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SUSTAINABLE RESERVOIR OPERATION: CAN WE GENERATE HYDROPOWER AND PRESERVE ECOSYSTEM VALUES?†

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ABSTRACT

Hydroelectric power provides a cheap source of electricity with few carbon emissions. Yet, reservoirs are not operated sustainably, which we define as meeting societal needs for water and power while protecting long-term health of the river ecosystem. Reservoirs that generate hydropower are typically operated with the goal of maximizing energy revenue, while meeting other legal water requirements. Reservoir optimization schemes used in practice do not seek flow regimes that maximize aquatic ecosystem health. Here, we review optimization studies that considered environmental goals in one of three approaches. The first approach seeks flow regimes that maximize hydropower generation, while satisfying legal requirements, including environmental (or minimum) flows. Solutions from this approach are often used in practice to operate hydropower projects. In the second approach, flow releases from a dam are timed to meet water quality constraints on dissolved oxygen (DO), temperature and nutrients. In the third approach, flow releases are timed to improve the health of fish populations. We conclude by suggesting three steps for bringing multi-objective reservoir operation closer to the goal of ecological sustainability: (1) conduct research to identify which features of flow variation are essential for river health and to quantify these relationships, (2) develop valuation methods to assess the total value of river health and (3) develop optimal control softwares that combine water balance modelling with models that predict ecosystem responses to flow. Published in 2008 by John Wiley & Sons, Ltd.

KEY WORDS: optimization; reservoir operation; hydropower; sustainability; riverine ecosystems; ecological valuation; natural flow regime

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INTRODUCTION

Water storage reservoirs typically provide multiple benefits of hydropower, water supply (municipal, industrial and agricultural), flood control and recreational opportunities. On the other hand, well-known detrimental effects include impoundment of free-flowing river habitat, blockage of fish migration and reduced water quality in reservoirs and downstream river reaches. Less-obvious effects include the interruption of geomorphological processes that maintain aquatic habitat diversity required to sustain healthy riverine ecosystems. Sustainability provides the broad context for weighing the benefits against the detrimental effects of dams and the flow schedules they impose.

Reservoir operations influence temporal flow patterns, which, in turn, influence the health of the downstream ecosystem. Healthy riverine ecosystems provide ecosystem services, including water supply, water reclamation, pollution abatement and groundwater recharge. River floodplains, slack-water habitats and riparian vegetation trap silt and nutrients, provide fertile soils, and protect the upland areas from flooding and erosion. The value of ecological support systems increases dramatically after species become designated as threatened or endangered.

We envision that future, holistic management strategies for reservoir projects will be designed to maximize both ecological benefits and those associated with energy production. In contrast, conventional reservoir management strategies typically optimize energy and producer-economic benefits and address ecosystem values only as constraints on reservoir releases and elevations. In this study, we reviewed research on reservoir optimization problems that explicitly include environmental objectives. These studies highlight progress towards developing sustainable management strategies for reservoir operations.

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We summarize the variety of ways in which environmental objectives are addressed in studies of reservoir release optimization. We begin by providing background on the conventional methods used to regulate for environmental health and conventional methods used to operate reservoirs. The next section describes a literature review and classification of environmental optimization methodologies followed by more-detailed descriptions of studies of each type. Finally, we describe the barriers between the current reservoir management and the desired future goal of sustainable reservoir operation.

BACKGROUND

Hydropower projects are operated primarily with the goal of maximizing the value of energy generated, while meeting constraints on upstream water supply and regulatory constraints on downstream releases. Regulatory constraints include those that address environmental concerns. Reservoir water-allocation problems typically solve for optimal water releases at one or more reservoirs. Objectives can be either linear or non-linear with respect to the amount of water released, which influences the choice of a solution method. Typical objectives are to minimize water deficits (linear) or to maximize hydropower production, revenue or profit (non-linear). Reservoir inflows determine the overall amount of water available to the system and represent the main source of uncertainty in reservoir water-allocation problems (Sale *et al*., 1982). Ouarda and Labadie (2001) reviewed both deterministic and stochastic methods used for optimizing reservoir operations. Deterministic, real-time operation programmes may represent multiple-reservoir hydrosystems and usually make short-term forecasts of inflows to reduce uncertainty. Stochastic optimizations seek solutions (flow releases) that are optimal under uncertainty. In practice, the only environmental considerations included in reservoir operation are legal requirements (e.g. minimum flow releases), which are represented as constraints.

METHODS

We reviewed 47 peer-reviewed papers and identified 29 studies that applied decision analysis or optimization techniques to problems involving both hydropower and environmental criteria (see Smith *et al*., 2007b). We excluded optimizations that did not involve flow releases as the primary decision variables.

We identified a variety of different approaches that have been used to quantify the effect of operational decisions on river ecosystems (Figure 1). In one or two cases, approaches could have been classified into more than one category. First, we distinguished between formal optimization approaches and those that apply game theory (i.e. decision theory). Decision theory is usually applied in situations involving multiple parties to a social conflict over water allocation, each with different objectives. The decision variables are usually a finite number of discrete management alternatives that are not under the control of one party. The value of hydropower generation differs among stakeholders involved in the decision process and the goal is to find equilibrium solutions that make

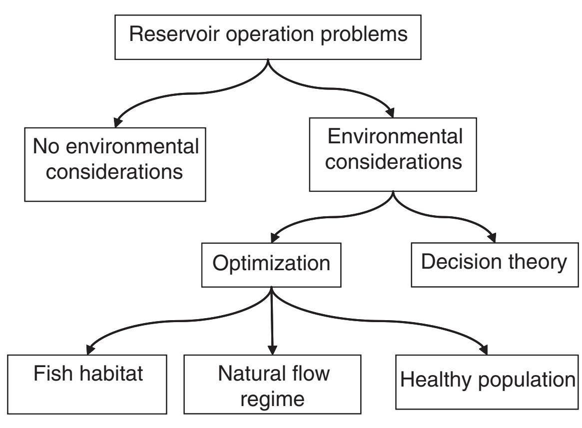

Figure 1. Classification of reservoir operation problems, focusing on those that addressed environmental considerations

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everyone happy, and, therefore, provide no incentive for cheating. Decision theory will not be discussed further in this review, as we focus on optimization approaches.

Most of the formal optimization approaches that consider environmental health involve multiple water demands. We identified optimization problems with three different environmental goals: (1) to provide flows needed for fish habitat, (2) to mimic the natural flow regime and (3) to provide flow regimes to support a healthy fish population (Figure 1). Each of these three problem classes is described below.

Fish habitat

The underlying assumption of the first problem class is that providing habitat within acceptable limits for selected fish species will protect fish populations, as well as the ecosystem. These optimizations focus on measurements of the abiotic environment, rather than the aquatic biota themselves. In some cases, fish habitat is defined in terms of hydraulic properties of water velocity and depth. In cases where water quality is an important limiting factor for fish habitat, relationships are established between flow and the limiting water quality parameter such as dissolved oxygen (DO) or temperature. The water quality approach has several advantages: (1) water quality is easy to measure, (2) tolerance limits for water quality variables are available for many aquatic species and (3) relationships between water quality and flow are relatively easy to quantify. Quantifying hydraulic fish habitat relationships, as described below, is much more difficult. Furthermore, fish population health shows a stronger relationship with water quality than with hydraulic habitat requirements, unless flows are extremely low. One might consider that adequate water quality is an absolute requirement. Once this is met, the presence of suitable combinations of depth and velocity play a secondary role in ensuring population health.

Natural flow regime

The second problem class adopts the philosophy that healthy river ecosystems require a natural range of variation in flow (Poff *et al*., 1997; Baron *et al*., 2002). The objective of these methods is to recreate natural variation in flow, while meeting constraints on water supply. This approach addresses an important failing of the habitat-based approach: the fact that maintaining the diversity of slackwater and channelized habitats with a suitable composition of substrates requires occasional channel-shaping flows, rather than simply a constant 'optimal' flow or non-optimal minimum flow. This is particularly important downstream of projects with large diurnal fluctuations, where a lack of rearing habitat for juvenile fishes can be devastating (Bain *et al*., 1988; Bowen *et al*., 1998).

Fish population

The third problem class focuses on model-predicted responses of fish populations to flow. This approach assumes that the model(s) used correctly reflect the important mechanistic effects of flow on fish and will result in the maintenance of healthy fish populations.

REVIEW OF OPTIMIZATION APPROACHES THAT INCORPORATE ENVIRONMENTAL GOALS

Homa *et al*. (2005) reviewed multi-objective optimization of reservoir operations, noting that only three included ecological objectives other than minimum flow constraints. In this study, we also found that nearly half of the studies (14 of 29) addressed environmental flows by including a constraint on minimum flow releases. Methods used to formulate and solve optimizations depended on the problem class (i.e. which environmental goals were addressed). Reservoir optimization methods for each of the three problem classes (habitat quantity, indices of hydrologic alteration and model-predicted fish population size) are described below.

Problems that target habitat goals

Optimization studies with fish habitat goals characterized either hydraulic or water quality aspects of habitat.

Hydraulic habitat goals. The most common way that habitat-based goals are considered by water allocation problems is to impose minimum flow constraints. A minimum flow is loosely defined as the smallest amount of flow that can be left in the river without harming downstream fish populations. In the USA, relationships between flow and two hydraulic variables, velocity and depth, are combined with fish preferences for habitat in depth-velocity space. This results in a relationship between the amount of suitable habitat and flow (Stalnaker, 1979; Bovee, 1982). Relationships between the quantity of suitable fish habitat and flow have been used to select regulatory minimum flows in numerous rivers (see, for example, Gibbins and Acornley, 2000). Because habitat-flow relationships are often unimodal with respect to riverflow (little suitable habitat is available when flows are very high or low), an optimal flow release for the downstream fish population or optimal range of flows, often exists.

Reservoir optimizations that consider hydraulic fish habitat nevertheless fail to produce solutions that are optimal for fish habitat for several reasons. First, relationships between flow and habitat are not specifically incorporated in reservoir optimization. Instead, fish habitat typically enters the problem via a constraint on flow releases at each time step. This minimum flow is not to the optimal value for fish, but rather a legally required value, usually arrived at through compromise among alternatives proposed by stakeholders in the hydropower licensing process and approved by hydropower regulators. Second, the environmental minimum flow is only one among several water demands considered as part of a multi-criterion decision problem.

Optimal flow releases (through the turbines of one or more projects) are typically defined as those that maximized energy production or value, while meeting water demands (e.g. Ryu *et al*., 2003; Harman and Stewardson, 2005). The details of implementation varied among studies that we reviewed. Studies that focused on economic issues used monetary objectives and dynamic programming methods (Edwards *et al*., 1999; Hodge, 2001). Some optimizations minimized flow deficits, rather than setting a hard constraint (Escudero, 2000; Bessler *et al*., 2003). For these, violations of minimum flow regulations were possible, particularly if minimum flows constraints were not assigned a high priority relative to other, non-environmental constraints.

Water-quality habitat goals. Water quality was another environmental factor considered in water allocation problems involving reservoir operations. Low DO in eutrophic reservoirs can kill fish and other aquatic biota, both in the reservoir and in the downstream tailwater (e.g. Chang *et al*., 1992). Higher flow releases prevent stagnation and reservoir stratification, thereby improving water quality in the upstream reservoir. Spill flows (non-generating flows not released through turbines) can ameliorate water quality downstream by re-oxygenating the water. We reviewed three studies that varied dam releases with the objective of meeting water quality objectives in reservoirs (Ward and Lynch, 1996; de Azevedo *et al*., 2000; Chaves *et al*., 2003). Examples of water quality criteria included in their objectives were: (1) to maintain sufficiently high levels of DO and (2) to maintain sufficiently low levels of phosphorus, nitrogen, biological oxygen demand, faecal coliform and chlorophyll.

Three studies in this category focused on temperature: Carron (2000) found transient, short-term (6 h) release volumes to minimize deviations from temperature optima for two fish species in the Green River, CO (pike minnow and trout), given cold reservoir release temperatures. Because of diurnal variation in air temperatures, pulse flows were found to be more effective than a constant minimum flow. Neumann *et al*. (2002) minimized violations of upper thermal criteria in the Truckee River, Nevado. Another study used an integer programming approach to choose selective withdrawals from different depths to avoid temperature violations (Willey *et al*., 1996).

Regulated flows also play an important role in maintaining non-river ecosystems, including wetlands and estuaries (Figure 2). When freshwater inflows to estuaries are too low, saltwater intrusion can lead to a loss of less mobile species or life stages (e.g. shellfish, juvenile fishes in nursery areas) with limited saltwater tolerance as the salinity gradient moves upstream. Quite a number of studies have addressed this question, as evidenced by a recent journal issue devoted to the topic (Estuaries Vol. 25, Issue 6B). Schluter *et al*. (2004) used a non-linear programming approach to minimize deficits in water deliveries. The main ecological concern was providing sufficient freshwater to the Amudarya River delta during low water years to prevent saltwater intrusion from the Aral Sea. At least three studies have considered the problem of determining freshwater inflows needed to maintain healthy estuarine ecosystems in Texas using a variety of methods (Li and Mays, 2000; Powell *et al*., 2002, and Ji and Chang, 2005). Li and Mays (2000) used an optimal control method to determine daily freshwater inflows to maximize harvest in three fisheries and to minimize violations of constraints on salinity and monthly inflows. Shellfish harvest was estimated using simple linear regression relationships with monthly inflows, but a complex hydrodynamic salinity model was required to estimate derivatives of salinity at a number of locations with respect to flow. A similar approach was used by Powell *et al*. (2002) to maximize fish and shellfish harvest in several Texas estuaries. Ji and Chang (2005) used empirical models to relate estuary salinity to fish harvest when solving for

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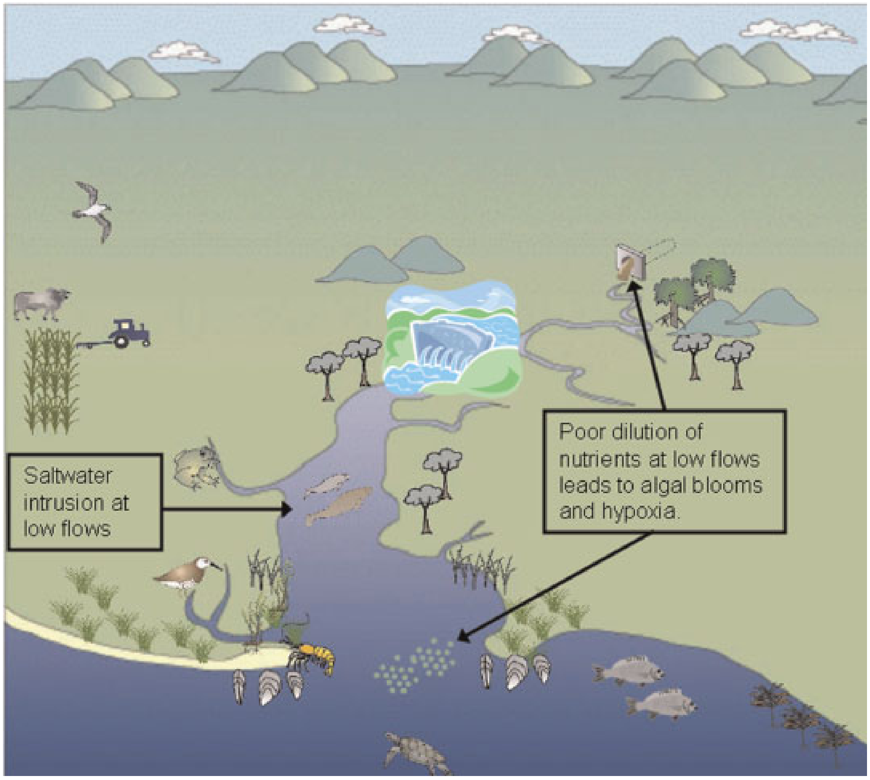

Figure 2. Effect of flows on water quality in coastal rivers and estuaries. This figure is available in colour online at www.interscience.wiley.com/journal/rra

freshwater inflows needed to sustain the estuarine fishery while supplying water for municipal drinking water and irrigation. In another example, Draper *et al*. (2003) used the real-time CALVIN model to implement an optimization with two constraints on flow releases: (1) mandated increases in flow to the Kern wildlife refuge in California and (2) mandated seasonal reductions in flow to the San Francisco Bay to protect salmon from entrainment into pumps used for water supply during their migration to sea. In a similar study, Jenkins *et al*. (2004) used the CALVIN model to address a variety of environmental goals, including dust suppression in Owens Lake and Mono Basin in California, minimum flows to wetlands and mandated reduction in Delta exports in San Francisco Bay during outmigration of Chinook salmon.

In most cases, these problems treated water quality as a constraint or a penalty term in the objective, rather than as an objective. When considered as a penalty term, significant violations have been observed in the solutions (e.g. Pulich *et al*., 2002). Because water quality is such an important absolute requirement for survival of fish and other aquatic biota, it might be more appropriate to give water quality goals priority over hydraulic habitat goals in multi-objective optimization.

Problems that target a natural flow regime

The role flow variability plays in maintaining the ecological health of rivers is beginning to be appreciated and incorporated as a goal in reservoir operation. Natural flow variability was considered as an objective by several studies (Shiau and Wu, 2004; Homa *et al*., 2005). One approach, using the PeakShave programme, considered regulatory restrictions on ramping and diurnal fluctuations, as well as minimum flows (Harpman, 1999). Homa *et al*. (2005) minimized the ‘ecodeficit’, defined as the area between unregulated and regulated flow duration curves at low exceedence probabilities (Figure 3). The ecodeficit is also the net volume of water now unavailable for instream flow needs due to water withdrawals. Shiau and Wu (2004) considered trade-offs between minimizing the

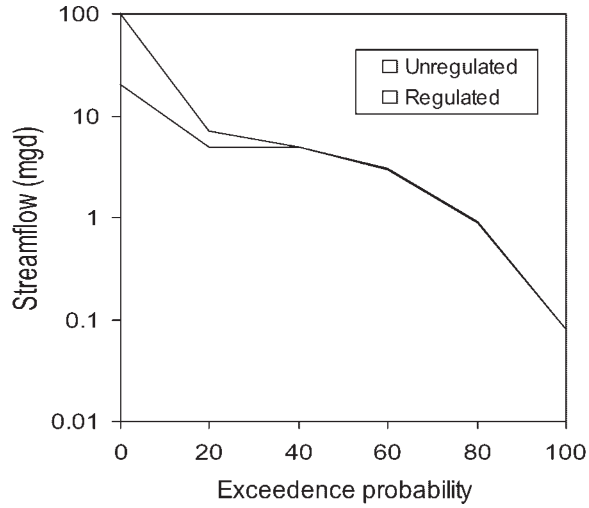

Figure 3. Definition of an 'ecodeficit'. Redrawn with permission from Homa *et al.* (2005)

degree of hydrologic alteration and minimizing water shortages, where hydrologic alteration was measured by the range of variability (RVA) approach. One advantage of the RVA approach is that the objective of statistically reproducing flow variation is almost trivially easy to quantify, and run-of-river operation is clearly a solution in cases when there is no upstream storage or water withdrawal.

However, the assumption that 'natural flows' are best for aquatic ecosystems is a tautological argument that depends on the idea that evolution has perfected the adaptation of the extant community to historical conditions and that any future change is undesirable and harmful to the ecosystem. Considerably larger investments in research would be needed to move beyond this assumption. However, a more scientific approach would seek to understand the admittedly complex relationship between flow regime and river ecosystems. A few attempts have been made to identify important aspects of the flow regime to fishes. For example, Hughes *et al*. (1997) developed a heuristic method of reproducing the 'essential components of flow'—base flows, freshets and small-medium sized floods by setting monthly low and high flow targets and a target high flow duration. Natural flows are used to guide the timing of high flow events in Hughes' approach. Suen and Eheart (2006) used a similar approach, but instead of assigning the highest value to statistically natural flow regimes, they defined ecohydrologic indicators based on the intermediate disturbance hypothesis, which predicts that species diversity will be highest when the frequency of disturbance is intermediate, as proposed by Connell (1978). Suen and Eheart assigned high ecological value to flow regimes with intermediate values of six ecohydrologic indicators (annual trend, dry season 10-day minimum, wet season 3-day maximum, number of high-flow events, mean duration of low-flow events and mean rate of flow increase).

Problems that target fish population viability

Although fish habitat goals are relatively easy to calculate or predict as a function of flow, different life stages of a fish species require different hydraulic and water quality conditions. Although simpler methods have been suggested for combining lifestages (Orth and Leonard, 1990), population models provide a more sophisticated alternative for integrating flow influences over life stages. Optimization studies that considered fish population viability either (1) included hydropower objectives with simplified, habitat-based fish objectives or (2) focused on more-detailed relationships between reservoir releases and fish, but neglected hydropower objectives. Two studies in the second category used population models for fall Chinook salmon in tailwaters to estimate optimal flow regimes to maximizing salmon recruitment. Both studies concluded that flow regimes with higher flows in spring and fall would benefit salmon populations most (Bartholow and Waddle, 1995; Jager and Rose, 2003). Jager and Rose (2003) also solved for a flow regime to maximize the diversity of spawning times (different 'runs')

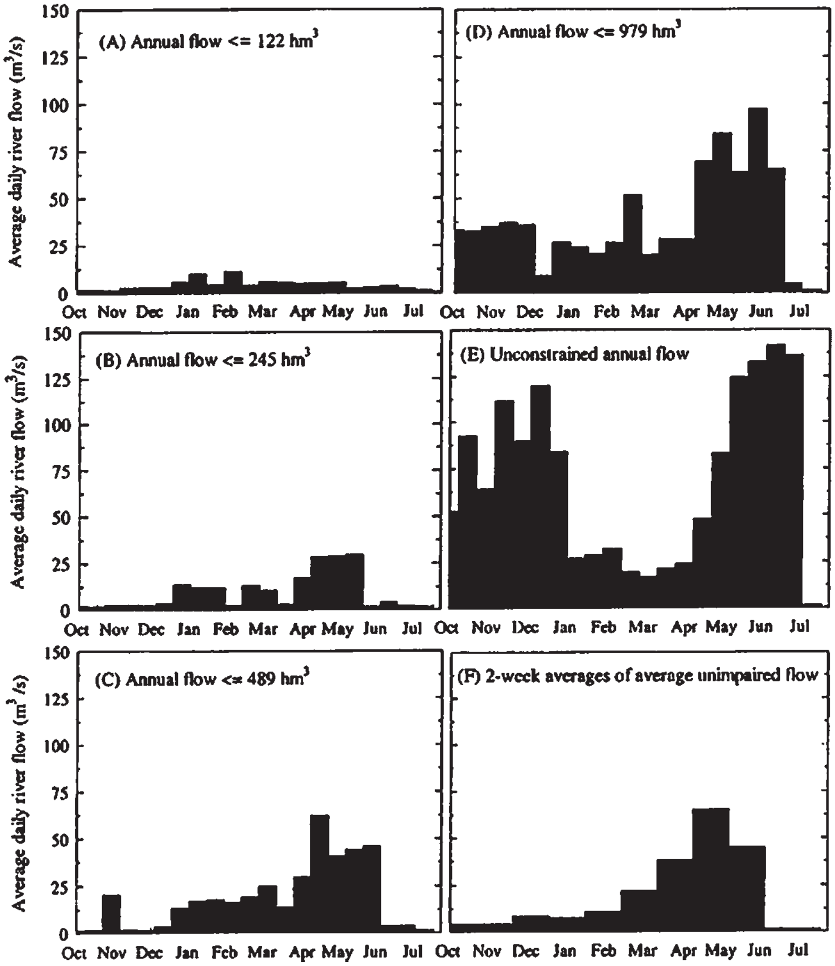

Figure 4. Optimal flow regimes that maximized the simulated recruitment of fall Chinook salmon smolt outmigrants for five scenarios representing a range of constraints on annual river flow (A–E). These can be compared with (F) the 2-week averages of natural flows. ($1\ \mathrm{hm}^3 = 10^6\ \mathrm{m}^3$ year). Source: Jager and Rose, 2003

represented among salmon that survived to migrate out of the river. The optimal flow regime for this problem included a pulse flow for adults of the smaller, late-fall Chinook run migrating upstream to spawn (Figure 4). Neither study explicitly considered the feasibility of solutions in terms of reservoir operations and competing water uses. However, the Jager and Rose study considered how flow regimes predicted to maximize salmon production differed when constrained by a range of levels of annual flow. Optimal flow regimes differed for wetter and drier years, with larger blocks of water first allocated in spring, then fall, as total annual flow increased (Jager and Rose, 2003).

The fact that pulse flows were found in the solutions above, without being requested as targets, suggests that providing a fixed minimum flow year-round does not always result in the best ecological outcome. Two studies, which we classified as minimum-flow constrained, also considered pulse flows as objectives. Harman and Stewardson (2005) optimized the use of tributary inflows to meet environmental targets in both baseflow and pulseflow in a regulated Australian river. The optimization produced a rule for initiating pulse flows when tributary inflows below the dam exceeded a threshold. However, results showed that optimal use of tributary flows to meet pulse flow targets reduced overall flow variability. In another study, Zagona *et al.* (2001) used RIVERWARE to analyse the potential for future pulse flows below Glen Canyon Dam on the Colorado River.

These two studies above used an optimal control framework (Figure 5) in which a fish population model was used in conjunction with a heuristic optimization algorithm (see Nicklow, 2000). Optimal control provides the flexibility

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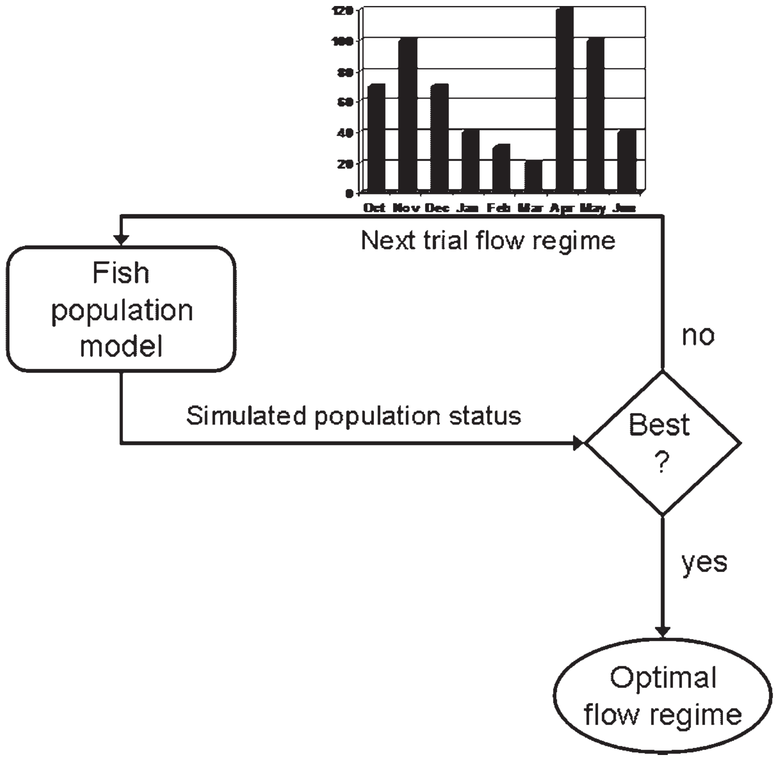

Figure 5. An optimal control framework for identifying optimal flow regimes for fish combines heuristic optimization methods with simulation models of fish population response

to use complex ecological models without sacrificing realism in representing the response of fish populations to flows.

Only a few studies developed comprehensive methods that consider both environmental objectives and other water demands. However, this was accomplished by simplifying ecological responses to flow. Sale *et al*. (1982) provide the earliest example of a formal optimization involving an environmental objective. Fish habitat was maximized for the limiting life stage. Bovee's (1982) method was used to estimate the amount of weighted usable area (WUA) for each fish life stage. Compared with current operations, the optimal solution suggested further draw down in the winter to permit storage of spring runoff to supplement low flows later in the year (Sale *et al*., 1982). One of the advantages of the approach presented by Sale *et al*. is that its solutions are found within a feasible space of storage reservoir operation. In a similar approach, Cardwell *et al*. (1996) combined two objectives: maximizing the habitat capacity for juvenile Chinook salmon, as estimated by WUA (Figure 6), and minimizing water supply shortfalls.

SCALE, UNCERTAINTY AND SUSTAINABLE OPERATION

Uncertainty has real effects on reservoir operation. By reducing uncertainty in reservoir inflows, operators can allocate less reservoir space for flood storage and increase the water provided for instream flows (Hamlet and Lettenmaier, 1999). Reservoir inflow, which depends on precipitation and runoff, was the main source of uncertainty in the water allocation problems reviewed here. Advances in long-term hydrologic forecasting can reduce uncertainty in reservoir inflows.

Uncertain inflows are handled differently in real-time and longer-term optimizations. Longer-term approaches consider uncertain inflows either by simulating historical flow regimes or by drawing flows from a flow-duration curve describing historical flows (e.g., Sale *et al*., 1982). Real-time approaches begin with mid-term monthly

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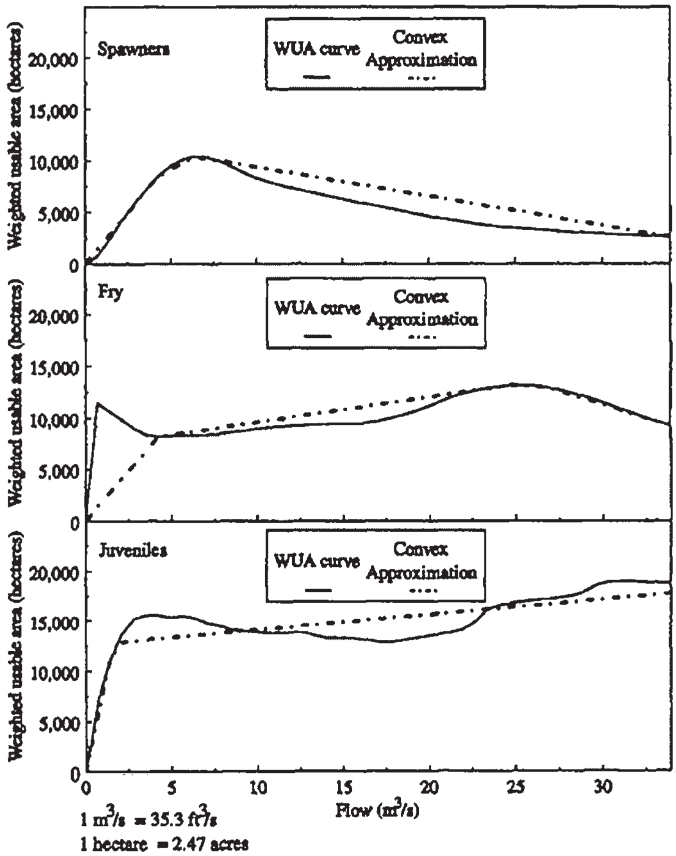

Figure 6. Flow versus habitat relationships and their convex piecewise approximations for three lifestages of Chinook salmon. Source: Cardwell *et al*., 1996

forecasts, and correct these projections over time. Uncertainty is minimized by operating over a short time horizon. Fluctuations in the value of hydropower are a second source of uncertainty for optimizations that use a monetary currency.

We believe that uncertainty associated with ecological responses to flow could be as great as that associated with reservoir inflows or hydropower markets. However, uncertainty in ecological responses to flow was considered in only a few of the studies we reviewed. Uncertainty in model-predicted water quality was considered in two studies (Carron, 2000; Vernula *et al*., 2004). Uncertainty in model-predicted fish recruitment was considered by Jager and Rose (2003).

Implementing sustainable reservoir operation will require efforts to make theoretical tools useful in practice, and will involve overcoming cultural and communication barriers between more-theoretical quantitative ecologists and more-practical engineers. We observed that real-time optimization schemes used in practice and theoretical schemes that provided guidance, but were not used to operate reservoirs served two different purposes. Theoretical studies had the goal of understanding a complex, multi-criterion problem, including the trade-offs involved and deriving general principles that could be used to guide operation of hydro-eco systems. Practical studies described new applications of existing decision support software adapted for the real-time operation of a particular hydro-eco system.

The two approaches differed in how they treated uncertainty. Studies interested in long-term predictions examined the influences of stochastic inflows, characterized by long-term historical records or a statistical model thereof (e.g. Sale *et al*., 1982; Lund and Ferreira, 1996; Newlin *et al*., 2002). This approach is very appropriate for evaluating the effects of climate change (e.g., Lettenmaier *et al*., 1999). Studies designed for real-time operation managed uncertainty in reservoir inflows by using a short time horizon.

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How can we help theoretical approaches to sustainable operation transition into practical tools for real-time reservoir operation? To implement an optimal flow regime, one must either find real-time solutions or extract seasonal operating rules from solutions to use in real-time decision support (Labadie, 2004). Smith *et al*. (2007a) propose that approaches using optimal control would be relatively easy to convert because they use simulation methods and can be modified to incorporate real-time inflows.

DISCUSSION

Most studies that consider environmental objectives associated with water allocation are multi-objective optimization problems. However, several short-term objectives can be combined into a single long-term goal of sustainability (Labadie, 2004). Discrepancies in the time horizons associated with energy and ecological objectives make it difficult to find integrated solutions. Ecological objectives tend to involve much longer time horizons than energy supply objectives. We would consider a hydropower project to be ecologically sustainable if the impoundment and flow regimes associated with it are operated decades into the future without environmental damage, such as loss of species.

The traditional approach of representing habitat requirements via constraints on minimum flow has advantages and disadvantages. The first advantage of this approach is that it assumes that the regulatory agencies have already quantified the ecological benefits of flow and used these in setting regulatory minimum flow releases. A second advantage is that it uses flow as a common currency, which simplifies combining environmental with non-environmental objectives. However, using regulatory minimum-flow constraints does not ensure that goals for fish habitat will be met for several reasons. First, as Loomis (1998) pointed out, setting minimum flows is a political process that balances environmental objectives with other, potentially conflicting goals. Consequently, it is unclear to what extent the goal of providing fish habitat is really addressed.

The choice of currency and valuation of ecological health is an important issue in optimizations that consider multiple criteria. Few studies used monetary values as a common currency in optimization, but results of several studies are relevant to the relative valuation of energy (Ward, 1987; Ward and Lynch, 1996; Edwards *et al*., 1999; Hodge, 2001; Newlin *et al*., 2002; Draper *et al*., 2003). Most of these focus on producer costs—the value of foregone energy production by hydropower owners. Hodge (2001) noted that the value of hydropower to consumers should be valued as the difference between the price of electricity produced by hydropower and the price of fossil fuels that would otherwise be purchased. The timing of flow releases during peak demand results in a price differential that increases the value of hydropower (Edwards *et al*., 1999). The economic costs of environmental flow requirements in the Trinity River, California were estimated by Newlin *et al*. (2002) and Draper *et al*. (2003) were considerably higher on the regional water market than on the statewide water market, suggesting that managing water allocation at the state level could significantly reduce the cost of environmental flows. Minimum flows and ramping rate requirements tend to reduce the proportion of flow and generation during peak demand, lowering the value of hydropower (Edwards *et al*., 1999). Harpman (1999) suggested that ramping rates have a larger economic impact than minimum flows in the Colorado River.

Although increased instream flows typically decrease hydropower revenue (producer costs), they may increase aggregate benefits to society. Loomis (1998) determined that the value of instream flows as aquatic habitat is higher than is assumed by most studies. Willingness-to-pay surveys showed that optimal flows (flows at which the value to the river ecosystem equals the opportunity cost of foregone hydropower or agriculture) are often significantly higher than minimum flows specified by law. A comprehensive ex-post analysis of the economic impacts of relicensing on the Manistee River determined that the aggregate benefits to society of flow-related license modifications were more than twice the cost to producers (Kotchen *et al*., 2006). This example illustrates that different results are obtained when optimizations using economic objectives focus exclusively on producer costs and when societal gains, such as avoided air pollution damage and benefits to recreational fisheries, are considered.

Multi-criterion decision analysis has been used to choose between a finite number of alternative flow regimes based on preference-based values assigned to different criteria, including those involving endangered species and other wildlife values. Flug *et al*. (2000) had stakeholders assign preferences for different flow regimes at Glen Canyon Dam, CO associated with their effects on a long list of criteria. Although decision theoretic approaches are

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not optimizations, *per se*, these studies address the question of how to value environmental flows relative to alternative water uses.

The role of optimization in reservoir operation has increased substantially. Optimization models played a relatively minor role in the past, with reservoir releases operated mainly on the basis of predefined rules tested using simulation models (Bessler *et al*., 2003). At present, most major river systems use optimization to identify the preferred release schedule, and refine this schedule using simulation. Even small river systems are now using optimization-based decision support systems. Because of this trend to rely on optimization, better methods are needed to incorporate ecological values as objectives. Among the approaches we reviewed, only real-time, minimum-flow-constrained methods using optimal control are actually in use. It is unlikely that any of the methods that incorporated population or water quality models is currently used to operate reservoirs. This suggests that further development and testing is needed to make these methods useful to the hydropower industry.

The three greatest barriers to progress are (1) the valuation of ecological benefits, (2) understanding the ecological effects of flow releases sufficiently well to quantify them and (3) lack of incentive for power producers. Valuation of river ecosystems and their services is one important area of research needed to facilitate implementation of reservoir optimizations that include ecological benefits (see Efroymson *et al*., 2007). When economic and power values are contrasted with ecological benefits, the latter tend to be devalued simply because they are difficult to quantify using a single currency. This difficulty of projecting multi-dimensional ecological benefits onto a plane tempts us to neglect them altogether. Valuation methods tend to be subjective and often appear to reflect the bias of the individual assigning value, rather than being founded on well-accepted, internally consistent principles. Nevertheless, scientifically defensible valuation methods exist, and have been applied to reservoir operation (e.g. Kotchen *et al*., 2006).

The second barrier is the lack of predictive power concerning the relationship between reservoir releases and ecological benefits. One important future research direction will consider the role of flow variability as it contributes to the ecological health of rivers. A scale-independent assessment of hydro-geomorphic impacts of 21 dams across the United States, found that their flow regimes changed profoundly (Magilligan *et al*., 2003). Recent efforts have been made to optimize flows by using the natural flow duration curve as a target (e.g. Shiau and Wu, 2004; Homa *et al*., 2005; Suen and Eheart, 2006). However, much of the science to support this paradigm suffers from tautological thinking (see Peters, 1976) in that it assumes that deviations from a natural flow regime are bad, but does little to understand why. Research directions should focus on understanding what components of flow regimes are most important for maintaining a healthy river and defining quantitative methods for meeting objectives that consider those critical components. For example, Magilligan *et al*. (2003) determined that restoring the frequency of pre-dam 5-year floods would provide high-enough flows to prevent disconnection of the riparian zone from river influence, independent of region, dam type or catchment size. In a study with similar objectives, Bovee *et al*. (2004) used hydraulic modelling to identify and protect 'persistent habitats' (patches of river that remain suitable over a wide range of flows). Such habitats are important for mussels and other sedentary organisms, which are often the first groups extirpated following impoundment.

The final barrier is the incentive structure for power producers, which is focused on producer value and neglects other societal values unless these are provided for by regulation. According to Nicklow (2000), the societal importance of environmental objectives is increasing far beyond those of singular commodity and amenity goals. After all, it makes little sense to discuss the sustainable use of water resources unless systems are managed using an integrated multi-objective strategy that incorporates environmental objectives (Nicklow, 2000). Progress will come by determining how to combine multiple short-term objectives into the one single, shared objective of long-term sustainability.

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