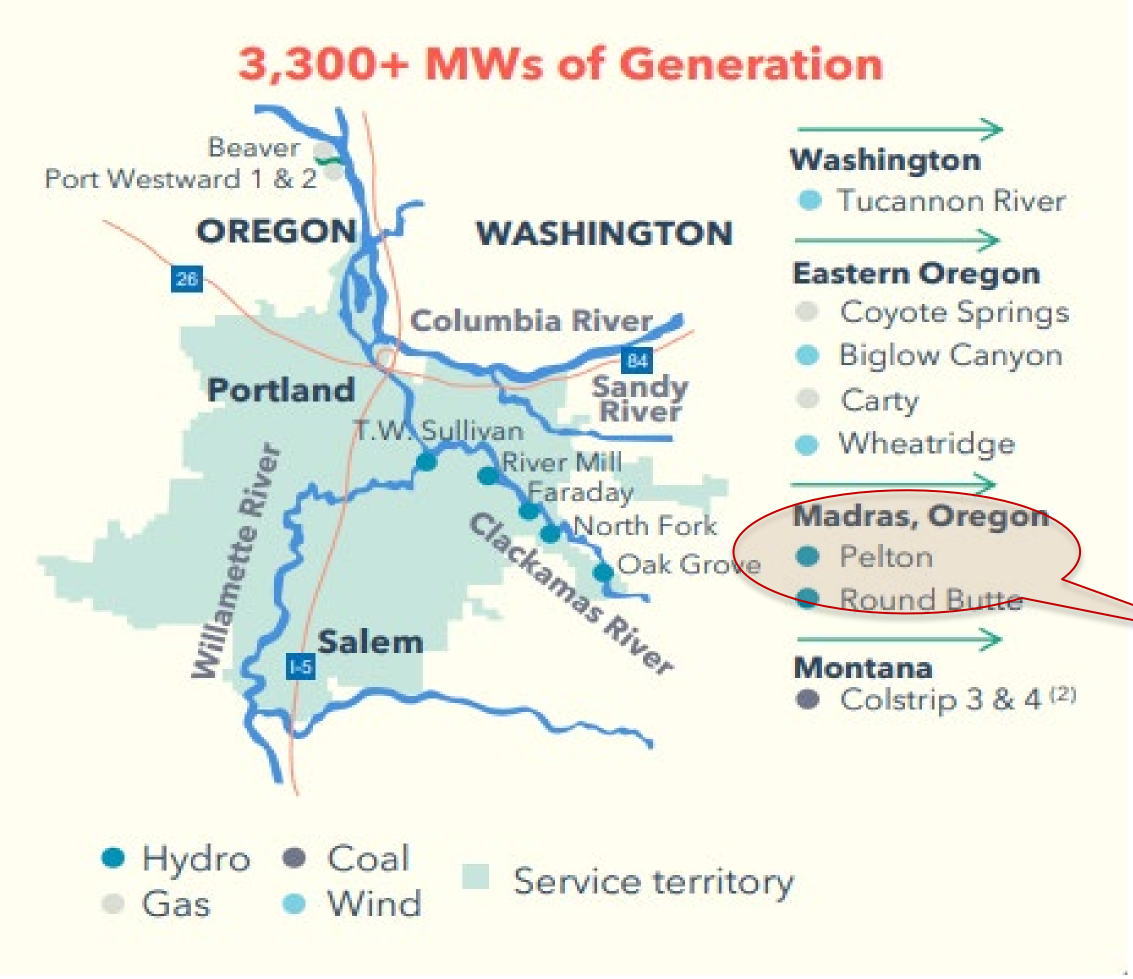
DE-EE0008944 – Exploring Multidimensional Spatial-Temporal Hydropower Operational Flexibilities by Modeling and Optimizing Water-Constrained Cascading Hydroelectric Systems



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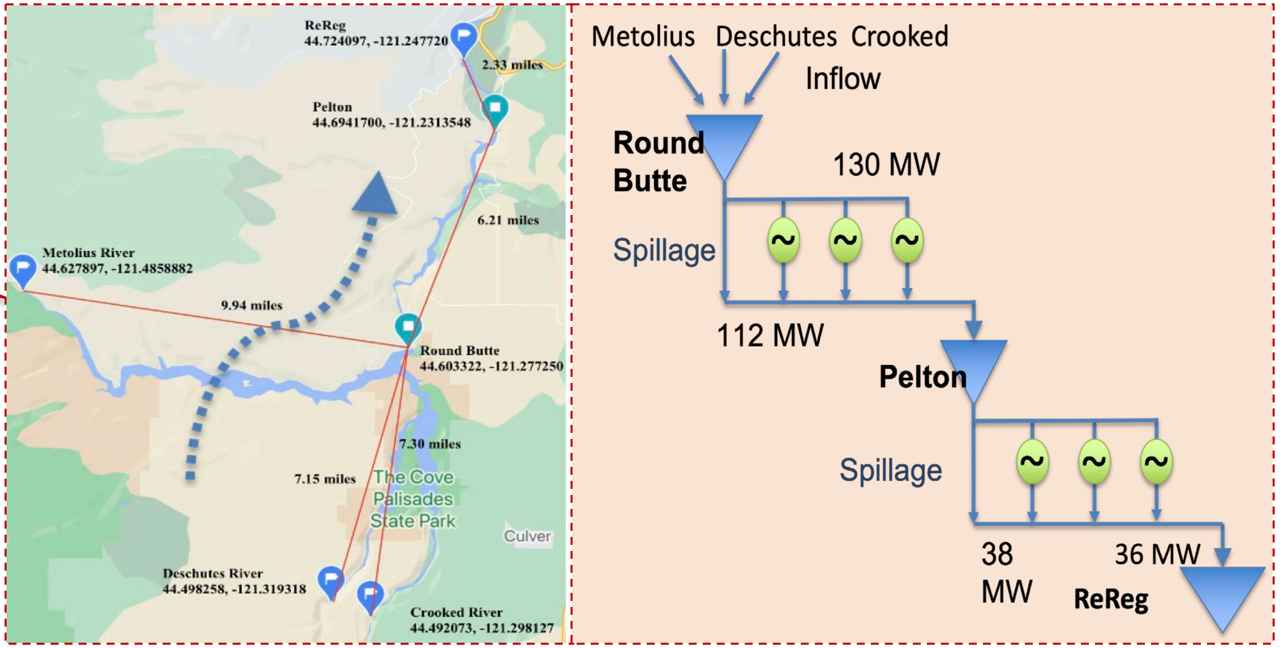
Presentation Date: July 26, 2022



Project Overview

Project Summary

Existing heuristic operation practices of cascading hydroelectric systems may predate renewable integration and prohibit fully utilizing their inherent flexibilities in providing valuable grid services. This project explores **enhanced water inflow forecasting models and advanced modeling and data-driven optimization approaches** to maximize the value of these resource-limited assets in providing **4-dimension enhanced operational flexibilities**—when, what reservoir, which hydro turbine, and how much water to be discharged/stored:

- Accurate water inflow forecasts to guide short-term operations and long-term reservoir draft-and-fill cycles;
- Rigorous models on physical and operating characteristics to explore inherent flexibility against uncertainties and information imperfectness.

Intended Outcomes

This project features several technology innovations that could lead to transformative changes in existing cascading hydroelectric system operation practices: (i) enhanced machine-learning-based **seasonal and day-ahead water inflow forecast models**; (ii) advanced **modeling and data-driven optimization approaches** to explore **multidimensional hydropower operational flexibilities**; (iii) simulation via **actual PGE data** to evaluate the effectiveness of the proposed approaches in enhancing hydropower flexibilities.

The project will leverage **existing PGE resources** including actual characteristics data of cascading hydroelectric systems as well as a library of existing and future cases.

Project Information

Project Information
Principal Investigator
• **Lei Wu**, Prof. of Electrical Engineering, Stevens Institute of Technology
Project Subcontracts
• **Neng Fan**, Associate Prof. of Systems & Industrial Engineering, University of Arizona • **Zhechong Zhao**, Senior Trading Analyst, Portland General Electric
Project Status
New
Project Duration
• Project Start Date: April 1, 2020 • Project End Date: May 31, 2023
Total Costed (FY19–FY21)
$372K (DOE: $230K; Cost Share:$142K)

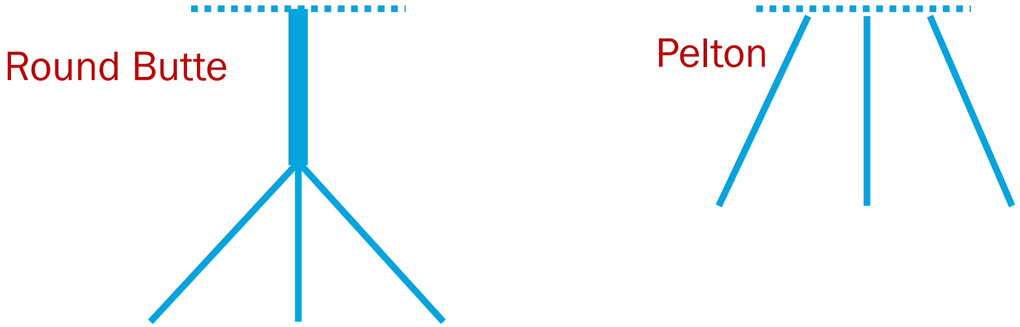
Project Objectives: Relevance

- Due to imperfect information on day-ahead and seasonal water inflows as well as complicated operation characteristics of cascading hydroelectric systems, the power industry usually resorts to **simplified heuristic reservoir operation practices**.
  - PGE adopts **heuristic draft-and-fill operation rules**: focus on utilizing available water inflows to maximize hydropower generation on a daily basis, are overly conservative due to reservoir regulation rules, and predate the integration of wind and solar.
    - *Water Inflow Calculation*: An in-house mass-balance calculation tool to estimate daily water inflow based on previous day information, which is then used to approximate the next-day total available MWh for factoring energy, contingency reserve, and load-following participations.
    - *Day-ahead Reservoir Evacuation and Hydro Turbine Operations*: Drafting the downstream pond overnight and shutting down upstream ponds, while starting up them in the morning to provide energy for the morning and afternoon ramps.
    - *Long-term Effects*: For seasonal drafting and filling operations, following a pre-specified limit on the draft of reservoirs, PGE usually starts to refill reservoirs by the end of January because of water inflow uncertainties in spring.

- The project findings on enhanced water inflow forecasting models and advanced modeling and data-driven optimization approaches will
  - Equip cascading hydroelectric systems with more physically efficient operations and financially profitable market participation;
  - Maximize the value of cascading hydroelectric systems in providing operational flexibilities to mitigate uncertainties, facilitate deeper penetration of renewables, and deliver widespread economic efficiency, reliability, and resilience benefits to the entire grid.

Project Objectives: Approach

- **Accurate day-ahead and seasonal water inflow forecast**
  - Hybrid Long short-term memory (LTSM) + ARMA forecast model
  - Quantile regression-based day-ahead probabilistic forecast model
  - Bayesian Neural Network-based probabilistic seasonal inflow forecasts with atmospheric indicators
- **Rigorous models to capture practical operation characteristics of cascading hydroelectric systems**
  - Calibration model to quantify water flow time delay between dams
  - Common tunnel-related energy loss model



- **Advanced Data-Driven Optimization Approaches**
  - A multistage robust optimization model for a hybrid hydro-thermal-solar/wind system, considering uncertainties of natural water inflow and power outputs of solar parks and wind farms
  - Effective solution approaches, including piecewise linear decision rules, uncertainty set partition strategies, and extended Column and Constraint Generation (C&CG) algorithm

Project Objectives: Expected Outputs and Intended Outcomes

Outputs:

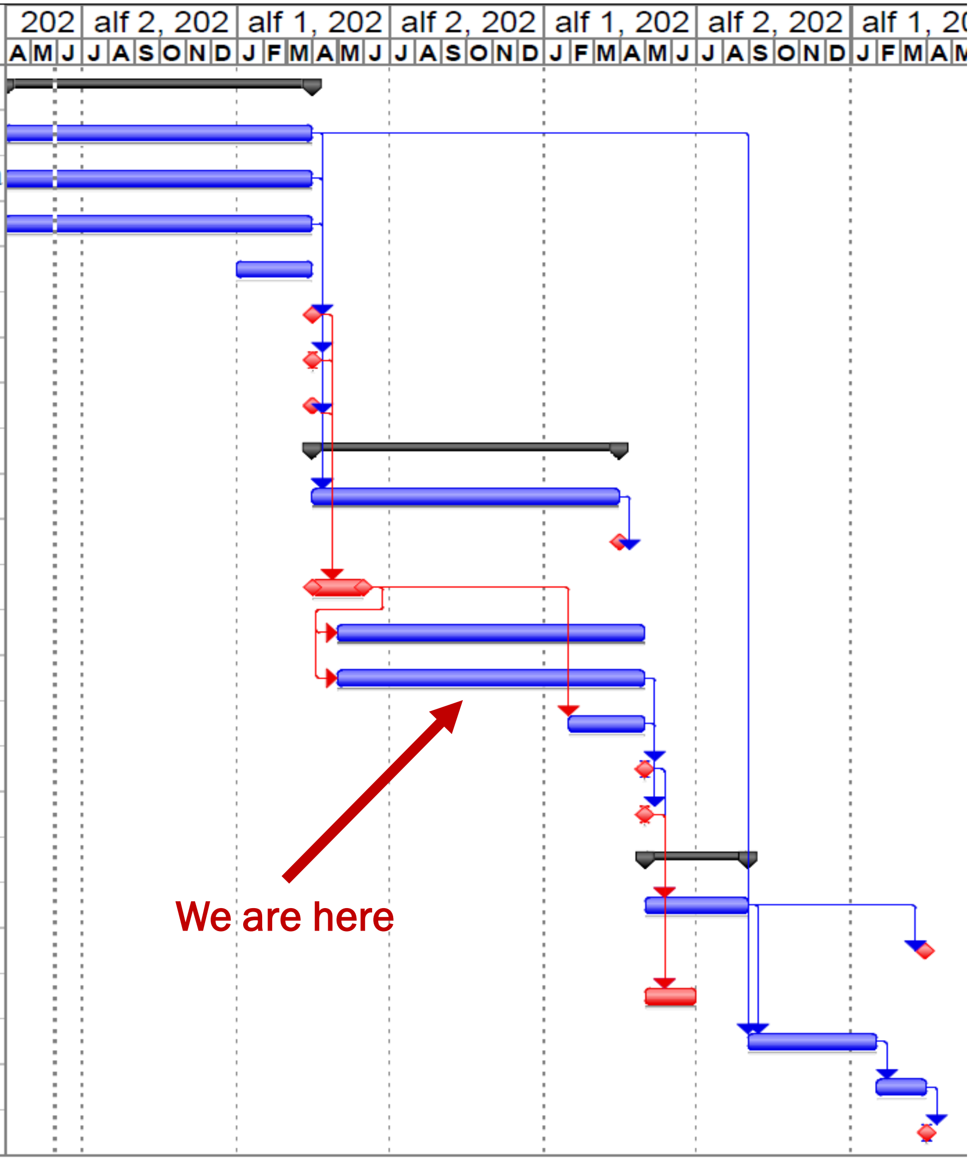
- Prototype frameworks for
  - Day-ahead water inflow forecast and optimal hydropower operation.
  - Seasonal inflow forecast and seasonal planning of water/reservoir elevation.
  - The proposed forecasting models and optimization algorithms will be customized according to PGE's specifications and need to maximize the value of cascading hydroelectric systems in providing operational flexibilities.
- Peer-reviewed journal and conference publications, and industry webinars.

Outcomes:

- After fully verifying the proposed approaches via the Pelton-Round Butte project against the PGE practice, seeking opportunities to adopt the project results in the PGE's scheduling operations.
- Disseminate project results and seek potential applications to other hydro facilities in the US, especially those located in the Pacific Northwest area since they share many similarities.

Project Timeline

Task Name
Performance Period I –Develop day-ahead water inflow forecast and operational strategies
Task 1 – Compile a library of relevant PGE cases for the evaluation
Task 2 – Develop machine-learning based closed-loop approach for day-ahead water inflow foreca
Task 3 – Develop models and solution approaches for day-ahead operational strategies of CHEs
Task 4 – Meetings with PGE's operation team and software vendor
Deliverable 1: Two sets of relevant PGE test cases
Milestone 1: Prototype closed-loop day-ahead water inflow forecast framework
Milestone 2: Prototype day-ahead operational strategies of cascading hydroelectric systems
Performance Period II – Develop seasonal water inflow forecast and operational strategies
Task 5 – Evaluate the developed day-ahead water inflow forecast and operation framework
Deliverable 2: Document on the evaluation of the day-ahead forecast and operation frameworks
Delierable 3: Critical Design Review 1
Task 6 – Develop probabilistic seasonal inflow forecasts with atmospheric indicators
Task 7 – Develop seasonal planning of water/reservoir elevations
Task 8 – Meetings with PGE's operation team and software vendor
Milestone 3: Prototype probabilistic seasonal inflow forecasts with atmospheric indicators
Milestone 4: Prototype prototype seasonal planning of water/reservoir elevation framework
Performance Period III – Evaluate the proposed frameworks and disseminate the results
Task 9 – Evaluate the developed seasonal inflow forecasts and water/reservoir elevations
Deliverable 4: Document on the evaluation of the seasonal forecast and planning frameworks
Delierable 5: Critical Design Review 2
Task 10 – Conduct further trial through simulation via future scenarios
Task 11 – Disseminate research findings
Deliverable 6: A report on testing results via future scenarios and the final reporting



Project Budget

Total Project Budget – Award Information		
DOE	**Cost-share**	**Total**
$1,000K	$250K	$1,250K

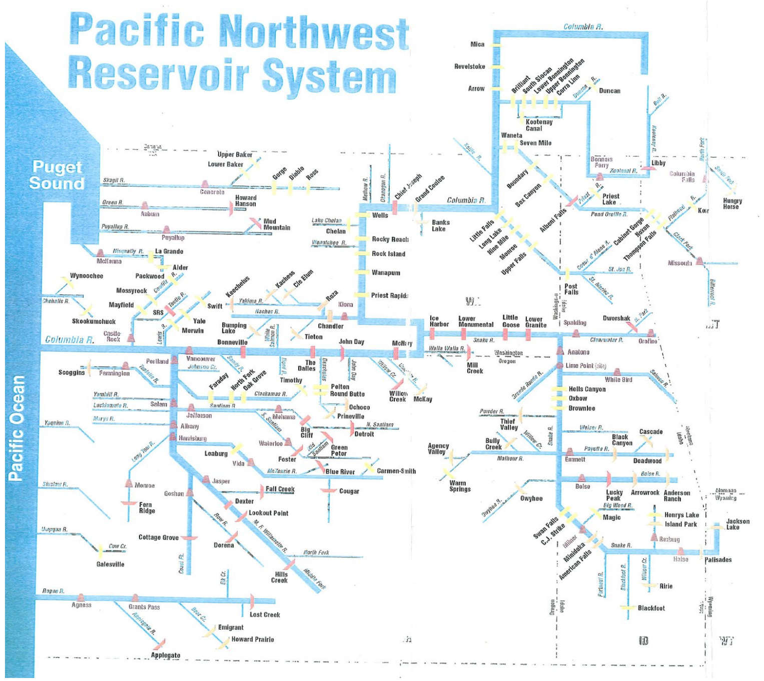
FY20	FY21	Total Actual Costs FY19–FY21
Costed	**Costed**	**Total Costed**
$60K	$312K	$372K

- The schedule and expense are currently slightly behind the original plan because:
  - The subcontract to PGE was settled about 6 months after the project started.
  - COVID-19 impacted the recruitment of students to join the project.

- The team is putting more student and faculty time into this project to accelerate the research progress and expenditure. The team will evaluate the performance of Tasks 6, 7, and 9 in fall/winter 2022 to determine whether a no-cost extension is needed.

End-User Engagement and Dissemination

- Stakeholder and/or end-user engagement strategy
  - PGE has been extensively involved as a subcontract, participating in formal group meetings on a quarterly basis as well as frequent informal meetings/calls/emails.
  - PGE’s Pelton-Round Butte project is used in this project for evaluation purposes, because its contract is structured in a “clean” way that does not have many stakeholders/shareholders involved, except for just one Tribe.
  - The proposed models and optimization tools are general and have the potential to be adapted to enhance the operational flexibility of other cascading hydroelectric systems in the US, especially those located in the Pacific Northwest area since they share many similarities.
  - The team plans to disseminate the project findings via industry-wide workshops, publications, and presentations to create broader impacts.



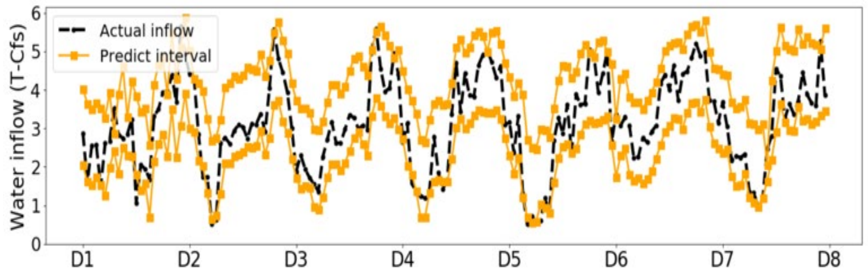
Performance: Accomplishments and Progress

- Technical accomplishments
  - Three Deliverables and Two Milestones
    - D1: Two sets of relevant PGE test cases based on actual historical data and future scenarios of resource portfolios.
    - M1: Establish a prototype day-ahead water inflow forecast framework.
    - M2: Establish prototype decision framework for day-ahead operational strategies of cascading hydroelectric systems in hybrid hydro-thermal-solar/wind systems.
    - D2: A documentation on the evaluation of the developed day-ahead water inflow forecast and cascading hydroelectric systems operations framework.
    - D3: Critical Design Review 1.

Performance: Accomplishments and Progress (cont.)

- Technical accomplishments
  - Economic and/or technical metrics
    - The proposed quantile regression-based probabilistic water inflow forecasting model, by **integrating upstream rivers' features as explainable variables**, outperforms other probabilistic forecasting models in terms of coverage capability and forecasting accuracy.

	Model	Proposed	PM2	PM3
predict interval coverage probability	Above 0.9	8.94%	10.12%	10.12%
	[0.1, 0.9]	81.54%	77.38%	76.79%
	Below 0.1	9.52%	12.50%	13.09%
continuous ranked probability score		454.20	478.00	521.34



    - The proposed multistage robust optimization model can realize hydroelectric units' operational flexibility to mitigate **variabilities and uncertainties** of renewables and loads, improve the **economic operation** of power systems, and enhance the **efficient operation** of other sources.

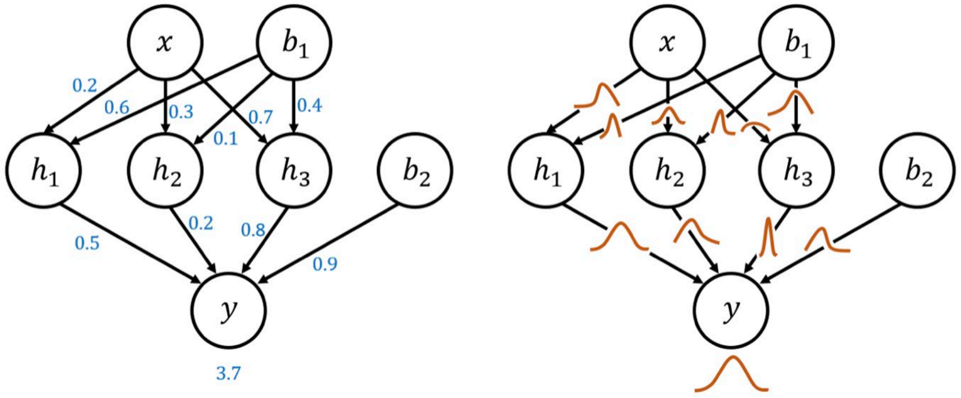
Time (h)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Without CHEs	2	2	2	2	2	2	3	3	3	3	3	3	3	4	5	6	6	6	6	6	6	6	3	2
With CHEs	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4

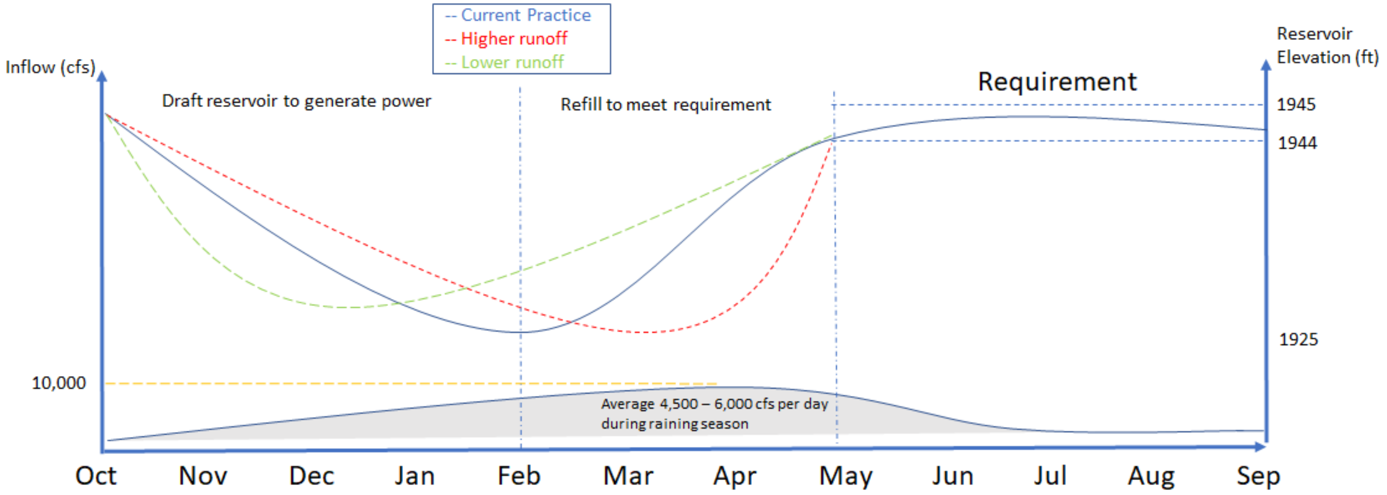
Performance: Accomplishments and Progress (cont.)

- Publications and presentations resulted from this project
  - Peer-reviewed journal articles (3)
    - Z. Zhong, N. Fan, and L. Wu, “A hybrid robust-stochastic optimization approach for day-ahead scheduling of cascaded hydroelectric systems in restructured electricity market,” *European Journal of Operational Research*, 2021. (under review)
    - Z. Zhong, N. Fan, and L. Wu, “Multistage robust optimization for the day-ahead scheduling of thermal-hydro-wind-solar power systems,” *IEEE Transactions on Power Systems*, 2021. (under review)
    - J. Xia, Y. Liu, N. Fan, Z. Zhao, and L. Wu, “On quantile regression-based probabilistic water inflow forecast and stochastic optimization for cascaded hydropower systems: a PGE study,” *IEEE Transactions on Sustainable Energy*. 2022. (under review)
  - Peer-reviewed conference paper (1)
    - Zhiming Zhong, Neng Fan, and Lei Wu, “Robust optimization for the day-ahead scheduling of cascaded hydroelectric systems,” *IEEE Power and Energy Society General Meeting*, 2022.
  - Technical Presentations (3)
    - L. Wu, Exploring Multidimensional Spatial-Temporal Hydropower Operational Flexibilities by Modeling and Optimizing Water-Constrained Cascading Hydroelectric Systems, DOE HydroWIRES Flexibility Workshop, March 2021.
    - Y. Liu, J. Xia, N. Fan, Z. Zhao, and L. Wu, Exploring Multidimensional Spatial-temporal Hydropower Operational Flexibilities by Modeling and Optimizing Water-constrained Cascading Hydroelectric Systems, INFORMS 2021 Water and Energy Session, 21-P-AM-7268-INFORMS, October 27, 2021.
    - L. Wu and Z. Zhao, Exploring Multidimensional Spatial-Temporal Hydropower Operational Flexibilities, CEATI HOPIG Webinar, April 2022.

Future Work

- Seasonal inflow forecasts and seasonal planning of water/reservoir evacuation
  - Bayesian Neural Network-based probabilistic seasonal inflow forecasts with atmospheric indicators
  - Models and solution approaches for seasonal planning of hydro generation and water/reservoir elevation





- Conduct further simulations via a library of future scenarios, make modifications/customization as needed to guide future PGE operation practice, and disseminate project findings to the industry including PGE's operation team & software vendors.

Q&A