Optimization of Water and Power Objectives Using RiverWare

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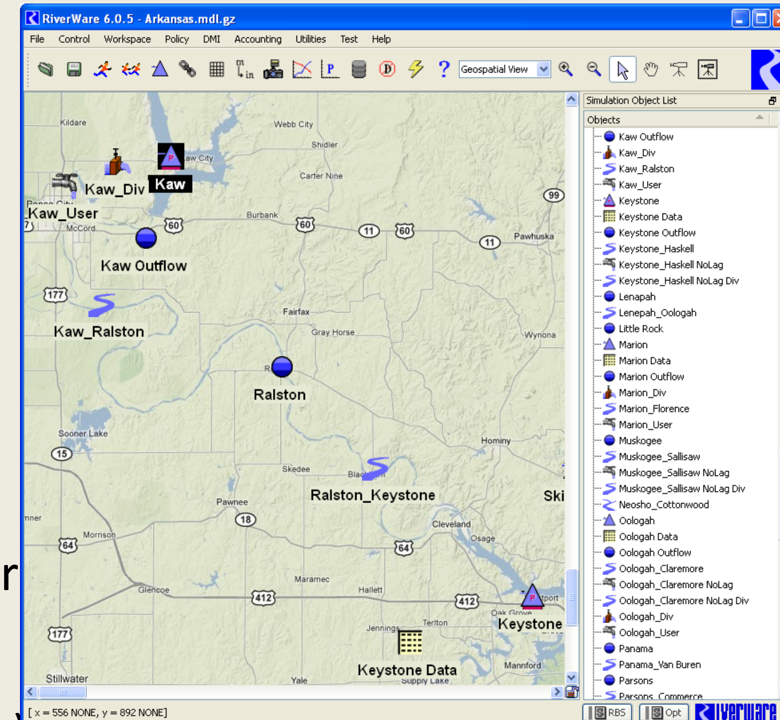
for Water and Environmental Systems (CADSWES)

A River System Modeling Decision Support Software

A CU-CADSWES product sponsored by the Tennessee Valley Authority, the Bureau of Reclamation and the U.S Army Corps of Engineers

RiverWare models….

- Reservoir and river hydrologic processes
- Consumptive use, losses, groundwater – surface water interactions
- Releases, regulated and unregulated spill
- Hydropower generation and hydropower/thermal power economics
- Multi-objective operating rules of any structur and complexity
- Timesteps sizes: 1hr to 1yr (incl daily, monthly)



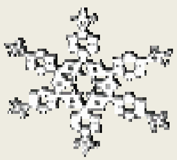
Many Uses of RiverWare:

- **Long term planning** of river/reservoir system for operating policies, yield analysis, climate change, flood risk and physical modifications of system.
- **Policy evaluation** – compare several policies with stochastic inputs and risk-based outputs (e.g. for NEPA analysis) with respect to critical decision variables.
- **Schedule today's operations** and water allocations.
- **Optimize hydropower** generation while honoring water management constraints; conduct FERC relicensing studies.
- **Forecast operations** over next few months or seasons and develop a plan for allocations, curtailments, exchanges, purchases, etc.
- **Water Accounting** for legal records
- **Negotiation** of international or state boundary agreements.
- **Involve stakeholders** for consensus decision-making.

Inputs to RiverWare include inflows to river/reservoir system. **Outputs** are all computed values.

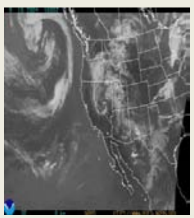
Pre-RiverWare: Generate Inflows and import

Inflow Forecast



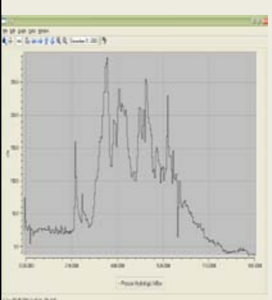
OR

Historical Hydrology



OR

Stochastic inflows



OR

Rainfall – Runoff Modeling

IN

Models interaction of

Hydrologic response of River /Reservoir system (includes Hydropower)

With

Multi-objective operating policies

OUT

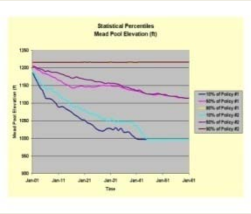
Post-RiverWare: Export outputs for further analysis/reports/DB

Operational Decisions and Plans

Accounting of Water

Predictions

Statistical Output



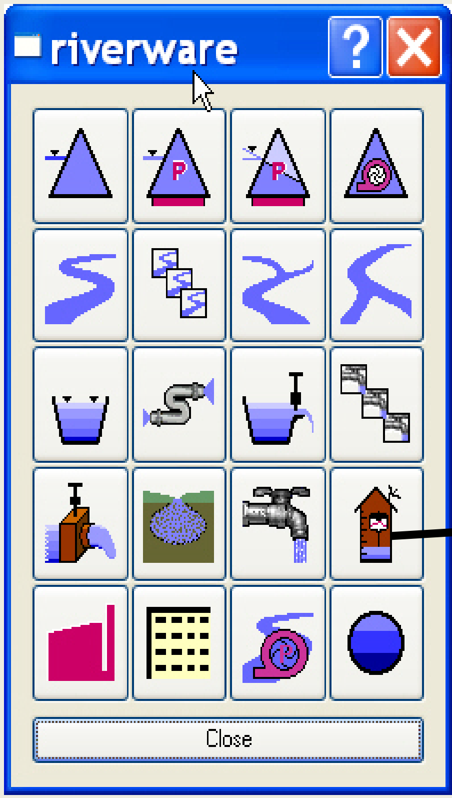
Policy Analysis

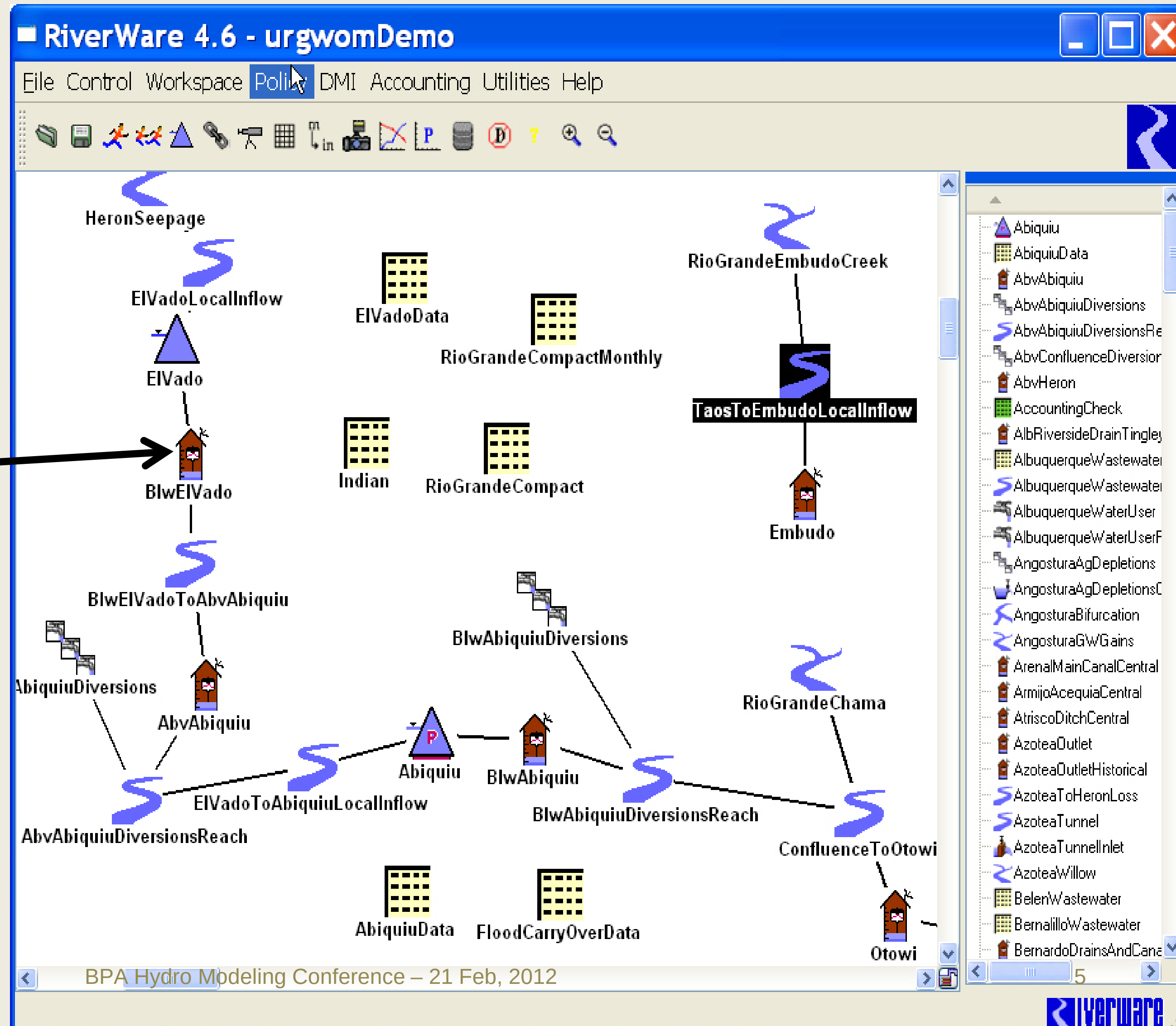
Economic Analysis

Environ analysis

Tradeoff Analysis

A model is constructed by linking together objects that represent the features of the system





Objects are pulled off the palette onto the workspace, given names and populated with data

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Objects on the Palette and Their Methods

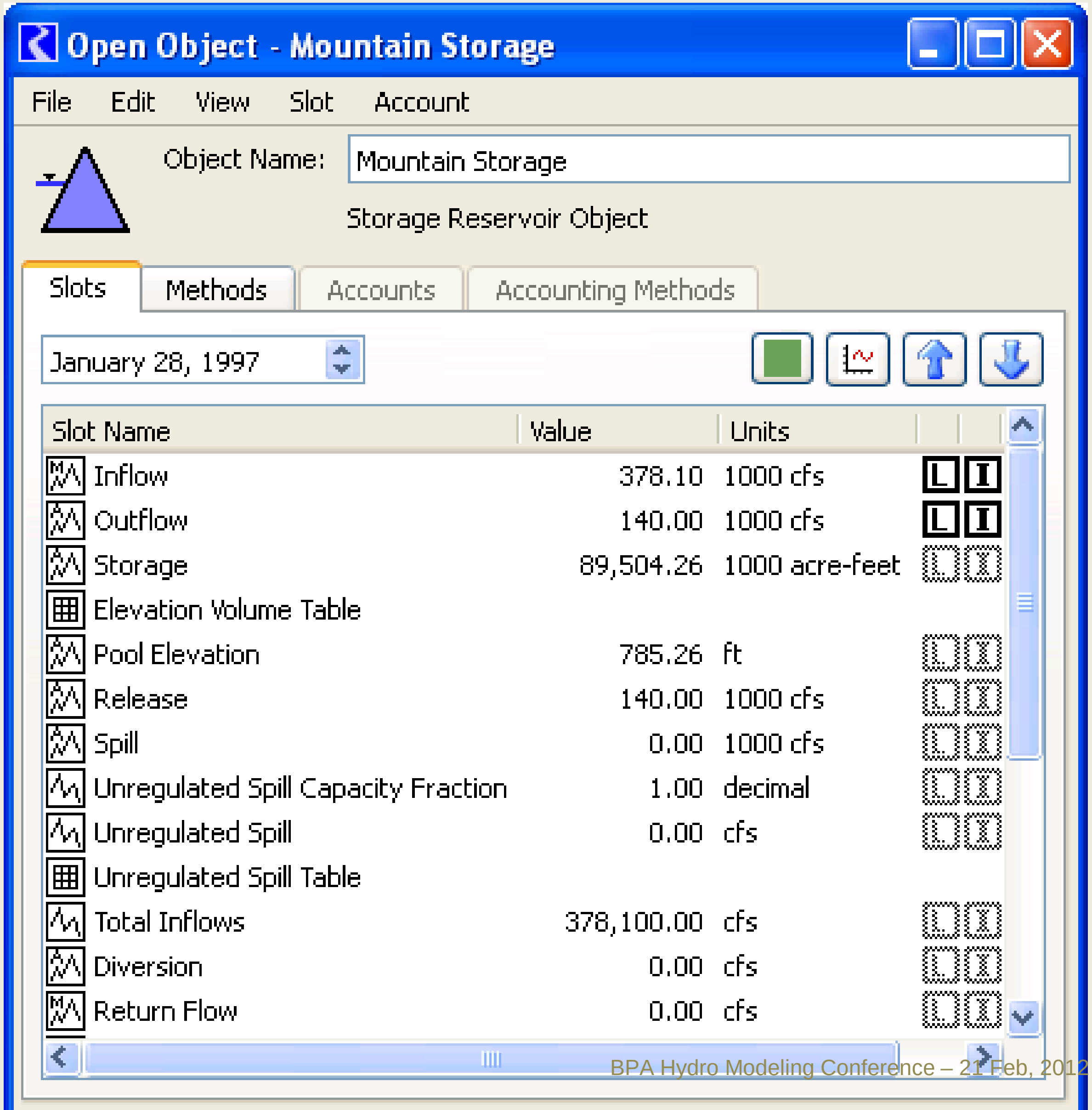
- **Reservoirs:** **Storage Reservoir** (*mass balance, release, spill)*

  Power Reservoir **Level** *(+ tailwater, power, energy, eis)*

  Sloped (*+ wedge storage)*

  Pumped Storage *(+ pump/generators)*
- **Confluence** and **Bifurcation** **-** *mass balance*
- **River Reach** **-** *routing, water quality*
- **Water User** - *demands, consumption, return flow*
- **Diversion** - *pumped or gravity diversion structure*
- **AggDistribution Canal** - *calculates diversion schedules, routes flows*
- **Canal** - *bi-directional gravity flow between 2 reservoirs*
- **Groundwater Storage** - *gw interaction for return flows, seepage, conjunctive use*
- **Stream Gage** - *input for river gage data; propagates flow value up- and downstream*
- **Inline Power Plant** – *generation is function of flow*
- **Pipeline** – *pipe flow including simple hydraulic loss*
- **Control Point** – *constrains upstream flood releases*
- **Thermal Object** - *economics of power system*
- **Data Object** - *user-specified data*
- **Pump** – *used to add head to a pipeline*
- **Pipe Junction** – *pipe modeling, remove or add flow to a pipe*

Double Click to open an Object and see…



SLOTS Tab
(data structures: time series, tables, scalars)

METHODS Tab
(physical process algorithms)

ACCOUNTS Tab
(ownership of water in this object)

Accounting Methods Tab – Methods applied to Water Accounts (Owners)

User-Selectable Methods

Select physical process algorithms for each object based on:

timestep size, resolution of inputs/outputs, institutional requirements

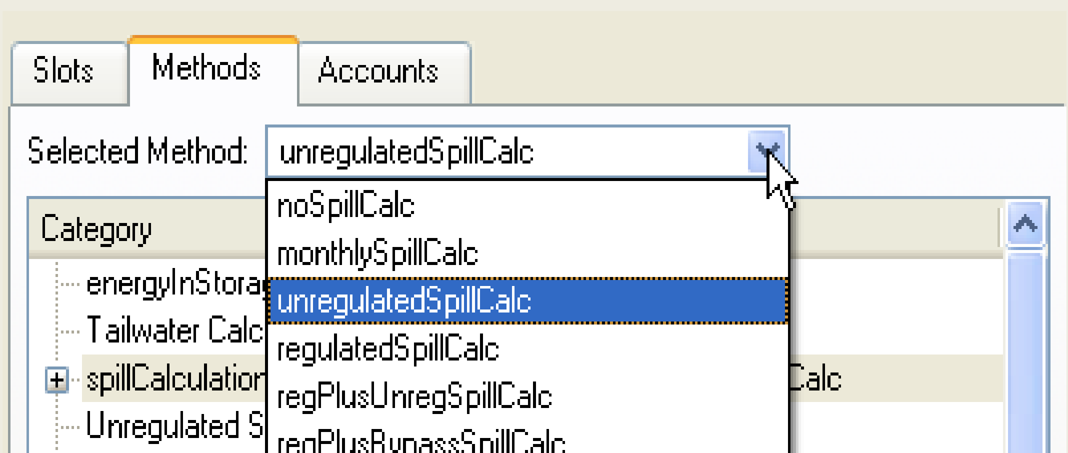
For Example:

River Reaches have **routing methods**

no routing, timelag routing, storage routing, impulse-response,Muskingum, Muskingum-Cunge, kinematic wave, etc.

Power Reservoirs **have power generation methods**:

plant power, unit generator power, plant efficiency curve, peak-base power, peak power equation, etc.



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RiverWare's Solvers

1. Simulation

models physical processes for a variety of input/output combinations (upstream/downstream; forward/backward in time)

2. Rulebased Simulation

simulation driven by user-specified operating rules (policy) expressed through an interpreted language. Solves each timestep completely then moves to next.

3. Optimization

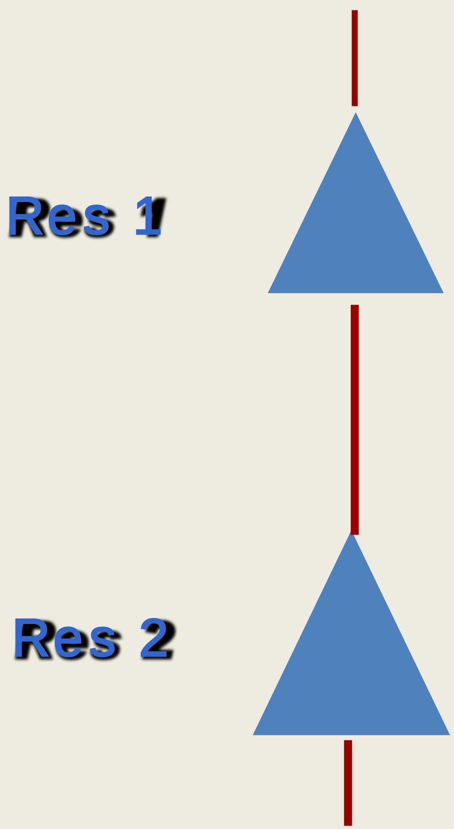
linear goal programming solution . Solves all timesteps and all objects at once.

4. Water Accounting (with or without rules)

Models ownership, water type and water rights; can be coupled with rules

Simulation

each object solves independently



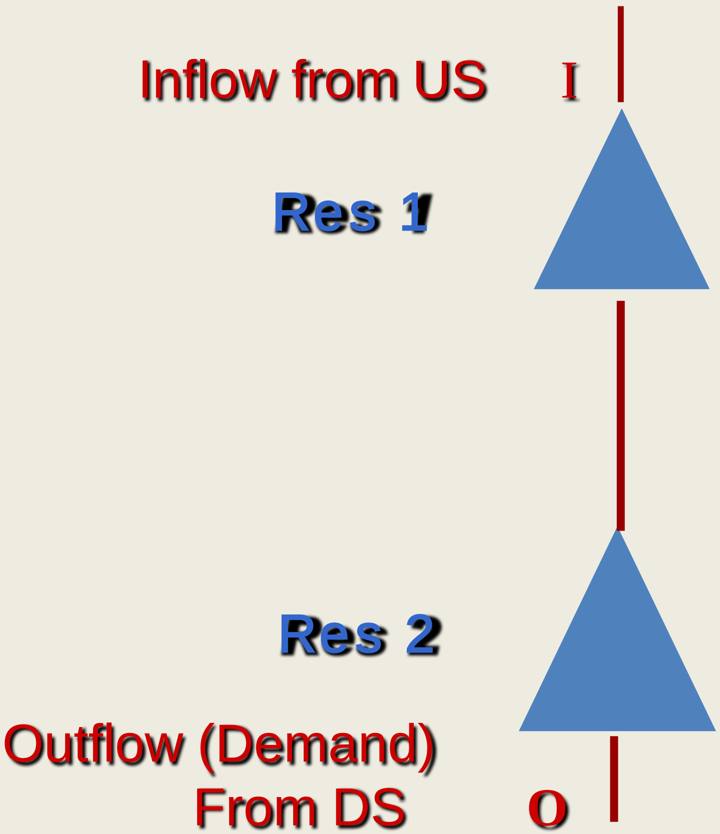
Each object has hydrologic equations

$$S_t = S_{t-1} + I_t - O$$

Objects solve when they have enough information; they compute and set their output values which propagate to other objects via links

Simulation

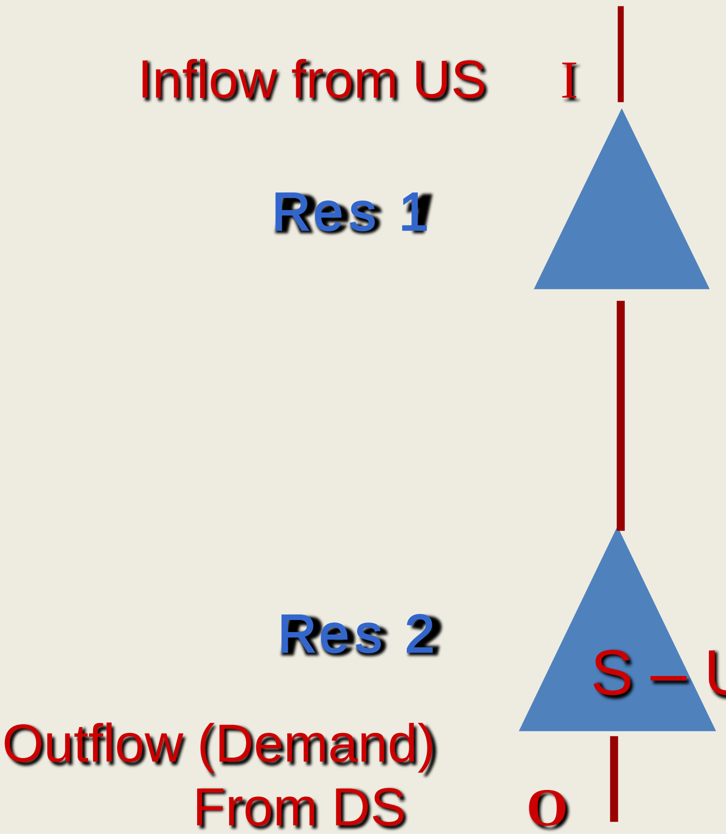
each object solves independently



Values can propagate both upstream and downstream

Simulation

each object solves independently



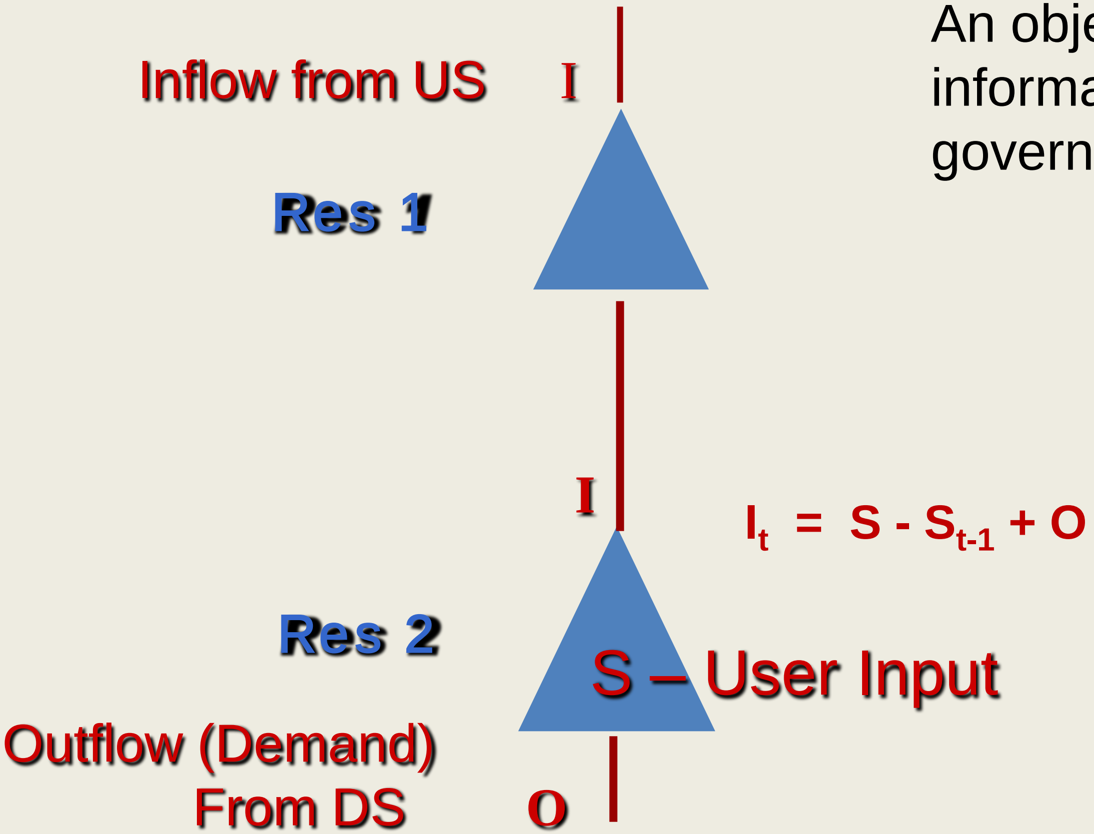
Values can propagate both upstream and downstream

User inputs can vary at each timestep and are possible on many different variables

Simulation

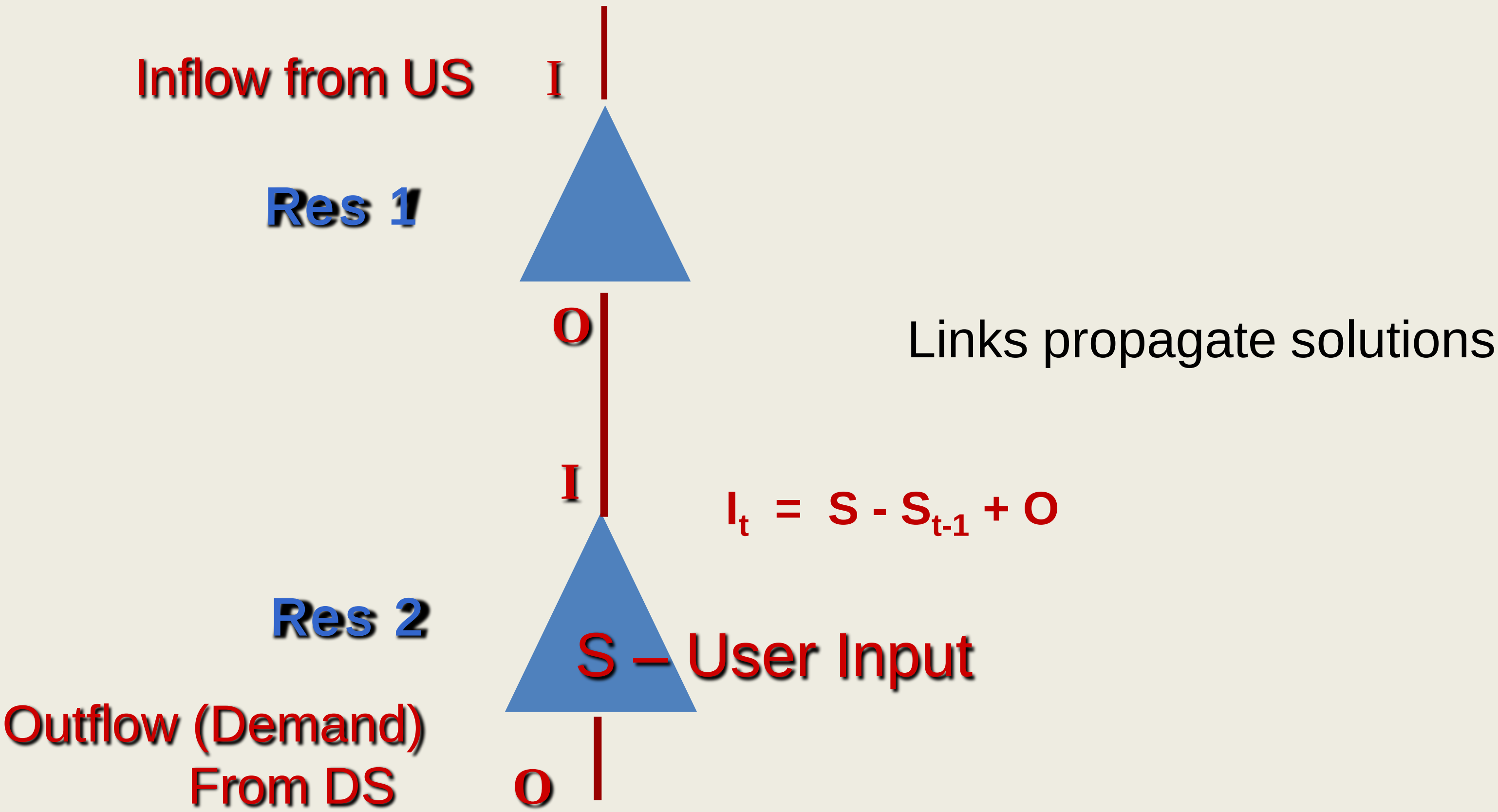
each object solves independently

An object solves when it has enough information to solve one of its governing equations



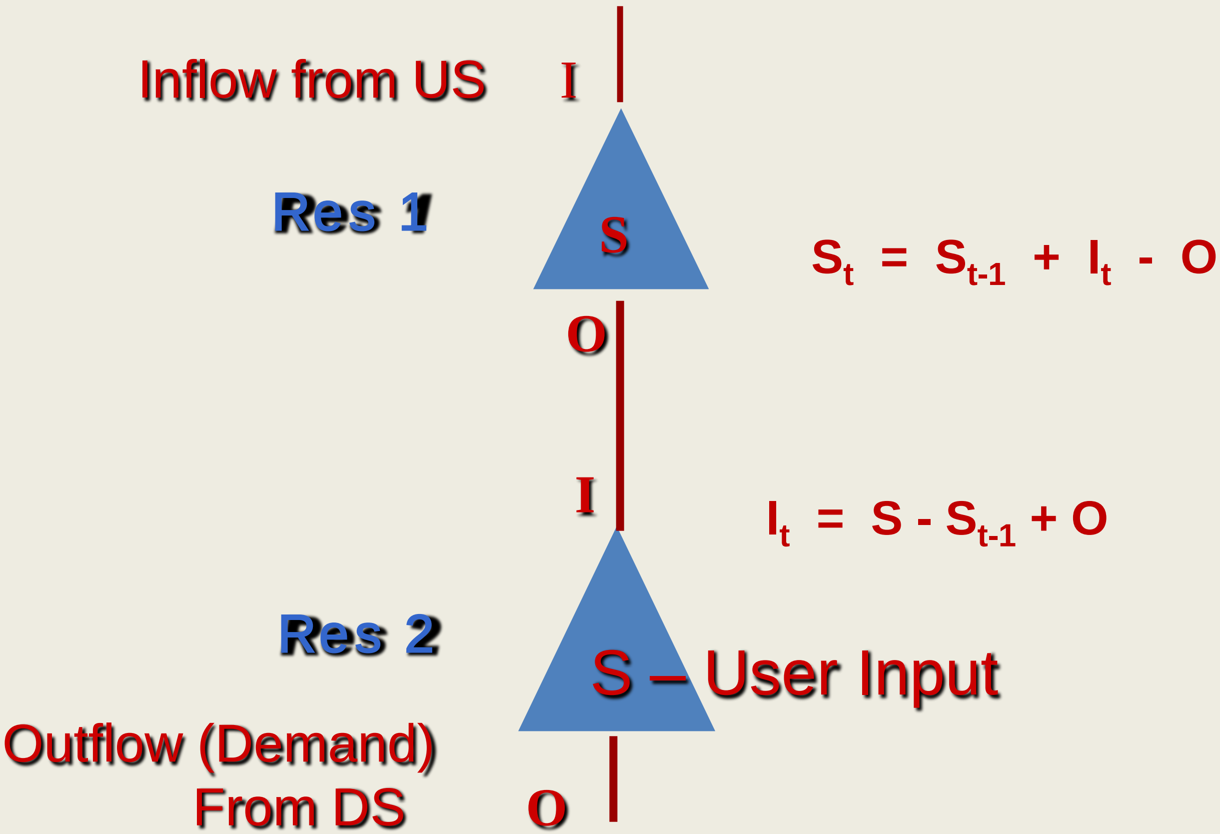
Simulation

each object solves independently



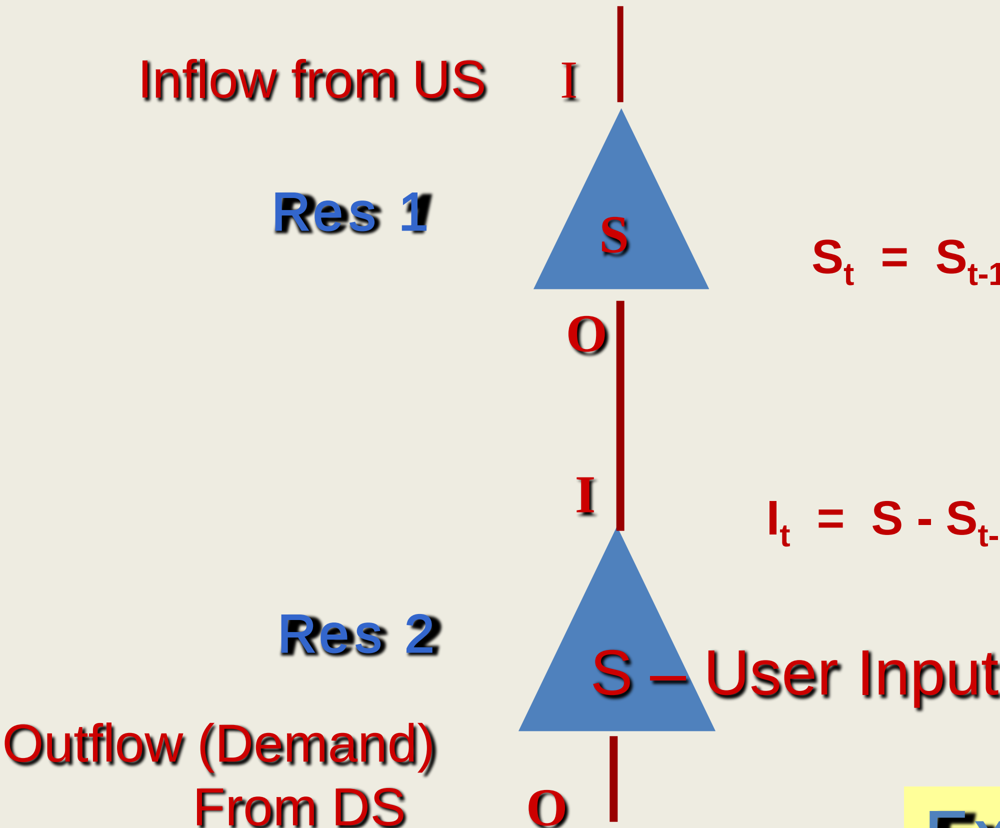
Simulation

each object solves independently



Simulation

each object solves independently



$$S_t = S_{t-1} + I_t - O$$

$$I_t = S - S_{t-1} + O$$

Exactly determined system

Multiple objective modeling

Different possible inputs serve different purposes.

River systems are operated for a variety of objectives

Multiple objective modeling

water delivery

Multiple objective modeling

Environmental
flows

Multiple objective modeling

Hydropower

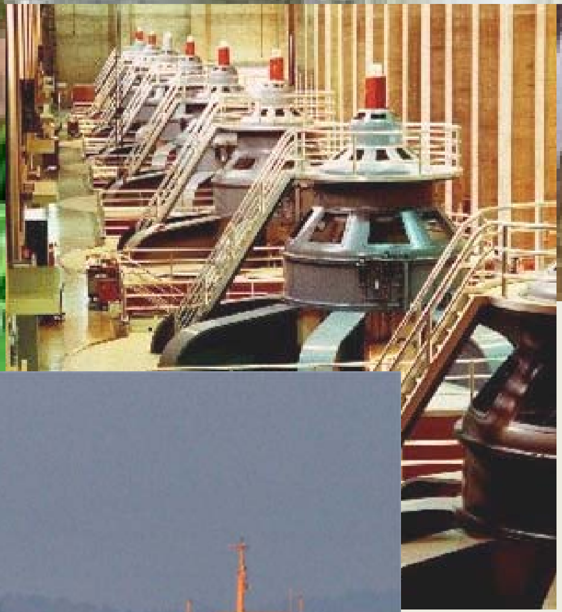
Multiple objective modeling

Recreation

Multiple objective modeling

Water Quality

Multiple objective modeling



Navigation

Multiple objective modeling

Flood Control

Multiple objective modeling

RiverWare's Multi-objective Modeling:

How to resolve conflicting objectives?

Flood Control

Water Supply

Navigation

Water Quality

Aquatic/Riparian
Habitat

Recreational Flows

Recreational Lake Levels

Hydropower

RiverWare's Multi-objective Modeling:

How to resolve conflicting objectives?

Flood Control	0.34
Water Supply	4.1
Navigation	25.1
Water Quality	9.8
Aquatic/Riparian Habitat	25.2
Recreational Flows	16.2
Recreational Lake Levels	102
Hydropower	101.9

A traditional approach…

Weights/Penalties

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RiverWare's Multi-objective Modeling:

How to resolve conflicting objectives?

Flood Control	0.34
Water Supply	4.1
Navigation	25.1
Water Quality	9.8
Aquatic/Riparian Habitat	25.2
Recreational Flows	16.2
Recreational Lake Levels	102
Hydropower	101.9

A traditional approach…

Weights/Penalties

Non-commensurate

Difficult to determine values

Difficult to predict/understand effects of weights/penalties on solution

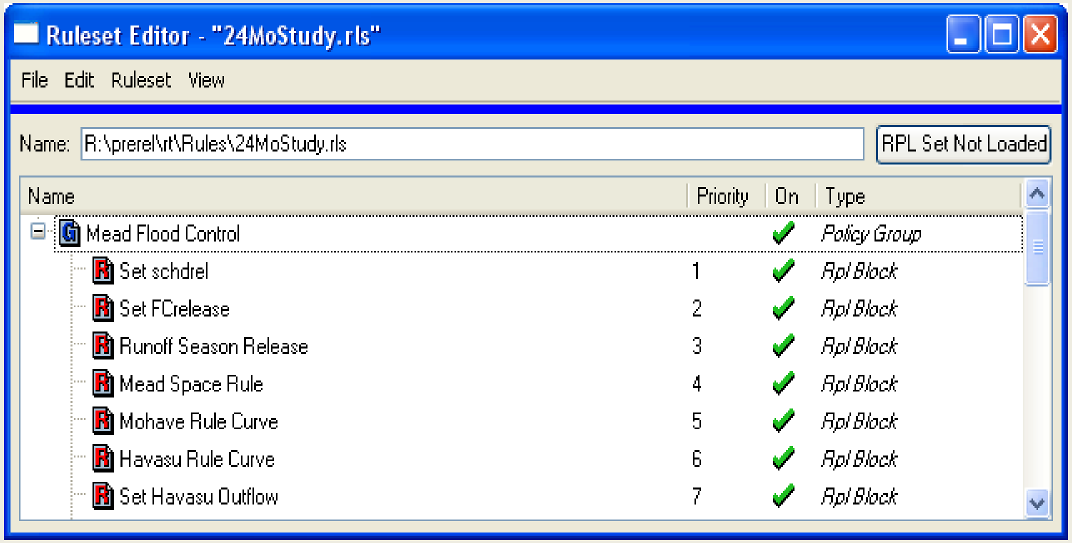
Operators and decision-makers cannot easily understand logic

RiverWare's Multi-objective Modeling:

How to resolve conflicting objectives?

Flood Control	1	
Water Supply	3	
Navigation	5	
Water Quality	2	Priorities
Aquatic/Riparian Habitat	4	
Recreational Flows	6	
Recreational Lake Levels	8	
Hydropower	7	

Rulebased Simulation



Simulation is under-determined

Operating policies are prioritized rules

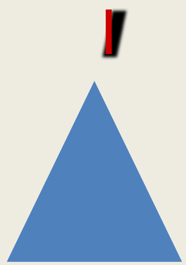
- IF (state of system)
- THEN (set decision variables)

Rules alternate with simulation to solve system

Rulebased Simulation

- Same set of decision variables as simulation
- Solves system at each timestep using a set of prioritized rules
- Rules set values such as releases and withdrawals based on state of the system after previous rule has fired
- After each rule is executed, the simulation propagates the effects of the rule
- Higher priority rules are special conditions and dominate lower priority rules which represent ideal conditions

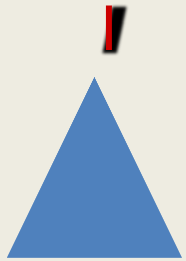
RBS example – Single Reservoir



Forecasted Inflow is Input

Not enough data for object to solve

RBS example – Single Reservoir



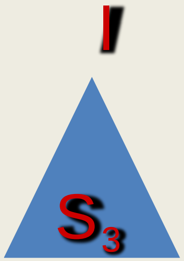
Forecasted Inflow is Input

Not enough data for object to solve

Instead of input values, we will provide a set of prioritized operating rules:

1. Release for flood control
2. Meet minimum flows downstream
3. Guide curve

RBS example – Single Reservoir

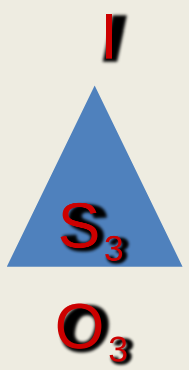


Execute lowest priority rule:

Rule 3: Set Storage to the guide curve

(value get a priority 3)

RBS example – Single Reservoir



Execute lowest priority rule:

Rule 3: Set Storage to the guide curve

(value get a priority 3)

Reservoir can now solve for its outflow

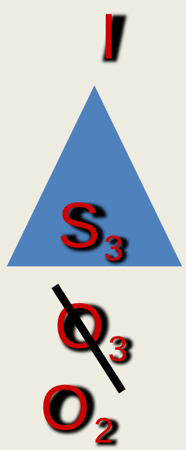
(also at priority 3)

The other policies must now be processed:

Rule 2: If Outflow < Min Flow

Outflow = Min Flow

RBS example – Single Reservoir



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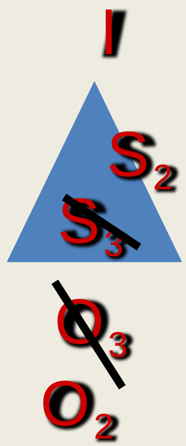

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(value get a priority 3)

Reservoir can now solve for its outflow

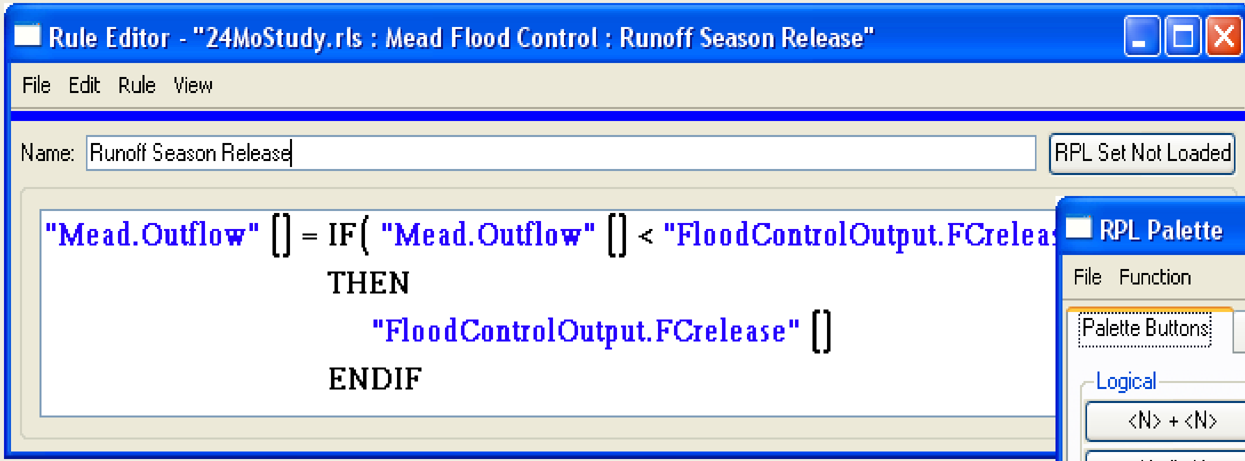
(also at priority 3)

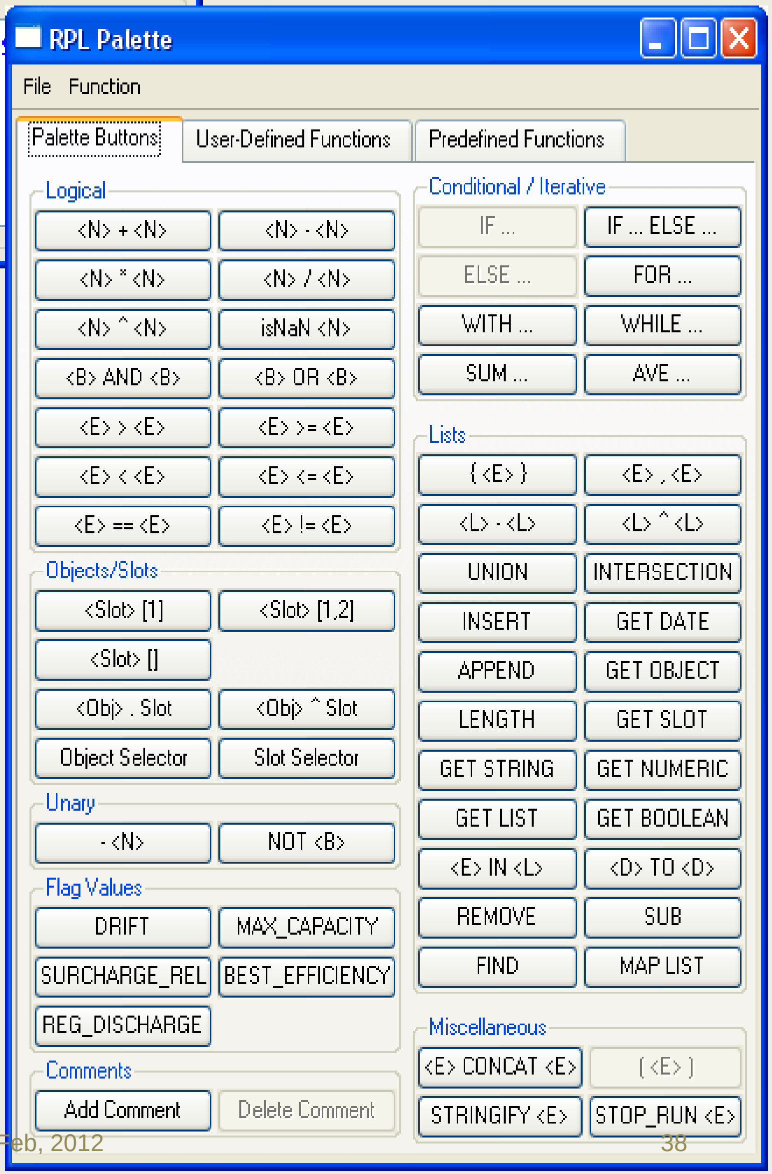
The other policies must now be processed:

Rule 2: If Outflow < Min Flow

Outflow = Min Flow

Reservoir solves for new storage at P2





Rule Syntax-directed Editor

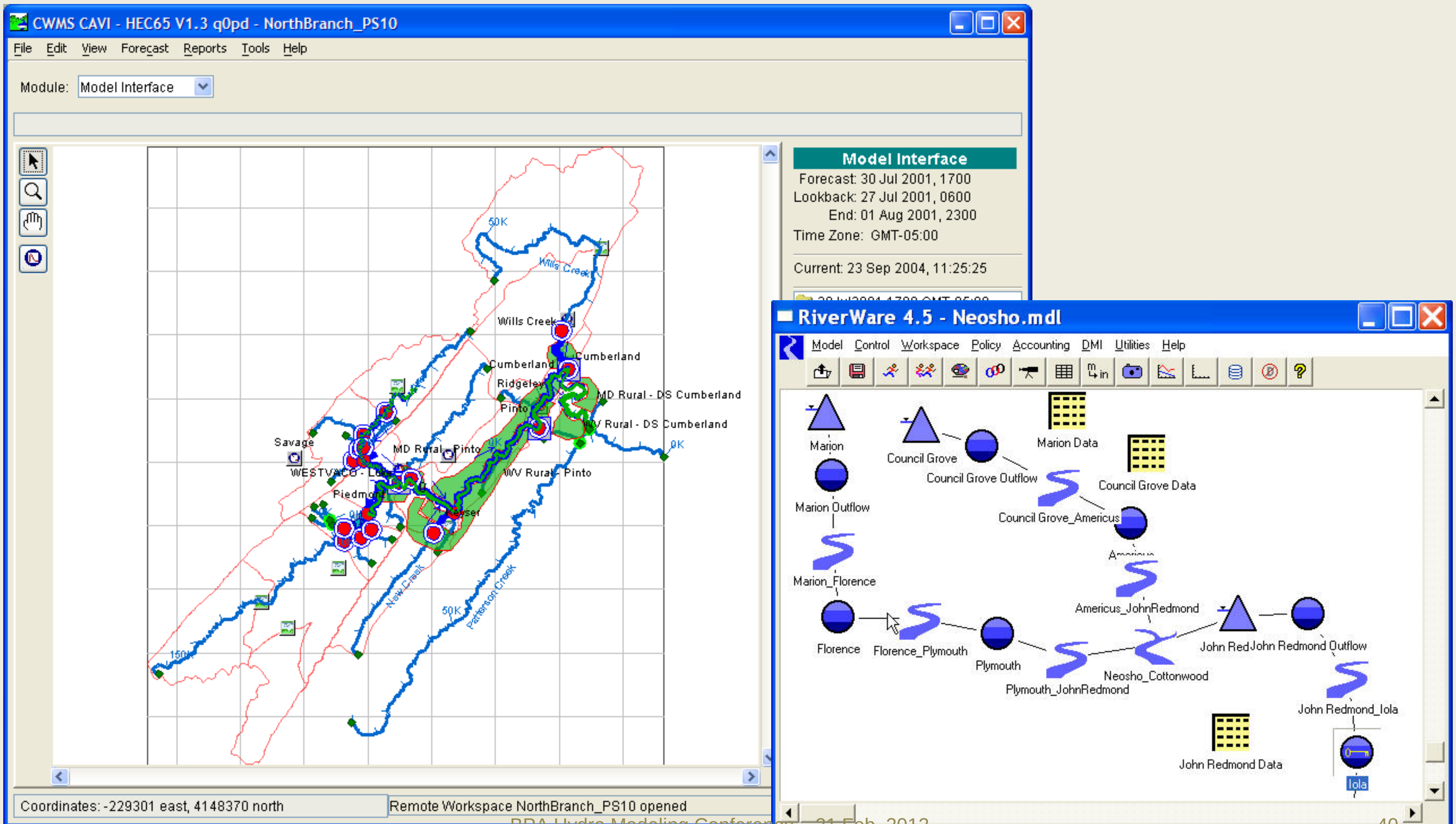
Rules Palette

US Army Corps of Engineers Flood Control Methods

US Army Corps of Engineers

- Previously implemented in Fortran, these methods find the flood control releases for all reservoirs in a basin with these objectives:
  - Balance storages with regard to operating levels
  - Evacuate flood pool as quickly as possible
  - Do not exceed regulation flows at downstream control points
  - Respect rate of change constraints
  - Calculate current and future releases based on current forecast, execute the current releases, move to next timestep and re-forecast.
- This is a global solution, but still fits into the object oriented approach in RiverWare

Integration of RiverWare in the Corps Water Management System (CWMS)



Water Ownership, Water Accounting, Water Rights

- “Paper” Accounting
- Storage, Instream Flow, Diversion Rights
- Classify Accts by Priority Date, Owner, Type
- Exchanges, Loans, Rents, Carryover, Accrual
- Drive the solution using (can be mixed):
  - User Inputs – Spreadsheet like solution
  - Mix with Rulebased Simulation
  - Water Rights Allocation
- Optional reconciliation

“Physical” vs. “Paper” water modeled in RiverWare

Paper Water - type and ownership (“color”):

Volume/flow of water classified by type or ownership. For example, a certain agency owns 5,000AF of 12,000AF of physical water in the reservoir.

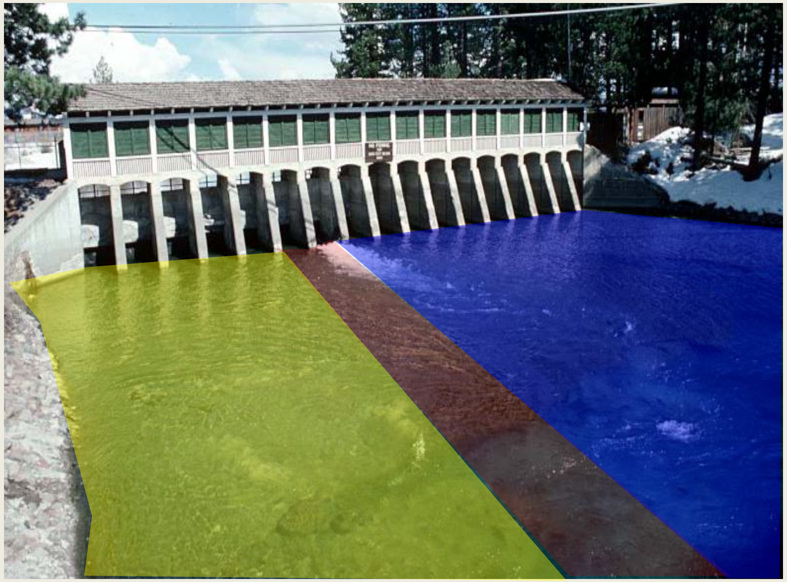
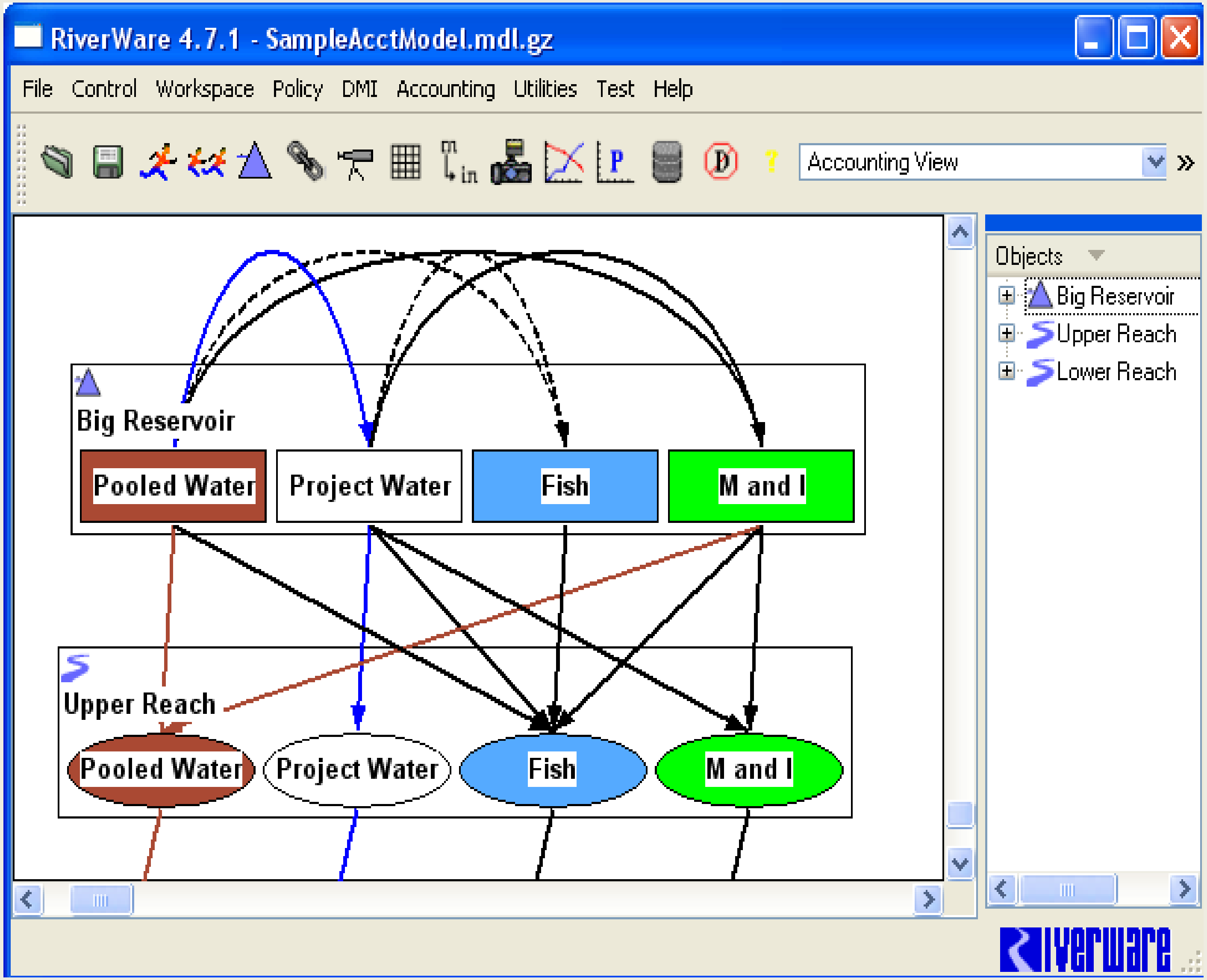


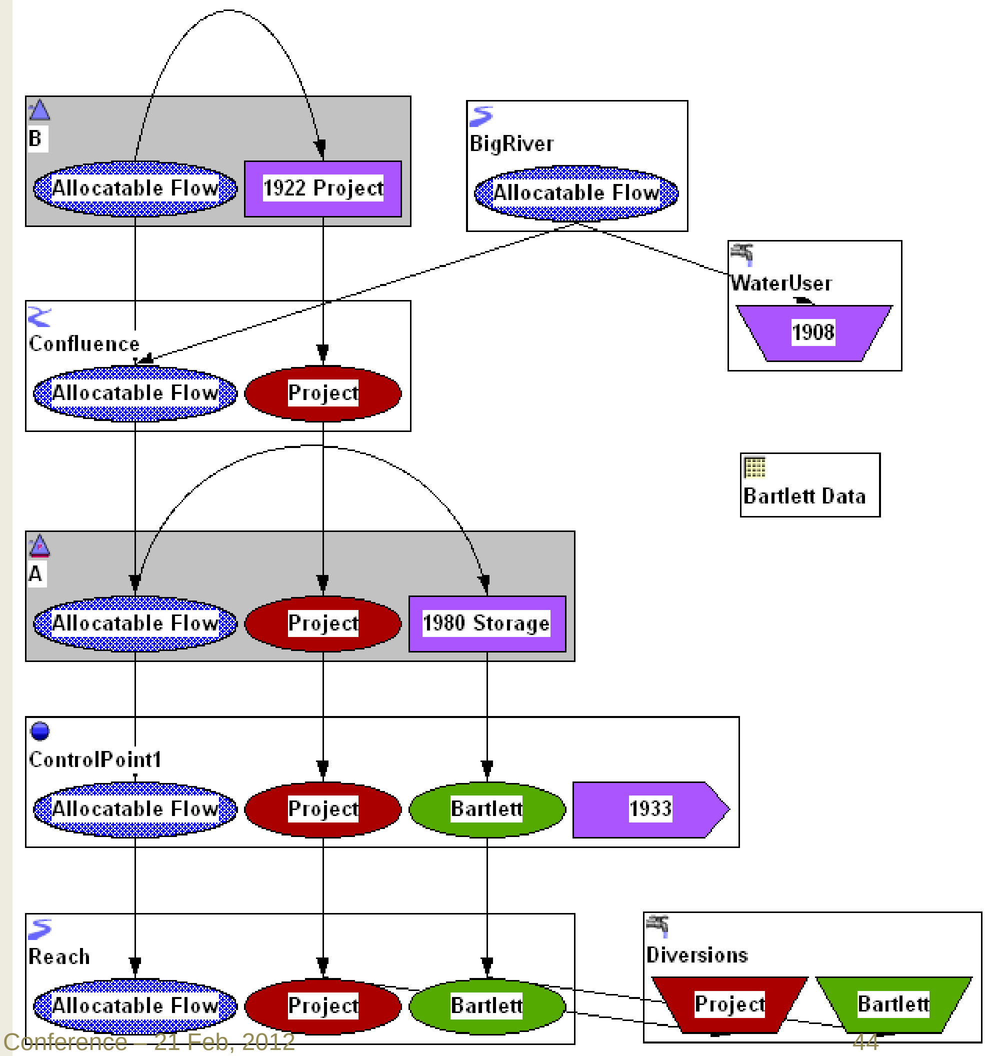
Diagram of Accounts



Water Rights Allocation Model

Rules executes "solver" (predefined function) that does the allocation one or more times:

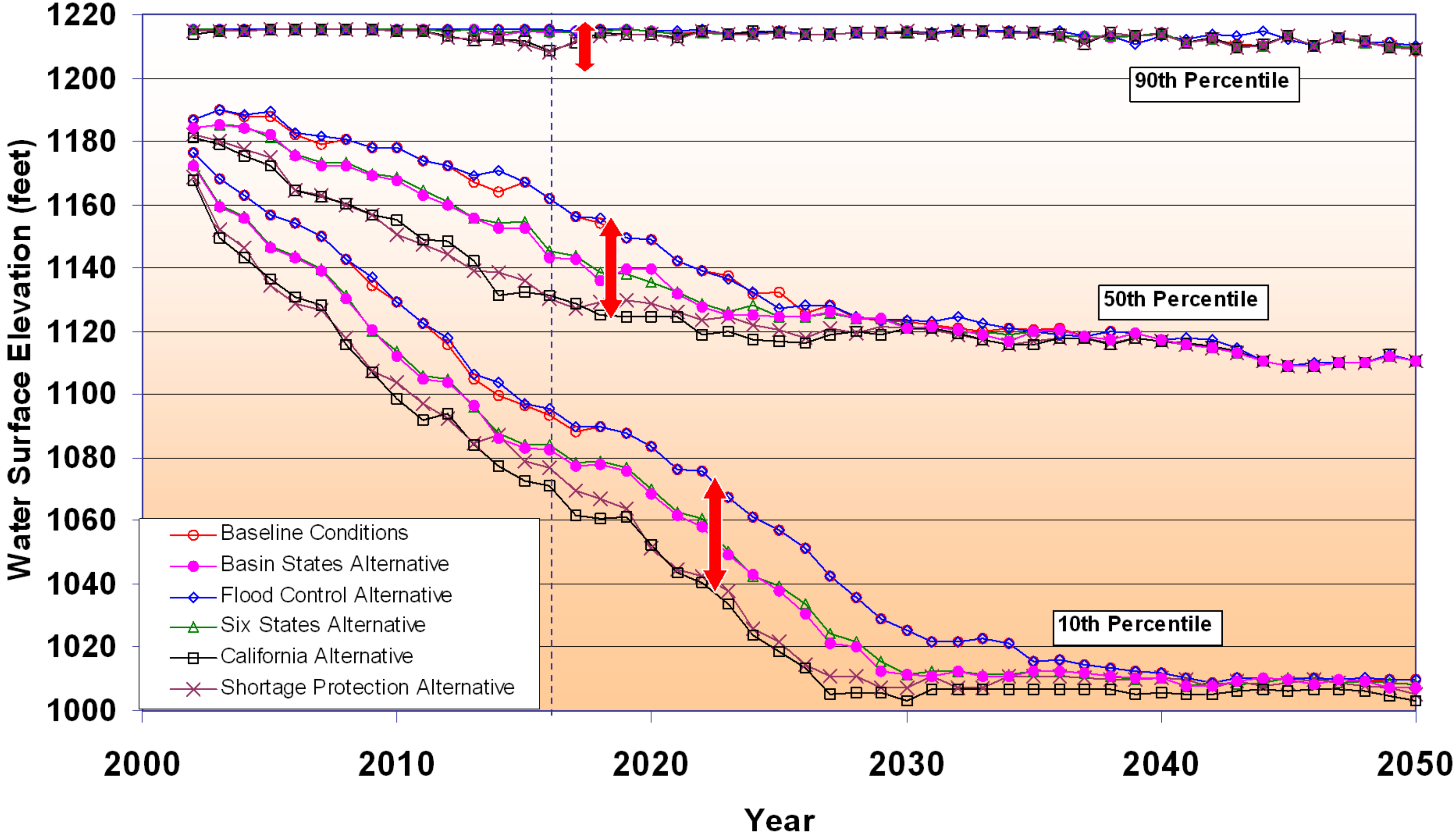
- Initial allocation, exclude instream flows rights
- Operate project water (releases from storage)
- Allocate again and include instream flow rights
- Repeat as necessary



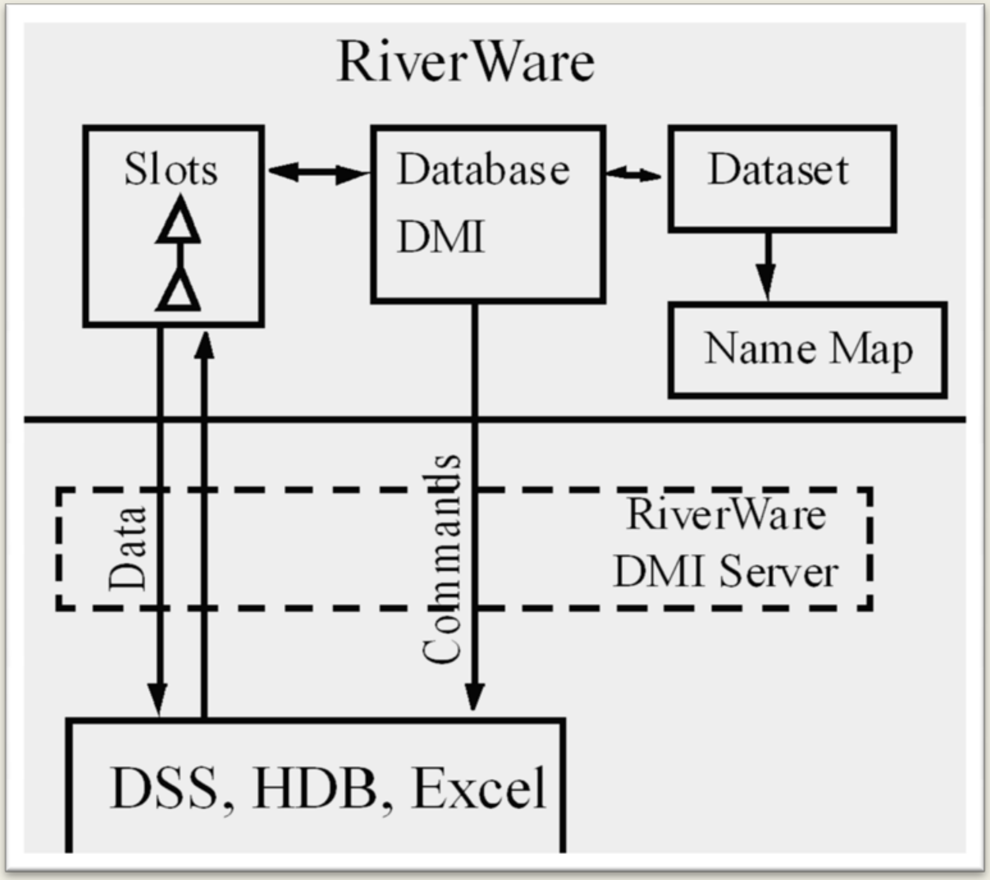
Multiple Run Evaluation

- Stochastic Input
- Stochastic Output
- Evaluate using GPAT (Graphical Policy Analysis Tool)
- Modes:
  - Concurrent
  - Consecutive
  - Iterative
- Distribute runs to many processors

Lake Mead Elevation
Interim Surplus Criteria Alternatives



Direct DSS, HDB, Excel Interface

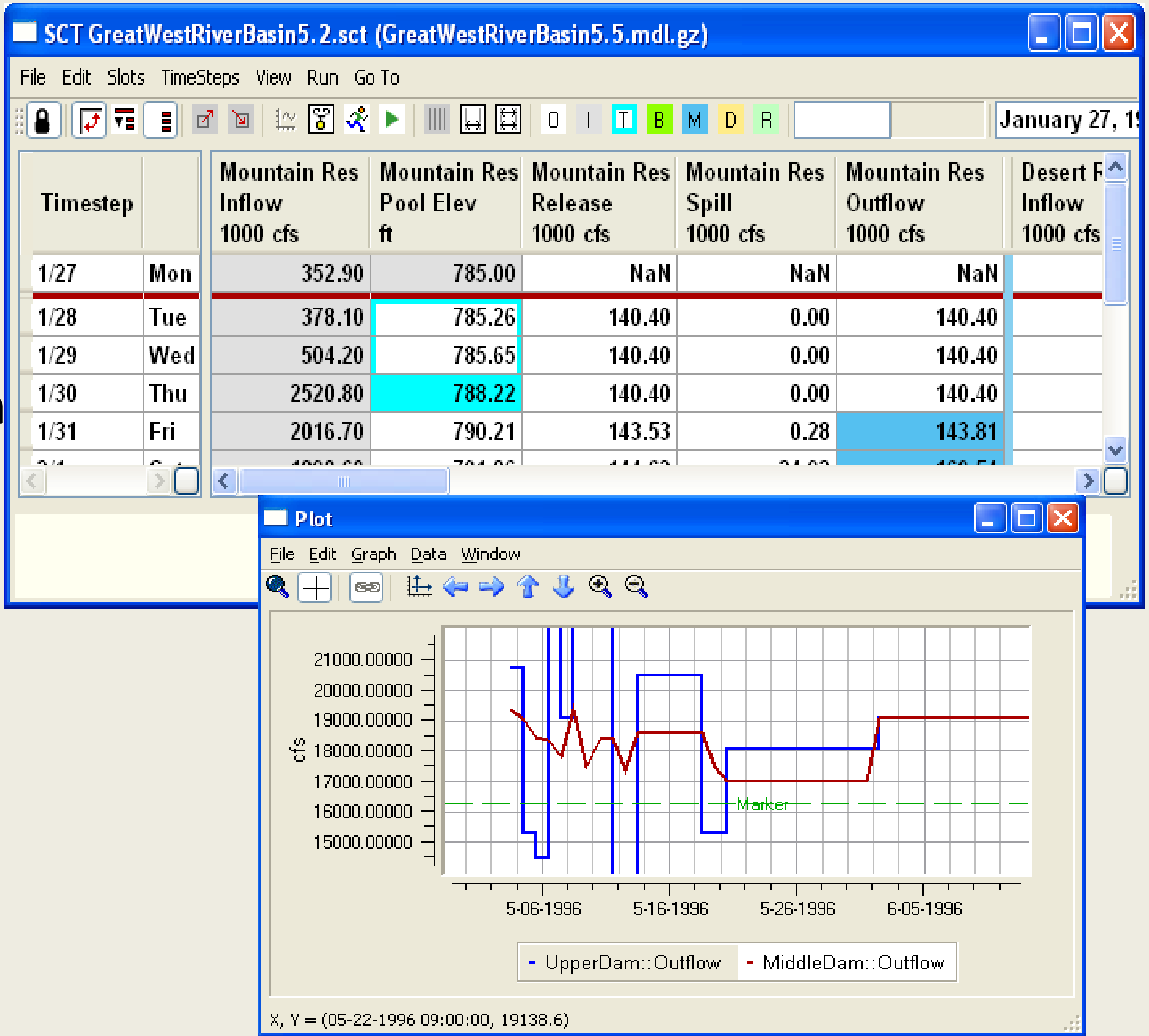


Water Quality

- Simple well-mixed Total Dissolved Solids (TDS)
- Dissolved Oxygen (DO), Temperature, TDS
  - 2-layer reservoir
  - coupled Reach Routing with Advection, Diffusion

Many other Features

- SCT
- Diagnostics
- Analysis Features
- Output option
- Multiple Run Management
- GPAT
- Scenario Manager



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Software Quality Assurance

- Professional software development processes
- Requirements, Functional Specifications and Designs are documented
- Code is peer-reviewed
- Source control
- Regression testing
- Formal bug reporting and tracking
- Team of experienced, professional software developers as well as water resources engineers

Optimization Overview

- What Kind of Optimization?
- Optimization Process
- Optimization Policy
- Ancillary Services
- Example: TVA Operational Scheduling
- Example: Mid-Columbia River and Wind Integration

Optimization

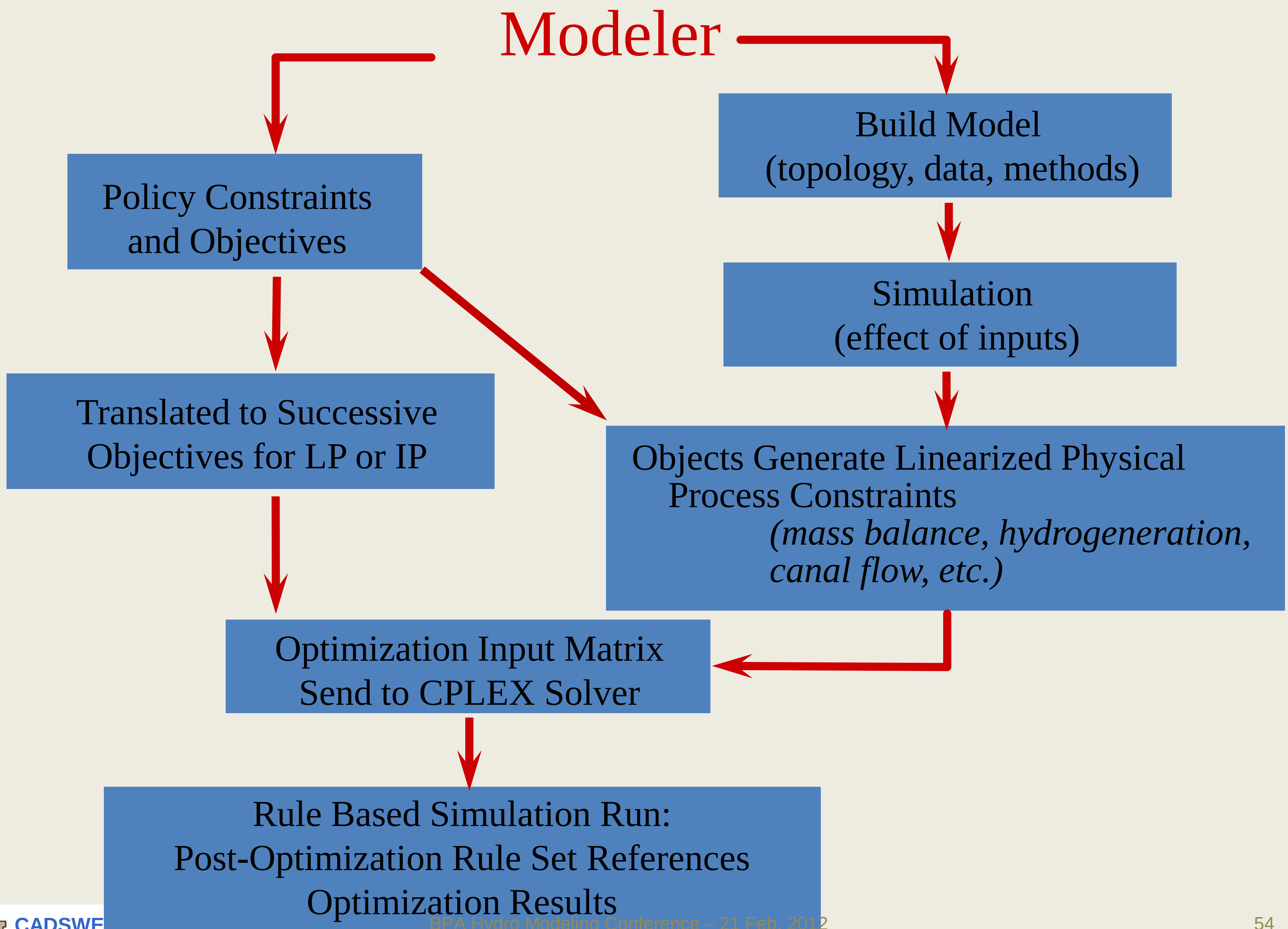
- Pre-Emptive Goal Programming
  - Multi-objectives without user-defined penalties
  - Policies (Goals) are Prioritized
  - Soft Constraints - Minimize infeasibilty
  - Economic (hydropower) objective
  - Linear or Mixed-Integer Programming
- Goals/constraints formulated in RPL Editor
- Variables automatically linearized
  - User controls approximation
- Physical constraints generated by objects as needed
- CPLEX solver
  - Can “tune” parameters
- Post-optimization Rulebased Simulation

Optimization Steps

Simulation → **Optimization** → **Rulebased Simulation**

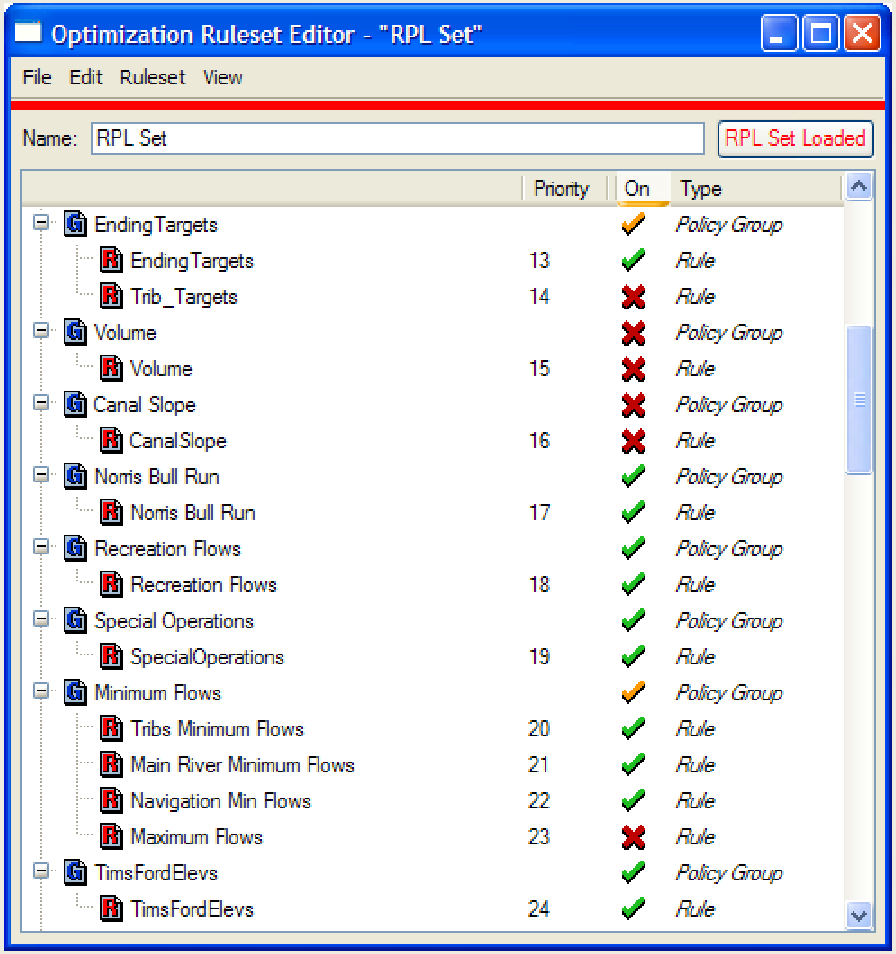
Simulation	Optimization	Rulebased Simulation
Compute consequences of input values	Solve a series of LP problems	Compute consequences of input values and selected optimal values

Automatic Generation of Optimization



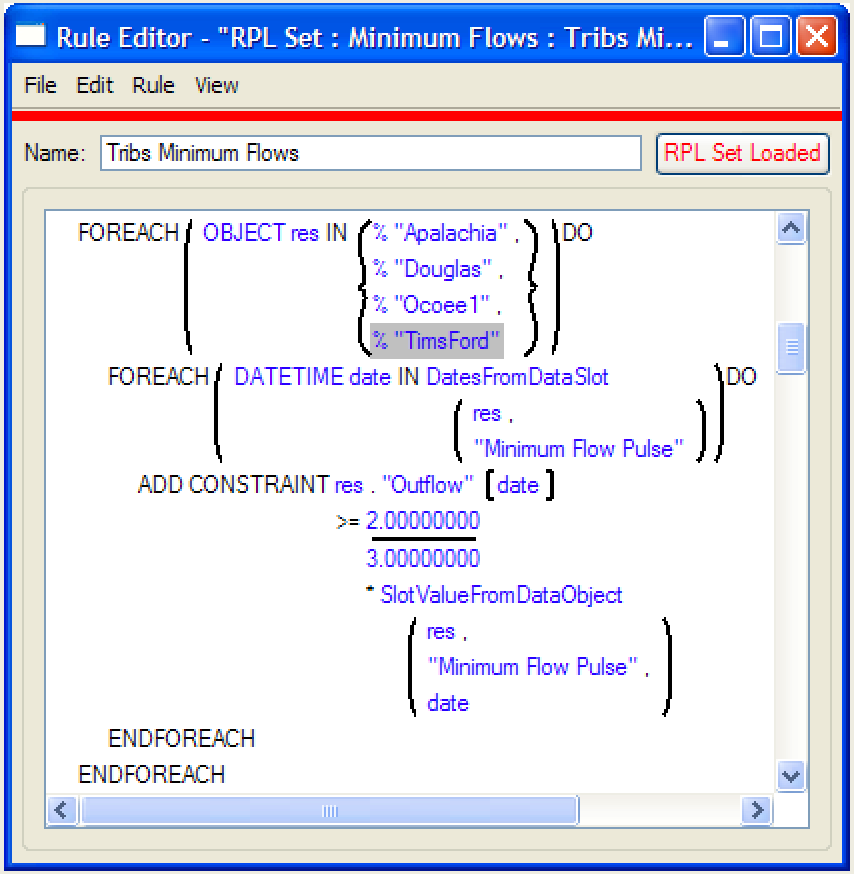
Optimization Policy Set

- Prioritized policy
  - From extreme conditions to normal operations
- Gradually remove the degrees of freedom from the solution with each priority



Optimization Statements

- Policy Constraints
- Objective Functions
- Reuses RiverWare Rule Language
- Functions
  - Encapsulate details
  - Reusable



Goal Programming Objectives

- Minimize or Maximize a function (e.g. power)
- Derived Objectives: Minimize violations of soft constraints
  - Summation – minimize total deviations
    - May be uneven, but total minimized
  - MiniMax – minimize the largest violation
    - May increase total deviations, but balanced
  - Repeated MiniMax
    - Continue after minimizing largest violation
    - Most common in practice

Hydropower Objective

- Pre-defined components
  - Links to reservoirs to calculate system totals
  - Optionally incorporates outside power
  - Optionally include pumped storage
- Short-term value of power alternatives
  - Linear – aka System Lambda, One price per period
  - Block – Decreasing value with increasing system generation
  - Thermal: Combine hydro and thermal to meet load
  - Buy power to meet load (Under development)
- Long-term alternatives
  - Value of water in storage (piecewise linear)
  - Ending storage targets

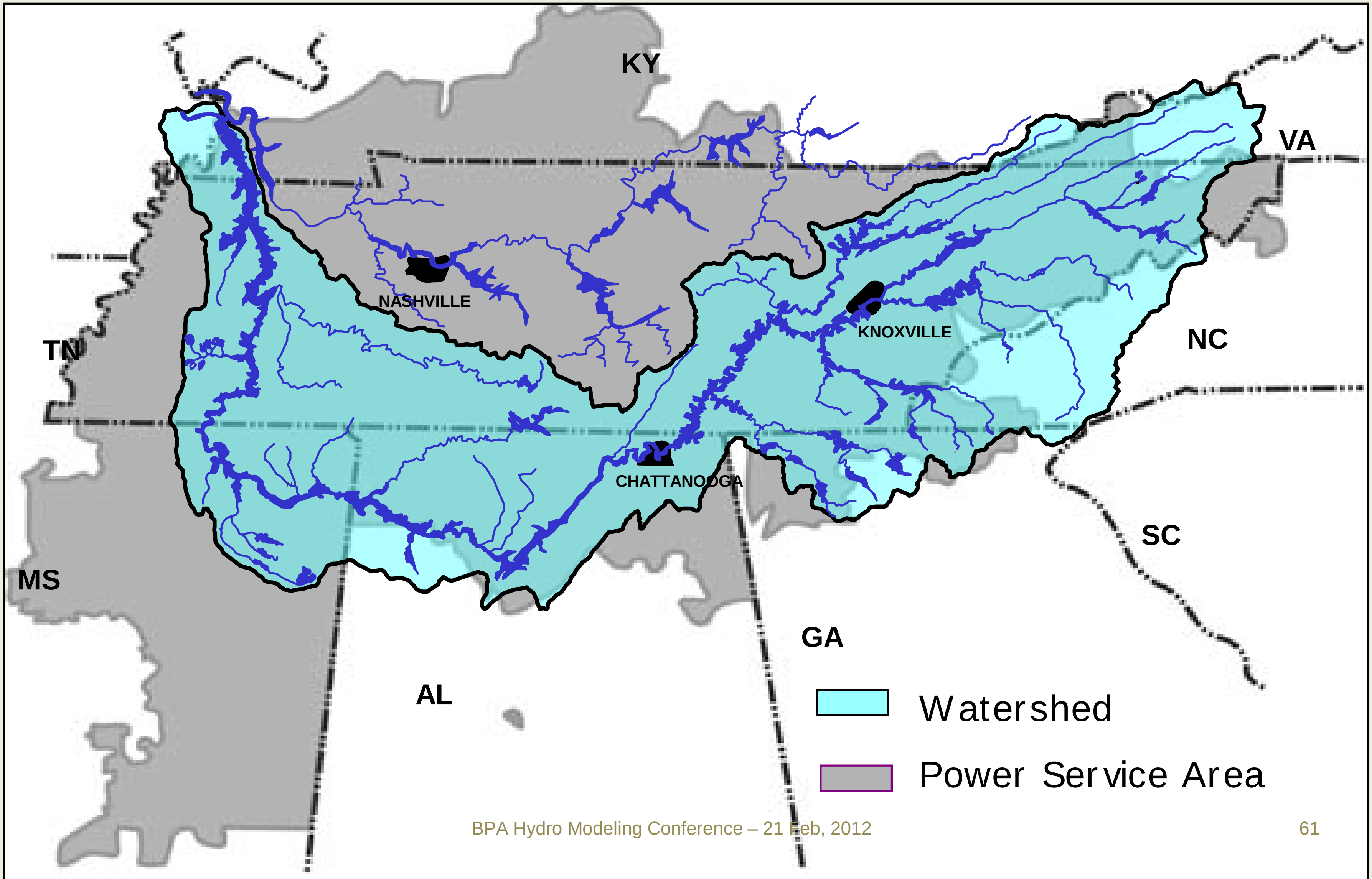
Ancillary Services
(under development)

- Regulation up, regulation down, Bidir. reg.
- Load Following
- Synchronous Condensing
- Non-spinning reserve
- Reactive power (designed, but postponed)
- Economics
  - Buy or Sell Services: Linear or Block Value
  - Cost of providing service

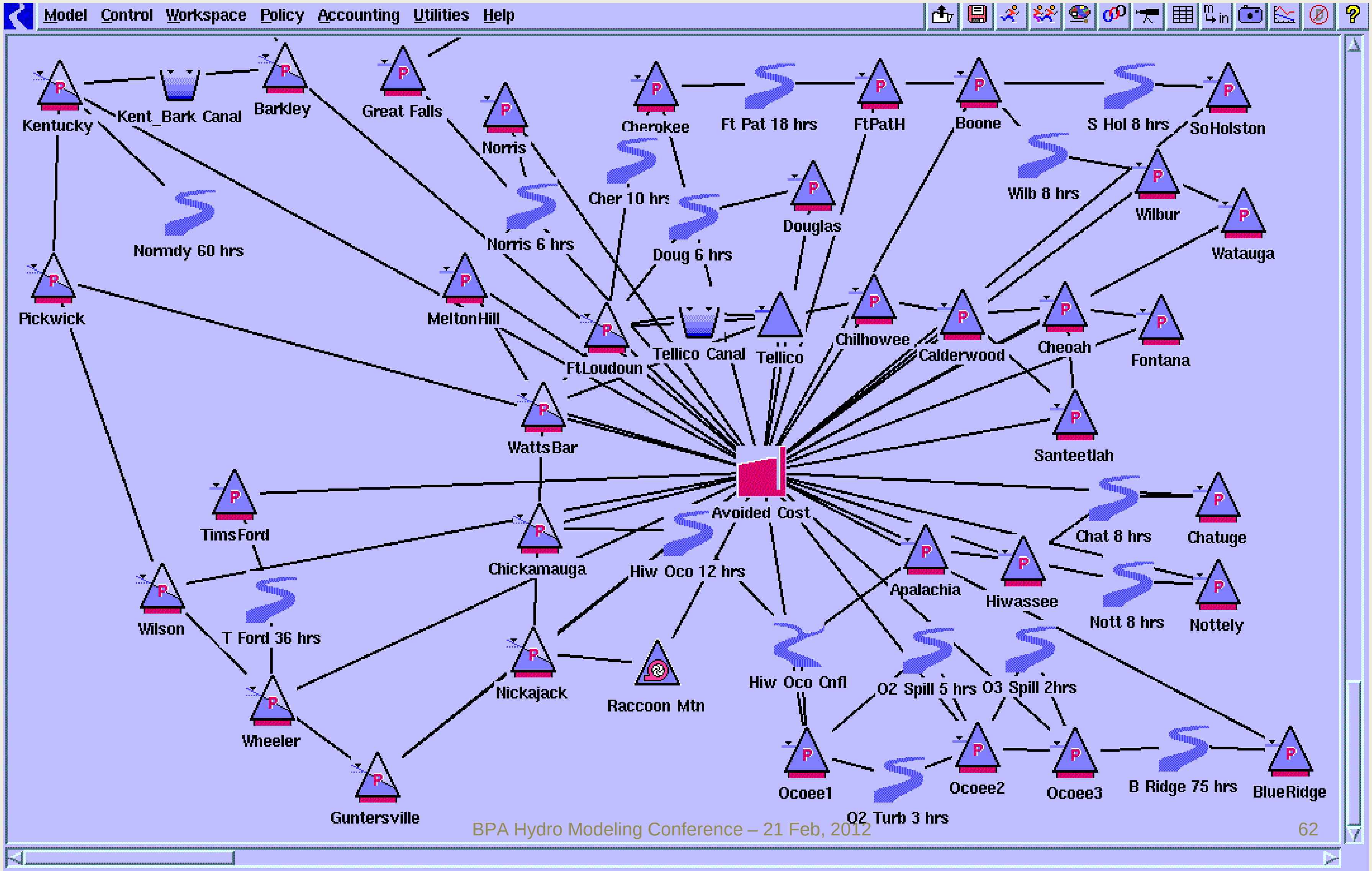
Recent Enhancement: User-Defined Variables

- Do-it-yourself RiverWare Enhancement
- Create Slots and Configure for each variable
- Add High Priority Constraints to Policy Set
  - Relate user variables to existing variables
- Add Real Policy at Natural Priority
- Add Post-Optimization Rule
- Example: Total Dissolved Gas

TVA in RiverWare



TVA in RiverWare



Multi-objective Policy for Multipurpose Res

Example – TVA

High Pri: Set some releases

Ending Targets (smaller res)

Operating Zones

Daily Release Volumes

Recreational Flows

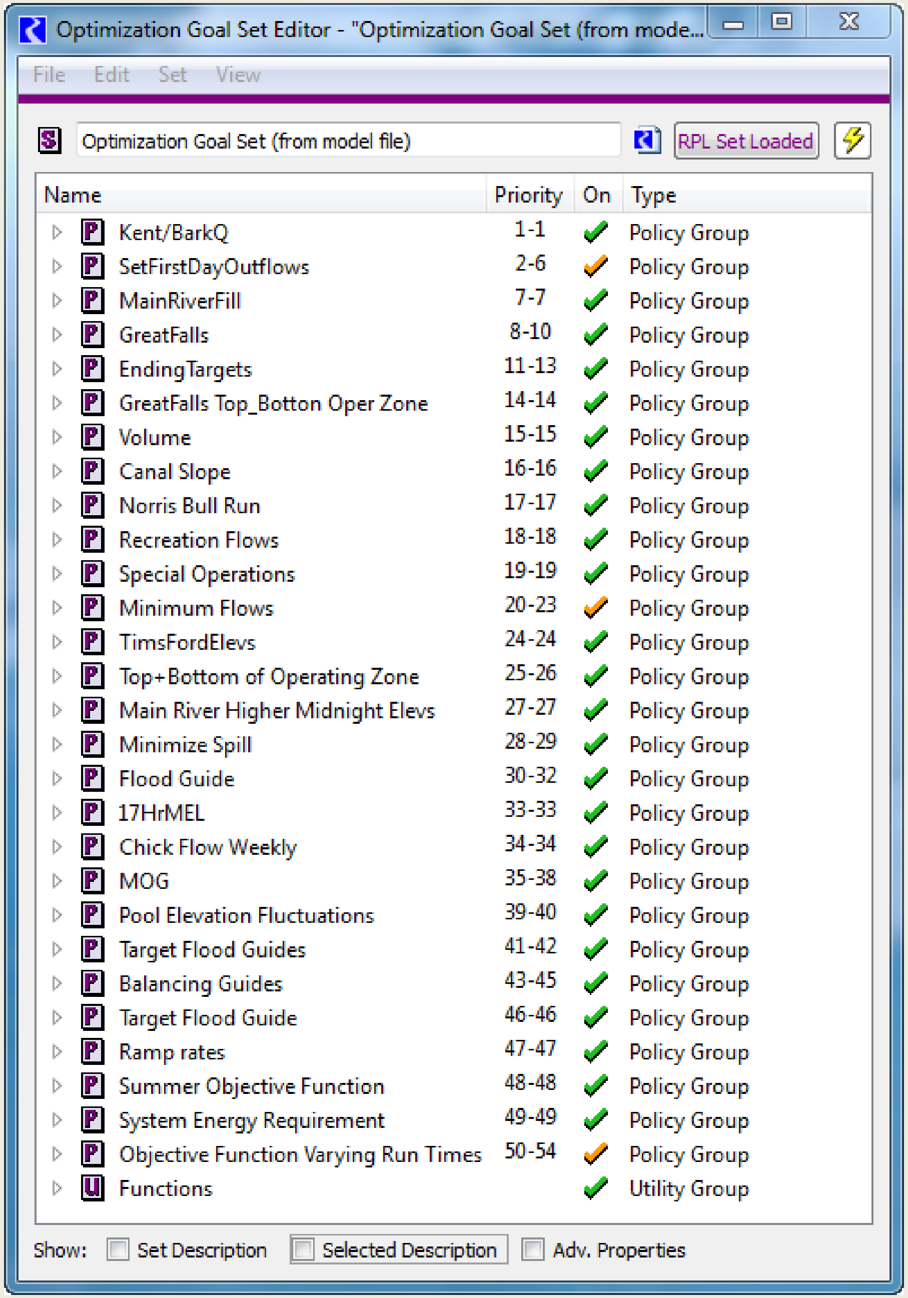
Special Operations

Seasonal Constraints

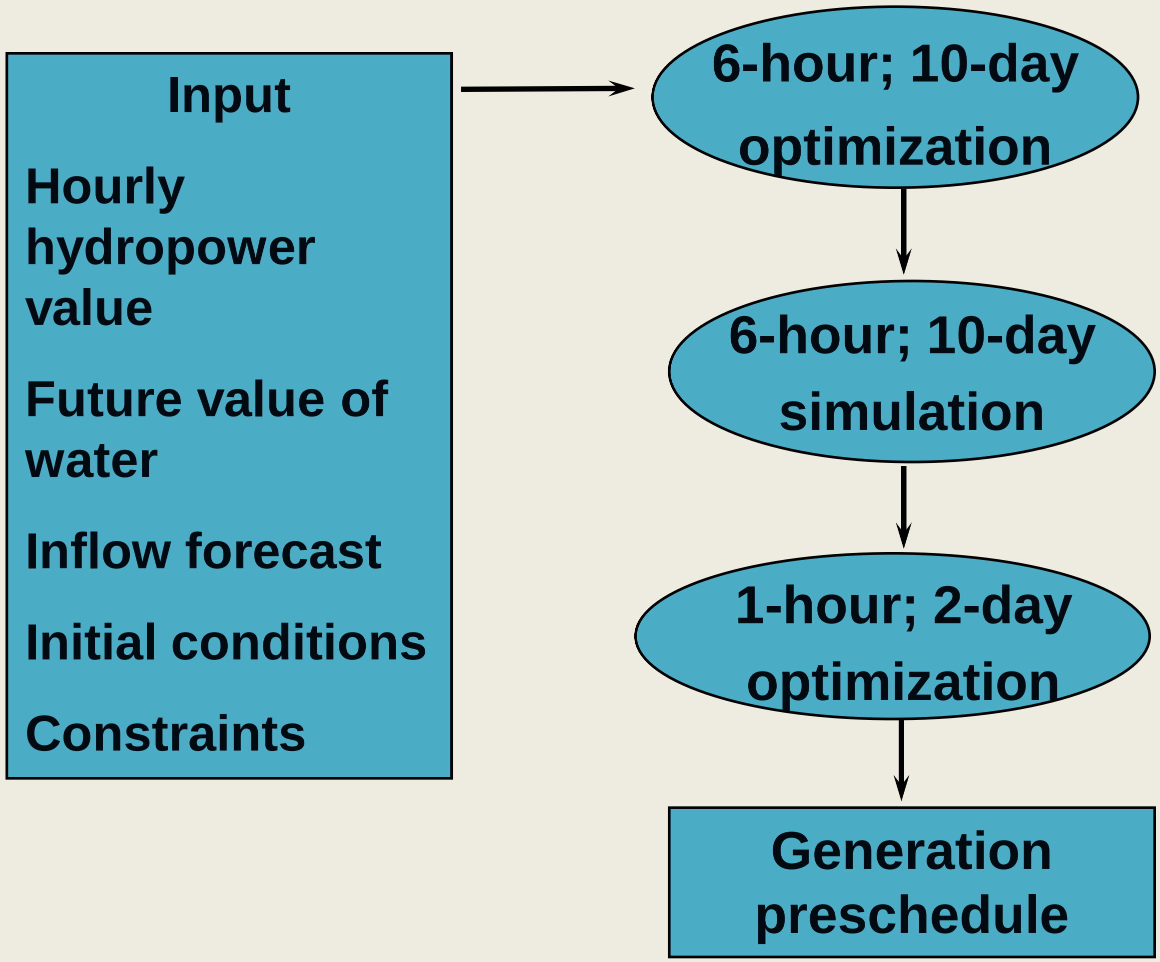
Minimum Flows & Avg Flows

Ramp rates and other Δ limits

Max Econ(Power) & Min Spill



Optimization process used in TVA's daily scheduling



RiverWare Application: Mid-Columbia Wind Integration

- Sponsor: Oak Ridge National Laboratory – Brennan Smith
- Principal Investigator: Edie Zagona, CADSWES
- Co-P.I.: Tim Magee, CADSWES
- Goal : Develop framework to evaluate impact of wind on hydro with realistic hydro model
- ORNL chose Mid-Columbia system
  - Highly-constrained system
  - High wind potential and existing wind
  - Willing participation from Mid-C utilities
- CADSWES developed Mid-C model and framework
  - Meetings with ORNL and Mid-C utilities to obtain physical and policy info and model validation

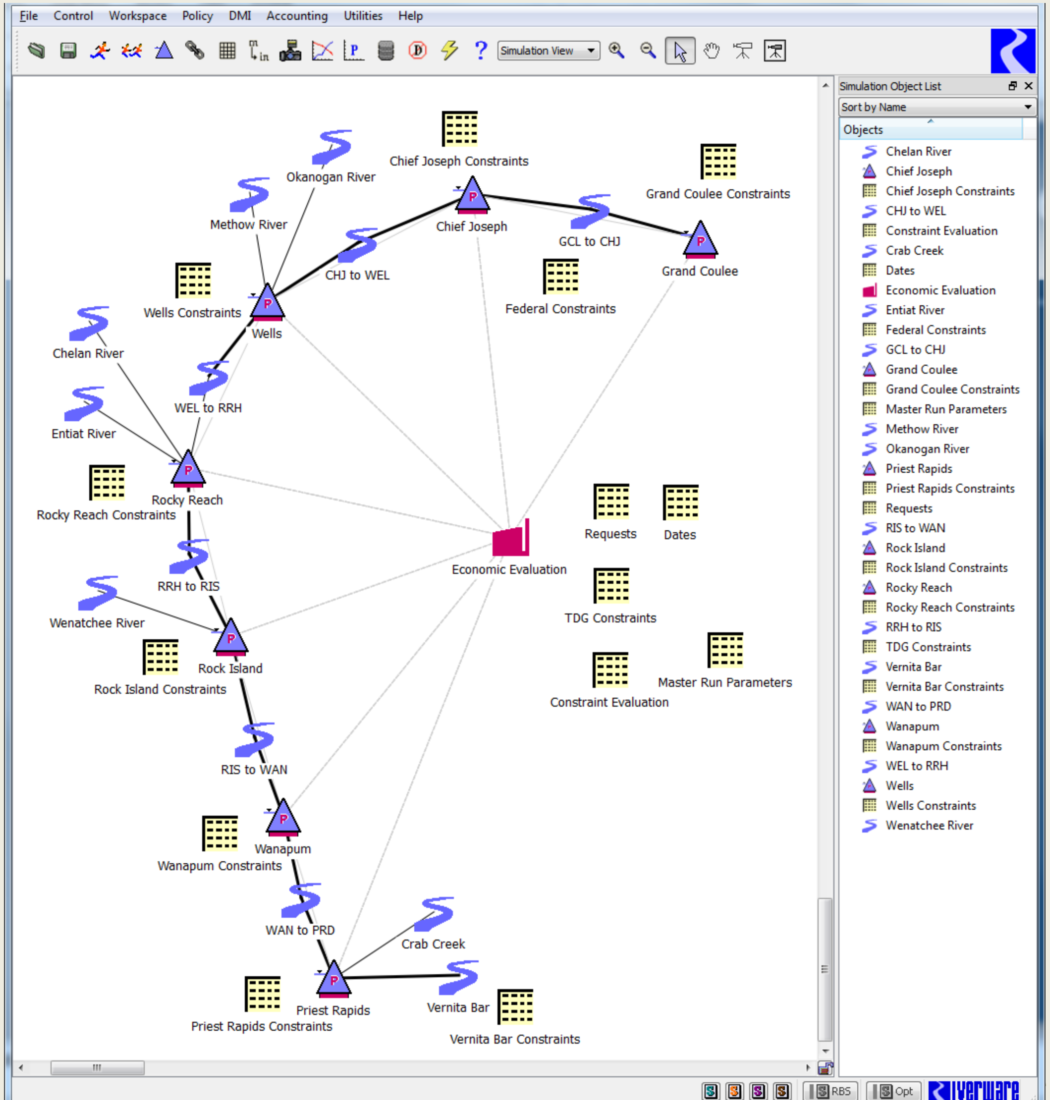
Mid-Columbia Hydro System

- 2 Federal projects
  - Grand Coulee – USBR
  - Chief Joseph - USACE
- 5 Non-fed projects
  - Local PUDs
  - Shares owned by participants
- Little storage – ROR downstream of Grand Coulee

System Overview – Policy and Constraints

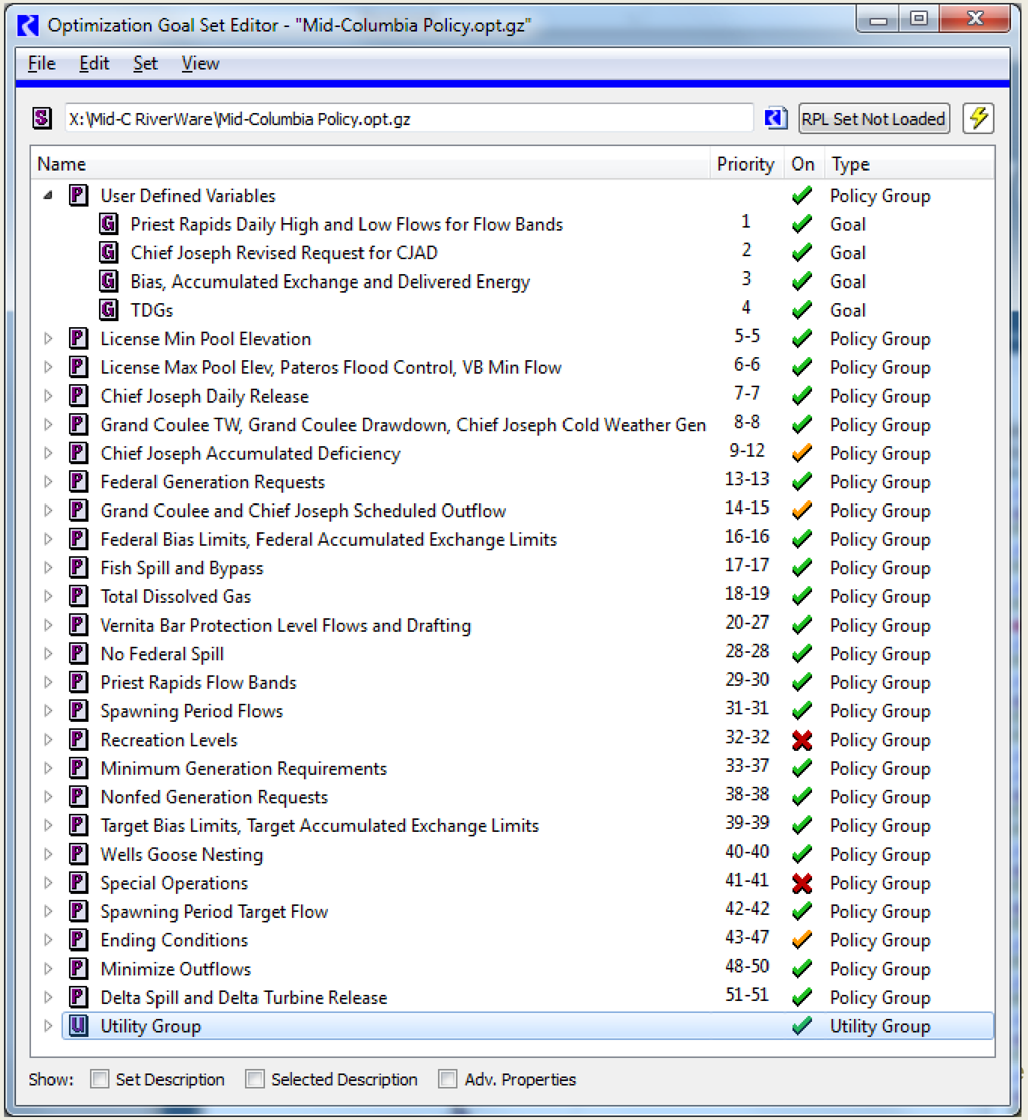
- Major Agreements Affecting Operations
  - Columbia River Treaty
  - Hanford Reach Fall Chinook Protection Program
  - Mid-Columbia Hourly Coordination Agreement
    - Coordinated scheduling of non-fed projects by Central
    - Non-feds (Central) coordinate with federal projects through bias
- Significant Environmental Constraints
  - Vernita Bar min/max flows – seasonal
  - Minimum spill for fish passage – Non-fed projects
  - Max total dissolved gas levels – limits spill

Mid-Columbia RiverWare Model



- Plant power tables based on unit data from Mid-C utilities and BPA
- Stage-flow-tailwater tables
  - Fed – equations from BPA
  - Nonfed – tables and curves from utilities or regression from observed data
- Storage and routing from Hourly Coordination Manual
- 6 tributaries included

Mid-Columbia RiverWare Model - Policy

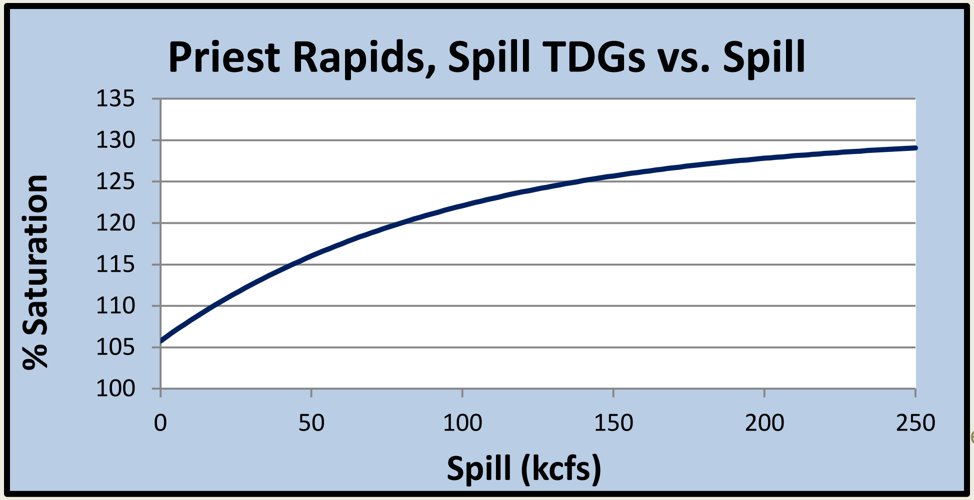


Name	Priority	On	Type
User Defined Variables		✓	Policy Group
Priest Rapids Daily High and Low Flows for Flow Bands	1	✓	Goal
Chief Joseph Revised Request for CJAD	2	✓	Goal
Bias, Accumulated Exchange and Delivered Energy	3	✓	Goal
TDGs	4	✓	Goal
License Min Pool Elevation	5-5	✓	Policy Group
License Max Pool Elev, Pateros Flood Control, VB Min Flow	6-6	✓	Policy Group
Chief Joseph Daily Release	7-7	✓	Policy Group
Grand Coulee TW, Grand Coulee Drawdown, Chief Joseph Cold Weather Gen	8-8	✓	Policy Group
Chief Joseph Accumulated Deficiency	9-12	✓	Policy Group
Federal Generation Requests	13-13	✓	Policy Group
Grand Coulee and Chief Joseph Scheduled Outflow	14-15	✓	Policy Group
Federal Bias Limits, Federal Accumulated Exchange Limits	16-16	✓	Policy Group
Fish Spill and Bypass	17-17	✓	Policy Group
Total Dissolved Gas	18-19	✓	Policy Group
Vernita Bar Protection Level Flows and Drafting	20-27	✓	Policy Group
No Federal Spill	28-28	✓	Policy Group
Priest Rapids Flow Bands	29-30	✓	Policy Group
Spawning Period Flows	31-31	✓	Policy Group
Recreation Levels	32-32	✗	Policy Group
Minimum Generation Requirements	33-37	✓	Policy Group
Nonfed Generation Requests	38-38	✓	Policy Group
Target Bias Limits, Target Accumulated Exchange Limits	39-39	✓	Policy Group
Wells Goose Nesting	40-40	✓	Policy Group
Special Operations	41-41	✗	Policy Group
Spawning Period Target Flow	42-42	✓	Policy Group
Ending Conditions	43-47	✓	Policy Group
Minimize Outflows	48-50	✓	Policy Group
Delta Spill and Delta Turbine Release	51-51	✓	Policy Group
Utility Group		✓	Utility Group

- Federal project constraints at higher priorities
  - Non-fed perspective
- Non-fed power constraints below nearly all environmental constraints
- Complex tracking of drafting and refill when meeting flow constraints
- Objectives balance accumulated exchange (bias) targets with maintaining max water

Total Dissolved Gas Modeling

- High TDG levels (nitrogen) cause gas bubble disease – high fish mortality
- Effectively limits spill – controlling constraint in high flow seasons
- Data and equations from existing models
  - Columbia River Salmon Passage (CRiSP) Model– University of Washington
  - SYSTDG – USACE Northwest Division



- $C_{Spill} = b - a\, e^{-kQ_{Spill}}$

Total Dissolved Gas Modeling

- Entrainment – a fraction of turbine release has same concentration as spill
- Compounding effect in cascading reservoir system

$$C_M = \frac{C_S(Q_S + Q_E) + C_{FB}\,(Q_T - Q_E)}{Q_S + Q_T}$$

- Nonlinear
- Non-separable
- Non-convex – cannot use piecewise linearization for optimization, potential local optima

Total Dissolved Gas Modeling

In Mid-Columbia RiverWare Model:

- $C_M = C_{M,Est} + \Delta C_M$
- $\Delta C_M = \frac{\partial C_M}{\partial Q_S} \Delta Q_S + \frac{\partial C_M}{\partial Q_T} \Delta Q_T + \frac{\partial C_M}{\partial C_{FB}} \Delta C_{FB}$
- First Order Taylor Series Approximation
- Iterative procedure using RiverWare batch mode
  - Partial derivatives calculated pre-run with estimates from previous run – expression slots
  - DMIs export Q_S and Q_T then import as $Q_{S,Est}$ and $Q_{T,Est}$
  - Convergence criteria on ΔQ_S, ΔQ_T
- Modified successive linear goal programming provides a heuristic solution

Mid-Columbia Wind Integration Modeling – General Framework

- Can be used with any wind model or wind level
- Wind incorporated as negative load
- Prevents "perfect forecast knowledge" effects
- One-week "Master" Run composed of 28 individual one-week runs
  - Hours 1-6 use "actual" net load – no forecast error
  - Hours 7-168 use net load forecast – any forecast model
  - Save output from hours 1-6 and move ahead six hours for next individual run
  - Now hours 7-12 use actual net load, updated forecast for hours 13-174; repeat for all 28 six-hour blocks
  - Master run outputs from first six hours of each individual run

Mid-Columbia Wind Integration Modeling – General Framework

- RiverWare batch mode script steps through all 28 individual runs with automated importing and exporting of data
- Metrics of system performance:
  - Constraint satisfaction – calculations from optimization goal set repeated in expression slots to evaluate degree of constraint violations
  - Spill as energy – not all spill is equal
  - Energy in storage – accounts for generation potential from all downstream projects
- General framework tested with synthetic wind scenario

Current Hydro-Wind Integration Research

- Funded by Hydro Research Foundation Fellowship
- Extend components of the Mid-Columbia project methodology
  - Realistic policy constraints
  - System metrics
  - Updating of wind and load forecasts
- Includes explicit economic objective
  - Constrained to meet local load and reserve requirements as well as non-power constraints
  - Additional generation and reserve capacity can be sold into energy and ancillary services markets
- Incorporate pumped storage
- Apply to hydro systems with varied characteristics

Current Hydro-Wind Integration Research – Modeling Methodology

- One-week scheduling run – schedules next 24 hours
  - Wind, load and hydrology forecasts
  - Sets energy and ancillary service bids into day-ahead market
  - Sets target pool elevations
- Followed by 24-hour operations run
  - Net Load from "actual" local load and wind plus day-ahead energy bid
  - Reserve requirements from scheduling run
  - "Real-time" energy market
- Objective:

$$Maximize \sum \begin{array}{c} Energy\,Value + Ancillary\,Services\,Value \\ -Value\ of\ Water\ Used \end{array}$$

- All non-power policy constraints apply

Current Hydro-Wind Integration Research – Impacts to Evaluate

- Ability to meet all non-power and power constraints
  - Policy/environmental constraints
  - Meet scheduled load
  - Maintain sufficient reserves
- System performance metrics
  - Spill as energy
  - Energy in storage
  - Modified capacity factor over various time horizons – flexibility
  - Reserve capacity
  - Ramping patterns
- Opportunity cost
  - Reduced energy bids into market
  - Reduced ancillary services bids into market