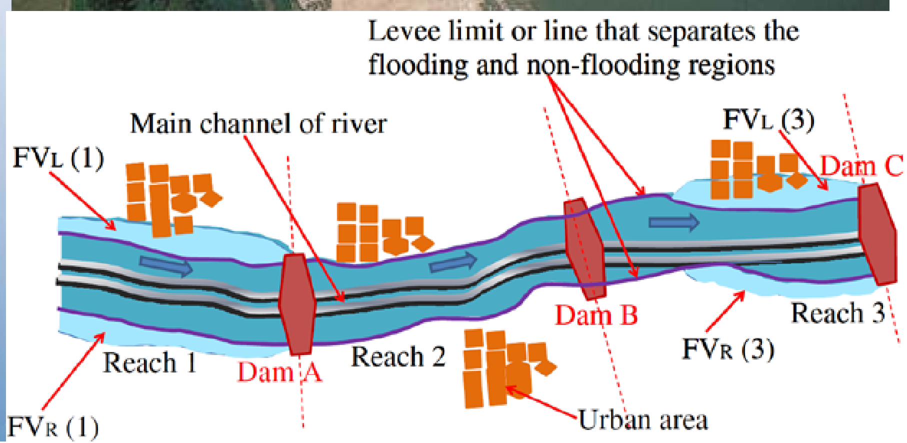
$$\frac{\partial \boldsymbol{u}_i}{\partial \boldsymbol{t}} + \boldsymbol{u}_j \frac{\partial \boldsymbol{u}_i}{\partial \boldsymbol{x}_j} = \frac{-1}{\rho} \frac{\partial \boldsymbol{p}}{\partial \boldsymbol{x}_i} + \nu \frac{\partial^2 \boldsymbol{u}_i}{\partial \boldsymbol{x}_j \partial \boldsymbol{x}_j} + \boldsymbol{g}_i$$

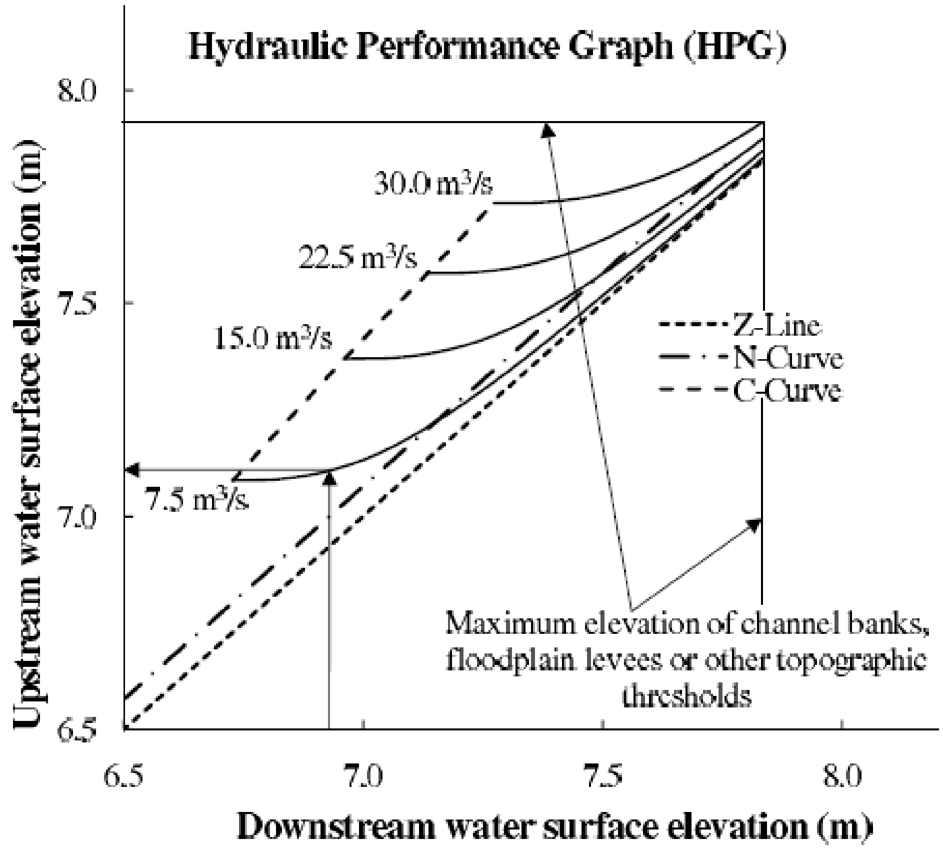
$$\frac{\partial \boldsymbol{u}_i}{\partial \boldsymbol{x}_i} = 0$$

1D Saint-Venant equations

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + g \frac{\partial h}{\partial x} = g(S_0 - S_f) \qquad \frac{\partial \boldsymbol{A}}{\partial \boldsymbol{t}} + \frac{\partial \boldsymbol{Q}}{\partial \boldsymbol{x}} = 0$$

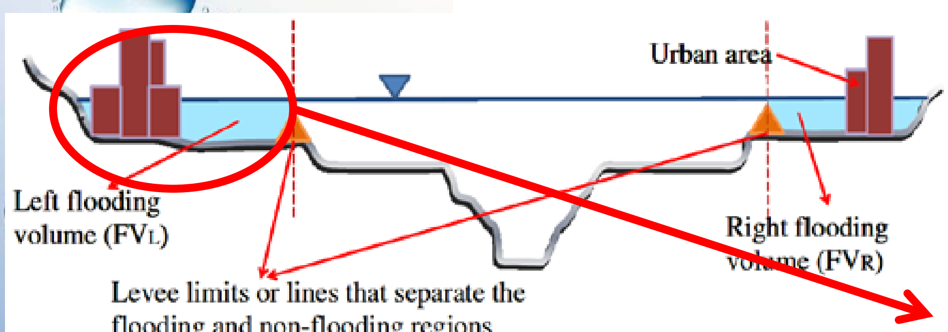
River system flow routing

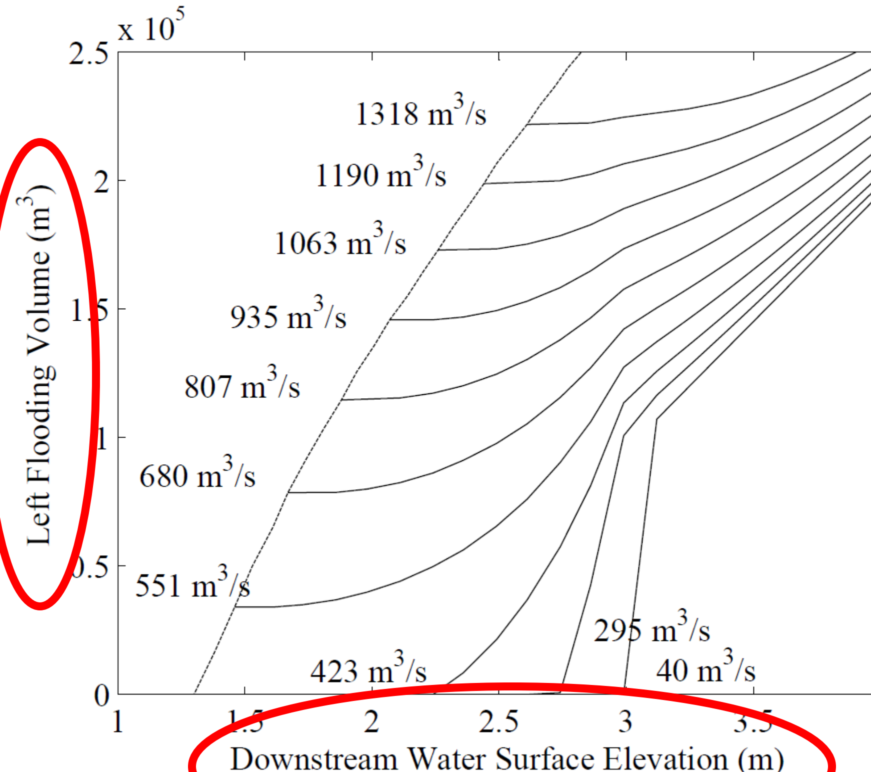




Hydraulic Performance Graph (HPG)

Flooding Performance Graphs (FPGs)





Left Flooding Performance Graph (HPG)

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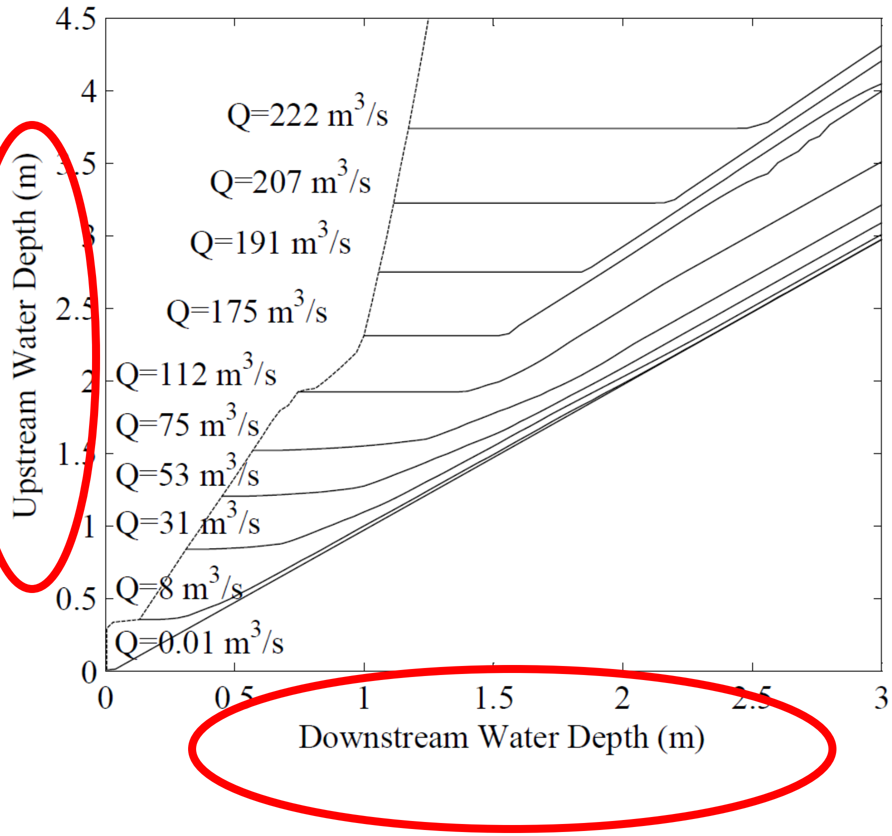
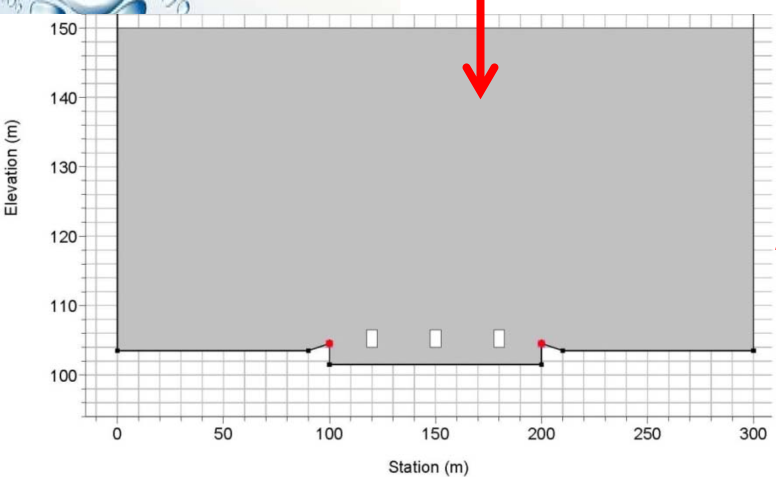
Rating Performance Graphs (RPGs)



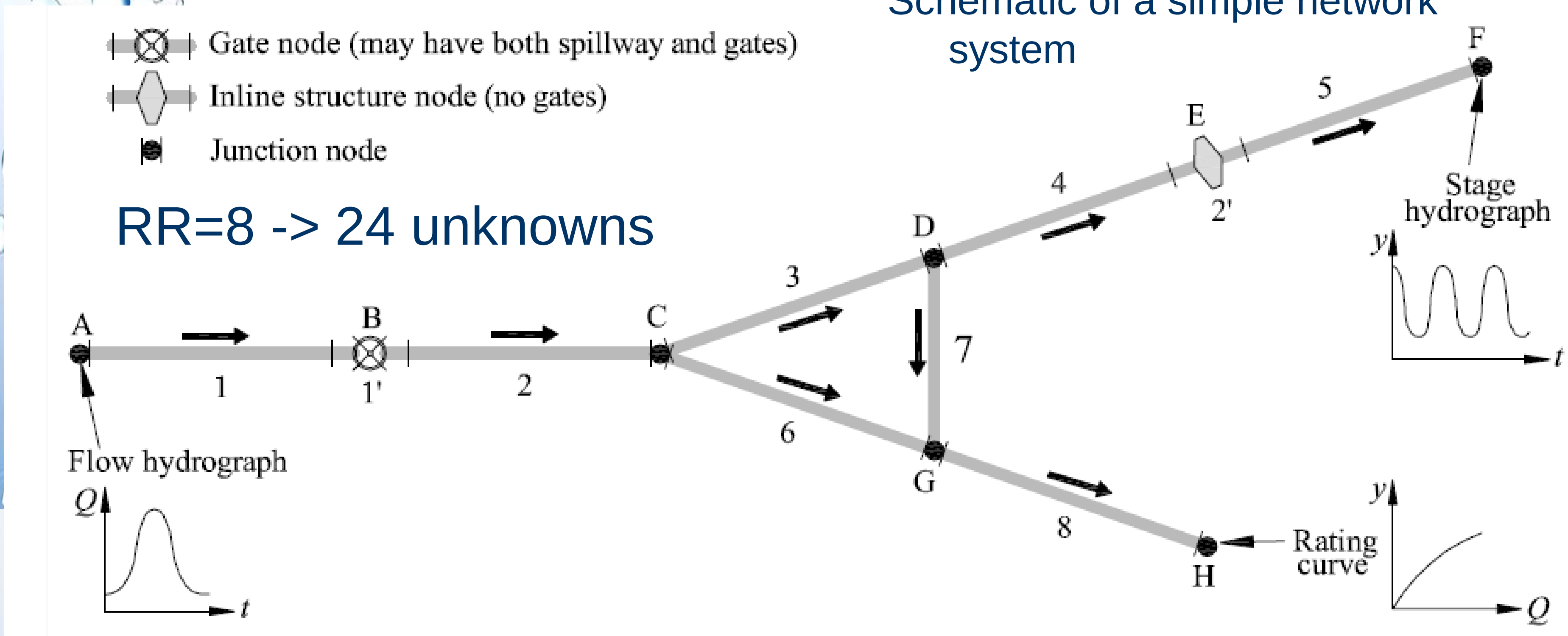


A different RPG for each vertical position of gates.

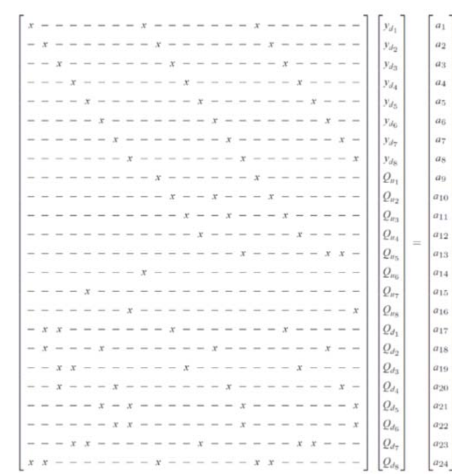
River system routing

Schematic of a simple network system

RR=8 -> 24 unknowns



- Conservation of mass -> 8 equations
- Continuity equations -> 5 equations
- External boundary conditions -> 3 equations
- Compatibility conditions -> 6 equations
- RPG's -> 2 equations

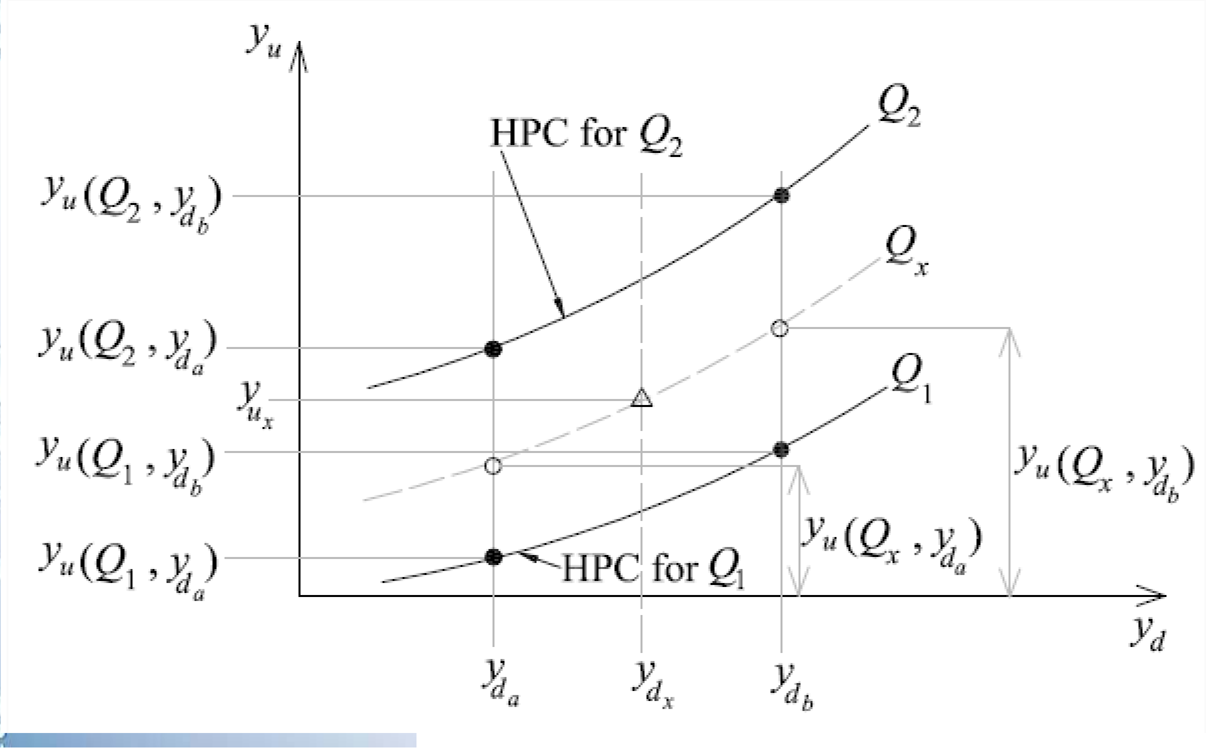


River system hydraulic routing (Cont.)

River network consisting of N reaches

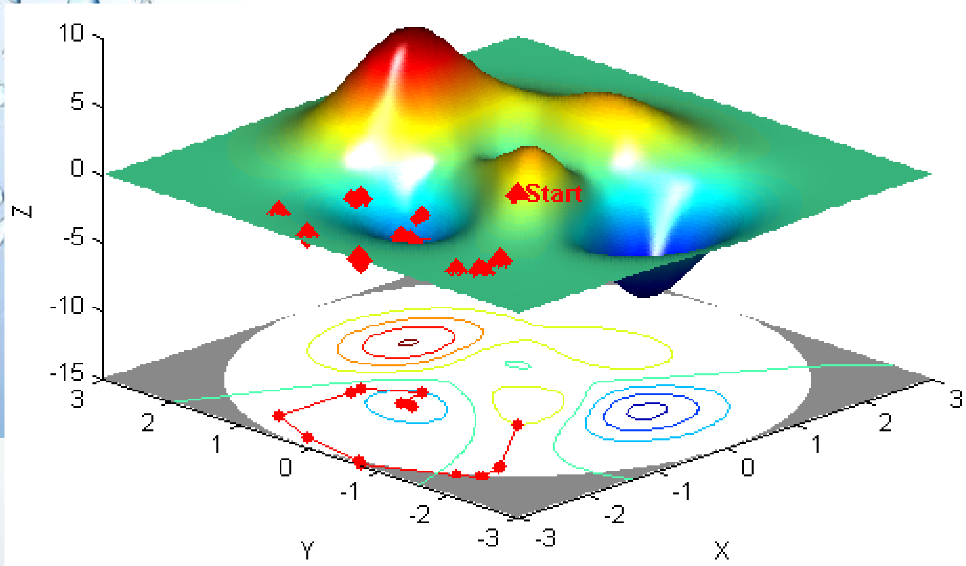
- 3N unknowns (Qu, Qd, yd of each reach)
- yu is known, estimated using HPG, yd and spatially averaged discharge

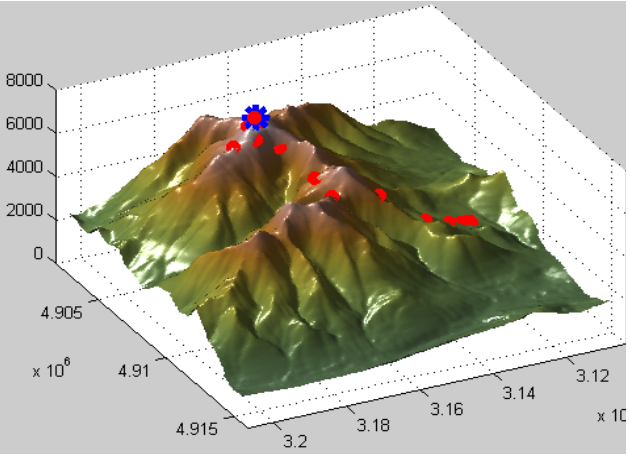
$$y_u^n = \mathrm{HPG}[y_d^n, \frac{1}{2}(\sum I^n + \sum O^n)], \forall j \quad (1)$$



Schematic of interpolation

Optimization component: Genetic Algorithms

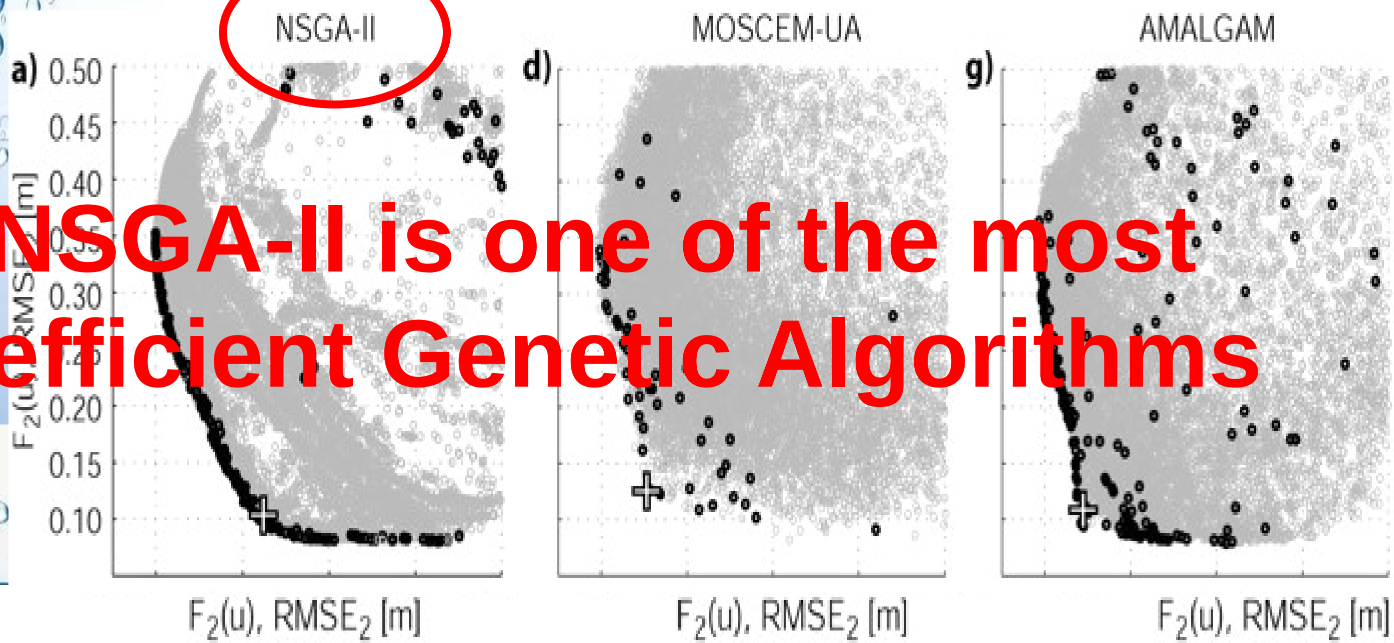




GAs is able to find the optimum set of solutions for multi-objective optimization

Handle constraints without the use of penalty functions

Optimization component: Genetic Algorithms (Cont.)



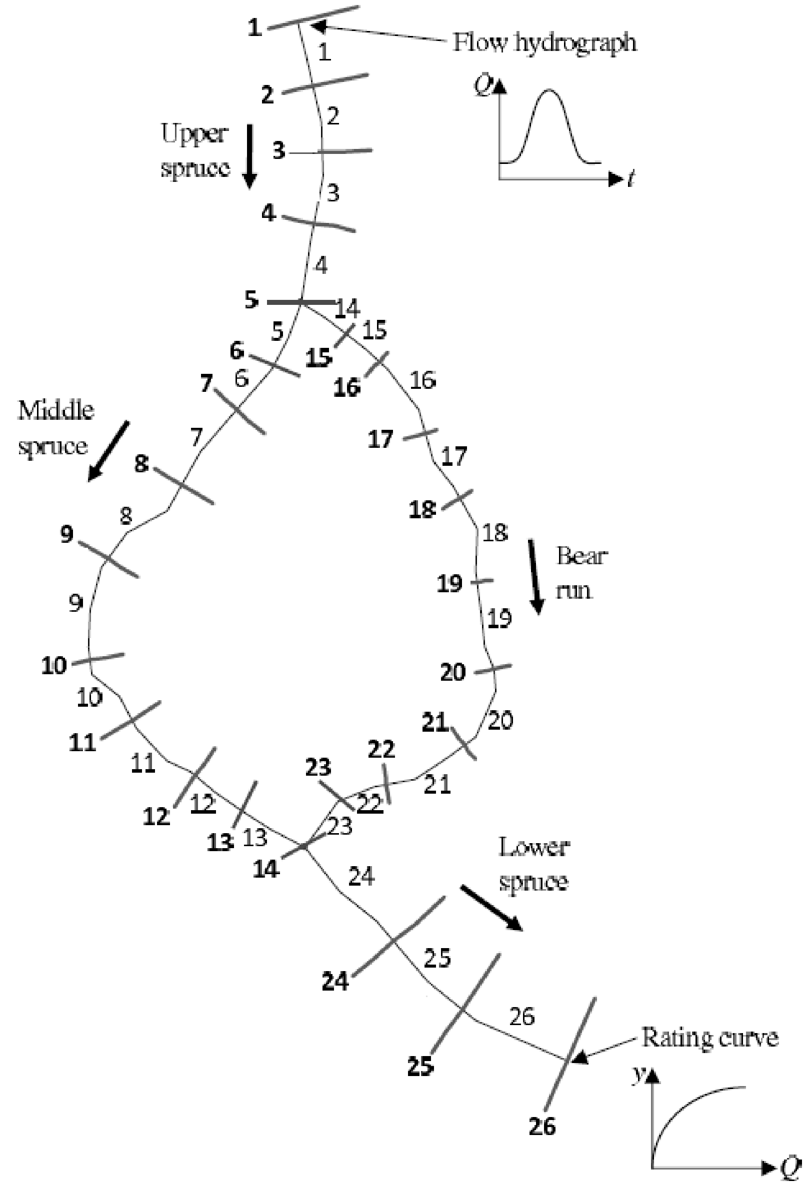
NSGA-II is one of the most efficient Genetic Algorithms

After Wöhling et al. (2007)

Combined with Newton based methods, NSGA-II may be even much better

Comparison of hydraulic component of proposed framework with the Unsteady HEC-RAS model

Looped river system adapted from an example in the Applications Guide of the HEC-RAS model (Hydrologic Engineering Center, 2010).



Plan view of looped river system (After Leon et al. 2011)

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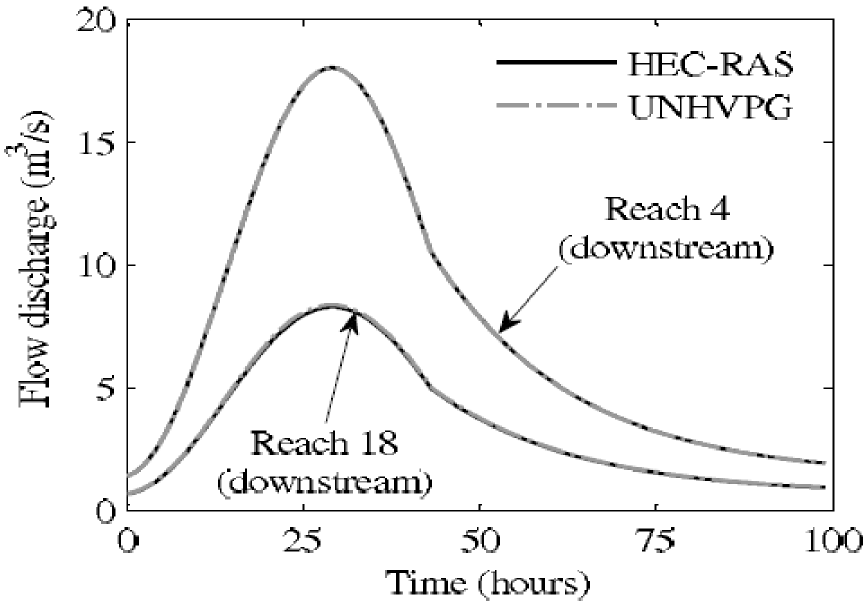
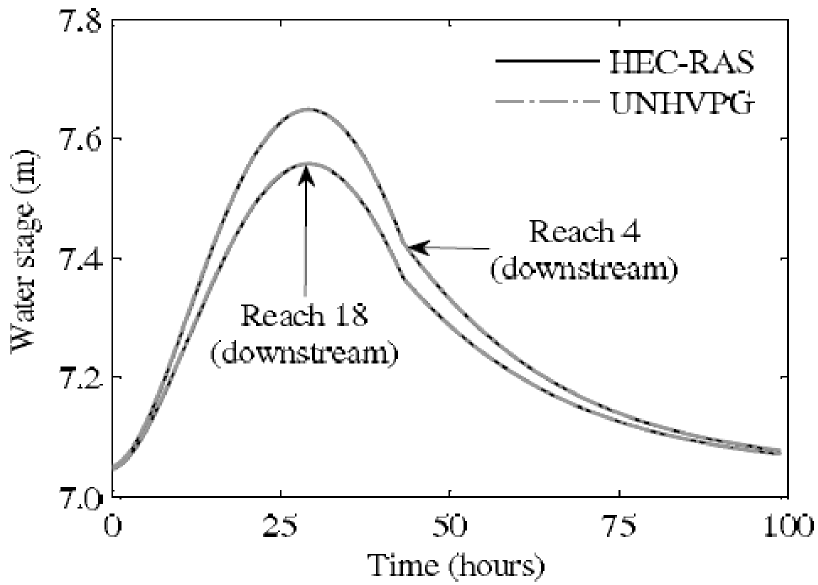
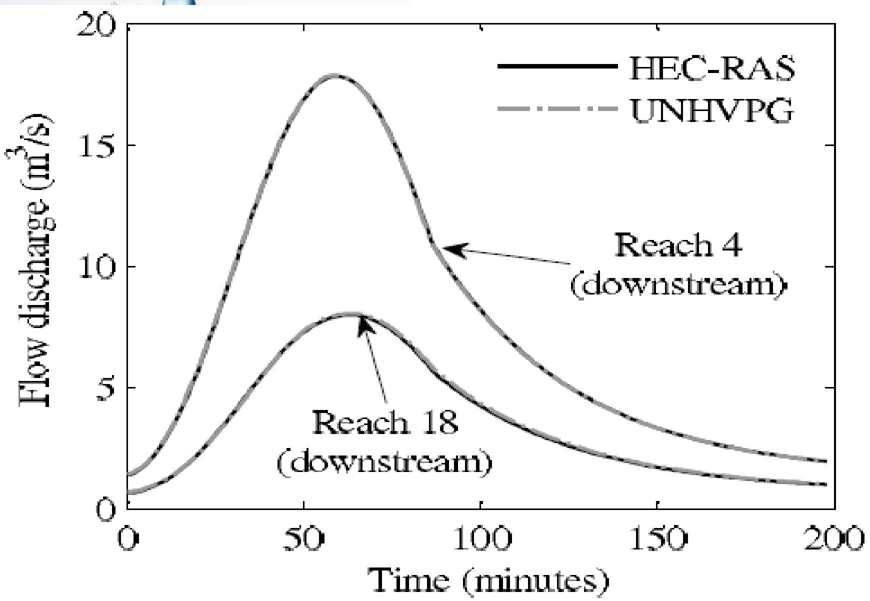
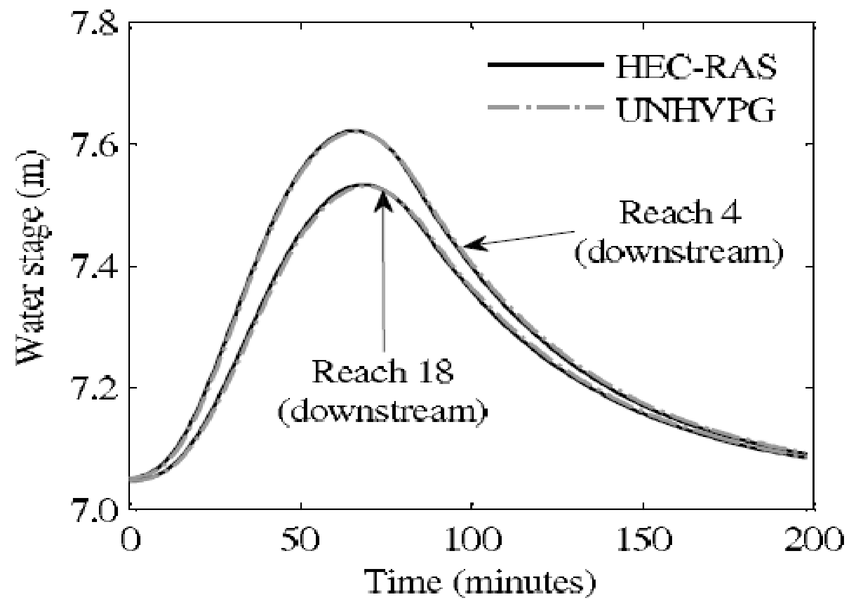
Slow flood wave





Fast flood wave





CPU Times

Description	UNHVPG Time (s)	HEC-RAS Time (s)
Case 1 (slow flood-wave)	218.8 ($\overline{\Delta t} = 9.77$ s)	752.7 ($\Delta t = 10$ s)
Case 2 (fast flood-wave)	7.3 ($\overline{\Delta t} = 10.27$ s)	52.6 ($\Delta t = 10$ s)

The results obtained with OSU Rivers (hydrodynamic portion are about 300% and 700% faster than those of the HEC-RAS model for the slow and fast flood-wave cases, respectively.

Robustness: Proposed framework is highly robust because instability issues are addressed during pre-computation of hydraulics

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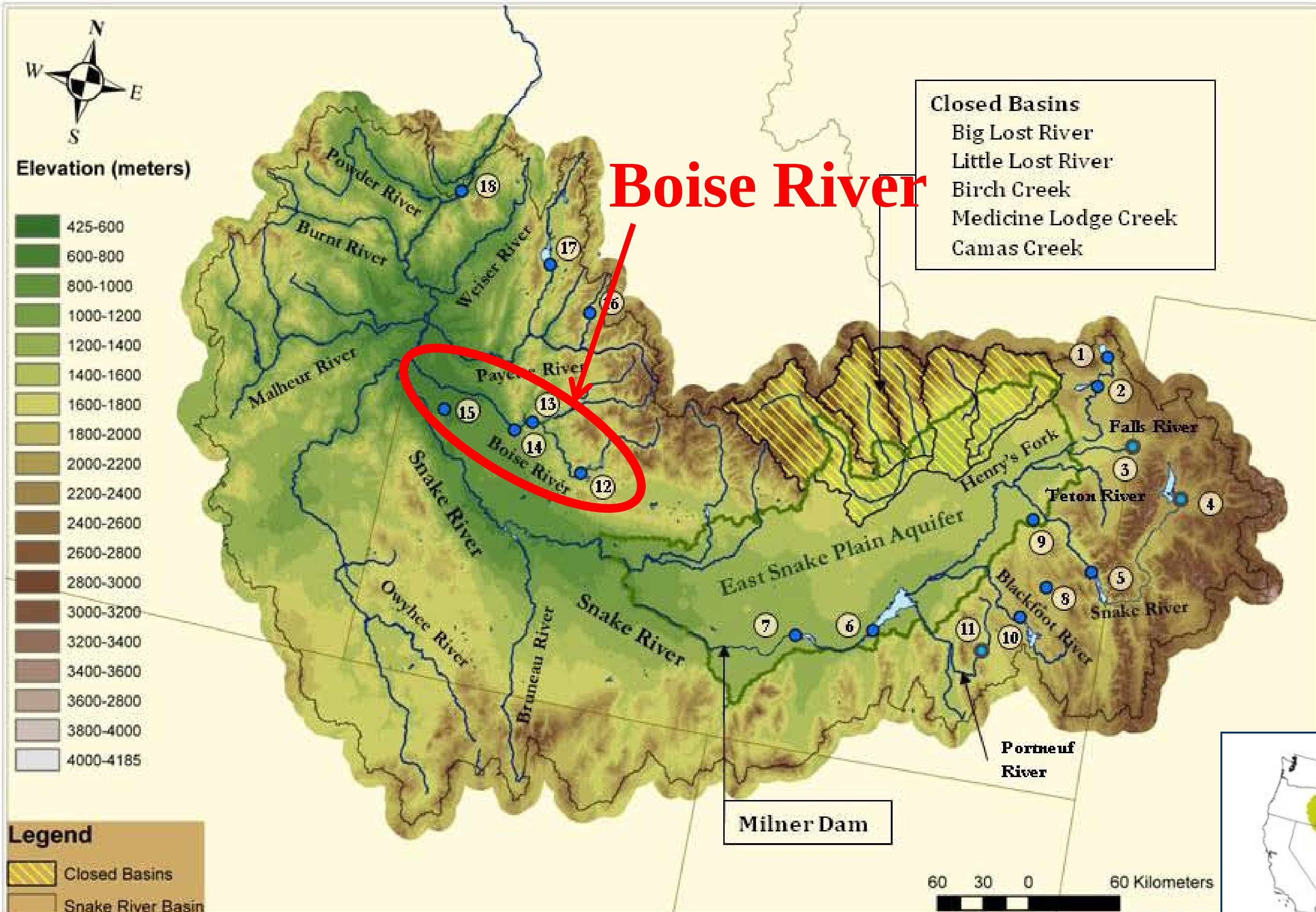
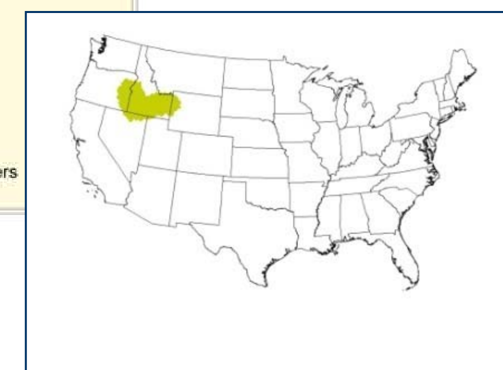
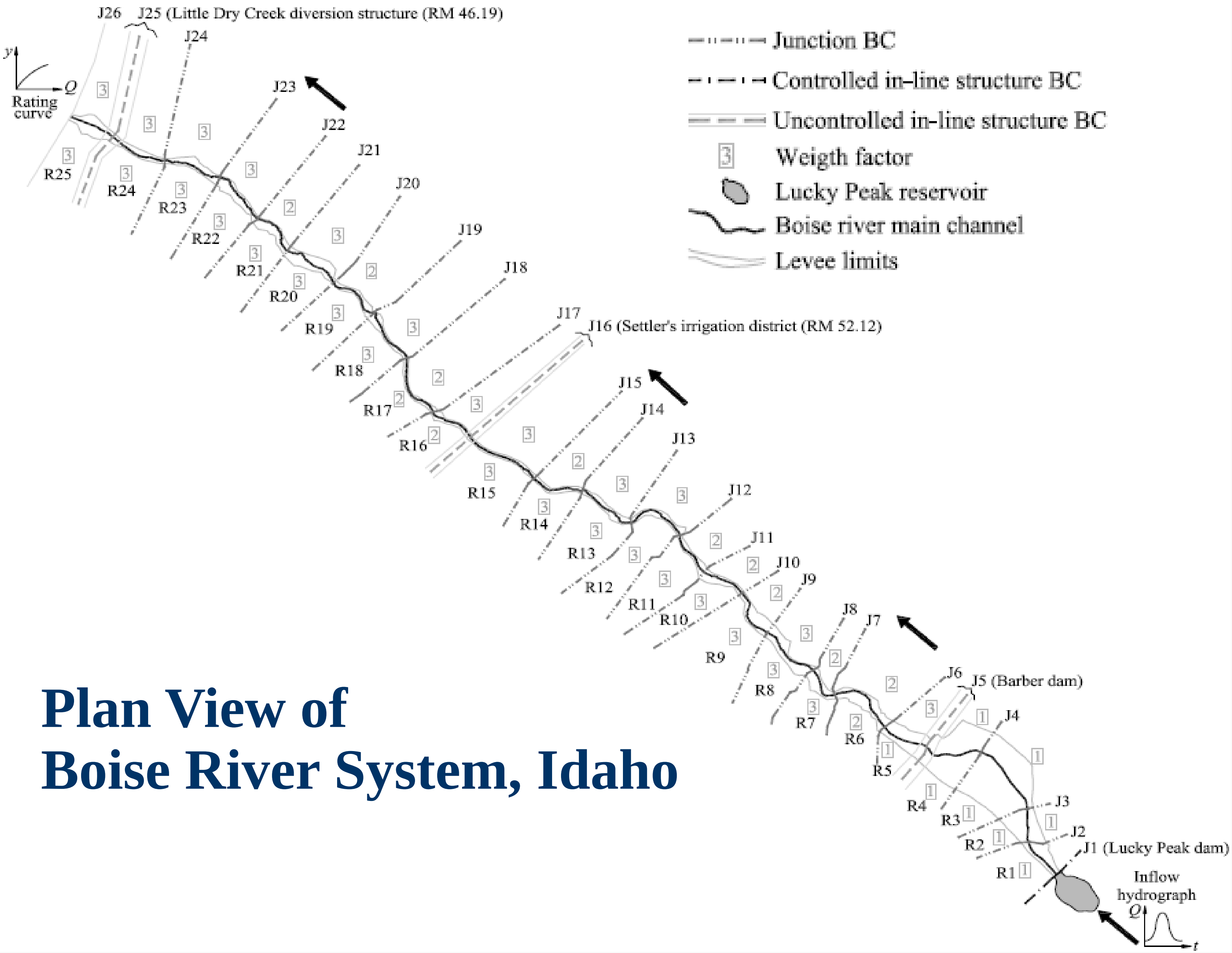
Application of proposed framework to the Boise River System (Idaho)





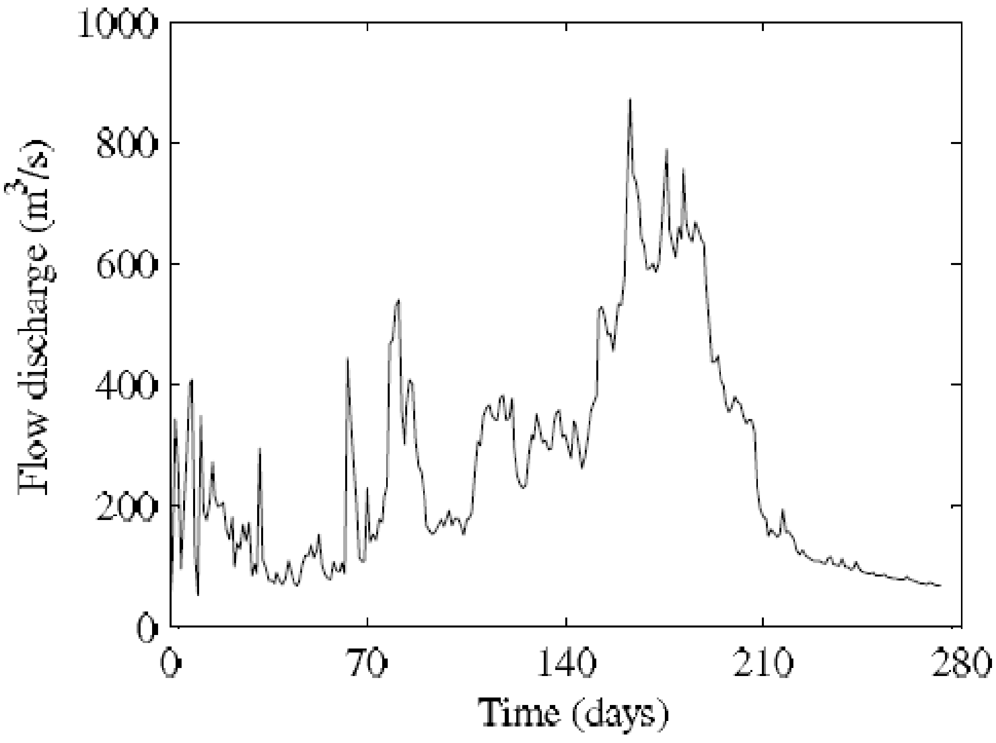


Plan View of Boise River System, Idaho

Inflow hydrographs

- Original inflow hydrograph - 50 years (from 01/01/2010 to 12/19/2059)-SWAT (Courtesy Prof. Sridhar, BSU)
- Simulation period of nine months (11/30/2041 to 8/30/2042) 274 days - maximum volume of inflow.
- Original inflow hydrograph represents natural flows at the location of Lucky Peak reservoir

Inflow hydrograph (SWAT) (11/30/2041 to 8/30/2042)



Modified inflow hydrograph

- Anderson Ranch reservoir (509.6 MCM) - 9 m3/s 03/07/2042 to 05/11/2042 to fill the reservoir.
- Arrow Rock reservoir (335.8 MCM) - 84 m3/s

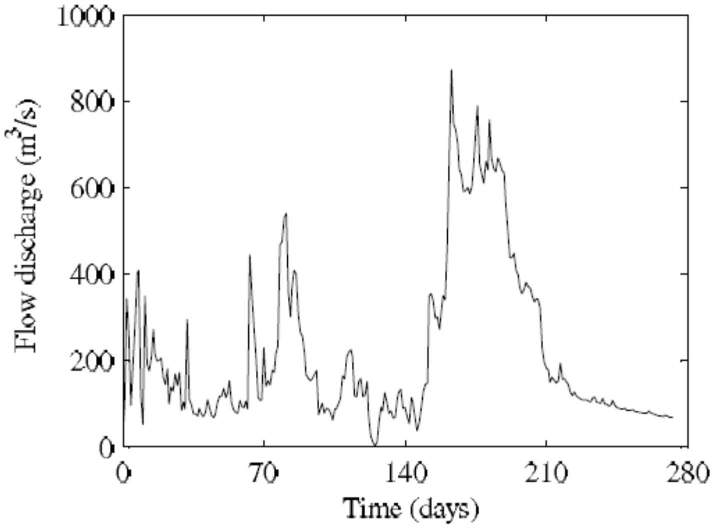
03/25/2042 to 05/10/2042 to fill the reservoir.

- Lake Lowell (196.6 MCM) - 51.5 m3/s

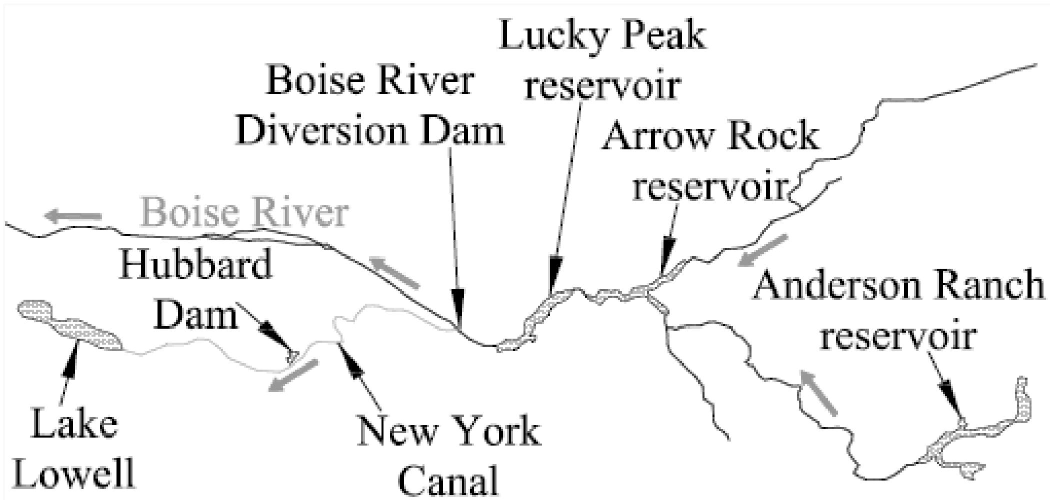
03/18/2042 to 04/30/2042 to fill the lake.

- Hubbard Dam (4.9MCM) - 10 m3/s

05/05/2042 to 05/09/2042 to fill the reservoir.

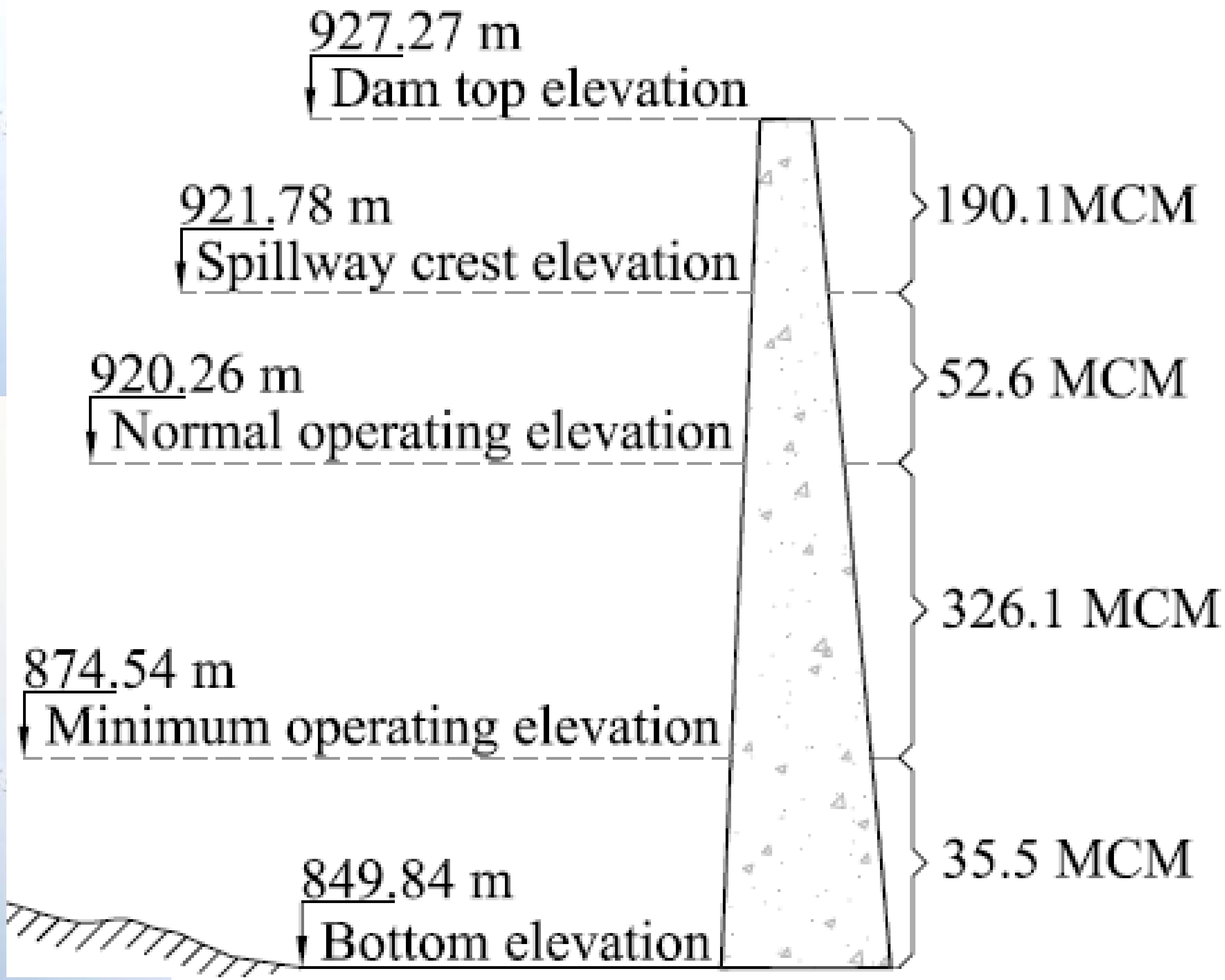


Inflow hydrograph subtracting active storage capacity of Anderson Ranch, Arrow Rock, Hubbard reservoirs and Lake Lowell.



Plan view of major storage reservoirs in the Boise river basin.

Stage-storage relationship of Lucky Peak reservoir



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Optimization objective (short-term)

$$\text{Minimize } f_1 = \sum_{i=1}^{\text{RR}} (w_{L_i} FV_{L_i} + w_{R_i} FV_{R_i})$$

Constraints:

Q > Q minimum ecological flows:

Outlet structure of Lucky Peak

- 6.71 m diameter steel-lined pressure tunnel (upstream end)
- Six sluice gates (downstream end)

Gates conveyance (hydraulic capacity) was smaller than that of tunnel

View of Lucky peak reservoir and associated structures.

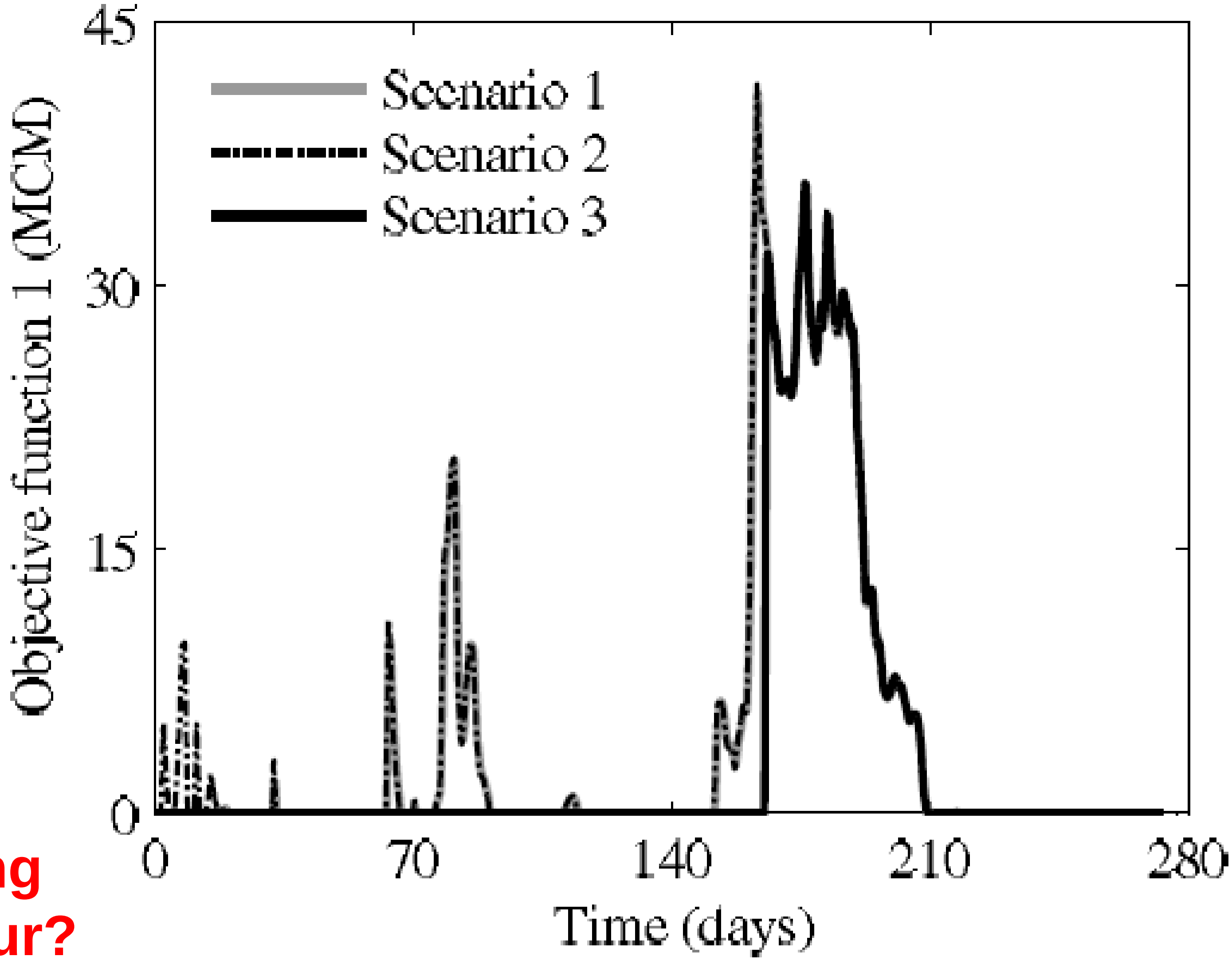
Simulated scenarios

1) Without gate operation (i.e. the gates are closed)

2) Assuming that Lucky Peak reservoir doesn't exist

3) With gate operation according to proposed framework.

Results



When flooding starts to occur?

Scenario 1 -> day 16
Scenario 2 -> day 2
Scenario 3 -> day 165

Objective function: **Flooding volume** for simulated scenarios

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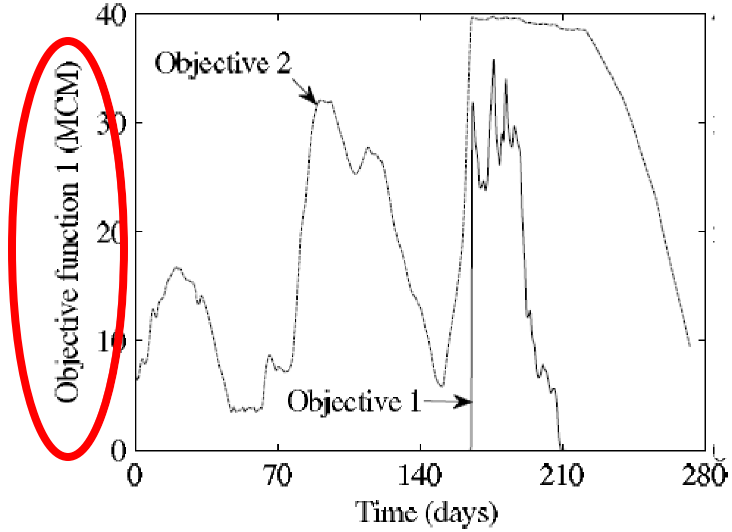
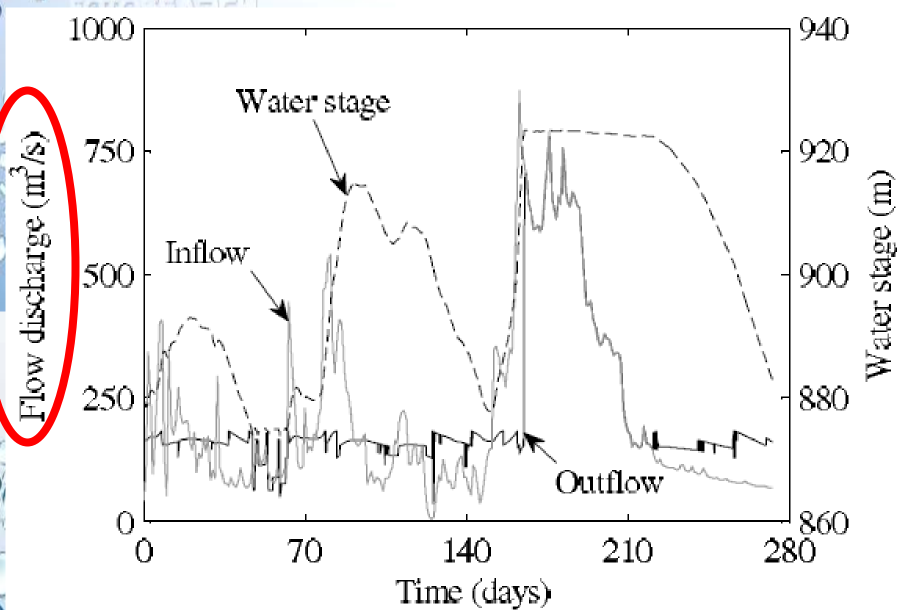
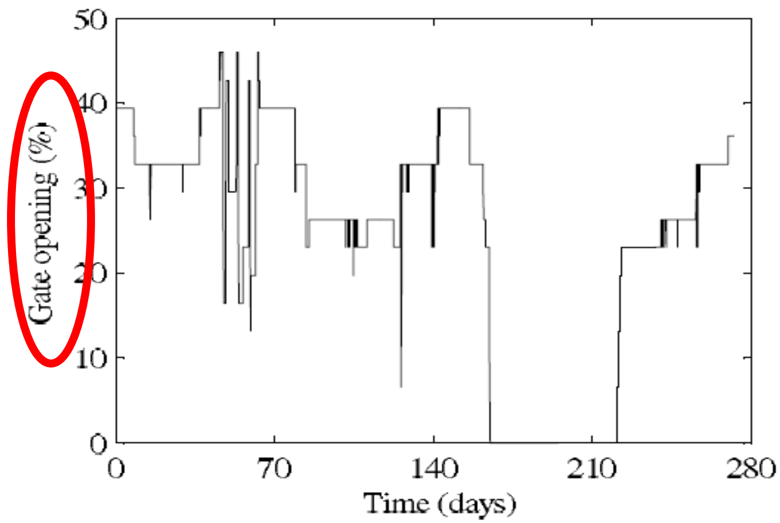
Results (cont.)



Results of objective functions for scenario 3 (proposed framework)



Inflow, outflow and water stage hydrographs at Lucky Peak reservoir



Gate operation (six gates) at Lucky Peak reservoir

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Optimization-simulation of reservoir operation for hydropower

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Objectives:

- Maximize Hydropower benefit by producing sufficient power to satisfy demand
- Flood Protection
- Ensure Adequate water levels in reservoir (for other objectives such as irrigation)

➢ Multi-objective optimization

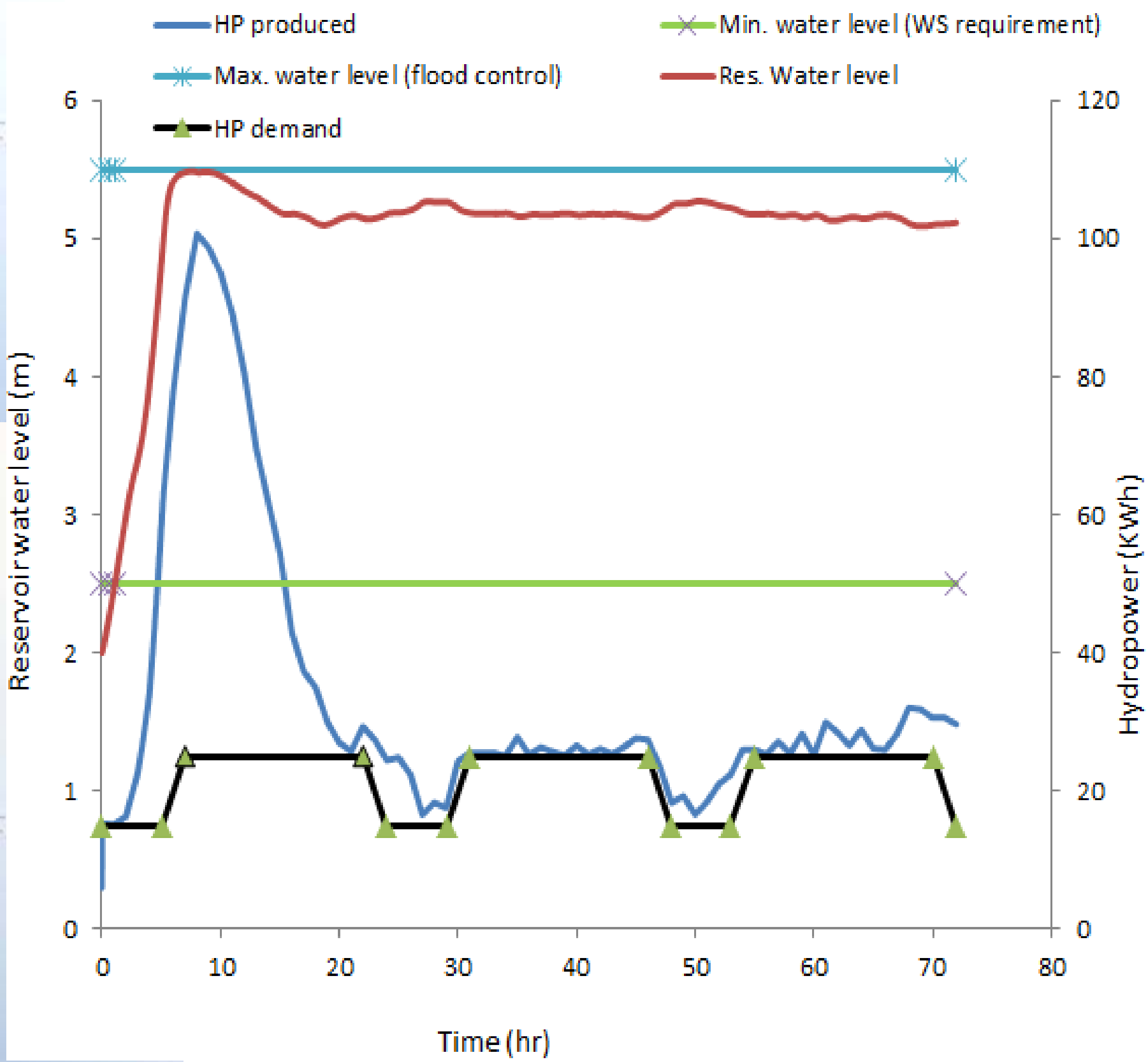
➢ Deterministic / Stochastic

A hypothetical example

- Single Reservoir with simple approach for reservoir routing
- Objective set as: Minimize (HP deficit)

  Minimize (HP produced – HP demand)
- Flood control & Water supply demand represented as constraints of max./min. water levels
- NSGA-II optimization algorithm

Results: 3-days ahead optimal operations



Work under progress or Near-future work

- Physical modeling
- Incorporation of uncertainty
- Combining Genetic Algorithms with Newton based methods for faster convergence

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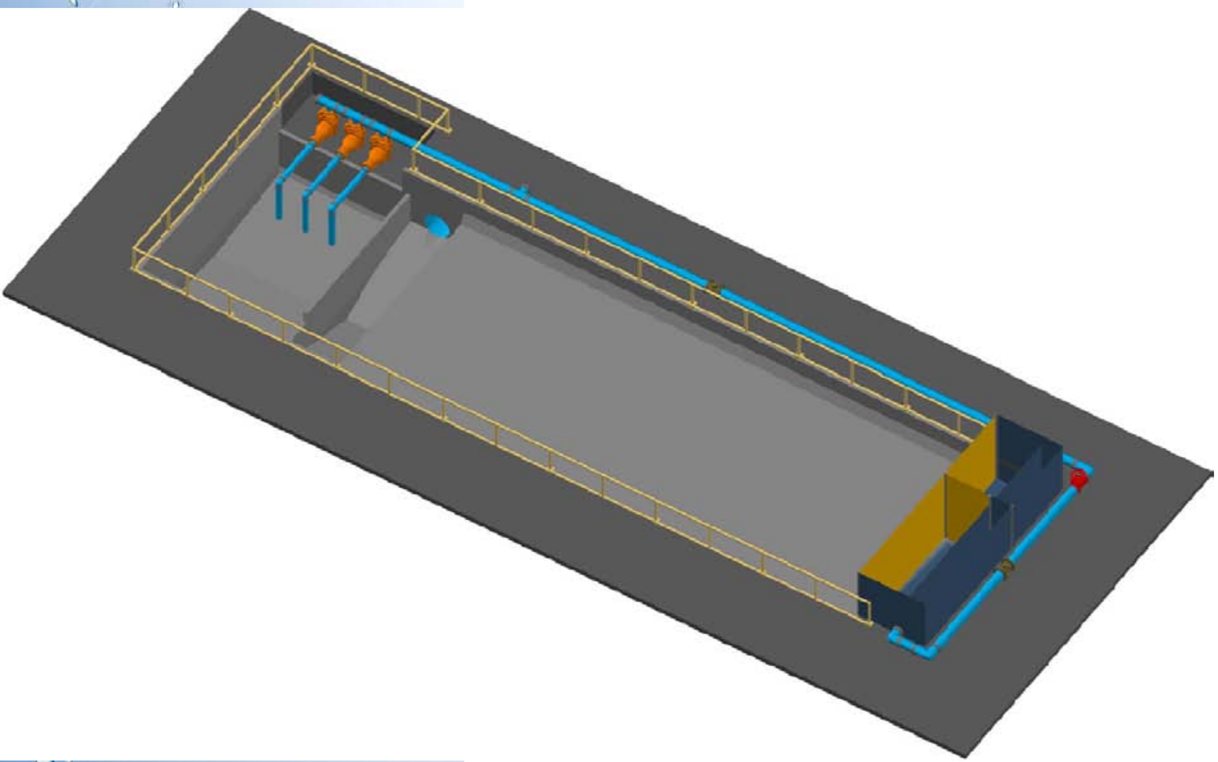
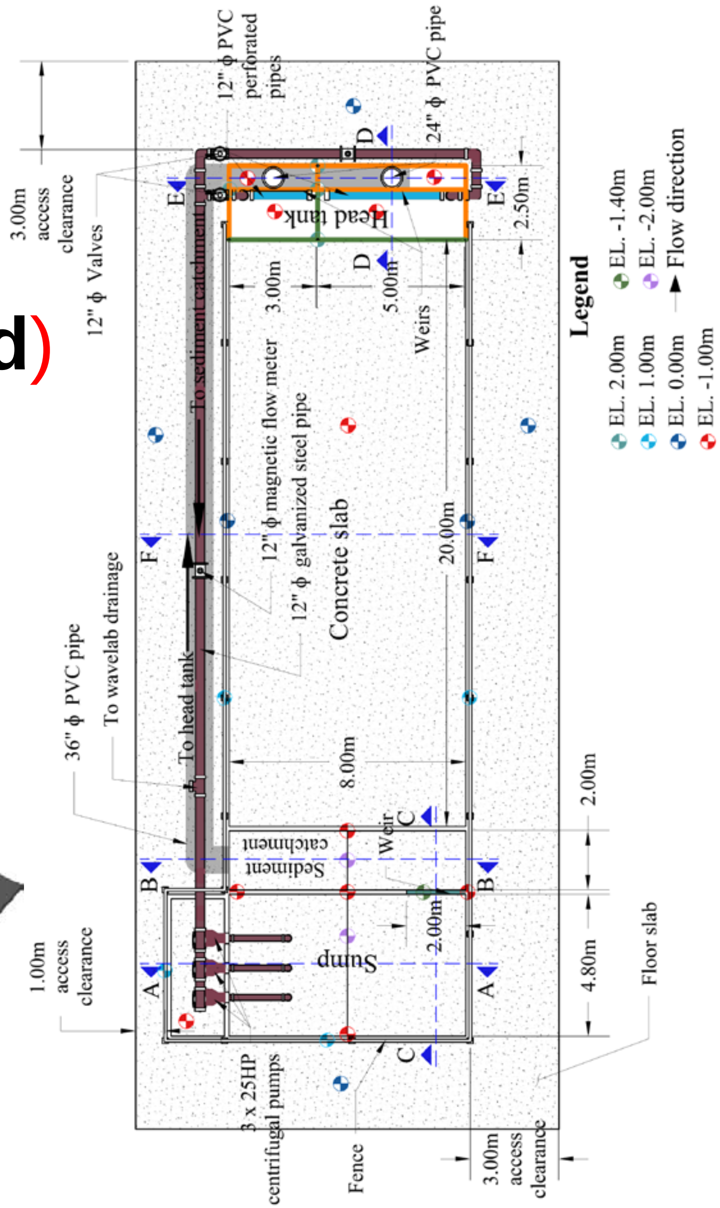
Work under progress or near-future work (Cont.)

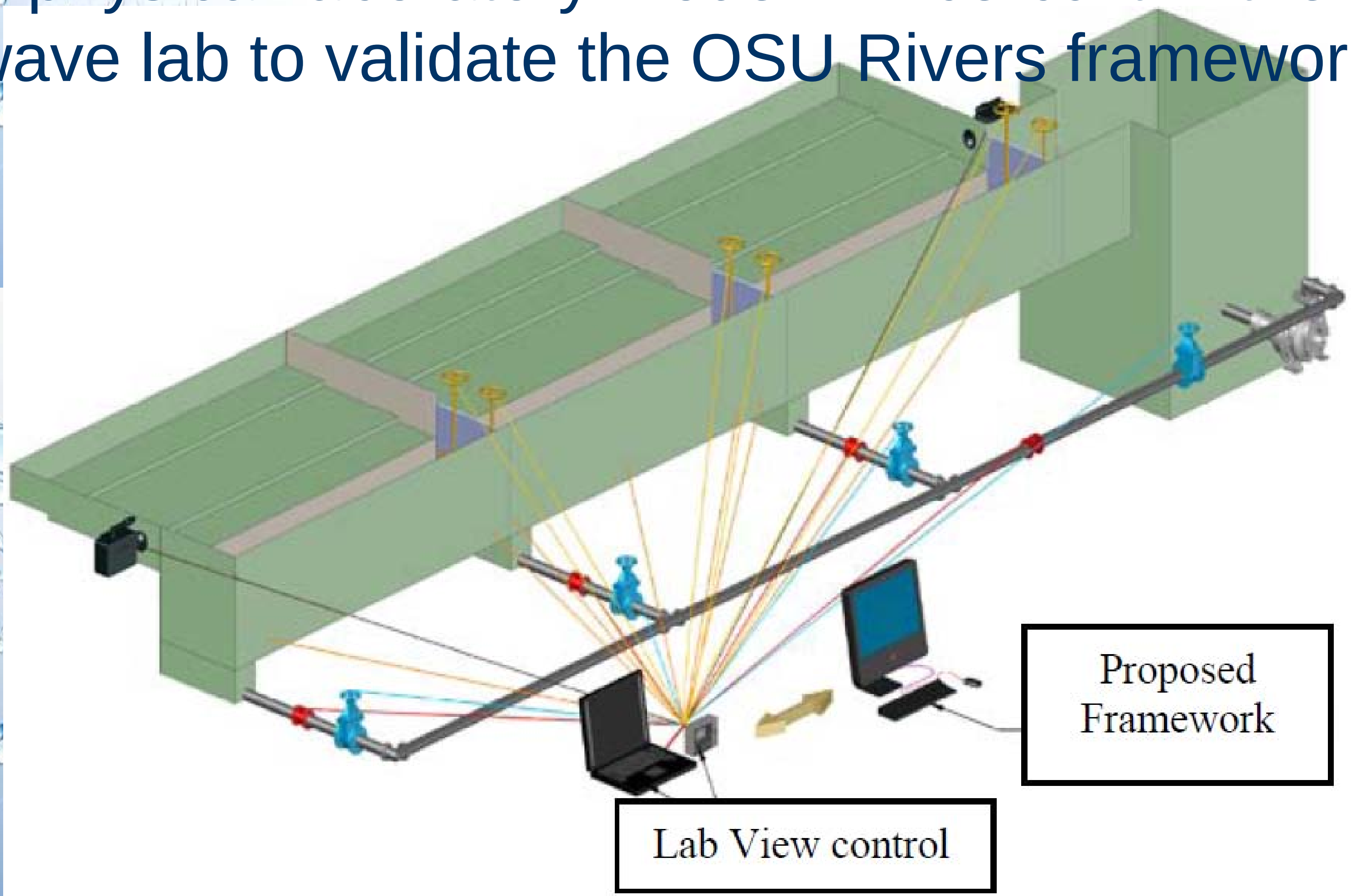
Multi-purpose river hydraulics research facility (**just got funded**)





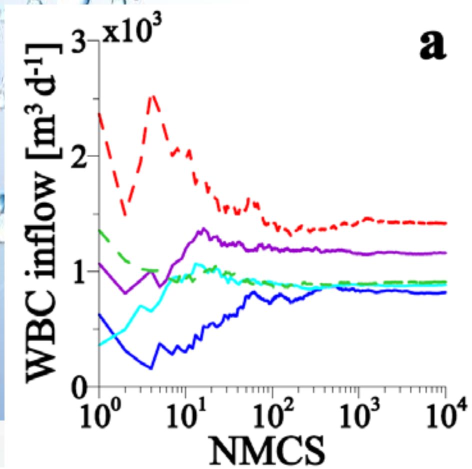
Work under progress or near-future work (Cont.)

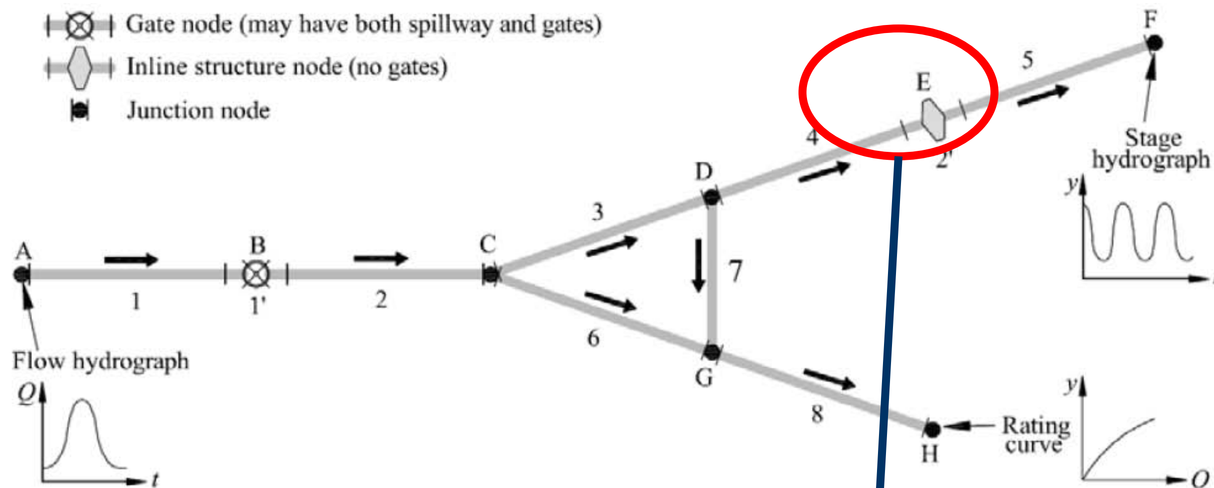
A physical laboratory model will be built in the OSU wave lab to validate the OSU Rivers framework

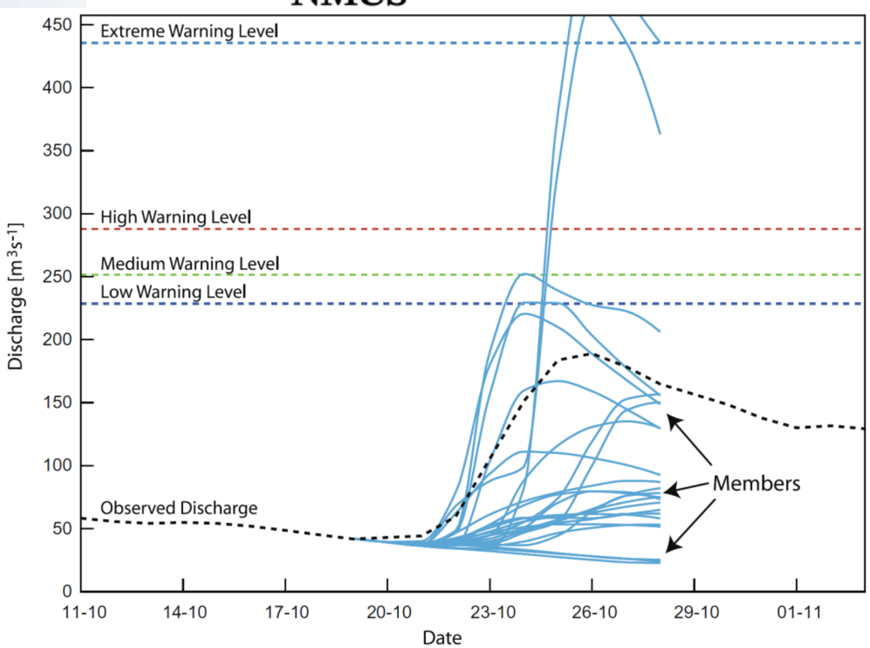


Work in progress

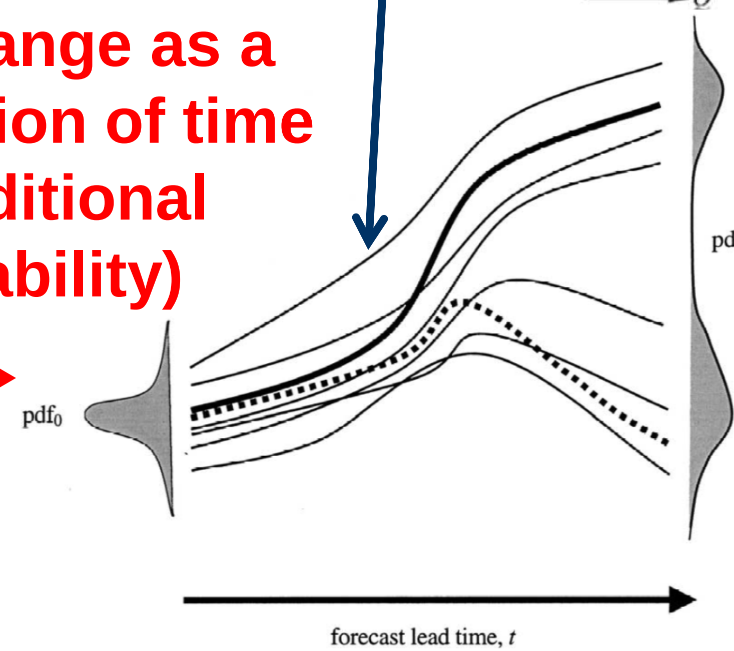
Incorporating uncertainty into reservoir operation







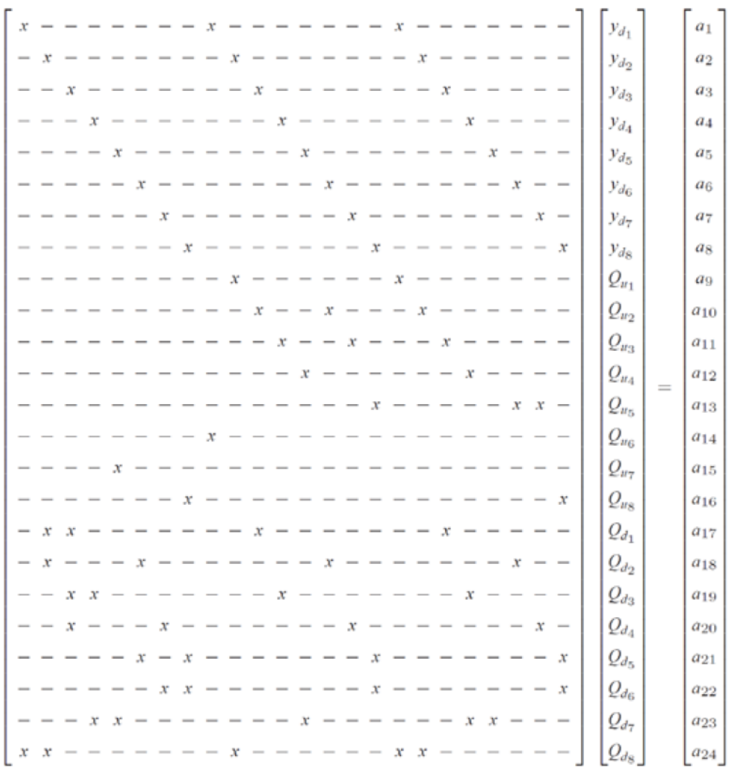
PDF change as a function of time (Conditional probability)



Work in progress (Cont.)

Incorporating Uncertainty into reservoir operation

Assembling, HPGS, RPGs, VPGs, FPGs, Continuity and compatibility conditions



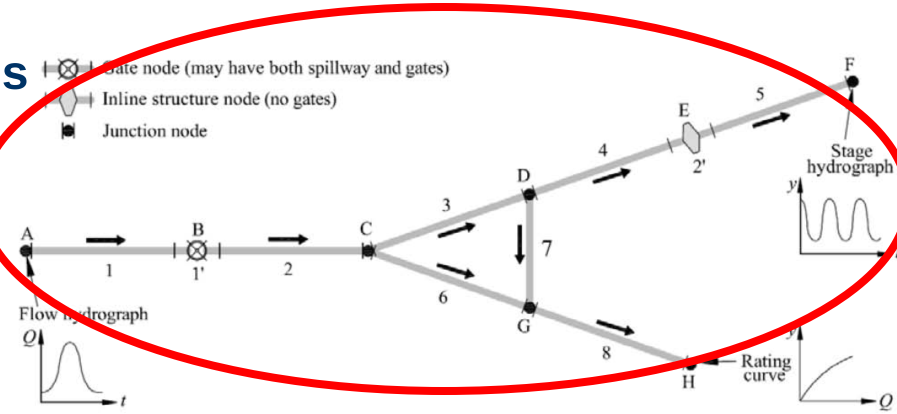
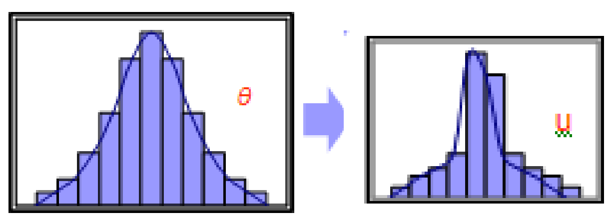


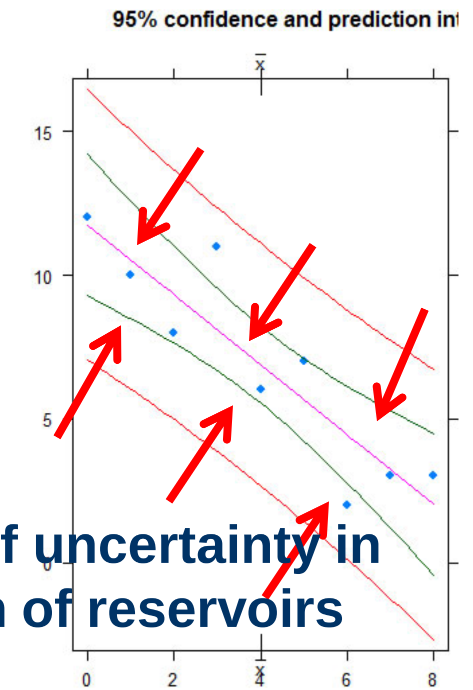
Fig. 7. Summary of equations for the simple network system in Figure 6 (After Leon et al. 2011)

Non-linear system of equations that describe the regulated river system

PDF change as a function of time



Probability distribution function for parameter θ



Reduction of uncertainty in operation of reservoirs

Many thanks for your attention!