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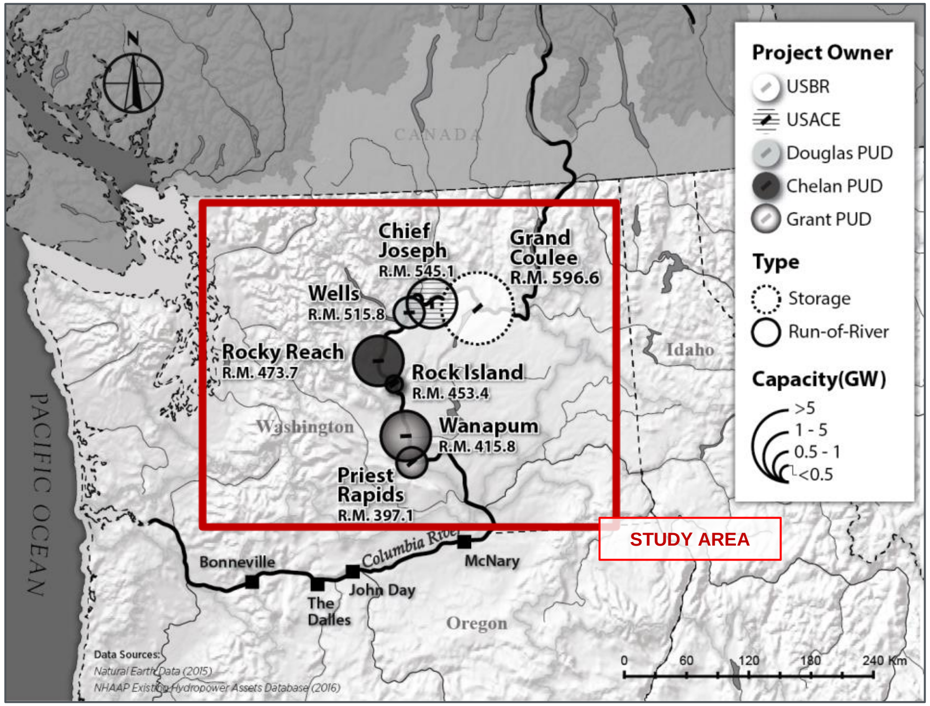
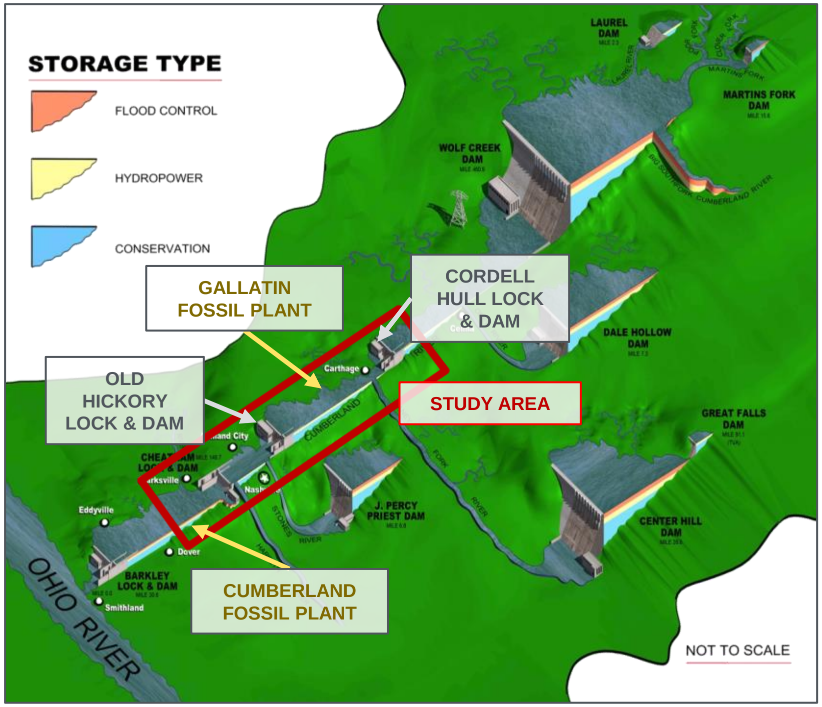


Columbia River Basin



Cumberland River Basin

Water Quality Modeling Improvements at Columbia and Cumberland River Basins

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Water Quality Modeling Improvements at Columbia and Cumberland River Basins:

The complexity of water quality dynamics cannot be currently represented in real-time hydropower dispatch systems. This project achieved implementation of the Total Dissolved Gas (TDG) implementation in real-time scheduling and the development of a model reduction technique to allow for real-time river system scheduling and optimization.

The Challenge:

Water quality scheduling advances are needed to enable hydropower operators to integrate real-time water quality dynamics into their optimization dispatch tools.

Partners:

Cumberland: Vanderbilt University, Lipscomb University, United States Army Corps of Engineers (USACE) Nashville District

Columbia: University of Iowa, Bureau of Reclamation, USACE Portland District, and Center for Advanced Design Support for Water and Environmental Systems (CADSWES), University of Colorado.

Next Generation Hydropower (HydroNEXT)

Optimization

- **Optimize technical, environmental, and water-use efficiency of existing fleet**
- Collect and disseminate data on new and existing assets
- Facilitate interagency collaboration to increase regulatory process efficiency
- Increase revenue streams for ancillary services

Growth

- Lower costs of hydropower components and civil works
- Increase power train efficiency for low-head, variable flow applications
- Facilitate mechanisms for testing and advancing new hydropower systems and components
- Reduce costs and deployment timelines of new PSH plants
- Prepare the incoming hydropower workforce

Sustainability

- Design new hydropower systems that minimize or avoid environmental impacts
- Support development of new fish passage technologies and approaches
- Develop technologies, tools, and strategies of evaluate and address environmental impacts
- Increase resilience to climate change

Next Generation Hydropower (HydroNEXT)

Optimization

- **Optimize technical, environmental, and water-use efficiency of existing fleet**
- Collect and disseminate data on new and existing assets
- Facilitate interagency collaboration to increase regulatory process efficiency
- Increase revenue streams for ancillary services

The Impacts

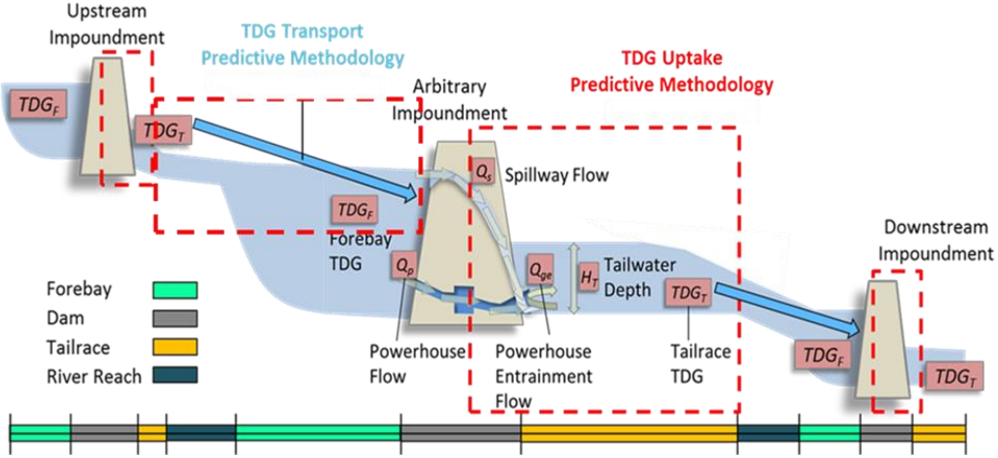
- Enhanced modeling tools to optimize hydropower operation scheduling and forecasting based on current and desired environmental conditions.
- TDG predictive equations and modeling capabilities in the real-time scheduling tool, RiverWare.
    - Optimized multi-objective system operations throughout the mid-Columbia River.
- Predictive equations that decrease computation time, increase accuracy, and improve co-optimization of energy and riverine water quality parameters.
    - Equations applied to the Cumberland River system for improved dissolved oxygen and temperature forecasting.

Technical Approach- Columbia

Columbia Technical Approach: develop a simplified physics-based mass-transfer model for total dissolved gas uptake and transport, to be implemented in Decision Support Systems (DSSs) and forecasting applications.

Methods:

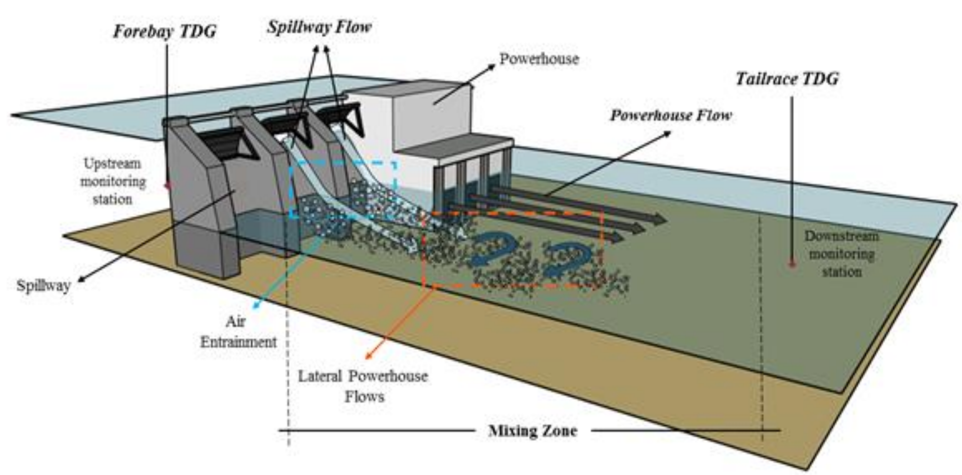
- Partitioned river system into uptake and transport regimes (see figure on top right)
- For uptake region, develop TDG representative equations based on physical processes of TDG production and mixing:
  - Air entrainment during spill in the tailrace
  - Air entrainment of powerhouse water into the spillway (see figure on bottom right)
- For TDG transport from upstream to downstream, analyze time lag of TDG plume between reservoirs



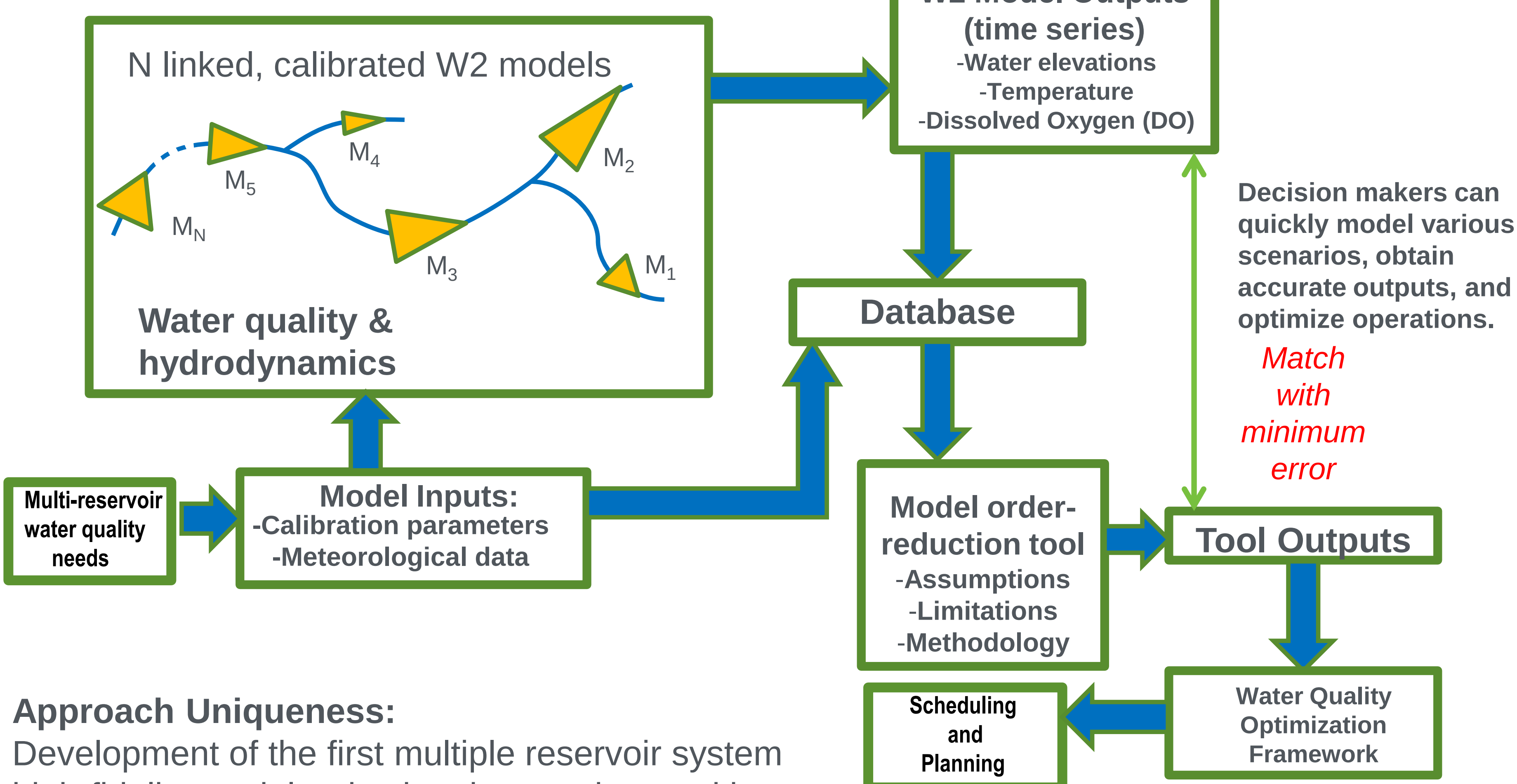
Approach Uniqueness:

- A simplified mathematical approach for complex river systems enables straight forward implementation in DSSs to reduce computation without a decrease in predictive accuracy.

- Unlike conventional TDG management techniques, this approach allows hydropower schedulers to quickly and accurately simulate multiple operational scenarios to minimize real-time and future TDG levels and meet hydropower reservoir multi objective targets.



Cumberland Model Overview



Approach Uniqueness:
Development of the first multiple reservoir system high-fidelity model reduction that can be used in operational scheduling, planning, and decision making.

Technical Approach- Cumberland

Mathematical Formulation and Analysis

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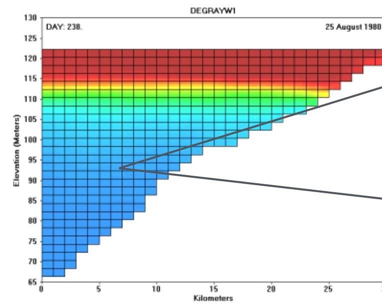
CE-QUAL-W2 Governing Equations:

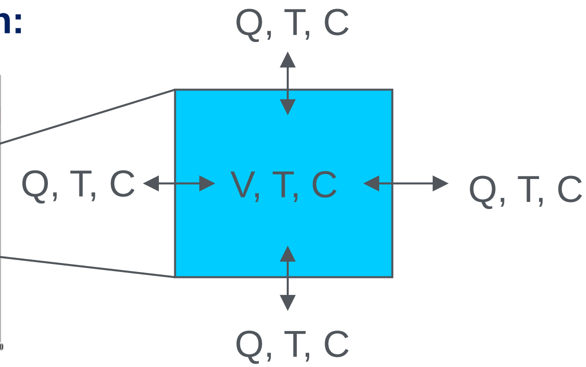
Equation	Governing equation assuming an arbitrary channel slope and conservation of momentum at branch intersections
x- momentum	$\frac{\partial UB}{\partial t} + \frac{\partial UUB}{\partial x} + \frac{\partial WUB}{\partial z} = gB \sin\alpha + g\cos\alpha B \frac{\partial \eta}{\partial x} - \frac{g\cos\alpha B}{\rho}\int_{\eta}^{z}\frac{\partial \rho}{\partial x}dz + \frac{1}{\rho}\frac{\partial B\tau_{xx}}{\partial x} + \frac{1}{\rho}\frac{\partial B\tau_{xz}}{\partial z} + qBU_x$
z-momentum	$0 = g\cos\alpha - \frac{1}{\rho}\frac{\partial P}{\partial z}$
continuity	$\frac{\partial UB}{\partial x} + \frac{\partial WB}{\partial z} = qB$
state	$\rho = f(T_w, \Phi_{TDS}, \Phi_{ss})$
free surface	$B_\eta \frac{\partial \eta}{\partial t} = \frac{\partial}{\partial x}\int_{\eta}^{h} UBdz - \int_{\eta}^{h} qBdz$

CE-QUAL-W2 is a high fidelity hydrodynamic and water quality modeling tool

Solved Numerically

CE-QUAL-W2 Solution:

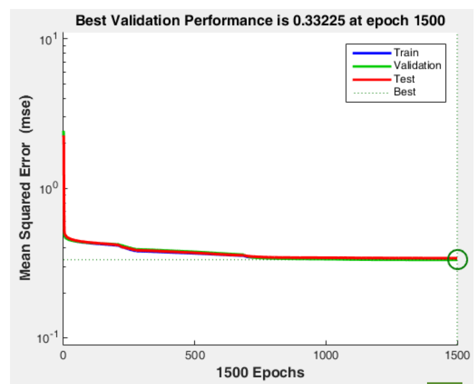


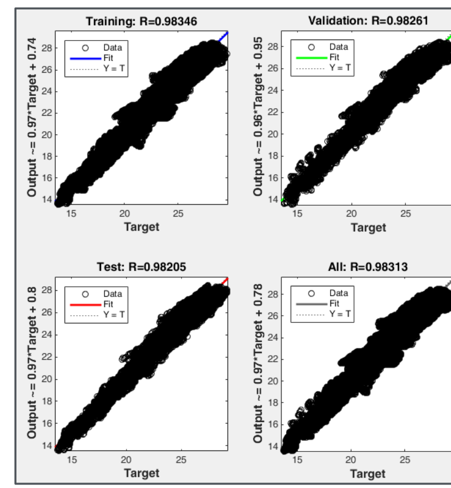


Simulation Model (CE-QUAL-W2) → **10-15 minutes**

Inputs and Solutions from Collection of CE-QUAL-W2 Runs

Train Artificial Neural Network:





Surrogate Model (ANN) → **1-2 seconds**

Surrogate Model for Future Prediction

Accomplishments and Progress- Cumberland

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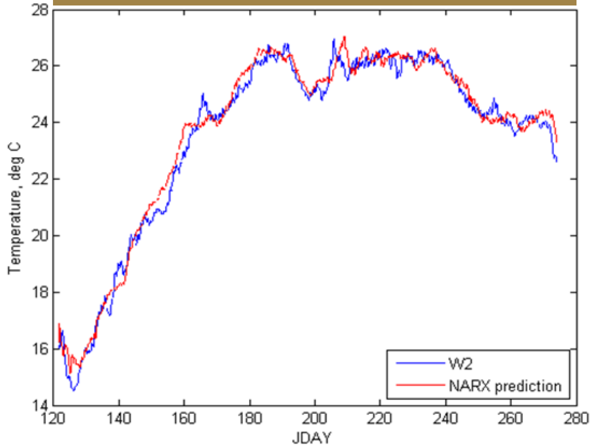
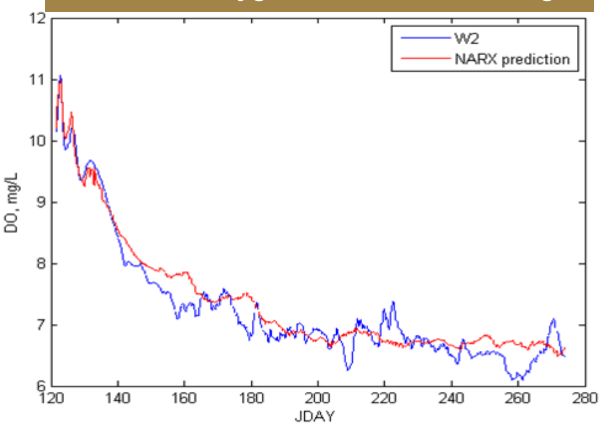
Surrogate Model Results: Temperature & DO

Temperature at Turbine Discharge

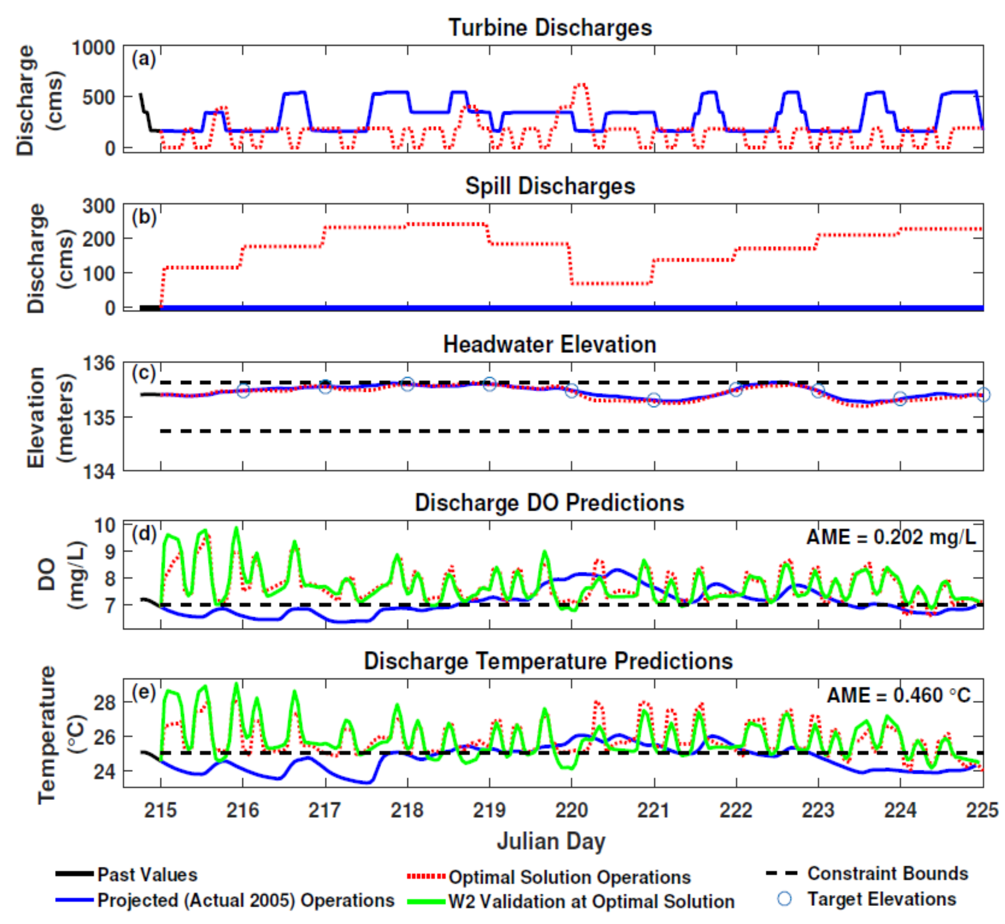


Dissolved Oxygen at Turbine Discharge



Model outputs show the difference between W2 (original water quality model) and a neural network model NARX (nonlinear autoregressive network with exogenous inputs).

Operating Period Optimization Results



Optimization over the 10-day scheduling cycle gives the operator/agency the best possible schedule to maximize generation while meeting all the water quality and operational constraints.

Accomplishments and Progress

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Columbia Project

- Derivation, calibration, and validation of TDG uptake equations (2015)
- Presentation at HydroVision Conference in Environmental/Social Track (2015)
- Technical Paper of the Year (3rd Place) at HydroVision Conference (2015)
- Technical paper published in HydroReview (2015)
- Journal technical article accepted for publication in the American Society of Civil Engineers (ASCE) Journal of Hydraulic Engineering (2016)
- Incorporation of TDG equations into RiverWare (2016)
- Developed methodology for TDG transport (2016)
- Submitted technical article to ASCE Journal of Water Resources Planning and Management (2016)
- ORNL Postdoc Research Symposium Poster Award (3rd Place) (2016)
- Technical note in preparation for Journal of Environmental Engineering (2016 planned submission)

Cumberland Project

- Technical paper and poster presented at HydroVision Conference (2014, 2015, and 2016)
- Website completed (2015)
- Discussions with USACE to implement software/website (2015)
- Completed optimization for one reservoir with USACE (2016)
- Journal article submitted (2016)

Water Quality Modeling Improvements Columbia and Cumberland River Basins

	FY2014				FY2015				FY2016			
	Q1(OCT-Dec)	Q2(Jan-Mar.)	Q3(Apr-June)	Q4(Jul-Sep)	Q1(OCT-Dec)	Q2(Jan-Mar.)	Q3(Apr-June)	Q4(Jul-Sep)	Q1(OCT-Dec)	Q2(Jan-Mar.)	Q3(Apr-June)	Q4(Jul-Sep)
Milestones / Deliverables												
Cumberland River Basin: ORNL will development of objective functions and model constraints in conjunction with system operators (users) and stakeholders	■											
Columbia River Basin: ORNL will provide a Total Dissolved Gas (TDG) equation development report that includes a summary of the literature review, supporting documentation, and references will be delivered for each module.		■										
Cumberland River Basin: ORNL will report on the collaboration with Vanderbilt to Validate reduced model system for the Cumberland River Cordell Hull reservoir.			■									
Cumberland River Basin: ORNL will provide prototype system for the Cumberland River Cordell Hull to U.S. Army Corps of Engineers Nashville District Water Management and Hydropower Operations. Columbia River System: ORNL and Iowa will prepare a procedure for the need and implementation of the developed TDG predictive equations in the optimization scheduling model for the Mid-Columbia River. Investigate the coupling of the generalized empirical TDG module to existing water operational models and document selected model incorporation challenges.				■								
Provide prototype system for Old Hickory to U.S. Army Corps of Engineers Nashville District Water Management and Hydropower Operations personnel.					■							
Mid-Columbia: Acquire modeling mathematical formulations for the simplified and the comprehensive TDG model documents and develop Simplified Model using Excel utilities						■						
ORNL will work with COE, Nashville District, and stakeholders to determine if additional demonstration and technology-transfer activities would be recommended and beneficial and if so suggest a strategy for implementation. The COE, Nashville, District will provide a memo summarizing the outcomes to date and level of acceptance of the operational developed water quality model							■					
Mid-Columbia River Basin: Project Final Report describing the development of TDG predictive equations for the Mid-Columbia river system and description of the implementation of the TGD algorithm into the real-time Mid-Columbia scheduling tool RiverWare, Submit results for publication in a peer reviewed technical Journal								■				
Communications trough meetings, and workshops, training to users from federal hydropower agencies, and hydropower schedulers, publication in scientific papers, conferences, and reports									■			
Deliver results about model simulations and optimization for the Cumberland River.										■		
Provide DOE and CADSWES a communication report on findings regarding feasibility for incorporation into RiverWare TDG predictive module developed in FY16 (tailwater to headwater TDG transfer).											■	
Send final report to DOE-HQ summarizing the Development, implementation, and optimization results of the optimization tool for the Cumberland River System and the Mid-C river system.												■

Project Budget

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$185k	$0	$320k	$0	$0K	$0

Partners, Subcontractors, and Collaborators:

Columbia River System:

1. IIHR Hydroscience & Engineering - University of Iowa (Dr. Marcela Politano, Dr. Alejandro Castro)
2. Bureau of Reclamation, Denver, Colorado (Merlynn Bender)
3. USACE Portland District (William Proctor, Mike Schneider)
4. CADWES, University of Colorado (Tim McGee, David Neumann, Mitch Clement, Dr. Edie Zagona)
5. Public Utility District No 1 of Chelan County (Scott Buehn)

Cumberland River System:

1. Vanderbilt University, Nashville, TN (Dr. Eugene LeBoeuf, Amy Shaw, Heather Sawyer)
2. Lipscomb University, Nashville, TN (Dr. Mark McDonald)
3. USACE Nashville District (Bob Snead, Jeff Gregory)

Oak Ridge National Laboratory:
(Dr. Boualem Hadjerioua, Kevin Stewart, Dr. Adam Witt, Scott DeNeale)

Communications and Technology Transfer:

Columbia River System:

- Memorandum of support of TDG modeling efforts from Public Utility District No 1 of Chelan County (2015)
- RiverWare and TDG workshop with CADSWES, ORNL, and PUDs (2015)
- Implementation of the TDG uptake equation into the CADSWES real-time scheduling tool RiverWare (2016)
- Webinar planned to discuss results and implications of both projects (planned for early 2017)

Cumberland River System:

- Memorandum of support of water quality modeling efforts from USACE, Nashville, District (2015)
- Water quality workshop held at Vanderbilt with 24 WQ experts (Vanderbilt, 2015)
- One Journal publication (submitted in 2016)
- Two PhD dissertations (2016, in progress)

Next Steps and Future Research

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FY17/Current research: Project completed in FY 2016

Proposed future research:

- Test and validate the TDG equations in other river systems
- Continue to improve the TDG transfer magnitude prediction methodology and its incorporation into RiverWare
- Case studies to assess tradeoffs in meeting hydropower system generation requirements and environmental objectives are now possible with new modeling tool – conduct such studies on other river systems
- Fine-tuning the optimization approach to further address stakeholder needs that may be identified following initial model implementation
- As envisioned by the USACE Nashville District, extension of the two-reservoir system to an entire, Cumberland River system-wide linked model capable of local and global optimization, further enabling model application to additional river systems