Prospects for Combining Energy and Environmental Objectives in Hydropower Optimization

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Abstract
Although optimization is often used to establish rules for timing flow releases below reservoirs, environmental concerns are rarely incorporated as objectives and are relegated to minimum flow constraints. Here, we review studies that derived rules for hydropower operation by solving optimization problems driven by environmental and other competing water uses. We discuss the challenges of selecting environmental objectives amidst ecosystem complexity and consider how hydro system optimization and environmental optimization are modeled with differing uncertainty, time scales, and hierarchy. We explore how specific objectives may vary with the time scale of operations and discuss examples of environmental models that could be compatible with hydropower optimization. Given the increasing value placed on the ecological sustainability of human activities, we suggest that new approaches are needed to identify essential features of flow variation as it promotes river health and find quantitative methods for bringing ecological sustainability into the multi-objective problem of sustainable reservoir operation.

I. Introduction

Hydropower is the nation's most important renewable energy resource. It provides up to 10 percent of the electrical energy produced in the U.S., depending on annual water availability. Water resource projects made feasible by hydropower benefits often provide important non-power benefits, such as water supply, flood control, irrigation, navigation, and recreation in reservoirs and downstream reaches. However, hydropower projects originally conceived, designed, and constructed to yield conventional single and multi-purpose benefits are gradually being refocused with stakeholder guidance to achieve the broader objective of sustaining the ecosystems, water resource systems, and electric power systems in which they are embedded. Adaptability to changing objectives and values is a key criterion for sustaining these systems (ASCE 1998), so it is reasonable to assume that optimization practices used to schedule hydropower and water resource systems must also be adaptable. To that end, we explore in this paper the prospects for including environmental (or ecological) objectives in the decision support systems that guide hydropower and river system scheduling.

The overarching objective for river system management, including hydropower scheduling, is sustainability, for which many definitions exist. ASCE (1998) describes sustainable development as the "process by which the economy, environment and ecosystem of a region change in harmony and in a way that will improve over time." Translating this broad definition into specific objectives and prioritizing those objectives is beyond the scope of this paper, but we assume herein that a "sustainability objective" invokes goals of energy and water availability as well as the health of animal (including human) and plant communities that depend upon the river and its riparian zones.

II. The Complexity of Modeling for River Scheduling

To help clarify the challenges of implementing environmental objectives, Figure 1 illustrates a hierarchy of modeling complexity with which schedulers, engineers, scientists, stakeholders, and regulators must contend as they strive for sustainable operations of river systems and hydropower projects. At the lowest level, Level 1 in Figure 1, the relationships between water control infrastructure, water routing, and hydropower production are understood well by experts and codified more or less adequately in modern decision support systems. Uncertainty at this level arises primarily from the variability of hydrologic inputs and demand for electric power. This type of uncertainty is managed adequately through stochastic modeling tools primarily based on meteorological variables* and appropriate consideration of the risks of flood damage, inadequate water yield, or inadequate energy availability. Uncertainty may also arise from the limited capability of utilities to develop and maintain accurate power versus flow and head characteristics for projects and individual units. This type of uncertainty is an ongoing challenge for future research and technology transfer efforts.

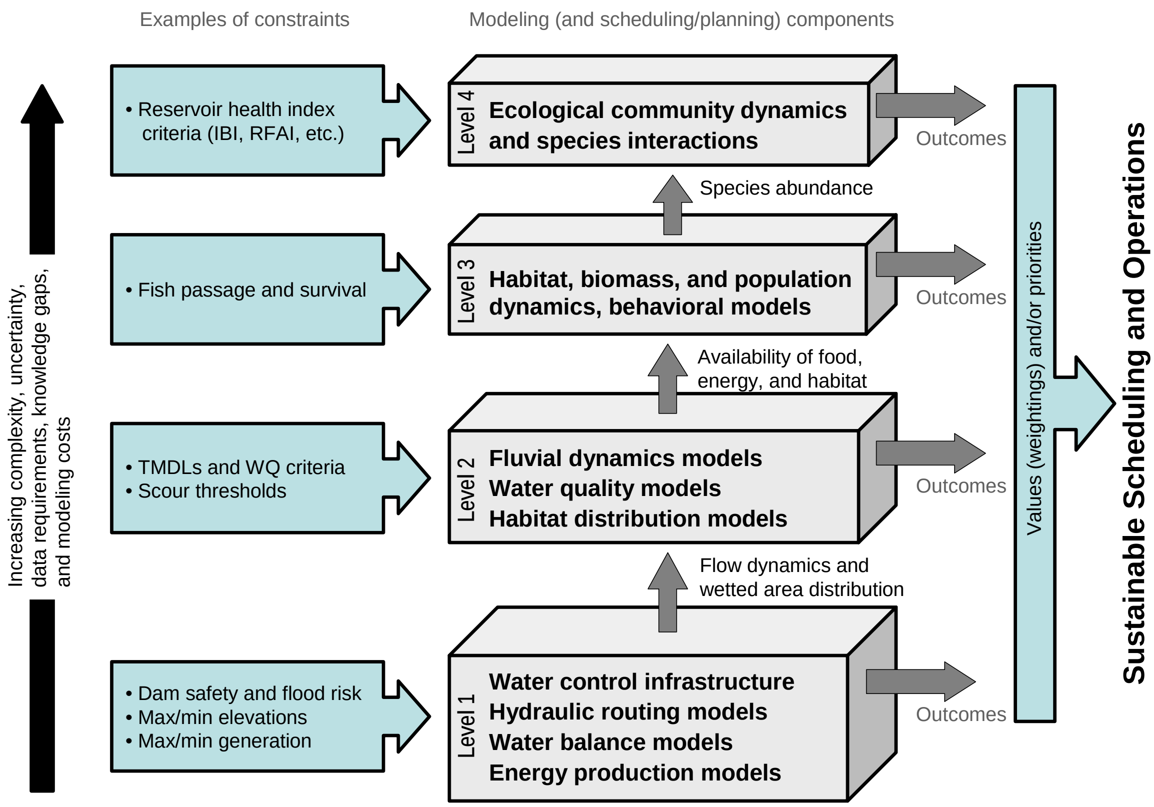

Figure 1. Hierarchy of modeling complexity in hydropower scheduling and planning (adapted from Smith et al. 2007).

Level 2 involves the fluvial and biogeochemical dynamics of river systems. Although mechanisms of sediment transport are well-documented, the heterogeneity of sediment properties and multiple modes of transport (bed, suspended, and wash load) impose additional sampling or data requirements for fluvial models. The relationships among water quality (temperature, dissolved oxygen, and nutrients, for example), water surface elevations, and discharge are well understood and codified in computational models that can translate water quality criteria back to reservoir operations policy. Uncertainty at this level arises from the sparseness of watershed biogeochemical input data and streambed condition data over time and space.

The next level of modeling complexity, Level 3, involves the population dynamics or habitat models for single species. The increased complexity begets uncertainty at this level due to (a) factors that are not included in quantitative and qualitative models that exist for modeled species (anadromous fishes and sturgeon, for example) and (b) inherent variability in responses of individual organisms. The existence of multiple species of concern within river systems necessitates combined models of habitat and population

* The impact of climate variability on energy and water resource systems and ecosystems is an important area of research that is beyond the scope of this paper. Interested readers may refer to Vanrheenen et al. (2004) and Lettenmaier et al. (1999).

interactions and represents the top level of complexity, Level 4, community dynamics. At this level, models are typically empirical, with community health assessed by assemblages (multi-species indexes) and linked to water schedules by regression models. This level can also include the complexity of human values and uses of the river as part of the community (IHA 2004).

This modeling complexity paradigm is relevant to water and hydropower optimization because some objectives are defined at the lowest level (e.g., water yield, firm power, hydropower revenue), while others are defined at the higher levels (e.g., habitat availability, survival, recruitment, health, aesthetics). Water control policies, implemented as schedules of reservoir releases and reservoir elevations, are “closely” linked to low-level objectives through mechanistic hydraulic routing and water power equations. High-level objectives are more “distantly” linked to water control policies because they must be related to those policies through additional models of water quality, fluvial dynamics, habitat, population dynamics, or community interactions. The practical implication of this “proximity” to reservoir control policies is that the levels at which objectives are defined affect the amount of data required, the uncertainty, the cost, and the time frame for decision-making in reservoir operations. Knowledge gaps or limited decision-making resources often require that high-level objectives be transformed to low-level constraints (e.g., minimum flows, required spill, or restrictions on fluctuations of reservoir elevation or generation). This transformation invokes the state-of-the-science, with its knowledge gaps and undertainty, that exists during specific milestone periods in the lifetimes of water resource projects. Hydropower relicensing processes, major project rehabilitation studies, preparations of biological opinions for aquatic species under the Endangered Species Act, and river system policy studies subject to NEPA review are examples of milestone periods.

III. State-of-the Art in Reservoir Optimization

Characteristics of reservoir water allocation problems include the objective and constraint functions, time horizon, time step, network topology of reservoirs and hydropower resources, and the level of detail to be coordinated. The boundaries of most decision support systems for river and hydropower scheduling include only Levels 1 and 2 of the hierarchy in Figure 1, but there are other hierarchies that affect the structure of optimization problems for operational time scales. The physical hierarchy of river systems and hydropower projects usually imposes a similar hierarchy on the decision support system. Thus, systems will be optimized at the project (reservoir) level first, then project decision variables (flows or generation dispatches) will be disaggregated by component optimization models into individual unit flows or generation dispatches. The time horizon and time scale of optimization models are often nested, with monthly or weekly time step models used to schedule over an annual horizon and to provide water or energy availability constraints for daily or hourly time step models over a weekly horizon.

Hydropower production or revenue as an objective or constraint renders an optimization problem non-linear, typically forcing controllers to choose between fast and robust but potentially less-accurate solutions via linearization of the problem, or slower and more-accurate but potentially unstable and non-global solutions of the nonlinear problem. Many commercially available decision support systems used to schedule hydropower and river systems in North America use linear programming to solve the long-term and short-term (hourly) river scheduling problems, with careful attention to how the power, head, and flow relationships are linearized. At hourly and shorter time scales, project loads (or discharge) from longer-term schedules may be disaggregated into efficient hydroelectric unit commitment and loading schedules with non-linear solvers, dynamic programming, or mixed-integer programming. Alternatively, non-linear solutions for short time scales may be obtained off-line and fit with non-linear regression models for use in operational scheduling (Georgakakos 1997). Applications of hierarchical scheduling systems include the Tennessee River Basin (Zagona et al. 2001, Adams et al. 1999), the Colorado River system (Harpman 1999, Yi 2003), and hydro systems in southern California (Draper et al. 2003; Newlin et al. 2002, Jenkins et al. 2004).

A. Survey of Environmental Goals in Reservoir Optimization Studies

Two comprehensive reviews have surveyed available methods for optimizing reservoir releases with some consideration of environmental goals (Homa et al. 2005, Jager and Smith, submitted). Both reviews found that most studies incorporate a low-level minimum-flow constraint rather than an explicit and quantified high-level ecological objective. The exceptions to this trend have targeted different ecological goals, including the Level 1 objective of minimizing deviations from a natural flow duration curve (Shiau and Wu 2006, Homa 2005), the Level 2 objectives of maximizing fish habitat (Cardwell et al. 1996, Sale et al. 1982) and minimizing sediment instability (Carriaga and Mays 1995), and the Level 3 objective of maximizing fish population viability (Jager and Rose 2003).

Optimizations that maximize fish habitat included 14 that focused on providing regulatory minimum flows and 9 that focused on providing flows that would protect water quality. Not all water quality problems focused on tailwater habitat. Several focused on maintaining reservoir water quality (e.g., sufficiently high dissolved oxygen and low temperature), which also protected downstream habitat (e.g., Chaves et al. 2003). Several others focused on ensuring adequate flows to downstream estuaries (e.g., Schluter et al. 2004).

Optimizations that minimized deviations from a natural flow regime ranged from one that simply considered ramping restrictions as an added constraint to those that penalized deviations from a natural flow regime, as measured either by the deviation between unregulated and regulated flow duration curve or by the range of variability index (Richter 1996), which measures how well the natural flow regime is statistically reproduced. We note that this approach makes two significant assumptions: (1) the unregulated flow regime is optimal for an ecosystem that is impacted by impoundment and (2) all aspects (time scales and magnitudes) of the flow regime are equally important. More research is needed to discern which aspects of a flow regime are most critical for sustainability in regulated river systems. For example, seasonal flow patterns that provide cues and habitat conditions required for fish spawning are likely to be important.

B. Examples of Environmental Optimization

Presented here are three examples of environmental objectives implemented as part of a river scheduling framework. The first two represent relatively simple intermediate-level objectives of maximizing dissolved oxygen through turbine aeration and maximizing survival of turbine-passed fish. They are significant because they have been implemented within functioning decision support systems for hydropower projects. The third example is significant for two reasons. First, it is designed to optimize a higher-level objective, and second, the complexity of the objective led the researchers to employ a heuristic optimization technique that may present a challenge to integration with hydropower optimization.

Dissolved oxygen optimization with aerating turbine scheduling

The improvement of dissolved oxygen (DO) levels and the provision of minimum flows to protect aquatic habitat in tailwaters are major environmental concerns, particularly for water resources projects in the Southeastern United States. Designs and technologies for environmentally advanced turbines and control systems have focused on improving levels of DO in turbine discharges to improve environmental performance (March and Fisher 1999). Environmental performance is evaluated primarily by the amount of DO uptake, while the hydraulic performance is based on the amount of aeration-induced efficiency loss (Hopping et al. 1999).

Typically, environmental monitoring systems provide data on the operations of environmental systems, monitor compliance, and provide environmental data for use in models and decision support systems. Environmental parameters include water temperatures, incoming DO values, downstream DO values, total dissolved gas, multiple differential pressures and corresponding air flow rates, oxygen flow rates (where appropriate), barometric pressure, and air temperatures. Hydraulic performance-related parameters, including unit status, power, flow rate, headwater level, tailwater level, gate opening, and efficiency are often monitored or computed as well. Using this timely information on both environmental conditions and unit operating conditions, a simple form of environmental optimization for dissolved oxygen improvement can provide increased DO levels in the turbine discharges with minimum energy losses. In terms of the complexity paradigm of Figure 1, this type of modeling and control invokes objectives and constraints at Levels 1 and 2 of the hierarchy. While measuring and controlling efficiency loss in turbines is a well-established practice within Level 1, models to predict DO uptake (a Level 2 objective) and aeration-induced efficiency loss are less than complete, with accuracy dependent on the empirical relationships and the similarity (or dissimilarity) of hydraulic conditions among aerating turbines. Results of DO enhancement modeling can be input to a bioenergetics model (e.g., Shiao et al. 1994) to simulate fish growth, which can be incorporated into an optimization framework to achieve a Level 3 objective of maximizing fish growth.

For example, the Tennessee Valley Authority's Norris Project includes two advanced, self-aerating turbines. Specially-shaped geometries for turbine components were developed and refined to enhance low pressures at appropriate locations, allowing the air to be drawn into an efficiently absorbed bubble cloud as a natural consequence of the design and minimizing energy losses due to the aeration (March and Fisher 1999). These Francis-type units contain options to aerate the flow through central, distributed, and peripheral air outlets. The environmental and hydraulic performance of these aeration options varies with the site's head and power output. An environmental monitoring and optimization system at Norris integrates with the plant's automation control system to monitor environmental parameters and receive optimization requests (load, flow, automatic generation control, etc.) from the control system (Adams et al. 1999). Under varying reservoir conditions and unit operating conditions, the environmental monitoring and optimization system chooses the optimized combination of units to meet the target DO level, minimize the aeration-induced efficiency losses, and satisfy the optimization request. The recommended unit loadings are then returned to the automated control system for execution.

At the Norris Project, each aeration option was tested in single and combined operation over a wide range of turbine flow conditions. For environmental performance, results show that up to 5.5 mg/L of additional DO uptake can be obtained for single unit operation, with all aeration options operating and a zero level of incoming DO. Efficiency losses during aeration range from 0 to 4 percent, depending on the operating conditions and the combination of aeration options. Compared to the original Norris turbines, the self-aerating replacement units provide overall efficiency and capacity improvements, weighted over the operating range, of 3.7 percent and 10 percent, respectively (March and Fisher 1999). This corresponds to an average additional annual generation of about 17,000 megawatt-hours for the Norris Project.

Fish passage optimization within unit dispatch

Numerical modeling and fish survival testing on a variety of hydro turbines demonstrate that there is a point of operation where the maximum number of fish passing through the turbine will survive (Franke et al. 1997, March and Fisher 1999). This zone of "safe passage" operation, which may differ somewhat from the point of maximum efficiency, typically depends on a variety of factors including upstream fish location, path through the turbine, turbine passage mortality by region, fish bypass characteristics, spillway mortality, and total dissolved gas generated during spilling.

Some of the advanced design concepts for "fish friendly" operation of Kaplan turbines have been implemented in the replacement units installed at the Chelan County Public Utility District's Rocky Reach Project, at the U. S. Army Corps of Engineers' Bonneville Dam, and at the Tennessee Valley Authority's Kentucky Dam (Franke et al. 1997, March and Fisher 1999). A design utilizing almost all of the advanced Kaplan concepts was developed, model tested, and recently installed at the Grant County Public Utility District's Wanapum Dam. For the Wanapum design, fish survival rates of 97% have been reported (Dresser et al. 2006). Efficiency improvements with the Wanapum design range from about 1% at best efficiency to 5% at maximum capacity (March and Fisher 1999). A simple form of environmental optimization for fish passage improvement is achieved by optimizing for fish survival performance when fish are detected near a turbine's intake (i.e., operating the turbine in the "safe passage" zone) and by optimizing for economic performance when fish are not present (March 2006).

Salmon recruitment optimization

Jager and Rose (2003) used simulated annealing to find optimal flow regimes to support Chinook salmon recruitment under different hydrologic conditions below the New Don Pedro Dam on the Tuolumne River, California. The decision variables were flows for each of 20 2-week periods between upmigration of spawners in the fall and outmigration of juveniles in spring. The Oak Ridge Chinook Model was used to predict the number of outmigrating juveniles produced by each candidate flow regime. This individual-based and spatially explicit model links reservoir releases to salmon reproduction and rearing success through a number of processes. First, this population exists on the fringe of Chinook distribution in southern California, where high temperatures make the lower river uninhabitable for much of the year. Thus, reservoir releases influence simulated salmon survival and development indirectly through temperature. Second, the amount of habitat available for spawning depends on flow releases, and the potential for superimposition of redds (nests) by later spawners increases when spawning habitat is in short supply. Third, extreme high flows causes scouring of redds and low flows lead to dewatering of redds during the winter, when eggs are incubating and alevin are developing. Fourth, juvenile salmonids are territorial, and the amount of suitable habitat available on any given day depends on flow releases. When flows are extremely low or high, smaller individuals are unable to secure foraging sites. Results predicted that as the amount of water available increased, flows should first be added in spring (during outmigration), followed by fall (during spawning migration). Both periods represent times when tailwater temperatures can be too high for Chinook salmon to tolerate when flows are low, but temperatures are reduced by bottom releases from the reservoir.

IV. Prospects for Integrated Energy and Environmental Objectives in Optimization

Integrating models of environmental responses with hydropower energy and water availability models is a challenging prospect, even if we defer the challenge of establishing relative value or priority among multiple objectives. One challenge in this endeavor is that tradeoffs between environmental, water, and energy objectives are seldom confined in scope to a single reservoir. Environmental benefits or impacts may be separable among multiple reservoirs, but energy and water benefits are linked, such that operational changes at one reservoir affect benefits at downstream reservoirs. Environmental optimization efforts have necessarily begun with single-reservoir studies for proof-of-concept, but practical solutions will be found in environmental and hydropower optimization for systems of reservoirs. For many ecological problems, optimizing over a system of reservoirs will continue to present a formidable computational task.

Some combined ecological and hydropower optimization problems can be structured in a way that lends itself to solution via linear programming methods (e.g., Cardwell et al. 1996 and Sale et al. 1982). Ecological problems that can be linearized without obscuring essential mechanisms may find their way into hydropower decision support systems more quickly than highly non-linear formulations. However, it is important that the essential features of the problem are adequately described--the approximate solution to the right problem is usually better than an exact solution to the wrong problem. The solutions to such problems can also be found by simulation using a so-called "greedy" algorithm – one that always chooses the change in flow that produces the greatest short-term improvement in long term coexistence between the river ecosystem and hydropower production. Sale et al. (1982) used a piecewise-linear habitat model to operate a reservoir to maximize fish habitat within the feasible space for reservoir operation, given other demands on water allocation. Cardwell et al. (1996) also used habitat, as represented by weighted usable area, to maximize salmon habitat and minimizing water supply shortfalls. Ringler and Cai (2006) found flow regimes that maximize economic benefits of water use in the Mekong River Basin. They used ecological valuation methods to determine water values for energy, fisheries, and wetlands. However, the relationships between values and flow were somewhat arbitrary. Wetland benefits were assumed to decrease with deviation from a natural flow regime. Profits from fish production were represented by an S-shaped function of flow.

Non-linear or heuristic solution methods will be needed to find optimal release schedules for problems that represent realistic flow-biology relationships, but such models may not find their way into operational scheduling for some time. Thus, in addition to integrating ecological models into hydropower decision support systems, it will be useful to integrate models of energy and water availability and value into complex ecological models to enable tracking of energy effects from ecological optimization. Although they are not guaranteed to find the global optimum, these non-linear or heuristic models may have important advantages. First, they can often find near-optimal solutions for ecological models, regardless of their complexity. This permits the ecologist to focus on the best-possible representation of linkages between flow and fish populations, rather than constraining the model to be simple enough to conform to certain solution methods by, for example, using only linear or convex relationships.

Time lags will play an important role in optimization of ecosystems and hydropower systems. For example, although mortality can occur at any time, most fish populations grow only once per year, when reproduction takes place. How can we measure the effects of a change in flow now on future fish reproduction? Two options might be to settle for minimizing mortality during non-reproductive periods and/or to maximize growth. Second, a solution with a short-term decline in population size (or growth) might ultimately reach a better endpoint than one that always increases. For example, high flows that maintain shallow, slow off-channel habitats likely have short-term adverse effects on fish populations, but ultimately provide important rearing habitat for fish larvae of many species (Scheidegger and Bain 1995, Bowen et al. 1998, Bowen et al. 2003).

V. Summary

We have reviewed the nature of objectives and constraints that are represented by models of hydropower systems, river systems, and ecosystems. Ideally, one would like to specify a high-level objective of maximizing the health of ecosystems, but there are knowledge gaps and model performance gaps that preclude one from connecting high-level objectives to schedules of turbine flows and generation. We have discussed examples of environmental optimization enhancements to existing decision support systems for hydropower dispatch, as well as an example that implements a high-level optimization of an ecological objective, albeit without integration into a decision support system.

The existence of intermediate constraints such as minimum flows and fixed water quality criteria is indicative of the need for further research on the relationships between stream and reservoir hydrodynamics and the responses of individuals, populations, and ecological communities. In particular, there is an acute need to evaluate and define what features of riverine and limnetic ecosystems are most critical to preserving biodiversity, and in turn, sustaining of river systems. These might include riparian vegetation and a diversity of hydraulic habitats, including floodplains and slackwater areas, and connections among populations to prevent local extirpations in the face of normal variability in flow and climate. We acknowledge that prioritization or relative valuation of the multiple objectives in river system management is a grand challenge for all stakeholders in river system management. However, the absence of consensus on such priorities neither obviates the need for nor lessens the informative value of integrated energy and environmental objectives in hydropower optimization.

We suggest a phased approach to integrating environmental objectives into hydropower optimization. Existing and emerging knowledge of ecosystems response to hydropower schedules can be integrated into decision support systems for river systems on a trial (shadow or offline) basis to reveal where inconsistencies in data requirements and transfer, time steps, feasibility of schedules, and other interfacing issues may require further research and development. Ecological optimization applications with high-level objectives, which may be too computationally demanding for operational scheduling, can be enhanced with hydropower computations to reveal tradeoffs or synergies between hydropower and ecological objectives. Like many optimization applications, both hydropower and ecological optimization applications will benefit from advancements in nonlinear optimization techniques and from more powerful computational resources.

VI. References

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