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FISH HABITAT OPTIMIZATION TO PRIORITIZE RIVER RESTORATION DECISIONS

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ABSTRACT

This paper examines and ranks restoration alternatives for improving fish habitat by evaluating tradeoffs between fish production and restoration costs. Optimization modelling is used to maximize out-migrating coho salmon (*Oncorhynchus kisutch*) from a natal stream and is applied as a case study in California's Shasta River. Restoration activities that alter flow and water temperature conditions are the decision variables in the model and include relocating a major diversion, increasing riparian shading, increasing instream flow, restoring a cool-water spring and removing a dam. A budget constraint limits total restoration expenditures. This approach combines simple fish population modelling with flow and water quality modelling to explore management strategies and aid decision making. Previous fish habitat optimization research typically uses single restoration strategies, usually by altering reservoir releases or modifying outlet structures. Our method enlarges the solution space to more accurately represent extensive and integrated solutions to fish habitat problems. Results indicate that restoration alternatives can be prioritized by fish habitat improvement and restoration cost. For the Shasta River case study, considerable habitat restoration investments were required before fish productivity increased substantially. This exercise illustrates the potential of ecological optimization for highlighting promising restoration approaches and dismissing poor alternatives. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: optimization; water management; restoration; salmon; habitat; instream flow; water temperature

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INTRODUCTION

Water resources are managed for multiple and competing uses, such as water supply, hydropower, flood control, recreation and environmental protection. Although human water uses have taken precedence in the past, rivers are now increasingly managed to support aquatic ecosystems and fisheries, in addition to traditional human water demands. Recent trends of valuing environmental water uses and services, combined with climate change and population growth, ensure that river management will continue to be highly constrained in the future and improving system performance will be an ongoing need.

Optimization is an approach to water resource systems analysis that explicitly seeks the best solution to a problem within constraints. It helps decision makers identify a better course of action than might otherwise have been found for complex problems when flexibility exists in systems (Labadie, 2004). An objective function expresses the goal of the model, which is maximized or minimized to arrive at an optimal solution. Constraints define the feasible region. The objective function and constraints are mathematical functions of decision variables and parameters. Decision variables are changeable values, limited by constraints, which are decided by optimization, and parameters are given (Hillier and Lieberman, 1967).

Until recently, environmental objectives were omitted from optimization models or modelled as constraints of legally required minimum instream flows to remove them from economic valuation and decision making (Draper *et al.*, 2003; Jenkins *et al.*, 2004). Over the past two decades, optimization models that include environmental objectives have been developed (Sale *et al.*, 1982; Cardwell *et al.*, 1996; Jager and Rose, 2003; Watanabe *et al.*, 2006). These are increasingly needed as systems are operated more tightly for urban and agricultural efficiency, hydropower, environmental sustainability, fisheries production and water quality (Labadie, 2004).

Environmental objectives in river optimization models vary between optimizing reservoir releases for downstream water quality (Neumann *et al.*, 2006), optimizing natural flow variability in regulated rivers (Harpman, 1999; Shiau and Wu, 2004; Homa *et al.*, 2005) and optimizing fish population viability with different hydraulic and water quality conditions (Sale *et al.*, 1982; Bartholow and Waddle, 1995; Paulsen and Wernstedt, 1995; Cardwell *et al.*, 1996; Jager and Rose, 2003; Watanabe *et al.*, 2006; Jager and Smith, 2008). We focus here on fish population optimization modelling. One striking feature of previous

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research is that the scope has been fairly narrow, with a primary focus on re-operating reservoirs for environmental benefits.

Sale *et al.* (1982) optimized fish habitat for multiple fish life stages by altering reservoir releases from one dam while modelling human water objectives as constraints. Cardwell *et al.* (1996) used multi-objective optimization to improve water supply reliability and available hydraulic fish habitat for multiple fish life stages in a simple reservoir-stream system by evaluating different instream flow prescriptions. Bartholow and Waddle (1995) and Jager and Rose (2003) did similar studies analysing seasonal flow regulation from a dam by pairing flow optimization with a Chinook salmon recruitment model where flow, water temperature and habitat capacity varied longitudinally. Jager and Smith (2008) provided a review of reservoir optimization studies that also consider downstream environmental protection. Watanabe *et al.* (2006) optimized riparian vegetation criteria rather than reservoir operations, although the solution space still was limited to a single restoration strategy. They paired simulation and optimization modelling to estimate efficient allocation of riparian vegetation to decrease water temperatures and protect salmon populations, given budget constraints.

The work by Paulsen and Wernstedt (1995) is notable because they used simulation and optimization to minimize costs of many salmon recovery measures, such as improving passage around barriers, improving spawning and rearing habitat and reducing harvest from the ocean, rivers and tributaries in the Columbia River Basin. A simulation model compared fish survival with different restoration alternatives, and optimization was used to minimize costs given the restoration decisions. Although this study was unique because it evaluated the cost and effectiveness of many diverse restoration options, it was cumbersome because it relied on a simulation model of each restoration action, as well as combinations of actions for input into the optimization model.

In this paper, we describe an optimization model that maximizes fish production subject to suitable flow and thermal habitat, where restoration alternatives improve instream flow and water temperature conditions. We apply our method using a case study maximizing fish habitat for one fish species based on coho salmon (*Oncorhynchus kisutch*) requirements in California's Shasta River. The model does not consider other human water uses but is constrained by restoration costs. By valuing the benefit to fish habitat with restoration costs, instream flow prescriptions and restoration decisions can be considered and evaluated in the context of water resource planning and management. This method could be used to model additional species or multiple rivers, although we modelled only one species for this proof of concept application.

We use a broader approach than most previous ecological optimization studies where decisions are limited to reservoir operation or other single-strategy restoration approaches and which can overly constrain problems to the solution area of only one party (i.e. water suppliers). The range of solutions in our formulation includes decisions for a variety of restoration alternatives and is broadly applicable to other rivers with fisheries problems requiring innovative river management. This approach quantifies habitat improvements from restoration alternatives to weigh decisions, prioritize proposed restoration actions and manage limited environmental water and budget allocations efficiently and creatively.

This paper begins with an overview of the Shasta River study site and biology of coho salmon. A description of the optimization model follows, including formulation and discussion of decision variables, economic costs, and limitations. Overall, results indicate that the tradeoff curve between restoration costs and habitat improvements is not smooth, some alternatives create large habitat or cost increases. Restoration costs are not indicative of habitat improvement, some relatively cheaper alternatives provide better fish habitat than more expensive alternatives. For the Shasta River case study, options exist to restore coho salmon habitat, although considerable investment is required before coho salmon populations increase substantially. This paper ends with a discussion of major findings and applications for this type of work.

BACKGROUND

Shasta River study site

The Shasta River is in Siskiyou County, California, and is the last major tributary to the Klamath River before Iron Gate Dam, the lowest dam on the Klamath River (Figure 1). Water quality and passage barrier problems in the Klamath River make major tributaries, such as the Shasta, Scott, Salmon and Trinity Rivers, important for the health and survival of native fish species. Historically, the Shasta River had a baseflow of approximately $5.7\,\mathrm{m^3\,s^{-1}}$ with higher flows during winter storms and spring runoff (National Research Council; NRC, 2004).

Today, water development and land-use practices have reduced flow to as little as $0.6\,\mathrm{m^3\,s^{-1}}$ in late summer and early fall. Fish productivity in the Shasta River is limited by low flow conditions and warm water temperatures. Low flow conditions are caused by surface water diversions, groundwater pumping and construction of the Dwinnell Dam. Increased water temperatures are primarily from low flows, loss of riparian vegetation, tailwater return flows and diversion of cooler springwater inflows. Additional habitat problems exist, such as gravel recruitment, barriers to migration and turbidity (NRC, 2004). There are four large

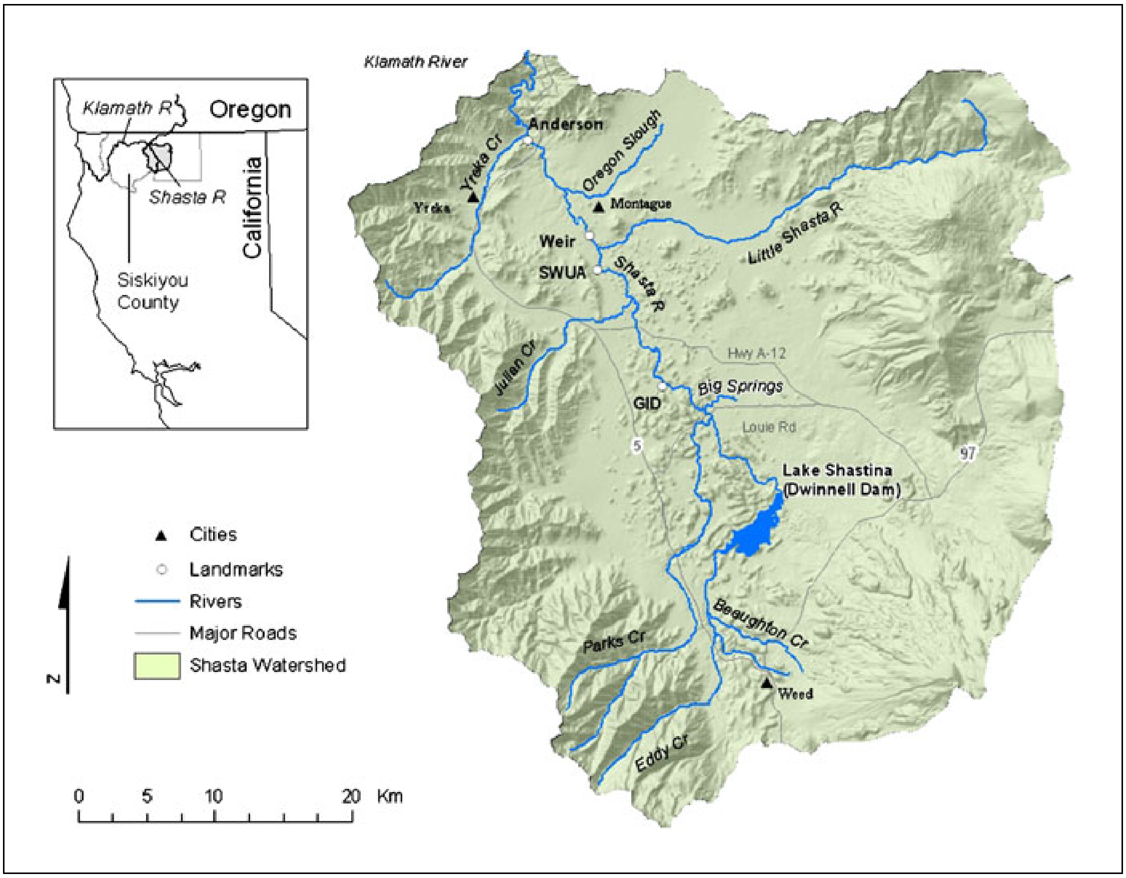

Figure 1. Shasta River watershed.

diversions from the Shasta River during the April–September irrigation season, belonging to the Montague Water Conservation District (MWCD), Big Springs Irrigation District (BSID), Grenada Irrigation District (GID), and Shasta Water Users Association (SWUA). There are also numerous small and moderate diversions throughout the basin.

The Dwinnell Dam, the only major dam on the Shasta River, impounds Lake Shastina at river kilometer (rkm) 65.4 (Figure 1). The Dwinnell Dam has a maximum capacity of 61 700 000 m^3 and is operated by the MWCD, providing water for agricultural users and the city of Yreka. Built in 1928, the dam is highly inefficient, losing more water to seepage than it provides to downstream users. Seepage from the dam may boost groundwater recharge in the watershed but may also raise water temperatures of groundwater springs. In addition to Shasta River headwaters, approximately 18 500 000 m^3 from Parks Creek is diverted to Lake Shastina in all but the wettest years, and the dam spills infrequently (i.e. 1964 and 1997) (Vignola and Deas, 2005). During dry years, the reservoir falls below dead storage.

Approximately 11 rkm downstream from the Dwinnell Dam is the confluence of Big Springs Creek. Big Springs is part of an extensive spring system, which prior to water development, provided the Shasta River with a constant 2.9 $m^3 s^{-1}$ of 11 °C water to the Shasta River (Mack, 1960). Today contributions from Big Springs Creek are approximately 2.0 $m^3 s^{-1}$ because of water diversions. Although the main spring source is only 3 rkm upslope from the Shasta River, lower flows combined with poor tailwater management and lack of riparian shading cause water temperatures to exceed 25 °C at the confluence with the Shasta River (NCRWQCB, 2006).

Coho salmon distribution and life history

Coho salmon are distributed throughout the north Pacific Ocean from Russia to Alaska and south along the North American coast. California is the southern extent of their range (Sandercock, 2003). Klamath basin coho salmon belong to the Southern Oregon/Northern California Coast evolutionarily significant unit, which was listed as federally threatened by the National Marine Fisheries Service in 1997 (NMFS, 1997).

Coho salmon have a 3-year life cycle and typically leave the ocean to begin spawning as early as September, although in the Shasta River most spawning occurs in November and December (CDFG, 2008). Redds may contain up to 3000 eggs, which incubate in gravels from approximately November to April. Alevins, a life stage in which hatchlings depend on a yolk sac for food, remain within gravel near redds for 2–10 weeks and prefer water temperatures between approximately 4 °C and 13 °C (McCullough, 1999). Juvenile coho salmon begin actively feeding as they enter the fry life stage beginning in February. Fry initially congregate together in shallow, low velocity water but separate and move to faster water as they grow. Fry typically rear in fresh water for an entire year and may move upstream or downstream to seek suitable habitat. Preferred water temperatures for juvenile coho salmon are approximately 12–14 °C. Maximum thermal tolerance is variable and may depend on factors such as stream size, acclimation, duration of thermal maxima and minima, food abundance, competition, predation, body size and condition (McCullough, 1999). Welsh *et al.* (2001) observed coho salmon only in streams with maximum weekly average temperatures below 16.7 °C in California's Mattole Creek, although Bisson *et al.* (1988) observed no mortality when daily maximum temperatures exceeded 24.5 °C in Washington State creeks following the Mount St. Helens eruption (and when cooler thermal refuges existed from groundwater contributions).

Smoltification occurs when juveniles adapt to saltwater and emigrate to the ocean, typically from March to June (CDFG, 2008). Water temperature and flow pulses provide migration cues for smolts. Wedemeyer *et al.* (1980) recommended that water temperatures remain below approximately 12–16 °C so that coho salmon do not emigrate early to escape warm temperatures. In the Shasta River, coho salmon are occasionally observed to smolt as age 0+ juveniles (rather than rear for a year), possibly from high productivity or elevated water temperatures in the system (CDFG, 2008). Coho salmon remain in the ocean growing and maturing before returning to natal streams to spawn, typically as 3-year-olds.

Historically, extensive spring-fed springs made the Shasta River arguably the most productive river in California for Chinook salmon, coho salmon and steelhead trout (Snyder, 1931). The spring-fed river provided cool summer water temperatures and relatively warm winter temperatures, ideal for salmon (NRC, 2004). In general, groundwater-dominated river systems, like the Shasta River, have a more stable flow and thermal regime than those dominated by surface water (Sear *et al.*, 1999). Today fall-run Chinook, coho and steelhead populations have declined drastically, although coho salmon are the only species listed under the Endangered Species Act (NMFS, 1997). Typically, less than 200 coho salmon return to the Shasta River each year, although run size varies, and has been declining in recent years. Forty seven returning adult coho salmon were counted in 2006 (CDFG, 2008), 28 were observed in 2008 and 7 in 2009 (C. Jeffres, University of California, Davis, Davis, pers. comm.). These numbers are not promising for long-term population viability, although if instream habitat were improved, natural stray of coho salmon from other streams would likely recolonize the Shasta River.

METHODS

Often environmental goods, such as fish stocks, are valued economically in mathematical modelling. Although methods of quantifying economic values of environmental goods exist (Loomis, 2000), the model described here was formulated to avoid direct economic valuation of fish production or fish habitat. Because coho salmon are a listed species, the federal government is required to protect coho salmon and their habitat (NMFS, 1997). Thus, maximizing out-migrating smolts is the objective, whereas the costs of proposed restoration activities form a budget constraint and are more readily valued.

Three life stages of coho salmon are modelled using network flow optimization. Weekly average flow and water temperature determine habitat capacity. The model evaluates multiple restoration decisions that decrease water temperature and/or increase instream flow to improve instream habitat for coho salmon. All other habitat considerations except water temperature and flow are ignored here. Decision variables of the model are restoration alternatives that improve habitat. Restoration choices include adding instream flow, improving riparian shading, relocating a major diversion downstream, removing a dam or restoring a large cool-water spring complex. All restoration choices are binary except adding instream flow and improving riparian shading, which are continuous variables. The model is constrained by conservation of mass and heat energy, habitat capacity as a function of instream flow and water temperature (where poor conditions reduce fish production in each life stage), fish demography, upper and lower bounds for instream flow and fish, and restoration costs. The model operates on a weekly timestep and is one-dimensional, so instream conditions change longitudinally but are assumed to be well-mixed laterally and vertically. It was developed in Microsoft Excel using Lindo Systems What's Best commercial solver (Lindo Systems Inc., 2005).

This application has 12 reaches, 10 in the mainstem Shasta River, one above the Dwinnell Dam and one in Big Springs Creek (Figure 2). Reach length varies by natural breakpoints, and average reach length is 8.7 rkm, with minimum and maximum lengths of 3.5 and 35.4 rkm, respectively. Input

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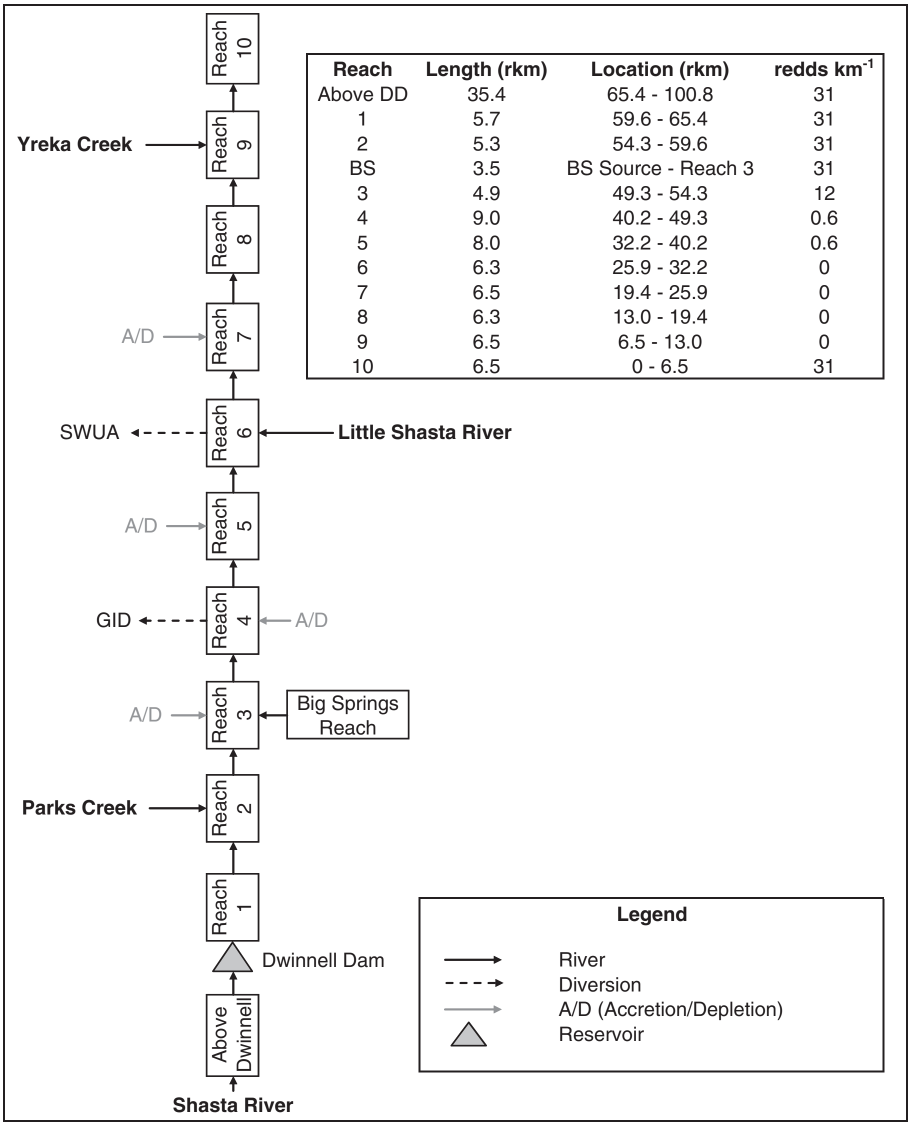

Reach	Length (rkm)	Location (rkm)	redds km^{-1}
Above DD	35.4	65.4 - 100.8	31
1	5.7	59.6 - 65.4	31
2	5.3	54.3 - 59.6	31
BS	3.5	BS Source - Reach 3	31
3	4.9	49.3 - 54.3	12
4	9.0	40.2 - 49.3	0.6
5	8.0	32.2 - 40.2	0.6
6	6.3	25.9 - 32.2	0
7	6.5	19.4 - 25.9	0
8	6.3	13.0 - 19.4	0
9	6.5	6.5 - 13.0	0
10	6.5	0 - 6.5	31

Figure 2. Shasta River model schematic with reach lengths, locations and redds.

data for each reach includes initial flow and water temperature, boundary conditions at tributaries, diversions (including accretions/depletions) and atmospheric heating (Figure 3). Input data are from a simulation model of the Shasta River (Null *et al.*, 2010). Atmospheric heating is applied during summer, and the rate of heating varies with the extent of riparian shading (derived from atmospheric heating rates estimated from 2001 simulated conditions) (Null *et al.*, 2010). Water and heat balances are simulated within the optimization model using a mass balance approach and do not explicitly incorporate thermal mass or travel time. Flow and water temperature at each reach and week determine the habitat capacity for alevin, fry and out-migrating smolts.

Formulation

This model maximizes the number of smolts out-migrating from the Shasta River:

$$\text{Max}F = \sum_{w} F_{a=3,w,r=10} \qquad \text{Maximize smolts} \qquad (1)$$

where $F_{a,w,r}$ is fish (count), a is the fish life stage (life stage three are smolts), w is week and r is river reach (reach 10 is farthest downstream). Fish were modelled as continuous variables rather than integers to speed model run time.

Physical constraints. The objective function is limited by many constraints, including those maintaining the physics

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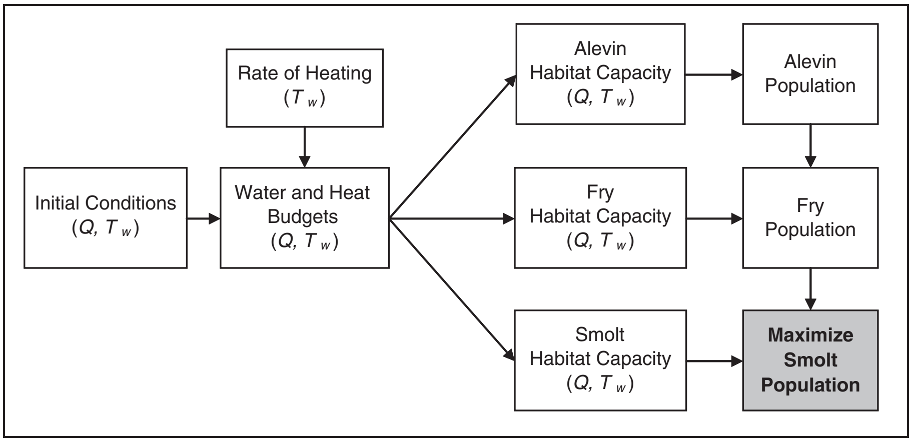

Figure 3. Fish production model flow chart.

of the system, such as conservation of mass and heat energy, and upper and lower bounding constraints.

$$Q_{w,r+1} = Q_{\mathrm{RD}w,r} + b_{w,r}, \forall w, r \qquad \text{Conservation of mass} \tag{2}$$

$$T_{w,r+1} = \frac{Q_{\mathrm{RD}w,r} * T_{\mathrm{RD}w,r}}{Q_{\mathrm{RD}w,r}} + \Delta T_{w,r}, \forall w, r \qquad \text{Conservation of heat energy} \tag{3}$$

$$l_{w,r} \leq Q_{w,r} \leq u_{w,r}, \forall w, r \qquad \text{Flow capacity bounds} \tag{4}$$

$$l_{a,w,r} \leq F_{a,w,r} \leq c_{a,w,r}, \forall a, w, r \qquad \text{Fish capacity bounds} \tag{5}$$

where $Q_{\mathrm{RD}w,r}$ is the flow from a given restoration decision ($\mathrm{m}^3\,\mathrm{s}^{-1}$); $b_{w,r}$ is the additional inflow or outflow such as tributaries, diversions, accretions and depletions ($\mathrm{m}^3\,\mathrm{s}^{-1}$); $T_{\mathrm{RD}w,r}$ is the water temperature from a given restoration decision (°C); $\Delta T_{w,r}$ is the estimated atmospheric heating or cooling within a reach (°C); $l_{w,r}$ is a non-negativity lower bound for instream flow ($\mathrm{m}^3\,\mathrm{s}^{-1}$); $u_{w,r}$ is an upper flow bound ($\mathrm{m}^3\,\mathrm{s}^{-1}$); $l_{a,w,r}$ is a non-negativity bound for fish (count); and $c_{a,w,r}$ is the carrying capacity for the maximum number of fish of each life stage at each week and reach.

Carrying capacity was estimated from user-defined parameters describing the maximum number of fish for each life stage, week and reach.

$$c_{a=1,w,r} = (\alpha_{a=1,w,r} * x_{w,r} * d_{a=1,w,r}) \quad \text{Alevin carrying capacity} \tag{6}$$

$$c_{a\neq1,w,r} = (\alpha_{a\neq1,w,r} * x_{w,r}) \quad \text{Fry and smolt carrying capacity} \tag{7}$$

where $\alpha_{a,w,r}$ is the maximum number of fish per redd (for alevin) or fish per rkm (for fry and smolt) (count); $x_{w,r}$ is the length of the reach (rkm); and $d_{a=1,w,r}$ is the maximum number of redds per rkm (count).

For alevin, we assume 2000 alevins per redd (Moyle, 2002), with the maximum number of redds further specified by reach (see Table I for fish biology parameters and Figure 2 for spatial parameters). The numbers of redds per rkm are user defined and were estimated here with the expert opinion of a fish biologist studying the Shasta River (C. Jeffres, University of California, Davis, Davis, pers. comm.) (Figure 2). In the Shasta River, coho salmon spawn primarily near Big Springs Creek and the mouth (Jeffres *et al.*, 2008). We assume that the maximum number of fry per rkm is 1865 fish (3000 fish mile^{-1}) (Table I), using a high estimate from Nickelson *et al.* (1992) (who estimated that fry number between 54 and 3444 fish mile^{-1} in Oregon coastal streams). Likewise, the maximum number of smolts per rkm is estimated to be 435 fish (700 fish mile^{-1}), within the bounds of 3–744 fish mile^{-1} provided by Nickelson *et al.* (1992). We used high maximum fish per rkm estimates as survival is further constrained by flow and temperature habitat conditions.

Table I. Life stage and timing parameters

Parameter	Description	Alevin	Fry	Smolt
α	Maximum fish	2000 redd^{-1}	1865 rkm^{-1}	435 rkm^{-1}
β	Timing mortality	1–22	1–52	9–26

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Habitat capacity constraints. Habitat capacity constraints link instream flow and temperature conditions with coho salmon survivorship and further reduce the carrying capacity limits discussed above (Figure 4). This approach is similar to the habitat time-series method used in Instream Flow Incremental Methodology (Bovee *et al.*, 1998), although we include a simple fish population model to explicitly maximize smolts rather than useable habitat. Here, fish die when suitable habitat does not exist, and marginal habitat reduces the number of individuals (i.e. some percentage of fish die from the preceding week).

$$F_{a,w,r} \le HC_{a,w,r} * c_{a,w,r} * \beta_{a,w,r}, \forall a, w, r \text{ Habitat capacity} \quad (8)$$

where $HC_{a,w,r}$ is the habitat capacity as a function of flow and water temperature (and is discussed further below) (percentage reduction in number of fish); and $\beta_{a,w,r}$ is a mortality parameter establishing the timing of each life stage (i.e. so most alevins survive in March and mortality increases in the shoulder seasons from January to May (weeks 1–22; %) (Table I). We assumed no mortality from non-flow and thermal criteria, essentially lumping density-dependent mortality with density-independent mortality that occurred from poor habitat conditions (density-dependent mortality estimates were unavailable for this system).

Instream flow and water temperature conditions that are not ideal for coho salmon reduce the survivors of each life stage from the maximum carrying capacity values in Table I, and is referred to as habitat capacity here. Lookup tables of survivorship with continuous values from flow and water temperature conditions are visualized in Figure 4 and were developed from ideal flow and water temperatures by life

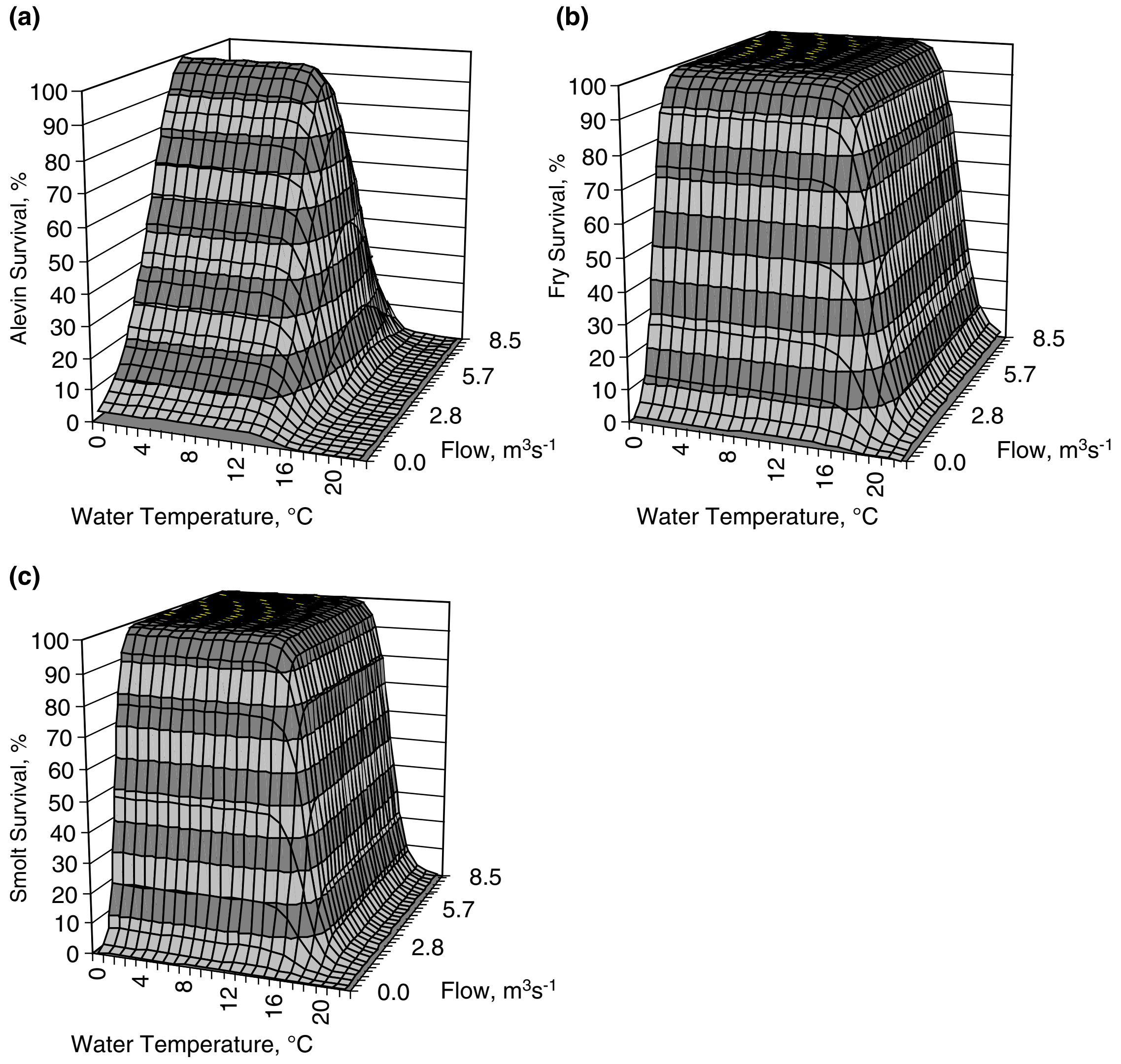

Figure 4. Flow and water temperature habitat capacity curves for coho salmon (a) alevin, (b) fry and (c) smolts.

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stage (Moyle, 2002; CBSED, 2005). See Null (2008) for sensitivity analyses for each surface. Given the uncertainty regarding the relationship between instream flow, water temperature and fish survivorship, the habitat capacities developed are academic for this analysis.

Instream habitat for the alevin life stage varies with a bell-shaped curve for flow conditions, so 100% of alevins survive at 5.1 $m^3 s^{-1}$ and survivorship declines with more or less flow (Figure 4). Lower flows can expose and desiccate redds, whereas higher flows wash away hatchlings or mobilize redd gravels (Sandercock, 2003). Here, water temperature affects habitat through a logistic relationship. At water temperatures greater than 11 °C, mortality increases with warmer temperatures. At 15 °C, 50% of alevins survive, and by 18 °C, only 3% of alevins survive. The fry and smolt habitat capacity curves are also represented by logistic surfaces (Figure 4). One hundred percent of fish survive when flow is at least 2.8 $m^3 s^{-1}$ for fry and at least 2.6 $m^3 s^{-1}$ for smolts. Survivorship declines at slightly higher temperatures for fry than smolts (Moyle, 2002). For fry, survivorship is 97% at 15 °C, 50% at 18 °C and 4% at 21 °C. For smolts, survivorship is 94% at 15 °C, 50% at 17 °C and 3% at 20 °C [developed considering coho salmon were absent in tributaries to California's Mattole River when weekly average water temperature exceeded 16.7 °C (Welsh *et al.*, 2001)].

For this application, habitat capacity was not reduced for very cold water temperatures because the Shasta River is partially spring fed and thus maintains water temperatures above zero. Additionally, we assume that preferred velocities of coho salmon for each life stage exist with ideal instream flows. In the Shasta River, abundant macrophyte growth provides mid-channel low velocity refuge for fish and substantial seasonal habitat for juvenile salmon (Jeffres *et al.*, 2008).

Fish demography and migration constraints. The objective function is constrained by fish demography to ensure that each life stage has fewer fish than the preceding life stage. A downstream access constraint for smolt also ensures that downstream reaches have adequate flow and thermal conditions during out-migration from the river.

$$\sum_r F_{a,w,r} \leq \sum_r F_{a,w-1,r} + \sum_r F_{a-1,w-1,r}, \forall a, w \qquad \text{Fry and smolt demography} \qquad (9)$$

$$F_{a,w,r} \geq F_{a,w,r-1}, \forall a, w, r \quad \text{Smolt downstream access} \quad (10)$$

There is no demography constraint for alevin because it is the first life stage modelled. The number of surviving alevin individuals is thus determined by maximum carrying capacity and mortality from poor thermal and instream flow conditions (Equation 8). Alevins are assumed to remain near redds and cannot move between reaches. Alevins emerge from January through May (weeks 1–22) (Table I), with most alevins emerging in March (CDFG, 2002). After 4 weeks, fish move from the alevin stage to the fry stage. Modelled emergence is not temperature dependent, although in reality, emergence is highly correlated with water temperature.

In the fry rearing stage, fish move between reaches to find the most favorable conditions. The total number of fry cannot exceed the number of alevin (Equation 9), nor exceed habitat capacity (Equation 8). Fry rearing lasts a full year (February to February).

Smolt demography ensures that total smolts cannot exceed the number of incoming fry (Equation 9) and cannot exceed habitat capacity (Equation 8). Smolts out-migrate from late February through June (Table I) (CDFG, 2002). In the model, out-migration can be completed in a single timestep (1 week), or smolts can hold in any reach to wait for suitable downstream conditions, but cannot return upstream. Smolts must swim downstream through all downstream river reaches without skipping reaches (Equation 10). Successfully out-migrating smolts are counted at the mouth of the river (reach 10). This model does not explicitly track numbers of fish in each life stage from reach to reach; rather, total numbers of fish in all reaches cannot increase from one life stage to the next.

Economic cost constraint. Total costs are limited by a budget constraint so restoration expenditures could be directly compared with coho salmon recruitment.

$$B \geq \sum_w \sum_r c_{RDw,r} \qquad \text{Restoration budget} \qquad (11)$$

where B is the total restoration budget ($) and $c_{\mathrm{RD}w,r}$ is the cost of a particular restoration decision ($).

Restoration options for the Shasta River alter instream flow and water temperature conditions, affecting fish habitat and ultimately the number of out-migrating fish. The cost estimates and assumptions for each restoration alternative are summarized in Table II and described below.

Decision variables

Additional flow. Instream flow prescriptions mitigate low flow conditions and limit atmospheric heating by increasing volume and reducing travel time. For the Shasta River, adding flow could be accomplished by reducing diversions, water marketing or instream flow releases from the Dwinnell Dam. Flow increases are bounded between zero and simulated weekly unimpaired flow (Null *et al.*, 2010). Flow is added at the existing water temperature of the reach, so

Table II. Habitat model decision variables and assumptions

Decision variable	Policy activity	Modelled effect[a]	Cost	Variable type
Additional flow	Reduce diversions, dam releases, water markets	↑Q in any mainstem reach below the Dwinnell Dam	\$900 per 0.03 $m^3 s^{-1}$ (1 $ft^3 s^{-1}$) for 1 week (TNC, 2005 estimates \$36–66 af^{-1})	Continuous
Move diversion	Move GID diversion downstream 10.5 rkm	↑Q for 10.5 km ↓T_w locally	Assumed at \$1 m	Discrete (binary)
Riparian shading	Actively replant riparian vegetation	↓T_w (reduce atmospheric heating)	\$4200 km^{-1} for conservation planting (Quinn *et al.*, 2001)	Continuous
Restore Big Springs Creek	Buy Big Springs property/water rights	↑Q, ↓T_w (preserve cool spring-fed T_w)	\$15 m (TNC)	Discrete (binary)
Remove the Dwinnell Dam	Remove the Dwinnell Dam	↑Q, ↓T_w (cooler initial T_w)	Assumed at \$15 m (not including water replacement)	Discrete (binary)

GID, Grenada Irrigation District; TNC, The Nature Conservancy.
[a] Q, flow; T_w, water temperature.

there are no temperature benefits from increasing flow. This temperature assumption holds even for reservoir releases because Lake Shastina is small, is subject to considerable drawdown (storage drops below dead pool in dry years) and exhibits thermal stratification for short periods during spring when releases from the hypolimnion last for only a few days (Vignola and Deas, 2005). Optimization does not explicitly model physical processes, so changes in travel time and atmospheric heating are not assessed.

Adding flow is a continuous variable and can be added to any reach on the mainstem Shasta River below the Dwinnell Dam (reaches 1–10) for \$900 per 0.03 $m^3 s^{-1}$ for a week (18 144 m^3 $week^{-1}$) (Table II). The Nature Conservancy (TNC, 2005) estimated that temporary leases on water rights cost \$36–66 per acre foot (af^{-1}) in the Shasta basin. For this study \$900 for 0.03 $m^3 s^{-1}$ (1 $ft^3 s^{-1}$) for 1 week was used as a conservative cost estimate.

Relocating the Grenada Irrigation District. Moving the GID diversion from its current location in reach 4 (rkm 49.2) to reach 5 (rkm 38.8) has been proposed to maintain flow in a portion of the river where salmon spawn while delivering contracted water to customers (TNC, 2005). The GID diversion was modelled as a constant 1 $m^3 s^{-1}$ from April through September. No changes were made to water temperature. This decision was modelled as a binary variable (0 or 1) under the assumption the diversion would be moved in its entirety. No cost estimates were available for relocating the GID diversion, so it was assumed to cost \$1 m for this exercise (Table II).

Increasing riparian shading. Increasing riparian shading reduces solar radiation and thermal loading in rivers (Rutherford *et al.*, 1997). It is especially effective when paired with other restoration measures that preserve cool-water temperatures in upstream reaches (Null *et al.*, 2010). Here, riparian shading can be added to all reaches below the Dwinnell Dam to reduce atmospheric heating. Water temperature data representing shaded conditions are from riparian shading simulation results (Null *et al.*, 2010).

Quinn *et al.* (2001) estimated that planting trees costs \$4200 km^{-1} for mangroves, flaxes and shrubs in a New Zealand river system (Table II). Increasing riparian vegetation was modelled as a continuous variable between 0 and 1. Zero represents no additional shading, and 1 represents full riparian restoration. Values between 0 and 1 represent partial shading, such as shading from shrubs or widely spaced trees.

Restoring Big Springs Creek. Simulation modelling indicates that restoring Big Springs Creek increases flow by approximately 0.9 $m^3 s^{-1}$, and water temperature remains between 10.4 and 12.6 °C at the confluence with the Shasta River in reach 3 where salmon spawn. Restoring Big Springs includes reducing diversions from Big Springs Creek and improving riparian shading along the creek. Flow and temperature data for restoring Big Springs Creek are from restored Big Springs simulation results (Null *et al.*, 2010). TNC (2005) recently paid \$15 m to buy 16.7 km^2 on Big Springs Creek (Table II). Restoring Big Springs Creek was modelled as a binary integer variable, so it is either restored completely or has current instream conditions.

Removing the Dwinnell Dam. Removing the Dwinnell Dam has been proposed by the NRC (2004) to improve habitat quality below the dam and regain access to 35.4 rkm of

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salmon spawning and rearing habitat above the dam. Removing the Dwinnell Dam would largely restore the natural hydrograph, as well as reduce current nutrient loading in the reservoir and possibly improve gravel recruitment, habitat criteria not considered here (NRC, 2004). Flow and water temperatures for this alternative are from unimpaired estimates, which assumed that upstream tributaries have been fully restored (Null *et al.*, 2010). No flow or water temperature changes were made to Parks Creek when the Dwinnell Dam was removed, although currently, 18 500 000 m^3 is diverted from Parks Creek to the Dwinnell Dam each year (Vignola and Deas, 2005).

Cost estimates for removing the Dwinnell Dam or similar sized earthen dams were unavailable[1], so removal costs were assumed to be $15 m, not including water replacement costs or lost agricultural value (Table II). This estimated cost is arbitrary but useful for the purposes of this proof of concept model. Removing the Dwinnell Dam was modelled as a binary variable (0 or 1), so the dam remains or is removed completely.

Limitations

This model was applied to the Shasta River as a proof of concept case study. We recognize that fish ecology and population dynamics were greatly simplified and could be improved in future applications. All instream habitat parameters except flow and water temperature were ignored, although other water quality impairments, predation, competition, stream productivity, barriers to migration, substrate and ocean conditions all influence to salmon survival and reproduction (NRC, 2004). Modelling more than one species would incorporate the effects of competition and predation on habitat and would avoid single species management.

The model had a coarse temporal and spatial representation. The weekly timestep eliminated important fish habitat criteria such as maximum daily water temperature, duration of elevated temperature and daily minimum water temperature. In actual river systems, the effects of daily high temperatures on fish are partially offset by the length and extent of nightly low temperatures, as well as other habitat criteria such as food abundance (NRC, 2004). However, weekly averaged temperatures are a common metric for fish health (Welsh *et al.*, 2001). Finer model resolution of future applications would improve results, and modelling multiple years would increase knowledge about how habitat and fish populations are affected by different water years, meteorological conditions and fish cohorts.

Given uncertainty regarding the relationship between instream flow, water temperature and fish survival, the habitat capacity curves developed are academic for this analysis. Detailed studies would help to develop more robust curves. Also, refinement of cost estimates would lead to more certain and applicable results. Believable cost estimates for all restoration options are an integral component of this method.

Flow and water temperature input data is from previous simulation modelling. This type of optimization, which evaluates multiple restoration alternatives, would be difficult without simulated flow and water temperature results. User-defined parameters were estimated from values reported in the literature, and sensitivity analysis was completed to better understand which parameters most influenced coho salmon recruitment. Although the model was sensitive to user-defined parameters shaping life stage carrying capacity and mortality, the values described above resulted in good fit with the observed coho salmon recruitment data in the Shasta River (CDFG, 2008). Model fit is discussed more in the Results section. Sensitivity analysis was also completed for the cost of restoration alternatives, which affects the relative effectiveness of restoration when compared with other alternatives but not the number of out-migrating smolts for each restoration alternative.

RESULTS

Fish habitat optimization helps to organize water resource management problems and test promising management actions. Results help quantify the tradeoffs between restoration costs and habitat improvements for coho salmon to aid planning and decision making. Results should be interpreted not by absolute numbers of fish as results have only been compared with recruitment data to test the model, but instead by relative numbers or percentage change in smolt production.

Some restoration options were effective at improving flow and thermal fish habitat and thus at increasing recruitment of coho salmon (Figure 5). Overall, recruitment was marginally improved when up to $430 000 was spent on riparian shading and instream flow, increasing recruitment from 5242 to 7436 smolts, a 42% improvement (Table III). Relocating the GID diversion was never optimal, which increased smolt production by only 70 fish from current conditions. Recruitment leveled until the restoration budget increased to $15 000 000. Removing the Dwinnell Dam improved out-migration to 24 909 smolts. However, restoring Big Springs Creek was also estimated to cost $15 000 000 and had a greater benefit, with 33 644 smolts.

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[1] Removing the Iron Gate Dam, an earthen dam on the Klamath River, was estimated to cost $20.1–55.3 m. The Iron Gate Dam is higher with a shorter span and also has an associated fish hatchery, intakes, fish trapping and holding facilities, as well as a powerhouse and appurtenant works (FERC, 2007).

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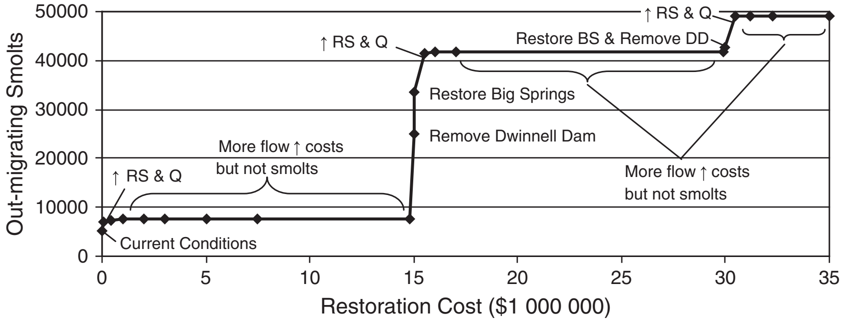

Figure 5. Restoration tradeoff curve (Q is flow, RS is riparian shading).

Restoration was most effective when multiple strategies were combined, such as adding flow and shading while restoring Big Springs or removing the Dwinnell Dam. Maximum recruitment was 49 044 fish when Big Springs Creek was restored, the Dwinnell Dam was removed, all reaches had maximum shading and approximately 17 580 000 m^3 of instream flow was added (sum of all weeks and reaches), a run representing unimpaired conditions from extensive restoration. The following sections discuss the effects of each restoration alternative for coho salmon recruitment in the Shasta River.

Current conditions

With current conditions, 5242 smolts out-migrated from the Shasta River. Assuming approximately 3% of smolts return as adults (CDFG, 2008), model results indicate that approximately 155 adult fish would return to the Shasta River, which is consistent with observed numbers of adults returning to the Shasta River (CDFG, 2008). Week 32 (6 August–12 August) created a bottleneck in the fry stage, which limited coho salmon recruitment. Week 32 had warmer thermal conditions than surrounding weeks, with water temperatures exceeding 25 °C (Figure 6). Flow was lower than previous and subsequent weeks in reaches 7–10. Alevin continued to enter the fry stage through the end of June, so until that time there was considerable flexibility in the model. Fish die-off occurred when habitat conditions worsened in July and August, reducing fry from 100 000 to 5242 individuals, a reduction of nearly 95%. The surviving fish reared primarily in the Big Springs reach, where flow and temperature conditions were most amenable to rearing coho salmon.

Additional flow and riparian shading

Instream flow and riparian shading are discussed jointly because they were most effective together, and some combination of the two was typically optimal. Supplemental flow without riparian shading produced only small improvements to recruitment because larger volumes of warm water were not beneficial for coho salmon (Table III). However, increased instream flows with shading were more advantageous, and the first increments of shading and flow improved habitat conditions the most (Figure 7). The initial

Table III. Smolt production, flow volume and cost by restoration alternative

Smolts (count)	Increase from current conditions (%)	Total flow (m^3)	Cost ($ m)	Restoration alternatives					
				Current conditions	Maximum flow	Riparian shading	Move diversion	Restore Big Springs	Remove the Dwinnell Dam
5242	—	0	0	X					
5427	4	2 217 000	0.12		X				
6951	33	0	0.24			X			
7436	42	2 777 000	0.43		X	X			
5312	1	0	1				X		
24 909	375	61 832 000	15						X
33 644	542	32 473 000	15					X	
41 638	694	30 661 000	16.9		X	X		X	
42 597	713	94 305 000	30					X	X
49 044	836	111 889 000	31.2		X	X		X	X

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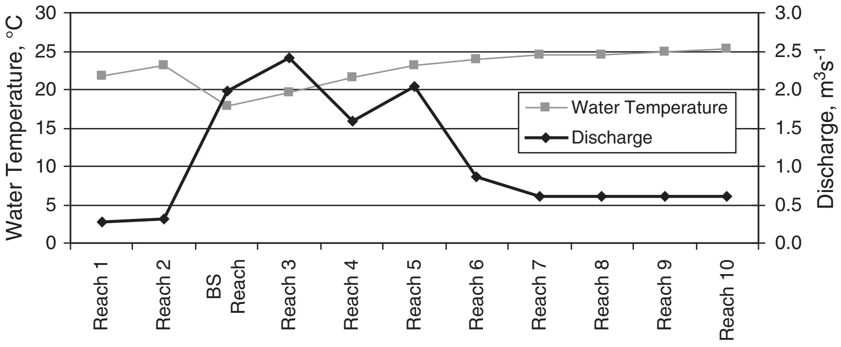

Figure 6. Week 32 (6–12 August) flow and temperature current conditions.

$20 000 of flow and shading improvements led to considerable increases in fish survival, although improvements to fish survival tapered with further flow and shading investments. The model typically opted to shade the reach below the Dwinnell Dam first, as it reduced atmospheric heating most. Riparian shading was rarely added to reaches 5, 8 and 9 because shading those reaches least reduced water temperature.

After Big Springs was restored or the springs were restored and the Dwinnell Dam was removed, it was always optimal to spend the next $100 000 of restoration funds to improve riparian shading in the upper reaches to maintain the cooler water temperatures. Again, the benefit to fish production was greatest from initial investments in flow and shading [Figure 7(b and c)]. When Big Springs was restored, improving riparian shading in the Big Springs reach, as well as reaches 3 and 4, became a priority to preserve the cooler water temperatures. Likewise, when the Dwinnell Dam was removed, reach 1 was the first to be shaded, followed by downstream reaches.

Relocating the Grenada Irrigation District

Relocating the GID diversion had little benefit to fish productivity. Using $1 000 000 to move GID increased outmigration by 70 smolts, whereas spending $425 000 on riparian shading and instream flow increased productivity by 2194 smolts (Table III). Results from previous simulation modelling (where heat energy fluxes were explicitly modelled) indicate that this option may reduce water temperature by approximately 1 °C for approximately 24.1 rkm (Null, 2008). However, the optimization modelling used here did not demonstrate appreciable habitat improvement.

Restoring Big Springs Creek

When Big Springs Creek was restored, recruitment rose to 33 644 fish, a 542% increase from current conditions. This restoration alternative had the greatest improvement in fish habitat and production of all modelled options, although week 32 still created a bottleneck in fry rearing when Big Springs was restored. This shows that meteorological conditions continue to create bottlenecks with restoration, although effects are not as severe. When Big Springs Creek was restored, the Big Springs reach and reach 10 were the most productive for coho salmon.

Removing the Dwinnell Dam

Removing the Dwinnell Dam benefited coho salmon production in the Shasta River, although not as much as restoring Big Springs Creek. Removing the Dwinnell Dam would be difficult in terms of politics, public support and water replacement; however, it could provide fish access to an additional 35.4 rkm of habitat. Model results suggest that removing the dam improved recruitment to approximately 24 909 fish, a 375% increase. Most spawning would likely take place in the long reach upstream of the Dwinnell Dam, as it had the best habitat conditions for the alevin life stage in terms of flow and water temperature. Sensitivity analysis showed that if reach specific carrying capacity were decreased (making space limiting rather than flow or water temperature conditions), then removing the Dwinnell Dam became more advantageous than restoring cool-water springs in Big Springs Creek.

The cost of removing the Dwinnell Dam was assumed to be $15 m for this study, although true cost estimates were unavailable. Sensitivity analysis on the cost of removing the Dwinnell Dam shifts the Dwinnell Dam point (center Figure 5) to the left or right but does not change smolt survival. However, if removing the Dwinnell Dam were substantially cheaper than restoring Big Springs Creek, then removing the dam could be the best option for restoring the Shasta River. Better cost estimates are needed to further refine this restoration option.

If the Dwinnell Dam were removed in conjunction with restoring Big Springs Creek, full riparian shading and supplementing instream flow, fish production increased the most. Results suggest that approximately 49 044 smolts

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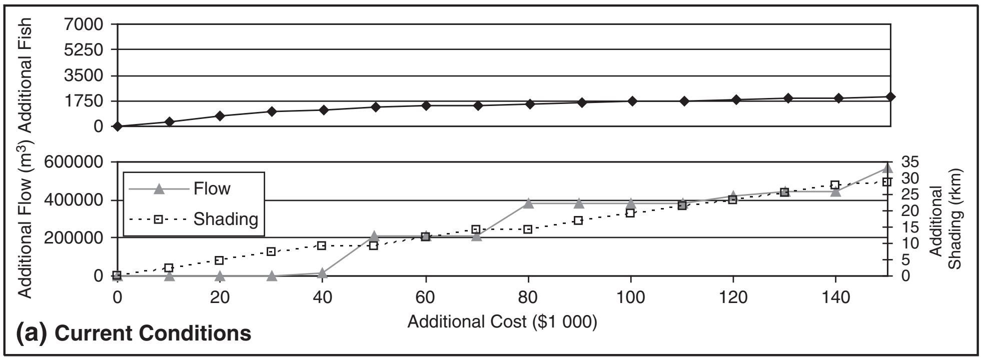
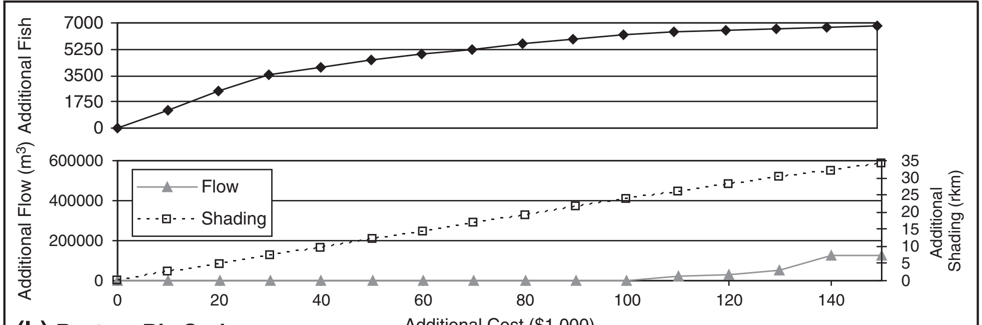
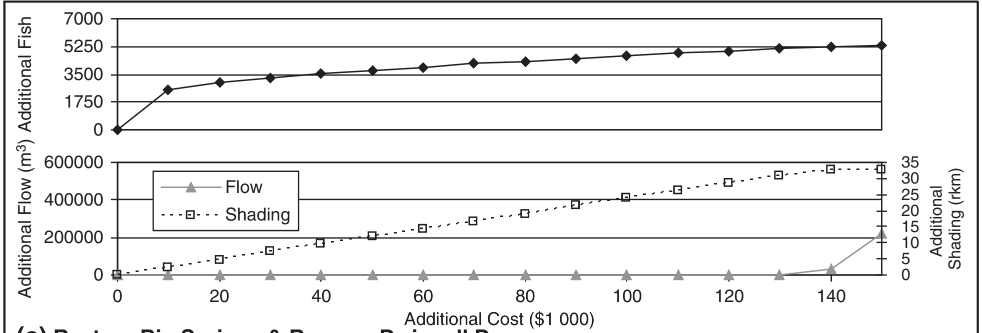


(a) Current Conditions



(b) Restore Big Springs



(c) Restore Big Springs & Remove Dwinnell Dam

Figure 7. Additional fish from increasing flow and riparian shading with (a) current conditions, (b) restoring Big Springs and (c) restoring Big Springs and removing the Dwinnell Dam.

survive under these conditions (Table III), which represent an unimpaired river for flow and water temperature. Other habitat criteria not considered here could then become limiting for coho salmon production (such as substrate or other water quality problems).

DISCUSSION

The optimization model described here illustrates an approach to compare habitat improvement for one fish species by linking flow-related and temperature-related restoration actions with restoration costs. This method combines fish population and habitat modelling to explore management strategies. It is a helpful approach for planning and decision making because it is flexible and allows many restoration options to be compared and integrated at once. Modelling increases understanding of the interaction between physical habitat, factors limiting recruitment and fish population dynamics for management purposes, such as which restoration options provide the most habitat improvement, given costs. Underlying assumptions can be easily changed as better data become available or to represent other river systems. This approach organizes water resources problems, develops testable hypotheses and compares estimated effectiveness of many restoration alternatives with expected costs.

This paper illustrates the relative value of different restoration activities for coho salmon productivity, providing a potential tool for local stakeholders, academics and decision makers to organize, explore and weigh decisions and justify or eliminate restoration decisions. Results from

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this approach demonstrate the benefit to fish from each restoration activity and integrated combinations of activities, as well as the associated costs and the quantity of water reduced from other uses. This enables water-use efficiency as well as economic efficiency of restoration decisions to be estimated by fish habitat. Estimating environmental water allocations necessary for restoration also helps to quantify impacts to other water users and land owners. This work examines a wide range of restoration alternatives instead of focusing solely on reservoir operations or modifications to manage rivers.

The money and water dedicated to restoration should accomplish as much environmental benefit as possible. Restoration programs consider costs when setting goals, quantifying improvements and comparing alternatives to know if environmental water dedications and restoration funds are being used efficiently. However, it is often difficult to know which restoration options will be most successful for enhancing instream habitat and protecting endangered species. Accountability of water use and economic costs is imperative in the urban and agricultural water sectors and has led to greater urban and agricultural benefits from limited water use. Environmental protection could improve if the environmental sector better related benefits of restoration programs with water uses and costs.

Of the single restoration actions evaluated, restoring Big Springs Creek provided the most improvement for fish habitat, increasing smolts by 542% (Table III). Removing the Dwinnell Dam improved recruitment by 375%, a significant increase though less than restoring Big Springs Creek. This is a major finding and would not have been observed if only reservoir operations or modifications were modelled. Restoring Big Springs Creek while also removing the Dwinnell Dam increased fish production by approximately 713% from current conditions. Increasing riparian shading and increasing flow without other restoration alternatives increased the number of fish out-migrating from the Shasta River by 42%. Relocating the GID diversion improved fish survival by 1.3%, the least effective option for improving fish habitat (Table III).

These results suggest that increasing instream flow improves fish habitat somewhat, but small flow additions with restoration that reduces water temperature improves habitat and fish survival more. This finding reiterates previous observations that adequate water quality for fish population health is a necessity, whereas instream flows are of secondary importance after minimum releases are provided (Jager and Smith, 2008; Null *et al.*, 2010). Evaluating the extent to which additional instream flow enhances instream conditions is an important branch of restoration science. Models that include non-flow variables in addition to flow (such as water quality, geomorphology, food abundance, etc.) indicate that improving non-flow limiting factors is often more helpful than increasing instream flow, resulting in higher quality instream habitat and more water for traditional water uses. This is especially true in systems like the Shasta River, in which salmon production is most limited by water temperature, and low flow conditions are only one cause of thermal impairment.

In the future, climate change and population growth will further stress river systems, making it difficult to achieve existing levels of water resource benefits and environmental protection. River systems and water resources will continue to be managed more tightly. The modelling described here is an appropriate approach to weigh alternatives and to manage uncertainty to make resource allocation decisions to protect native species in tightly operated river systems. Furthermore, managing rivers to enhance instream conditions for native species, such as salmon, could provide a buffer against poor ocean conditions or other unforeseen habitat degradation associated with climate change.

The optimization model described evaluates multiple restoration alternatives to improve fish habitat over several life stages while considering restoration costs as constraints. We demonstrate that optimization is a worthwhile method to improve understanding of the economic tradeoffs of restoration decisions and better prioritize restoration alternatives for water resource and fisheries management. Specific findings include the following:

- Restoration alternatives can be ranked in terms of value to fish habitat and restoration cost.
    - For the Shasta River, restoring Big Springs provided the most benefit. Removing the Dwinnell Dam, adding flow or shading were good secondary improvements.
- The tradeoff curve between economic costs of restoration and number of out-migrating smolts was not smooth; some alternatives were corner points that resulted in large increases in cost or fish productivity.
- Fish productivity had an upper bound in the model, at which point, additional flow or water temperature habitat enhancement measures had little or no value. Other habitat criteria may then be limiting fish production (which could be the focus of future restoration activities).
- Bottlenecks in the life history of fish still occurred when restoration activities had improved instream conditions, although the consequences were less severe. Restoration could provide a buffer against poor ocean conditions or possible habitat degradation associated with climate change.
- Improving water quality (rather than increasing quantity) was beneficial for fish where water quality was limiting productivity. Protecting cool-water sources and maintaining

cool-water downstream improved habitat more than simply increasing flow.

- Modelling suggests that substantial investment in fish habitat was needed before recruitment increased in the Shasta River.
- Optimization is a helpful approach for managing ecosystems as well as traditional water uses.

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