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# Seasonal-Scale Optimization of Conventional Hydropower Operations

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## Abstract

This paper describes HydroSCOPE, a systems level simulation and optimization tool being created at Sandia National Laboratories. The tool couples a simulation model called ResMod with optimization software (DAKOTA) to perform tradeoff and scenario analysis of medium- to long-term hydropower operations. Results for an example multi-objective optimization formation for a portion of the Willamette Basin are shown. HydroSCOPE is being developed as part of a multi-year, multi-laboratory project, and will eventually be integrated with a day-ahead optimization model, a hydrologic forecasting tool, and a method for specifying environmental indicators.

## Introduction

Sandia National Laboratories (SNL) is creating a systems level simulation and optimization tool that can be used to perform tradeoff and scenario analysis of medium- to long-term hydropower operations. The tool, called HydroSCOPE (Hydropower Seasonal Concurrent Optimization for Power and the Environment), uses seasonal forecasts of water availability to examine operational alternatives designed to balance power generation, operational constraints, competing water users, and environmental performance. Outputs from this tool will help to define near- and long-term optimized operational strategies to ensure that short-term decisions are compatible with long-term environmental and power generation goals. The tool also aims to identify and prioritize reservoir operation strategies that, if improved, could provide the greatest gain for the least amount of investment.

The development of HydroSCOPE is part of a multi-year, multi-laboratory project. The goal of the overall project is to create a simulation and optimization tool set that can help to operate conventional hydropower plants more efficiently, providing more electricity revenue while enhancing environmental benefits and minimizing undesirable impacts. HydroSCOPE's emphasis on seasonal, systems-scale analysis will improve the tool set's ability to account for longer-term trends in water availability and discharge requirements.

HydroSCOPE has thus far been built to represent one test case, but is designed to be flexible and appropriate for implementation with different hydrologic systems. The current version of the tool is based on a hydrologic model developed for the Willamette Basin, which is located in Oregon State and feeds into the Columbia River. The tool is currently populated with coarse-grained, historical data for the Willamette. All information provided here should be considered an evolving example of the potential use of the seasonal-scale optimization tool, rather than a fully implemented application.

## The ResMod Model

HydroSCOPE consists of a simulation model called ResMod and an optimization tool that uses ResMod to find optimal release schedules based on flexible objectives and constraints. ResMod captures many of the purposes served by a reservoir within a complex hydrologic system. The model simulates water balance and temperature for reservoirs and rivers, as well as power generation, revenue, and environmental performance. The model includes sub-components for each of these factors, the system of which is solved to calculate the change in each factor over time. Figure 1 shows an influence diagram outlining the important components of ResMod. The model includes two general types of stocks associated with hydropower operation: water (within reservoirs and rivers) and energy (including temperature and hydroelectric power capacity). The model uses a systems-level approach, so although finer-grained representation is possible the analysis focuses on system-wide feedback and interdependencies.

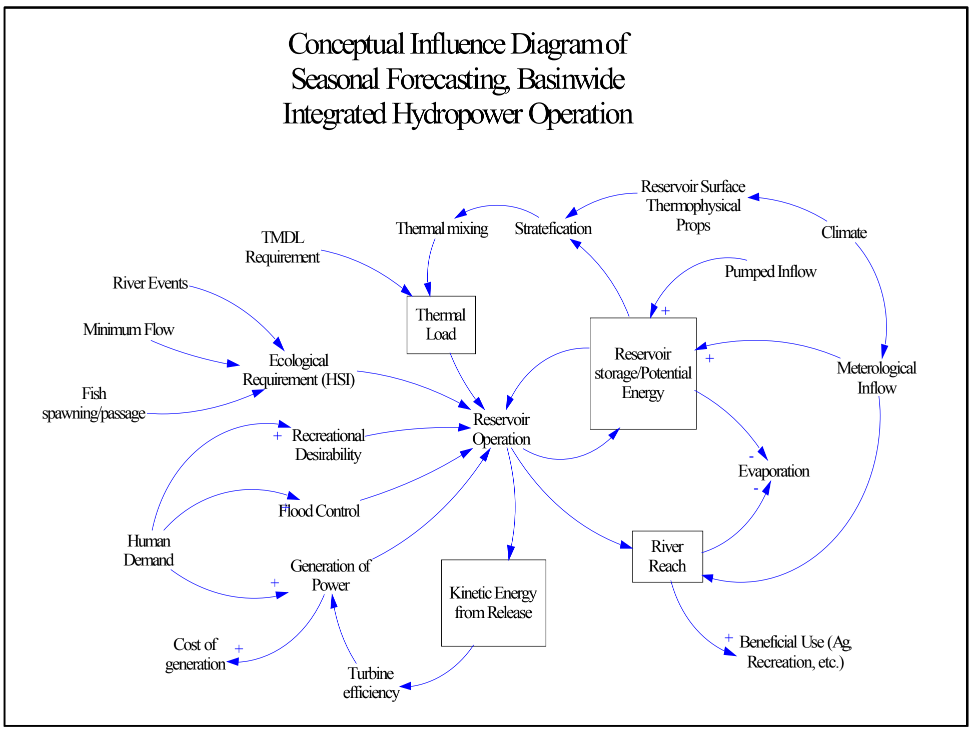


Figure 1 - Influence diagram outlining the important rates and stocks in the ResMod simulation model (shown for a single reservoir and river reach).

The key rate processes that determine changes to the hydrologic and energetic stocks are also shown in Figure 1. Hydrologic components are influenced by inflows, reservoir discharge, water use, and evaporation. Influences to the energy components include stratification and thermal mixing of the reservoir, surface heat exchange, hydrologic flows, and point source inputs and outputs. ResMod is based on the Willamette Basin Temperature TMDL model (Lowry et al. 2008), but has been modified to create a more generic and robust framework. Additional functionality was also added, particularly with respect to power generation, revenue, and environmental performance.

Each reservoir in the model is treated as one dimensional within each horizontal layer, and the number of layers is variable and dependent on the thermal structure of the reservoir. Rivers are split into homogeneous reaches, where each reach is between one and 20 miles in length. Inflows include tributary inflow, industrial and municipal discharges, and groundwater. Outflows include withdrawals for municipal, agricultural, and industrial use, as well as losses to groundwater. The governing equations that define the processes in the model are solved using finite difference numerical approximation in both space and time. The key processes are inflows and outflows, surface heat exchange, inter-layer flows, mixing due to surface wind shear, and mixing due to density gradients. Diffusive flux between each layer is simulated but its impact is minor when compared to the other influences.

The simulation model currently uses the MATLAB development environment. MATLAB contains a wealth of native programming functions that apply well to this problem, and also provides maximum flexibility for the code to interact with other (non-MATLAB) codes. In addition, MATLAB offers the ability to create user-interfaces for specifying simulation inputs as well as for visualizing outputs. The MATLAB environment also allows accessing MySQL database structures, which enable large-scale common data storage and is likely to be useful for sharing information across all the modeling components of the overarching, multi-lab project.

## Optimization strategy

HydroSCOPE couples ResMod with an optimization software package called DAKOTA. DAKOTA (Design Analysis Kit for Optimization and Terascale Applications) is an open-source software toolkit created at Sandia National Laboratories (Adams et al. 2010). It can be used to implement optimization, uncertainty quantification, and sensitivity analysis, and was designed for use with large-scale engineering projects (Adams et al, 2010). The framework for communication between ResMod and DAKOTA is shown in figure 2. Objective functions and constraints (including environmental and operational constraints) are defined within DAKOTA. The optimization software feeds a release schedule to ResMod, which simulates the effects of using that particular schedule. ResMod sends the outputs from that simulation, including hydrologic, temperature, power generation, and reservoir status information, back to Dakota. Dakota assesses those outputs based on the established objectives and constraints, and the process repeats.

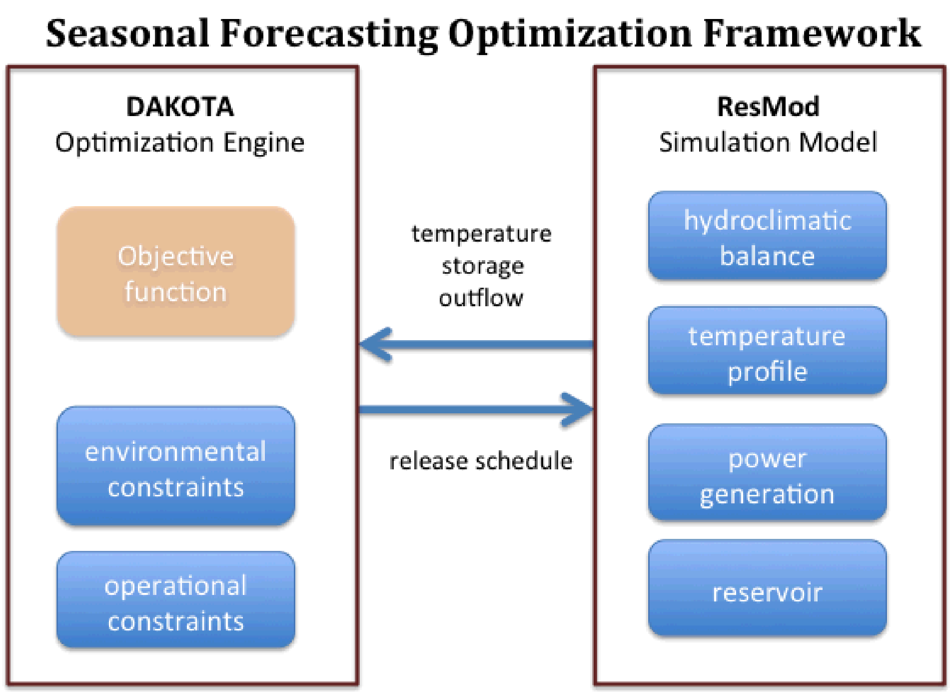


Figure 2: Communication structure of HydroSCOPE framework.

HydroSCOPE is designed to be flexible, and can be adjusted to work with various optimization schemes. Any of these schemes are likely to be analogous to solving a general optimization problem:

$$\begin{aligned} &\text{minimize} && F(\underline{s}, t) \\ &\text{subject to} && \underline{h}(\underline{s}, t) = 0 \\ & && \underline{g}(\underline{s}, t) > 0 \\ & && \underline{S}^L < \underline{s} < \underline{S}^U \end{aligned}$$

$F(\underline{s}, t)$ is the overall objective function or functions at time $t$; $\underline{s}$ is a vector of bounded state variables; $\underline{h}(\underline{s}, t)$ is a set of equality constraints; and $\underline{g}(\underline{s}, t)$ is a set of inequality constraints. The state variables for the hydropower problem are release schedules, both upper and lower bounded by restrictions on reasonableness.

Objectives and constraints used with the HydroSCOPE tool will depend on the specific needs of the site being modeled. The objectives $F(s, t)$ are likely to include maximizing revenue, minimizing environmental damage, and maximizing environmental benefits. The optimization scheme might be set up to include multiple objectives based on these issues, one of these objectives, or objective(s) that are designed to combine multiple issues in one equation. For example, an objective function that seeks to maximize revenue might also include a component that penalizes the result if an environmental objective is not met. Constraints in HydroSCOPE might include operational or environmental constraints. For example, minimum flows, maximum ramp rates, and flood control requirements are likely to restrict release schedules.

With so many options available for designing the optimization scheme, the specific objectives and constraints chosen will greatly affect the output of the optimization. The example described here is based on historical data for the Willamette Basin, and is being used to explore different formulations of objectives and constraints. Potential constraints for this site include minimum flows, rule curves, maximum ramp rates, and temperature requirements. We are also working closely with our partnering laboratories to explore considerations of habitat suitability, hydro-climatic uncertainty, and hydropower best practices. We are currently testing different combinations of objectives and constraints, and looking at the best ways to design the optimization problems so as to take into account both environmental and revenue from power generation. Results from an initial optimization scheme and sensitivity analysis are shown in the next section.

## Preliminary Results

We have begun to test our optimization strategy using a one-week planning horizon for a portion of the Willamette Basin. The optimization problem is initialized using historical data for Cougar reservoir and the surrounding river reaches, which constitute an upstream section of the basin. DAKOTA optimizes the system by varying daily releases over a weeklong period. The objective functions for this example include maximizing revenue from power generations and minimizing the average temperature of releases. Two hard inequality constraints were included in this example: minimum flow requirements for the river downstream of the reservoir and maximum temperature requirements for reservoir releases. Thus, the optimization problem was

$$
\begin{array}{ll}
\text{minimize} & F1(\underline{s}, t) \\
 & F2(\underline{s}, t) \\
\text{subject to} & g1(\underline{s}, t) < 0 \\
 & g2(\underline{s}, t) < 0
\end{array}
$$

where $F1(\underline{s}, t)$ is the negative of revenues from power generation, $F2(\underline{s}, t)$ is the average temperature of water released from the reservoir, $g1(\underline{s}, t)$ is the minimum flow requirement minus the flow, and $g2(\underline{s}, t)$ is the temperature minus a maximum temperature requirement. A multi-objective genetic algorithm (MOGA) is used to solve the optimization problem (Adams et al. 2010).

Output for the multi-objective example described above is shown in figure 3. The blue dots show the results of the ResMod model for different release schedules. The x-axis shows an environmental indicator based on the average temperature of releases, and the y-axis shows revenue from power generation. The red dots show the Pareto front for this configuration, or the set of points for which no objective can be improved without losses in another objective. This Pareto front can be used to understand the trade-offs that must be made in one objective to create gains in another objective. The Pareto front indicates an inverse relationship between power generation and the temperature of reservoir. Maximizing revenue from power generation will result in higher release temperatures, and vice versa.

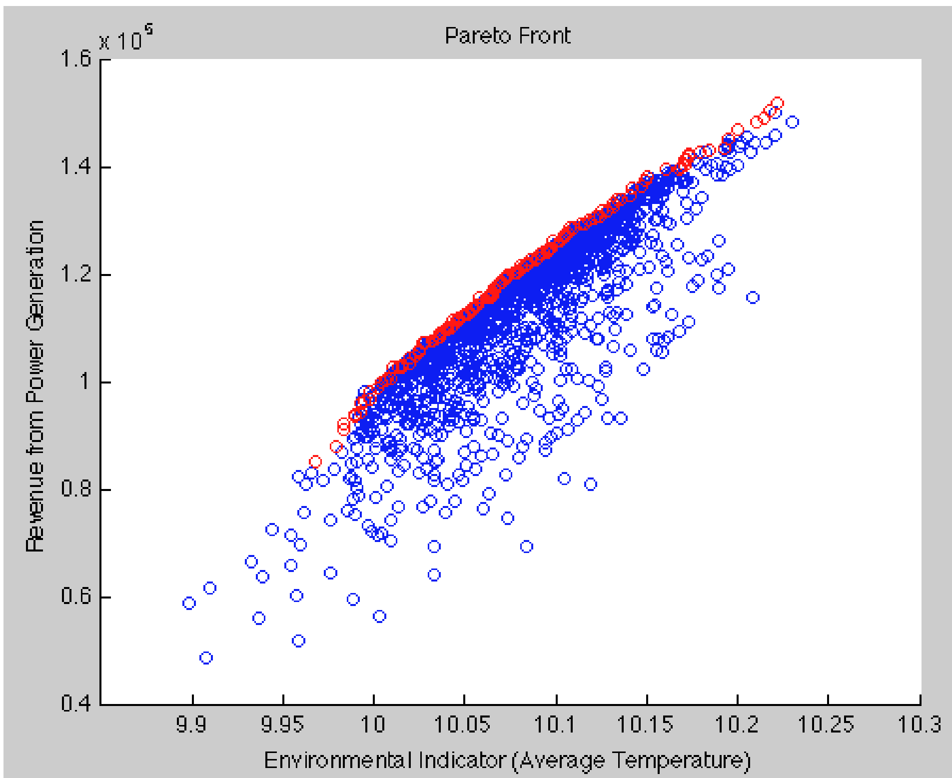

Figure 3: Pareto front for maximizing revenue and minimizing average temperature of releases.

Along with the optimization problem, we evaluated the sensitivities of released outflow relative to the objective functions and constraints. Figure 4 shows the objective function values based on sampling of outflow at three different rates for six days, including 10%, 105%, and 200% of historical flow. As noted, the highest power output does not correspond to the greatest average temperature. Intuitively, the greatest benefit to power generation occurs at the largest daily release for all six days, while the highest temperature occurs at power output less than the maximum. This particular optimization scheme has not considered a set of environmental constraints that are sufficient to require limiting the release schedule.

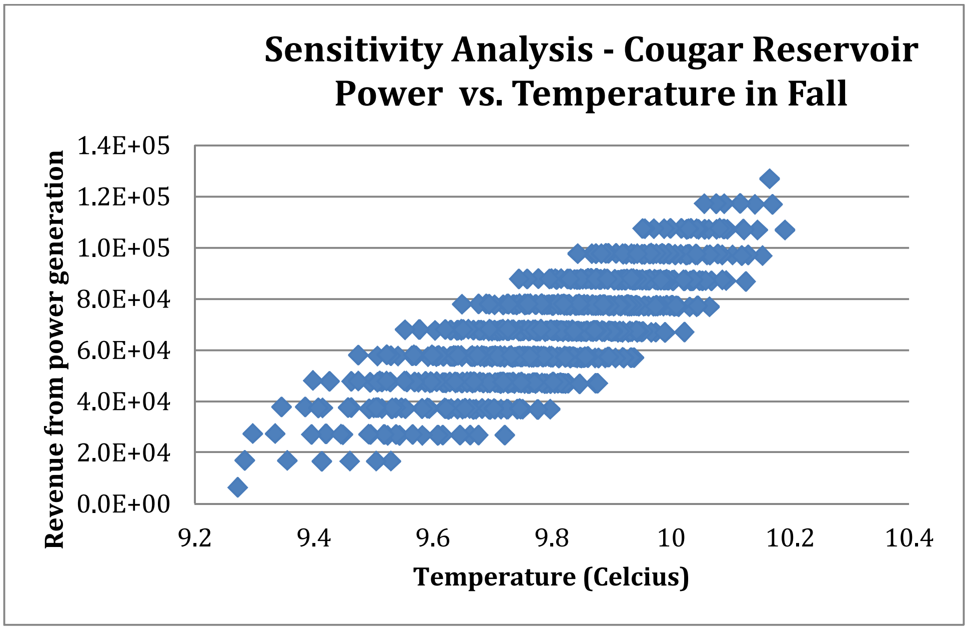


Figure 4: Sensitivities of reservoir daily release (six days) relative to objective functions. Each point indicates the two objective functions at a sampling release point.

**Conclusion**

The Pareto front shown in figure 3 can be used to understand the trade-offs that must be made when optimizing revenues and environmental objectives. For this preliminary optimization, the curve is relatively linear. We are seeking operational space where a small decrease in environmental objectives may lead to a large gain in revenues, or vice versa. This will help to identify areas where coexisting environmental or power generation goals can be met and potentially improved. Multi-objective modeling is computationally intensive, but the insight it gives about tradeoffs may prove to be very important.

This project is ongoing, and we expect the results and optimization strategy to evolve throughout the rest of the project. In addition to evolution of the seasonal-scale optimization tool, we expect to improve our integration with other tools being created for this multi-laboratory project. A model is being created to predict stream flows that will be used as inputs to the day-ahead optimization tool. Environmental indicators being created for one subtask of this project will be used to form our objective functions, so as to best indicate the effects of different seasonal-scale hydropower operation strategies to environmental concerns. Finally, a day-ahead optimization tool will use the output from our seasonal-scale optimization to ensure that their results account for long-term issues.

## References

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