http://users.owt.com/chubbard/gcdam/highres/dam08.jpg

http://www.kpbs.org/photos/2010/apr/16/4329/

Optimized Hydropower with Integrated Wind Generation on the Mid-Columbia River

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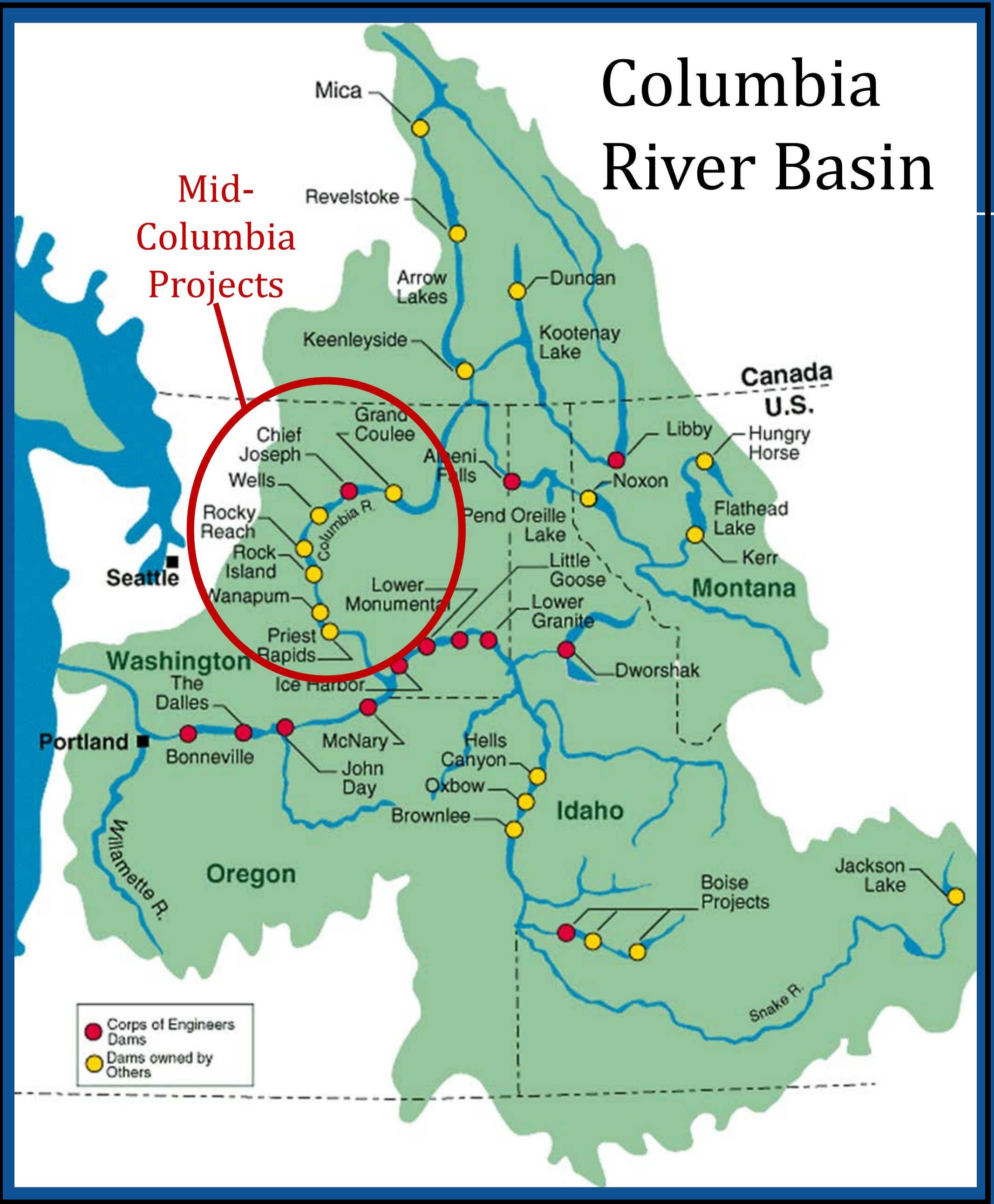
RiverWare User Group Meeting, February 1, 2012

Project Overview

- 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



http://www.nwd-wc.usace.army.mil/report/colmap.htm

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

System Overview – Policy and Constraints

- Major Agreements Affecting Operations
  - Columbia River Treaty

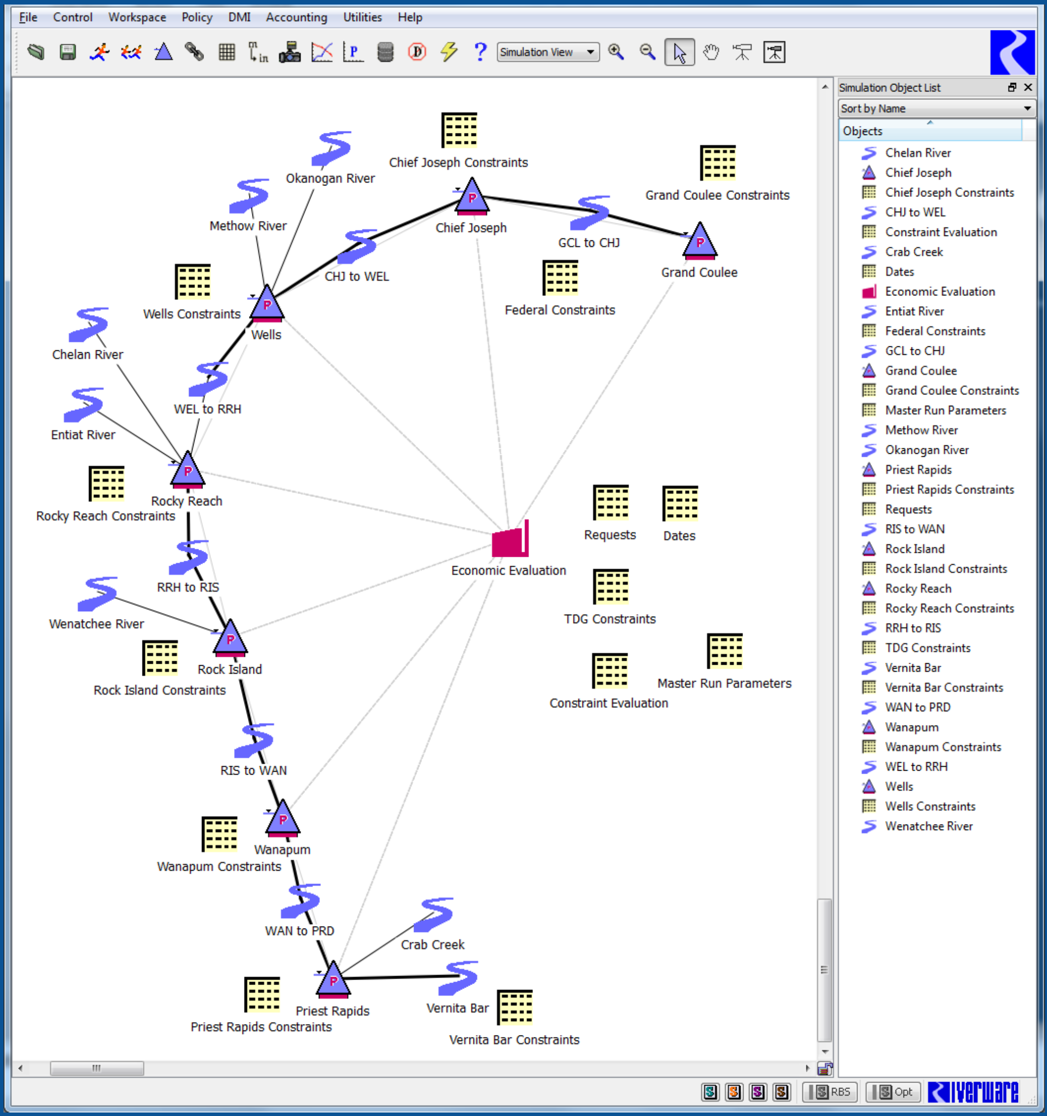
    - Canada provides flood control; U.S. provides power in exchange
  - Hanford Reach Fall Chinook Protection Program
  - Mid-Columbia Hourly Coordination Agreement

    - Coordinated scheduling of non-fed projects by Central

    - Non-feds (Central) coordinate with federal projects through bias

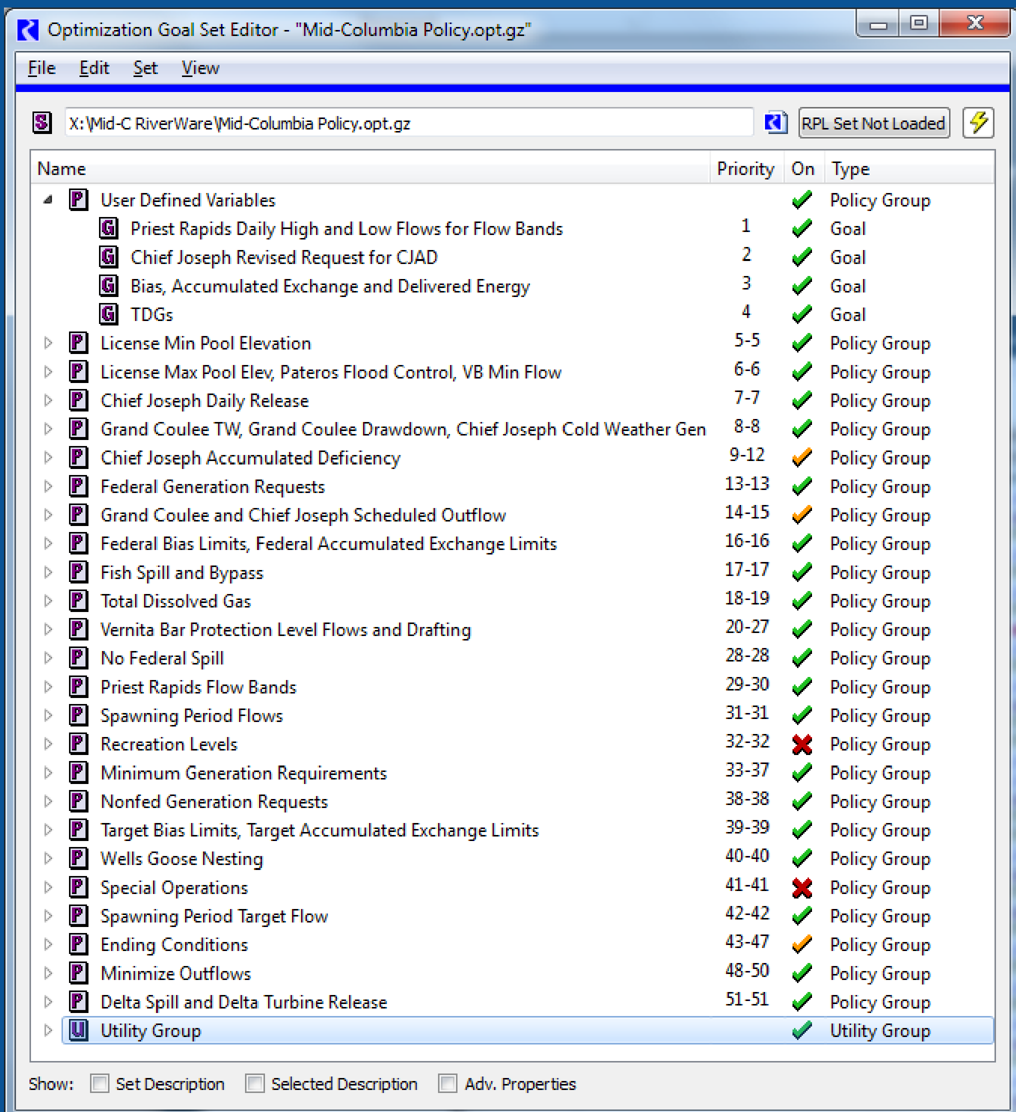
- Significant Environmental Constraints
  - Vernita Bar min/max flows – seasonal
  - Minimum spill for fish passage – Non-fed projects
  - Max total dissolved gas levels – limits spill

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

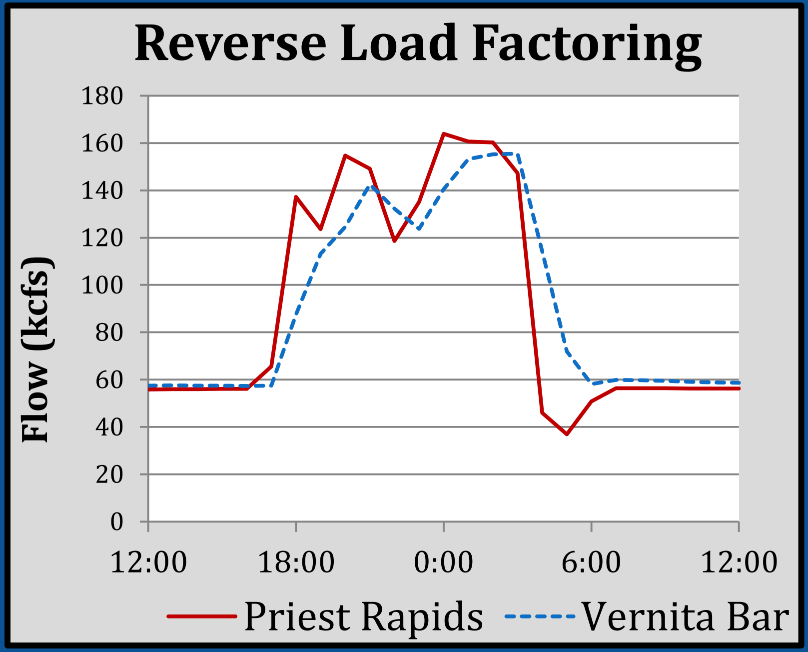
Mid-Columbia RiverWare Model - Policy



- 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

RiverWare Enhancement – Autoregressive Outflow Adjustment for Reaches

- Motivation: Flow constraints at Vernita Bar during salmon spawning season
  - Reverse Load Factoring – high Priest Rapids outflows at night to prepare for low max flow during daylight hours
  - Delayed response at Vernita Bar described as something like bank storage



- Multiple linear regression using only Priest Rapids outflow from previous time steps was unsatisfactory
- Regression using routed Priest Rapids outflow and Vernita Bar flow from previous hour fit data well

RiverWare Enhancement – Autoregressive Outflow Adjustment for Reaches

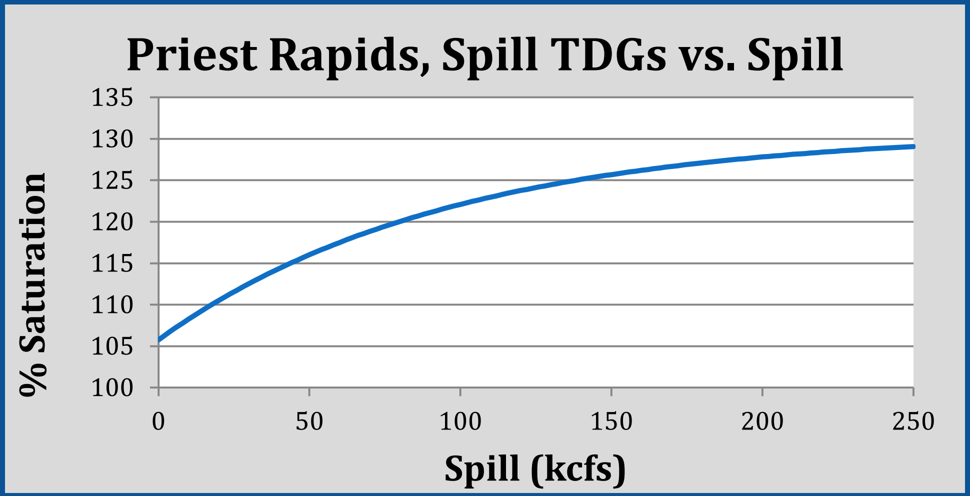
- Autoregressive Outflow method in Outflow Adjustment category

$$Reach.Outflow_t = B_1 Routed\ Flow_t + B_2 Reach.Outflow_{t-1} + B_3 Reach.Outflow_{t-2} + \ldots + B_N Reach.Outflow_{t-N+1}$$

- RiverWare first calculates Routed Flow (any routing method) then applies weighted average using Reach Outflow from any number of previous time steps – autoregressive terms
- User sets the weighting coefficients

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

Wind Integration Modeling – General Framework

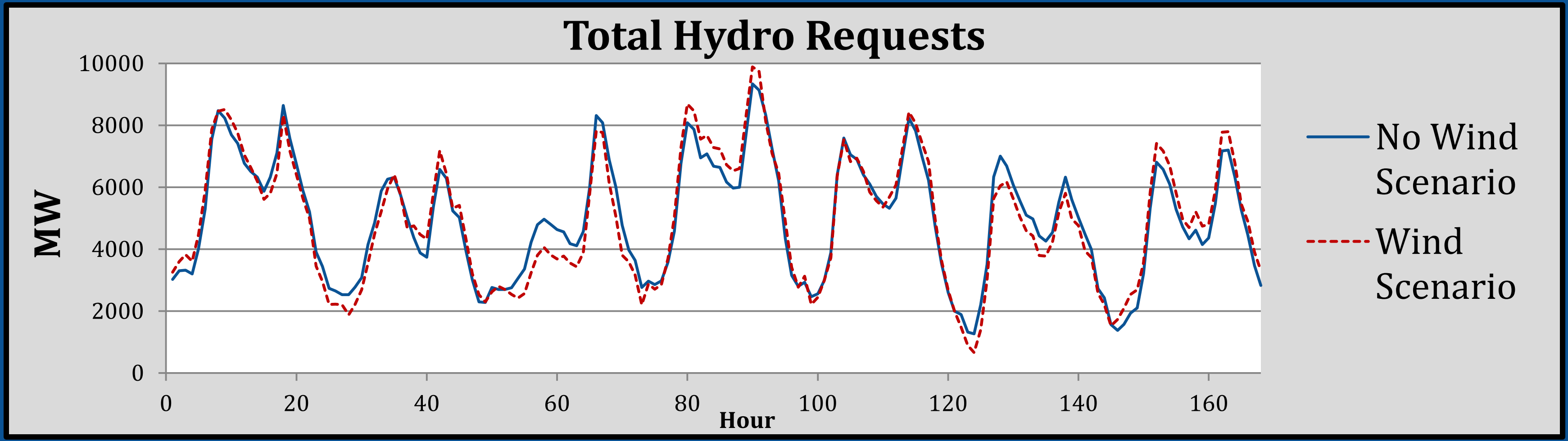
- Can be used with any wind model or wind level
- Wind incorporated as negative load
- Prevents "perfect forecast knowledge" effects
- One-week "Master" Run composed of 28 individual one-week runs
  - Hours 1-6 use "actual" net load – no forecast error
  - Hours 7-168 use net load forecast – any forecast 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

Wind Integration Modeling – General Framework

- Batch mode script steps through all 28 individual runs
  - Automated import and export of data by DMIs
  - Incorporates iterative TDG routine
- 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

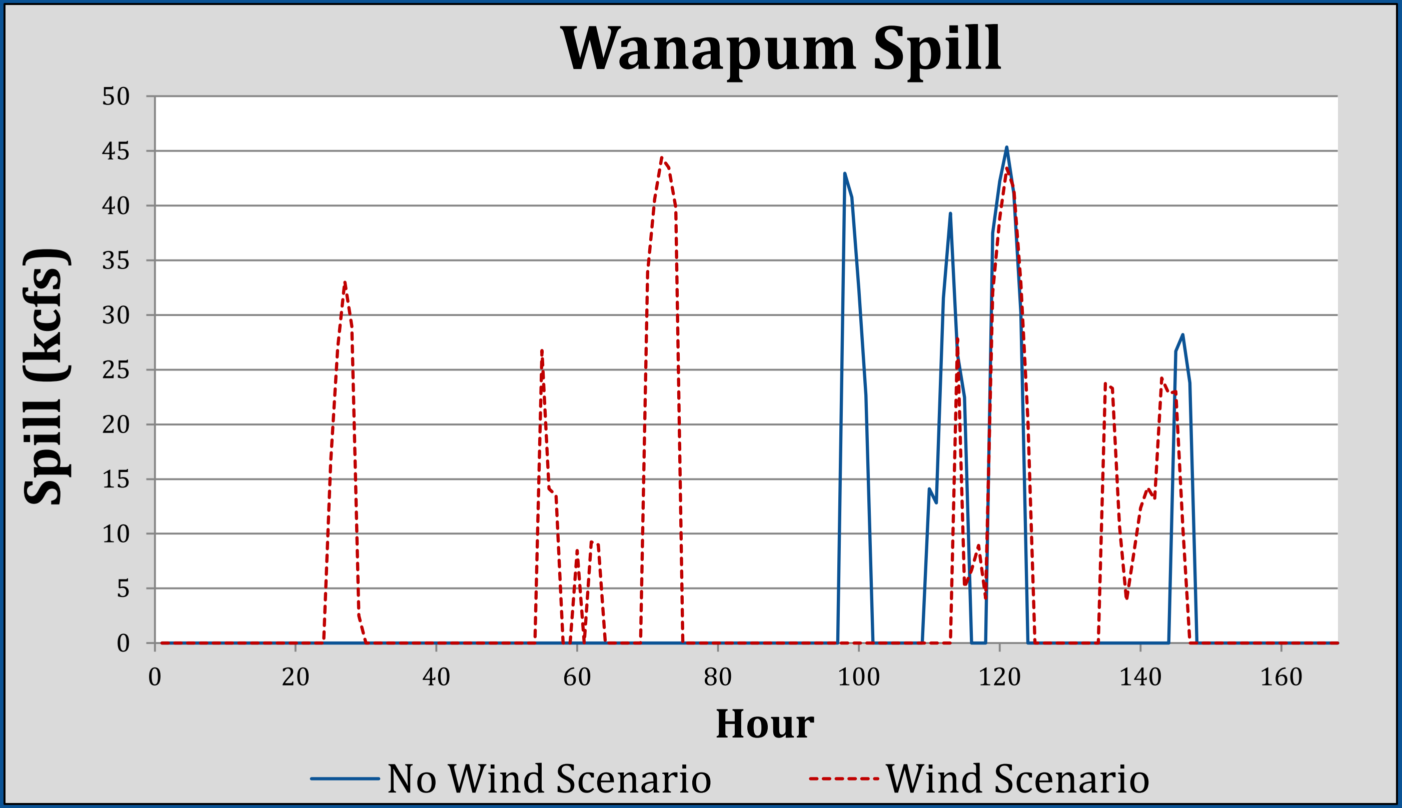
Wind Integration Modeling – Synthetic Wind Model for Testing

- Wind = f(previous wind, avg profile, random var)
  - Daily profile based on observed BPA wind, scaled
- Wind forecast weighted to previous wind for short lead time, tends to average profile for longer lead times
- Assumes wind displaces constant thermal source
  - Total hydro generation approximately equal



Wind Integration Modeling – Sample Results

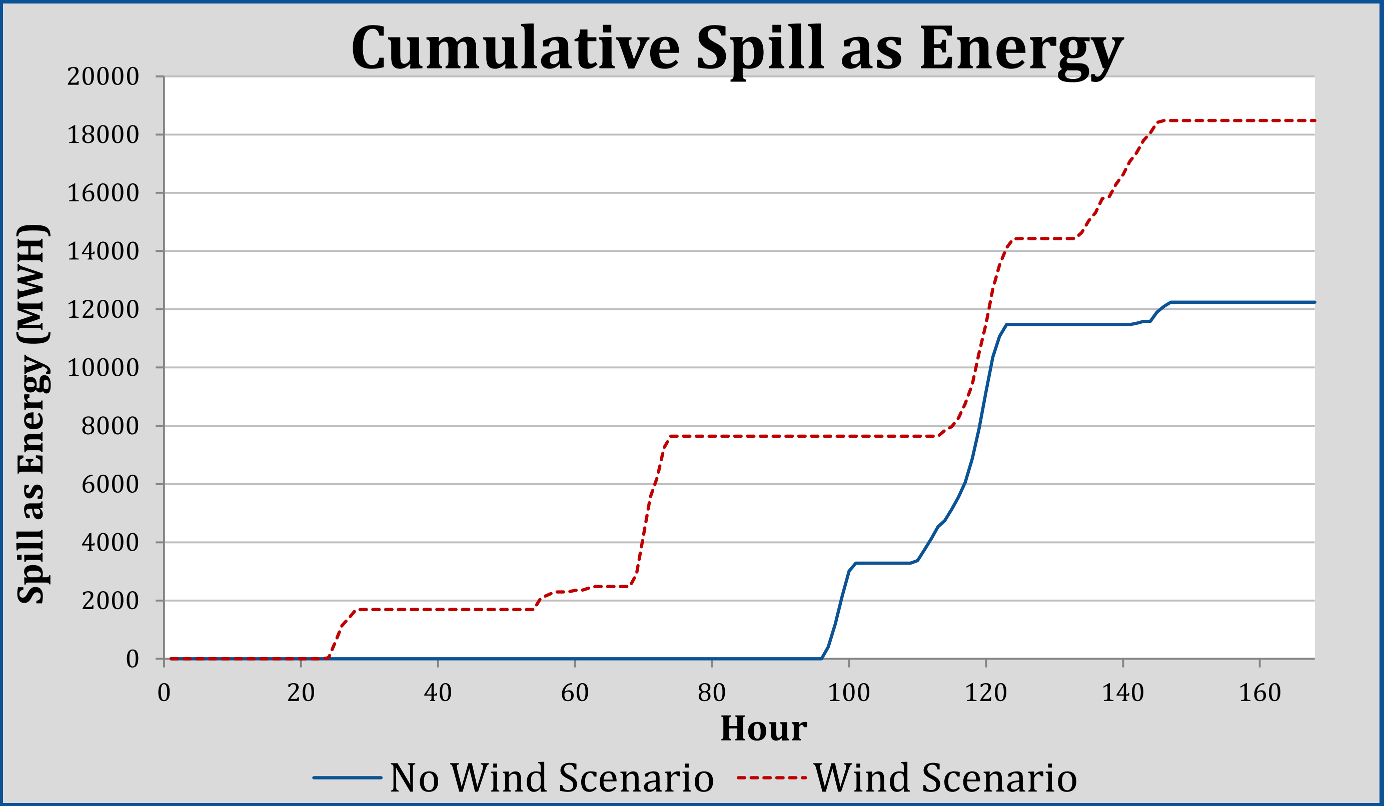
- Spill time series - increase in spill events for the wind scenario



*Sample results are for demonstration of the methodology only. They are not based on a validated wind scenario and should not be used to draw conclusions about the impacts of wind integration

Wind Integration Modeling – Sample Results

- Increased spill leads to higher spill as energy



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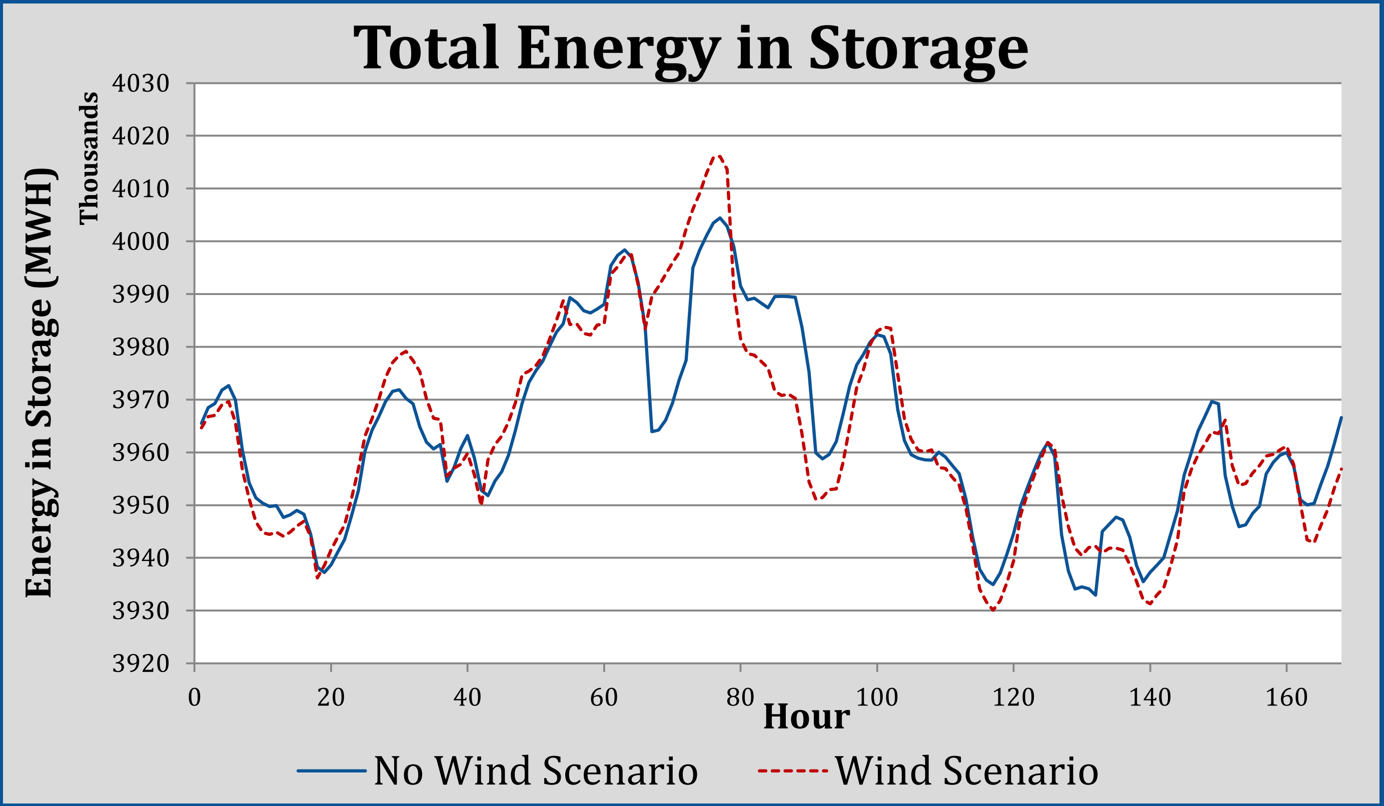
Wind Integration Modeling – Sample Results

- Differences in energy in storage



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Project Accomplishments

- Realistic model of Mid-Columbia system, including non-power constraints, to demonstrate effects of wind integration
- Incorporated TDG modeling in optimization
- Advancement in successive linear goal programming in RiverWare

Mid-Columbia Hydropower and Wind Integration

- Final report available

- Next steps:
  - Mid-Columbia Utilities putting model into operational use
  - Use of model and framework for additional studies
  - Extension of components of methodology to other systems, adding explicit economic objectives based on market prices for energy and ancillary services