Designing Instream Flows to Satisfy Fish and Human Water Needs

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Abstract: The relicensing of nonfederal hydropower projects and the mandated reevaluation of federal water projects require policy makers to balance the human use of water with instream releases for environmental values. To meet the need for planning level tools for instream flow determination, we develop a flexible multiobjective optimization model. The model considers both the size and frequency of water supply shortages and the habitat available for fish species as the fish progress through life stages. We use a habitat capacity metric to combine expected mortality, the fraction of a life stage in a particular month, and the areal habitat needs per individual fish. The model incorporates human water supply concerns such as monthly variations in human water demand, water-year types, and flood control restrictions. We apply this monthly optimization model to a west-slope Sierra Nevada stream used for municipal and agricultural supply and for supporting an anadromous fish population. Results identified a range of alternative solutions that involve trade-offs between water shortage levels and fish population capacity.

INTRODUCTION

Conflict between competing uses of river basins has intensified as society seeks to protect environmental integrity while concurrently making more demands on the water resource. The multiple, often-conflicting objectives of reservoir management include hydropower production, municipal water supply, water supply for irrigation, flood control, lake recreation, downstream recreational boating and fishing, and maintenance of ecosystem integrity. The managed use of resources for multiple purposes involves many federal and state agencies and is addressed explicitly in several statutes and regulations (e.g., National Environmental Policy Act, the Federal Power Act, and the Central Valley Project Improvement Act). No reservoir operation plan can fully satisfy the conflicting demands on the system, and thus reservoir management schemes must seek to use the water resources as efficiently as possible. Solutions that satisfy multiple objectives are neither straightforward nor easily agreed upon, but ultimately decisions must be made. Systems analysis tools provide one way of identifying potentially acceptable solutions.

Minimum flow regulations have become an increasingly visible issue for water resources managers. The primary conflict is between releases to maintain ecosystem integrity downstream, versus the use of stored water to meet hydropower, recreational, and water supply needs. The relicensing of hundreds of nonfederal hydropower dams has combined with other instream flow conflicts to increase the demand for methods to generate minimum flow requirements that balance socioeconomic and environmental objectives. This study presents a flexible planning-level tool to help water resources managers develop acceptable instream flow requirements.

Few previous reservoir operations studies have included both water supply and instream flow objectives explicitly. Past systems analysis work has usually addressed water supply objectives with a predetermined minimum flow requirement as a constraint. The basic structure of these reservoir operations models is described by a simple mass balance equating the change in storage to the difference between inflow and outflow

$$S_i - S_{i-1} = I_i - (W_i + M_i) \quad \text{for all } i \tag{1}$$

where $S_i \equiv$ reservoir storage at end of period i; $M_i \equiv$ mass of water diverted from reservoir to water supply uses during period i; $W_i \equiv$ water released from reservoir during period i; and $I_i \equiv$ inflow to reservoir during period i.

These models supplement this basic mass balance structure with flood control, capacity, and carryover storage constraints and maximize a function of water delivery. Frequently, operational rules are incorporated as additional constraints. Goal programming, integer programming, linear programming, and dynamic programming are some general models that have been used both to generate operating rules for reservoirs and to size potential reservoirs (Yeh 1985). Environmental constraints take the form of predetermined minimum release requirements.

Increased research into instream flow issues paralleled the increased concern with the needs of both recreational users and downstream fish populations. Palmer et al. (1982) show the impact of increasing environmental flow-by requirements on the yield of a reservoir system. Flug and Montgomery (1988) use simple benefit functions to quantify the boating, fish habitat, and rafting benefits from instream releases from a reservoir. Flug and Ahmed (1990) propose a methodology, using 22 specific natural resource attributes in their example, to quantify and characterize different preferred flow regimes. Flug et al. (1990) evaluate four methods of generating alternative flow regimes that maximize weighted linear combinations of simple benefit functions for boating, fishing, and whitewater rafting.

Two studies considered the instream flow objectives but not reservoir operation objectives. Franc (1993) presents a method developed by a hydropower utility for assessing minimum flow requirements and generating new ones. This model (FISHN) determines flow schedules that provide equivalent amounts of habitat as a baseline case that reflects operation under current minimum flow regimes. The model allows two ways of determining the best minimum flow scenario: one chooses the flow that maximizes the amount of habitat produced by an incremental increase in minimum flow; the other chooses the flow that minimizes the marginal cost (in lost hydropower production) of producing additional habitat. No linking of habitat capacity across life stages is considered. Harpman et al. (1993) use similar habitat information in a biological model to relate flow to fish population. The model links habitat available at each life stage through a mortality

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estimate from one life stage to the next. A habitat density parameter is used to allow the amount of habitat at the previous life stage to limit the habitat requirements at the next life stage. This parameter is based on both the effective habitat in the previous life stage and time period, and a multiplying factor derived from mortality rates and habitat density (Waddle 1992).

A study by Sale et al. (1982) was the first to incorporate the standard habitat measure of weighted usable area (WUA) into a traditional systems analysis framework for reservoir operation. This optimization model seeks to maximize the minimum WUA over multiple fish species and life stages. The percentage of the maximum WUA possible for a life stage serves as a surrogate for the actual objective of maximizing the fish population. A binary periodicity coefficient indicates the presence or absence of a life stage in each time period (e.g., month or season). The habitat measure did not attempt to integrate the habitat needs of different fish life stages.

CONCEPTUAL OVERVIEW

This paper presents a methodology to generate alternative minimum flow regimes that consider both multiple human water uses and the needs of fish at different life stages. We develop a flexible optimization model for use in planning for instream flow determination. The multiobjective model considers both water supply and fisheries objectives and relates minimum flows to fish populations by linking the habitat available for different life stages.

The model generates instream flow alternatives that maximize fish populations and reduce water supply shortfalls. We cast other objectives such as flood control and downstream recreation as system-wide constraints. To address the range of hydrologic conditions, the model can tailor minimum instream release schedules to water availability. For wet, normal, dry, and critical water-year types (see the optimization model section), we can consider the relative instream flow needs of each life stage and the effects of instream releases on fisheries and human water demands. Multiple solutions using different relative weights for water supply and fisheries objectives give trade-offs between the competing objectives. The optimization model is designed to serve as a planning-level model to identify alternative minimum flow requirements. Model results can then be used with simulation models to more precisely forecast the resultant hydrology and the effects on both fish and water supply.

We also develop a habitat capacity metric to link the habitat requirements of the different fish life stages. We approximate the relationship between flow and available habitat by the WUA measure developed through instream flow incremental methodology (IFIM) studies (Bovee 1982, 1986). The habitat capacity measure developed here links the habitat requirements for different life stages of the fish, considering likely survival rates and areal requirements. Habitat capacity is used as a surrogate for the fish populations in the optimization model. Other factors, such as stream temperature and pulse flows for upmigration and out-migration, can affect the fish population and can be incorporated into the habitat capacity framework.

The next section presents the method to link the habitat available at different life stages into a measure of habitat capacity. We then describe the optimization model and potential modifications. The final two sections describe the application of the modeling framework and draw conclusions.

HABITAT CAPACITY FRAMEWORK

The habitat needs of a population vary through a year with fish life stage and environmental conditions. Here we assume that habitat is the limiting factor in fish population. Habitat needs are described empirically by life-stage-specific flow versus habitat curves. This study considers an anadromous species, the chinook salmon (*Oncorhynchus tshawytscha*) and assumes that the habitat needs can be adequately described by three freshwater life stages of the fish: spawning, fry, and juveniles. Maximizing fish populations for an anadromous species implies maximizing the number of juveniles that outmigrate from the stream to the ocean. We assume that habitat requirements for spawners determine the available habitat for the resulting immobile egg and alevin life stages of the fish. Similar assumptions and habitat requirements could be made for resident species.

To combine the habitat needs of the various life stages, we translate the amount of habitat available from a given flow, WUA, into a habitat capacity for each life stage and month based on three factors: (1) the maximum percentage of any given life stage that exists in the river during each month (α); (2) the survival rate to the juvenile life stage (β); and (3) the area of habitat required for each individual at a given life stage (γ). A relative value for the amount of available physical habitat at any given life stage links habitat requirements across months, τ, and fish life stages, g. This habitat capacity measure ($HC_{g,\tau}$) indicates the maximum number of out-migrants that could be supported by a given flow during a month. This value must be calculated for every life stage in existence during that month. The month with the lowest value for $HC_{g,\tau}$ will produce the fewest number of out-migrants and will be the "bottleneck" in habitat for the fish population. For a specific life stage and month, the habitat capacity is calculated by

$$HC_{g,\tau} = \frac{\beta_g \mathrm{WUA}_g(Q_\tau)}{\alpha_{g,\tau}\gamma_g} \tag{2}$$

where $\mathrm{WUA}_g(Q_\tau)$ = weighted usable area for life stage g provided by flow level Q in month τ; $\alpha_{g,\tau}$ = fraction of life stage g population that exists in life stage g in stream during month τ; β_g = likelihood of survival to juvenile life stage from life stage g if habitat is not a limiting factor; and γ_g = amount of habitat needed per individual in life stage g. A more detailed description of these three factors follows.

Fraction of Life Stage ($\alpha_{g,\tau}$)

The alpha factor indicates the relative importance of a month to a life stage. It is the fraction of the total number of individuals from a particular life stage that exist in the river during a given month and therefore require habitat during that month. At the extreme it indicates the presence or absence of a life stage in the river during the month. It serves a similar function as the periodicity coefficient in the formulation by Sale et al. (1982), but we allow $\alpha_{g,\tau}$ to take on values between zero and one. The WUA is weighted by the inverse of this factor to reduce the importance of habitat for a life stage during months when few individuals exist in that life stage. If only a small fraction of the total number of individuals in a life stage depends on habitat in a specific month, then that month is unlikely to be the bottleneck constraining fish populations. The lower the value of $\alpha_{g,\tau}$, the greater the number of out-migrants the same amount of habitat (as measured by WUA) can support. As $\alpha_{g,\tau}$ goes to 0, $HC_{g,\tau}$ goes to ∞, and habitat ceases to be a limiting factor for life stage g in month τ.

We define $\alpha_{g,\tau}$ as the maximum rather than the average or minimum fraction of the life stage that exists during a given month. Because individuals may spend less than a month in a given life stage, using the maximum fraction to define $\alpha_{g,\tau}$ ensures that the amount of habitat available corresponds to the maximum population of fish expected in that life stage during that month. The value of $\alpha_{g,\tau}$ can be estimated using fish population models, field studies, or through consultation with fish biologists. The parameter $\alpha_{g,\tau}$ has the dimensions of (individuals of life stage g occupying river during month τ/total number of individuals in lifestage g during the year).

Survival (β_g)

Expected survival is an obvious factor to link life stages. Harpman et al. (1993) used the expected survival between life stages. Here we consider the survival rate from a given life stage to the start of the juvenile life stage. By weighting WUA at a given life stage by the survival rate to the juvenile life stage, we effectively tie the habitat requirements at any life stage to the juvenile life stage. Higher survival rates from life stage g indicate that more habitat is necessary for life stage g to support the same out-migrant population. The value of β_g can be estimated using fish population models or can be taken from field study reports (e.g., EAEST 1992a,b, EBMUD 1992). The survival rate is assumed to be independent of the available habitat; this is an obvious approximation. The parameter β_g has the dimensions of (number of juveniles/total number of individuals in life stage g).

Areal Habitat Required (γ_g)

Both the type and amount of habitat needed per individual vary based on life stage. The life-stage-specific WUA curves account for the different types of habitat needed for different life stages. Likewise, the area needed per individual within a life stage is crucial to linking the habitat needs between the different life stages. As individuals grow they need more area for foraging. The needed habitat per individual, γ_g, provides the link between amount of habitat and number of individuals that can be supported by the habitat. In combination with the $\alpha_{g,\tau}$ and β_g factors noted previously, this provides an estimate of the number of out-migrants that can be supported by the habitat associated with a given flow. The value of γ_g can be based on laboratory or field studies (Waddle 1992) and has the dimensions of (area/individual in life stage g).

A dimensional analysis of these factors and how they interact to form the habitat capacity criteria is shown next

$$HC_{g,\tau} = \frac{\beta_g \mathrm{WUA}_g(Q_\tau)}{\alpha_{g,\tau}\gamma_g} = \frac{\left(\frac{\text{juveniles}}{\text{individuals in } g \text{ during year}}\right)(\text{area})}{\left(\frac{\text{individuals in } g \text{ during } \tau}{\text{individuals in } g \text{ during year}}\right)\left(\frac{\text{area}}{\text{individual in } g}\right)} = (\text{juveniles}) \quad (3)$$

As such, this habitat capacity measure is similar in spirit to the effective habitat framework described in Harpman et al. (1993) and more fully detailed in Waddle (1992). The $HC_{g,\tau}$ differs from the effective habitat concept in the following ways: $HC_{g,\tau}$ is explicitly measured as the expected number of fish in the juvenile life stage rather than as an effective area; it allows for the existence of multiple life stages in a single period; it considers subsets of life stages (as exist in any given period); and it allows a given life stage to exist for multiple periods.

Incorporating Nonhabitat Factors

Although habitat capacity is a useful surrogate for the effect of flow levels on number of out-migrants, per capita habitat requirements are not the only flow-related factors. The egg and alevin life stages require threshold flow levels to prevent dewatering of redds. Individuals preparing to out-migrate (the smolt life stage) also require adequate flow levels to enable out-migration from the stream. These factors are independent of the expected out-migrant population. These requirements can be incorporated into an optimization framework by requiring predetermined minimum flows during appropriate months.

Stream temperature can also play a major role in determining fish survival. Low flows in hot months can increase water temperature, increase stress on fish populations, and kill fish. Temperature also influences the timing of fry development and out-migration because fry metabolism increases with higher stream temperatures in winter months. To account for the effects of temperature on habitat, we use two additional factors: $T1_{g,\tau}$ shifts the flow versus habitat relationship to require either more or less flow to yield the same amount of habitat; and $T2_{g,\tau}$ changes the amount of effective habitat that is available to the fish. The effect of these factors on the available habitat is expressed by the following equation:

$$t\mathrm{WUA}_g(Q_\tau) = T2_{g,\tau}\mathrm{WUA}_g(Q_\tau - T1_{g,\tau}) \quad (4)$$

where tWUA = temperature modified WUA; $T1_{g,\tau}$ = offset factor for WUA for given month and life stage; and $T2_{g,\tau}$ = factor to modify amplitude of WUA curve for given month and life stage. These factors result in temperature-related changes to the habitat versus flow relationships that are similar to those derived through more mechanistic approaches (Bovee 1982; FERC 1993).

In the case where high temperatures would make otherwise acceptable habitat unavailable, we shift the flow-versus-habitat relationship by the first of these temperature parameters, $T1_{g,\tau}$. This parameter is the additional flow needed to produce the same amount of habitat. Here we assume the original habitat-versus-flow relationship holds true except that higher flows will be required to make the same amount of acceptable habitat available. The flow-versus-WUA curve will be shifted to the right (Fig. 1). In the cases where we assume nonzero values for $T1_{g,\tau}$ (e.g., for juveniles during the spring), this assumption is reasonable because habitat rises sharply in response to flow and then plateaus. Using the $T1_{g,\tau}$ factor simply increases the flow level at which the plateau level is reached.

The second way the model accounts for the effects of temperature is by modifying the relationship between habitat and flow by assuming a constant multiplying factor, $T2_{g,\tau}$. This factor is dimensionless, equals one if temperature does not affect habitat, and controls the amplitude of the WUA curve. If $T2_{g,\tau}$ is less than one, a given flow results in less habitat; if $T2_{g,\tau}$ is greater than one, the flow results in more habitat (Fig.

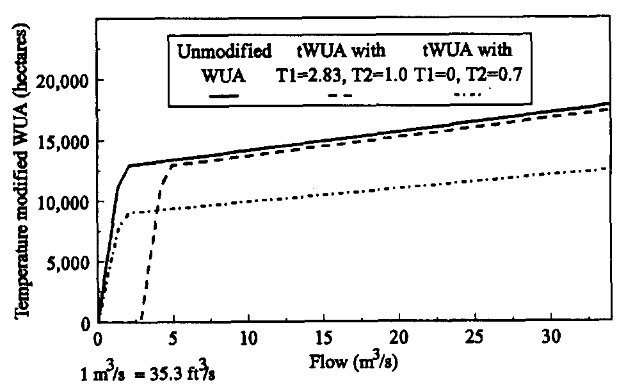


FIG. 1. WUA versus Flow Relationships Can Be Modified to Account for Temperature Effects by *T*1 and *T*2; These *t*WUA versus Flow Relationships Are Examples Based on Linearized, Life-Stage-Specific WUA Curves

1). The $T2_{g,\tau}$ factor was set greater than one in the winter when increased flows resulted in higher stream temperatures, higher growth rates, and higher rates of premature exit and mortality. Fig. 1 gives an example of the type of changes that could be incorporated to approximate temperature-induced changes in the habitat versus flow relationships.

OPTIMIZATION MODEL

The role of the optimization model in the planning process is to identify alternative minimum flow regimes. To be effective as a planning tool, the model must be flexible enough to address additional concerns, priorities, and objectives that may be articulated during the decision-making process. We model the reservoir system in a conventional linear programming format (Yeh 1985) with a large (monthly or weekly) time scale for the hydrology. The dual objectives are to minimize water supply shortfalls and maximize the habitat capacity. Mass balance requirements serve as constraints. Although the optimization model is restricted by structural limitations of the solution method (in this case linear programming), it must maintain an appropriate degree of technical detail. Without such detail the model and its results lose credibility and, therefore, usefulness. For this case study, two factors warrant such consideration: multiple classes of hydrologic year type, and seasonally variable flood control requirements. For simplicity, the model detailed next only considers a single reservoir and a single diversion.

Objectives

The fish population objective (Z_{HC}) seeks to maximize the sum, over all year types, of the minimum $HC_{g,\tau}$ encountered during each year type. This serves as a surrogate for maximizing the number of outmigrants.

$$\text{maximize: } Z_{HC} = \sum_{y \in Y} \min_{\text{all } g,\tau} HC_{g,\tau} \quad (5)$$

where the newly introduced subscript y denotes year type (critical, dry, normal, and wet), and Y = set of year types.

Year-type classifications are standard in some areas with widely variable hydrology (Waddle 1992; California State Water Resources Control Board 1978, 1993; Somach 1990) and are used in the optimization model here. The year-type concept is distinct from the idea of a critical period for operational design. Whereas a critical period can include a multiyear drought and can depend on the difference between demand and supply, year types are simply a way to classify the abundance of water in a specific year. Eq. (5) weights the minimum habitat expected for each year type equally. Alternatively we could weight habitat during a given year type to its frequency of occurrence, or use alternative weighting schemes to consider interdependency between year types. Decision makers can experiment with various weighting schemes to allocate appropriate habitat levels to the different year types.

Water supply objectives (Z_{WS}) seek to minimize both the maximum and the sum of the anticipated shortfall in supply. Symbolically, these are expressed as follows:

$$\text{minimize: } Z_{WS_1} = \max_{\text{all } i} (D_i - M_i) \quad (6)$$

$$\text{minimize: } Z_{WS_2} = \sum_{\text{all } i} (D_i - M_i) \quad (7)$$

where subscript i refers to time periods; D_i = municipal water demand in period i; and M_i = mass of water diverted for supply in period i [as defined in (1)]. We note that D_i and M_i are defined for each individual time period. We describe the relationship between individual time periods and specific cyclical periods and year types later. Different weights could be placed on extreme water deficits or on deficits encountered during specific water-year types.

The subscripts i and τ both refer to time periods; i represents each individual time period while τ refers to a cyclical period (e.g., months or seasons). Individual time periods (and, therefore, the cyclical time periods) are not required to have the same length; one time period could involve multiple months while another could be only a few weeks or days. For clarity, we refer to subscript i as a period and subscript τ as a month. The subscripts are related as follows:

$$\tau = (i - 1)(\text{mod } T) + 1 \quad (8)$$

where T = number of cyclical periods (months); and mod is a standard function that returns the remainder (modulus) after a number $(i - 1)$ is divided by the divisor (T). We require $N >> T$ where N is the total number of individual time periods (i) used in the optimization.

Individual time periods i are classified into specific year types in advance by the user. Therefore, each individual time period is associated both with a specific cyclical period (e.g., the month of April) and a specific year type (e.g., a dry year). The year type definition can be based on present inflow, previous year's inflow, forecasts of inflow, or some combination of these parameters. Although this gives a wide range of flexibility in defining year types, the method cannot consider year types conditioned on reservoir storage level. Adapting the optimization model to this type of water-year definition is an area for further study.

To generate multiple alternatives, we use the weighting method of multiobjective programming (Cohon 1978). The weighting method combines the objective functions into a new objective function Z through a linear weighted sum

$$Z = \lambda_{WS} Z_{WS_1} + \lambda_{WS} Z_{WS_2} + \lambda_{HC} Z_{HC} \quad (9)$$

where λ_{WS} and λ_{HC} = weights for water supply and habitat capacity objectives (5)–(7). For simplicity, we assign equal weight (λ_{WS}) to the two water supply objectives. The magnitudes of λ_{WS} and λ_{HC} can be adjusted to account for differences in magnitude between Z_{WS} and Z_{HC} and allow comparison of objectives measured in widely different units.

Other objectives can be considered as appropriate for the particular reservoir system. Potential additional objectives could consider the average water supply shortage, the duration of water supply shortfalls, the average habitat available during specific months, the average available flood storage reservation, the relative variation in reservoir levels, or recreational values. Alternatively, the additional objectives may be formulated as constraints, as outlined next.

Constraints

To constrain the problem, we use the mass balance approach typical of previous systems analysis research in reservoir operation and design (1). Other constraints require the actual release (W_i) during the period to be greater than or equal to the minimum instream fish release ($FR_{y,\tau}$) for that month (τ) and year type (y).

$$FR_{y,\tau} \leq W_i \quad \text{for all } i \quad (10)$$

Downstream water withdrawal rights, downstream recreational concerns, or other considerations may require this minimum instream release to be above a certain value. This type of additional constraint is easily incorporated.

Eq. (10) defines a minimum stream flow, but not a maximum allowable release. This allows higher flows that may reduce the available habitat. Because present regulations do not generally include a maximum instream release requirement for habitat purposes, the model does not include such a constraint.

Additional constraints can be added that define a maximum allowable release.

To incorporate the habitat capacity framework presented earlier, we use WUA curves to relate habitat to the minimum release. To use these nonlinear and potentially concave WUA curves as definitional constraints in a linear programming structure, we approximate the WUA curves through standard convex piecewise linearization techniques (Loucks et al. 1981; Hillier and Lieberman 1974).

Other constraints enforce diversion capacity [(11)], reservoir capacity [(12)], dead storage [(13)], and flood control requirements [(14)]

$$M_i \leq AC \quad \text{for all } i; \quad S_i \leq K \quad \text{for all } i \qquad (11, 12)$$

$$S_i \geq DS \quad \text{for all } i; \quad S_i \leq FC_\tau \quad \text{for all } i \qquad (13, 14)$$

where AC = aqueduct capacity; K = reservoir capacity; DS = dead storage level of reservoir; FC_τ = maximum reservoir level allowed during month τ because of reservoir capacity constraints; and S_i = reservoir storage level at end of period i [as defined in (1)].

A final constraint [(15)] ensures that total required releases over the simulation period do not exceed total inflow by constraining final storage to be at least equal to initial storage.

$$S_0 \leq S_N \qquad (15)$$

Other constraints may be added to the model as appropriate. Minimum flows for downstream recreation during certain months could be specified; a constraint set could prevent large fluctuations in reservoir levels between months; constraints could require diversions or reservoir releases to meet senior water rights. If we can express political, economic, or other social issues of concern as a linear combination of storage, release, or diversion in a given month or over multiple months, it can be used as a constraint. Incorporation of more detailed policy considerations, such as pulse flows for upmigration and out-migration, may be more appropriate during a later phase of the planning process. The concerns can be addressed using sophisticated simulation models for reservoir operations, fish populations, or socioeconomic responses.

Although many systems applications to reservoir operations choose to use a linear decision rule to relate releases to storage (ReVelle et al. 1969; ReVelle and Kirby 1970; Loucks 1970; Houck 1979; Joeres et al. 1981), we choose not to constrain the problem further. This results in an optimistic projection of the operational abilities of the system. This is appropriate for the intended use of this model as a planning-level tool.

APPLICATION—A CENTRAL VALLEY STREAM

To illustrate the use of the model, we generate alternative minimum flow schedules for a multipurpose reservoir on a tributary river in California's Central Valley. We use available data for unimpaired flow estimates, reservoir sizes, and water supply demand for both agricultural and municipal purposes. Four year types (critical, dry, normal, and wet) are defined, based on levels of unimpaired flow for the basin. Year-type designations depend solely on unimpaired flow in the basin and are unaffected by the optimization model. Besides flood control, capacity, and dead storage constraints [(11)–(14)], we impose an additional constraint that requires flows greater than 1.42 m^3/s [50 cubic feet per second (cfs)] for all months for downstream recreation. We opt not to use constraints to maintain constant lake levels or minimum diversions.

Flow versus weighted usable area curves were obtained from the U.S. Fish and Wildlife Service (FWS 1994). Fig. 2 shows these relationships and their convex, piecewise linear approximations. Due to the convexity requirements for linear programming, the bimodal relationship for fry habitat with flow was approximated as unimodal. The peak associated with low flow (1.42 m^3/s or 50 cfs) was assumed to be an artifact of the IFIM process. Therefore, the linearized convex approximation ignores the peak at 1.42 m^3/s (50 cfs) and instead uses a peak of 24.8 m^3/s (875 cfs) as consistent with the remainder of WUA curve; this assumption was made after consultation with fisheries biologists.

Values for the three factors α, β, and γ, were taken from an individual-based chinook salmon recruitment simulation model calibrated for the basin of interest (H. I. Jager, in review, 1996). Tables 1 and 2 give values for the decimal fraction of the entire population existing in a given life stage in a given month (α), the fraction of the population in each life stage surviving to become juveniles (β), and the area needed to support one individual (γ).

Values for λ_{WS} and λ_{HC} [see (8)] were varied to generate

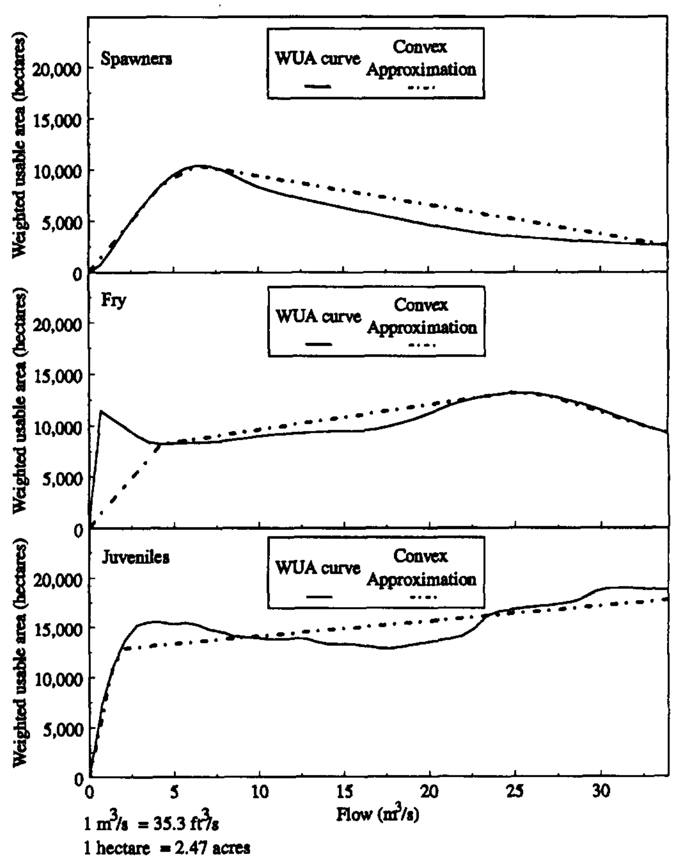


FIG. 2. Flow versus Habitat Relationships and Their Convex Linear Piecewise Approximations for Three Life Stages

TABLE 1. Value for $\alpha_{g,\tau}$, Maximum Fraction of Life Stage Existing During Specific Month

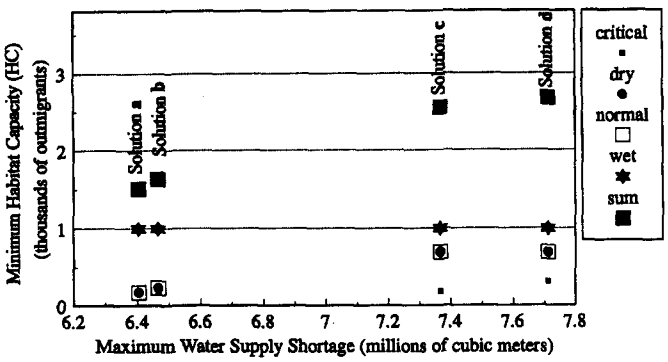
Month (1)	Spawners (2)	Fry (3)	Juveniles (4)
October	0.343	0.001	0.001
November	0.622	0.001	0.001
December	0.622	0.052	0.001
January	0.598	0.255	0.001
February	0.501	0.535	0.001
March	0.222	0.729	0.009
April	0.044	0.691	0.142
May	0.001	0.404	0.116
June	0.001	0.240	0.076
July	0.001	0.039	0.003
August	0.001	0.025	0.002
September	0.001	0.002	0.001

Note: Default values of 0.001 are used if no individuals of that life stage exist during a specific month.

TABLE 2. Values for β_g, Fraction of Individuals That Survive to Juvenile Life Stage, and γ_g Habitat Needed per Individual for the Three Life Stages

Life stage (1)	β_g (2)	γ_g (3)
Spawners[a]	0.11	0.05 ft^2
Fry	0.15	5.92 ft^2
Juveniles	1.00	6.49 ft^2

[a]Survival rate during spawning season applies to survival rate of eggs.



1 million cubic meters = 0.81 thousand acre-feet

FIG. 3. Model Generates Four Solutions (a, b, c and d) Using Different Weights on Habitat Capacity and Water Supply Objectives (Minimum Habitat Values Are Shown for Critical, Dry, Normal, and Wet Year Types; Their Sum Is Also Given)

multiple alternatives. These included scenarios where nearly all weight was on one objective and virtually no weight on the other and scenarios that gave both objectives substantial weight. This was a straightforward application of the weighting method of multiobjective programming (Cohon 1978). Results were generated in a few minutes on a 486 personal computer (PC) using GAMS/Minos (Brooke et al. 1988), a commercially available algebraic modeling system. These results comprise the initial stage of determining appropriate instream flows.

Fig. 3 shows the resulting trade-offs between habitat capacity and water supply for four model-generated solutions. Solutions generated using a high value for λ_{WS} and a low value for λ_{HC} (see Table 3) are characterized by lower habitat capacity and lower water supply shortfalls. For each solution, Fig. 3 shows the calculated habitat capacity for wet, normal, dry, and critical years and the sum over the four year types. Habitat capacity is plotted against the maximum shortfall experienced during the period of record. For clarity, we choose to plot the value for only one of the two water supply objectives.

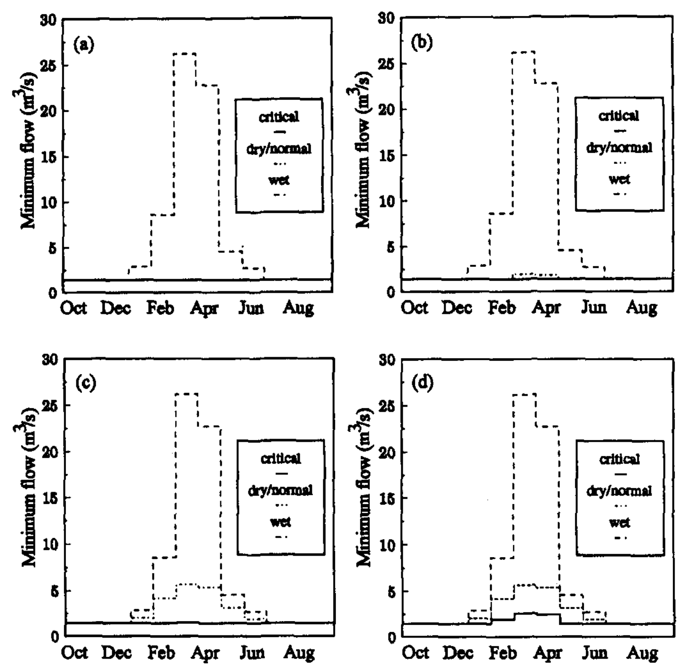
Fig. 4 gives the corresponding minimum flow schedules. The high flows that the model allocates during the fry life stage (February, March, and April) indicate that habitat is limited during the fry life stage. Early spring flow levels of 25.5 m^3/s (900 cfs) maximize fry habitat, whereas flow levels during the rest of the year do not maximize habitat for spawners (flows at 7.08 m^3/s or 250 cfs) or juveniles (flows greater than 28.32 m^3/s or 1,000 cfs). Had another life stage been the limiting factor, the flow that produced the maximum habitat for that life stage would have been allocated. Therefore, fry habitat is the bottleneck for fish populations. Comparison of Figs. 4(a)–(d) shows that the importance of fry habitat is independent of the objective weights.

Both Figs. 3 and 4 show the minimum flow schedule to be insensitive to the characterization of a year as dry instead of normal. This insensitivity implies that there is no water supply benefit to increasing normal year flows and decreasing flows during dry years. Alternative water year classification methods

TABLE 3. Values for Objective Function Weights λ_{HC} and λ_{WS} for Four Solutions

Solution (1)	Objective Function Weight λ_{HC} (2)	λ_{WS} (3)
a	1.0	16.2
b	1.0	1.6
c	1.0	.6
d	1.0	0.3

Note: Habitat capacity measured in millions of outmigrants, water supply measured in millions of cubic meters; objective function weights are relative and can be adjusted by the model user; 1,234,000 m^3 = 1,000 acre-feet.



1 m^3/s = 35.3 ft^3/s

FIG. 4. Model Generates Four Sets (a, b, c, and d) of Minimum Flow Regimes for Critical, Dry, Normal, and Wet Year Types Using Different Weights for Habitat and Water Supply Objectives

may change this trait. Because wet-year flow requirements are insensitive to objective weights, we conclude that minimum flows supplied during wet years do not influence the water supply.

After reviewing the results shown in Figs. 3 and 4 with experts in fish ecology and water supply, we can modify the optimization model to generate other, more acceptable solutions. Whereas the initial flow schedule may produce acceptable amounts of habitat, these flow schedules may be inappropriate because of factors such as temperature and the need for out-migration flows in the spring and fall. The temperature effects can be addressed using the factors outlined in the optimization model section to modify the flow versus habitat relationships. Out-migration flow requirements can serve as additional constraints. Figs. 5(a) and 5(b) show minimum flow schedules generated using two different values of objective weights and values of $T1_{g,\tau}$ of 2.12 m^3/s (75 cfs) for the spawning life stage during the spawning season (October through January). $T2_{g,\tau}$ was kept at 1.0 for all life stages and months. Figs. 5(c) and 5(d) show corresponding flow schedules without modifications for temperature but with minimum flow requirements for out-migration in May of 7.08, 14.16, 21.24, and 28.32 m^3/s (250, 500, 750, and 1,000 cfs) for critical, dry, normal, and wet year types, respectively. Similar modifications

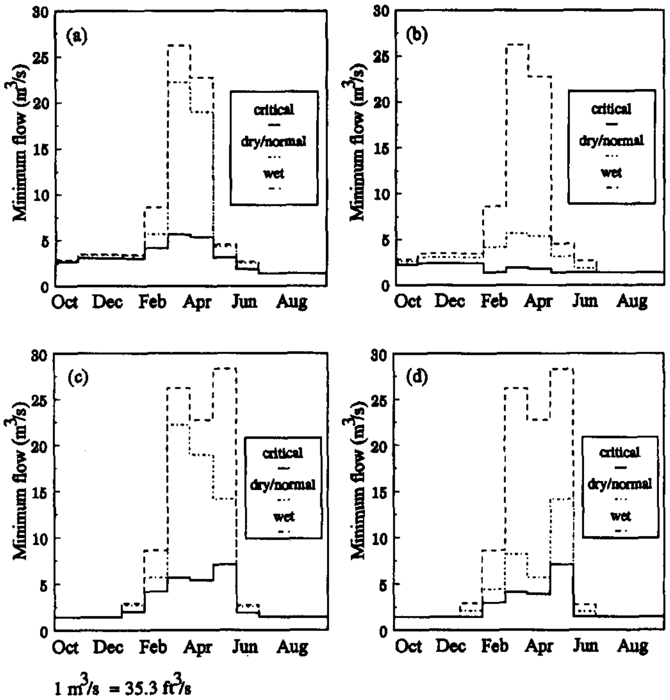


FIG. 5. Minimum Flow Regimes Generated Using $T1$ = 2.12 m^3/s during Spawning Season for Two Different Values of Objective Function Weights a and b, and Requiring Pulse Flows of 7.08, 14.16, 21.24, and 28.32 m^3/s (250, 500, 750, and 1,000 cfs) during May (during Critical, Dry, Normal, and Wet Year Types) for Two Different Values of Objective Function Weights c and d

can be made to the year-type definition and the water supply objective if the minimum flow requirements are inappropriate from a water supply planning context.

After more acceptable instream flow schedules are generated, simulation models for reservoir operation (e.g., HEC5), fish populations (H. I. Jager, in review, 1996), and socioeconomic impacts can be used to evaluate the proposed flow requirements and further modify the optimization model. We can change the relative objective weights (λ_{WS} and λ_{HC}), add constraints, or use different objective functions. In this way, the optimization model plays an important role in the planning process for determining appropriate instream flow requirements.

CONCLUSIONS

This work presents a planning level model to generate minimum instream flows that balance environmental and water supply objectives. The modeling effort goes beyond simply evaluating minimum flow regimes to actually generating new alternatives that satisfy multiple water demands. The optimization model is flexible, easy to modify, and allows minimum flows to be based on hydrologic year types. Various case-specific concerns can be accommodated through modification of objectives and constraints. Through modification of objective function weights, we generate a range of minimum flow scenarios and analyze trade-offs between different objectives. Other objectives or constraints can be added to address recreational benefits, duration of water supply shortfall, or maintenance of minimum pool elevations.

This paper also presents a mechanism for linking habitat capacity across various fish population life stages. The habitat capacity measure developed here allows modelers to identify where the bottleneck will occur in habitat capacity so that water can be released during months when it would have the greatest beneficial impact. The habitat capacity framework can address nonhabitat-based relationships between flow and fish populations by making modifications to the model structure to incorporate pulse flows and temperature impacts. In this example, the bottleneck for habitat was the fry life stage. Results also show minimum flow requirements to be insensitive to the classification of hydrologic year type as normal or dry and show no impact of wet-year flows on water supply shortfalls. Further research may be appropriate to determine more sensitive year-type classifications. Appropriate model modifications can be made in consultation with outside fisheries or water supply experts to iterate to better solutions.

The modeling structure is simple enough for a wide range of water resources professionals to understand and implement (PC-based), yet we can connect the minimum flow regimes generated here with sophisticated simulation models for both reservoir operation (e.g., HEC5), fish populations (H. I. Jager, in review, 1996), and socioeconomic effects. The framework is simple enough to allow iterative modification by the systems modelers, the fish biologists, and the water supply managers. In that way it suits its intended function as a planning-level model.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

AC = aqueduct capacity;
D_i = municipal water demand in period i;
DS = dead storage level of reservoir;
FC_τ = maximum reservoir level allowed during month τ because of reservoir capacity constraints;
$FR_{y,\tau}$ = required instream fish release during particular year-type and month;
g = life stage of the fish;
$HC_{g,\tau}$ = habitat capacity measure indicating maximum number of outmigrants that could be supported by given flow during a month;
I_i = inflow to reservoir during period i;
i = subscript referring to individual time periods;
N = total number of individual periods, i;
K = reservoir capacity;
M_i = mass of water diverted from reservoir to water supply uses during period I;
S_i = storage in reservoir at end of period i;
T = number of cyclical periods (months);
$T1_{g,\tau}$ = temperature offset factor for WUA for given month and life stage;
$T2_{g,\tau}$ = temperature factor to modify amplitude of WUA curve for given month and life stage;
tWUA = temperature-modified WUA;
W_i = water released from reservoir during period i;
$\text{WUA}_g(Q_\tau)$ = weighted usable area for life stage g provided by flow level Q in month τ;
Y = set of year types;
y = subscript denoting year type (critical, dry, normal, and wet);
Z = combined objective function (linear weighted sum of habitat and water supply objectives);
Z_{HC} = fish population objective;
Z_{WS} = water supply objectives;
$\alpha_{g,\tau}$ = fraction of life stage g population that exists in life stage g in stream during month τ;
β_g = likelihood of survival to juvenile life stage from life stage g if habitat is not limiting factor;
γ_g = amount of habitat needed per individual in life stage g;
λ_{HC} = weight for habitat capacity objective;
λ_{WS} = weight for water supply objective; and
τ = cyclical time period (e.g., month).