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Key Points:

- A new approach for operating reservoirs to support the downstream ecology of regulated rivers is developed called "environmental hedging"
- Environmental hedging maximizes downstream biological success with seasonal uncertainty while meeting human water demands
- Folsom Dam operations modeled with hedging outperform other policies, including current practice, for environment and water supply metrics

Supporting Information:

- Supporting Information S1
- Table S1
- Table S2
- Table S3

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Environmental hedging: A theory and method for reconciling reservoir operations for downstream ecology and water supply

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Abstract Building reservoir release schedules to manage engineered river systems can involve costly trade-offs between storing and releasing water. As a result, the design of release schedules requires metrics that quantify the benefit and damages created by releases to the downstream ecosystem. Such metrics should support making operational decisions under uncertain hydrologic conditions, including drought and flood seasons. This study addresses this need and develops a reservoir operation rule structure and method to maximize downstream environmental benefit while meeting human water demands. The result is a general approach for hedging downstream environmental objectives. A multistage stochastic mixed-integer nonlinear program with Markov Chains, identifies optimal "environmental hedging," releases to maximize environmental benefits subject to probabilistic seasonal hydrologic conditions, current, past, and future environmental demand, human water supply needs, infrastructure limitations, population dynamics, drought storage protection, and the river's carrying capacity. Environmental hedging "hedges bets" for drought by reducing releases for fish, sometimes intentionally killing some fish early to reduce the likelihood of large fish kills and storage crises later. This approach is applied to Folsom reservoir in California to support survival of fall-run Chinook salmon in the lower American River for a range of carryover and initial storage cases. Benefit is measured in terms of fish survival; maintaining self-sustaining native fish populations is a significant indicator of ecosystem function. Environmental hedging meets human demand and outperforms other operating rules, including the current Folsom operating strategy, based on metrics of fish extirpation and water supply reliability.

We forget that the water cycle and the life cycle are one.
Jacques Cousteau

1. Introduction: Reservoir Operations for Downstream Environmental Management

Balancing reservoir operating objectives is challenging given the trade-offs in meeting hydropower and water supply demands, protecting the environment, and managing floods and droughts. As a result, the design of release schedules requires metrics that quantify the benefit and damages created by releases to the downstream ecosystem. These release schedules should support making operational decisions under uncertain hydrologic conditions, including drought and flood seasons. This study addresses this need and develops a reservoir operation rule structure and method to maximize downstream environmental benefit while meeting human water demands. The result is a general approach for hedging downstream environmental objectives.

Typical reservoir operations regulate releases based on infrastructure limitations, water availability, water demand, and economic concerns [*Klemeš*, 1977; *Loucks et al.*, 1981: *Yeh*, 1985; *Lund and Ferreira*, 1996; *ReVelle*, 1999; *Labadie*, 2004; *Harou et al.*, 2009; *Lund et al.*, 2017]. Separate release targets for downstream ecological needs [*Arthington*, 2012] are generally based on: (a) habitat extent and suitability [*Sale et al.*, 1982], (b) downstream modeled fish populations [*Cardwell et al.*, 1996; *Cioffi and Gallerano*, 2012; *Jager et al.*, 1997; *Jager and Rose*, 2003; *Null and Lund*, 2011], and/or (c) environmental goals based on specified hydraulic, hydrologic, water quality or political metrics [*Tharme*, 2003]. Resulting flow regimes may approximate the "natural" flow regime [*Palmer and Snyder*, 1985; *Poff et al.*, 1997; *Harman and Stewardson*, 2005; *Suen and Eheart*, 2006; *Vogel et al.*, 2007; *Richter and Thomas*, 2007; *Wang et al.*, 2016] or may be developed using a more biophysical-social-hydrologic approach [*Poff et al.*, 2010]. Habitat and population modeling seek release schedules to maximize habitat capacity and thereby species (usually fish) survival at each of several life history stages. To meet environmental goals, a typical reservoir operation strategy is to release available water until the environmental target goal, such as a minimum instream flow, is met. Making releases that mimic the natural flow regime assumes that fish and other wildlife are adapted to the local natural flow pattern so any alterations are assumed to harm the native ecosystem. All of these modeling approaches rely on expert opinion and empirical data when developing target release goals, validating modeling results, or measuring effectiveness of modeling recommendations.

Environmental flow operations often are modeled by simulation or optimization methods. Most modeling studies represent environmental goals as a constraint on other operations, usually as a minimum instream flow requirement [*Homa et al.*, 2005]. These models constrain releases to account for (a) water availability from storage and inflow from the current and previous period, (b) flood control needs, and (c) storage needs for minimum drought and carryover (e.g., human and economic) requirements. *Waddle* [1992] augments these approaches with an equation that remembers changes in fish population size between modeled release periods. *Sale et al.* [1982], *Cardwell et al.* [1996], and *Cioffi and Gallerano* [2012] advanced optimization approaches by using stochastic reservoir inflow rather than using fixed water year types. Release decisions for both simulation and optimization models are typically made monthly over a water year. *Jager and Rose* [2003], instead, model 2-week time steps. The natural flow regime literature simulates release decisions with calculations of hourly, daily, or weather-event periods, depending on the concern. Some models explicitly employ environmental goals as a single objective [*Sale et al.*, 1982; *Jager and Rose*, 2003; *Null and Lund*, 2011], while others represent environmental goals within a multiobjective optimization model [*Cardwell et al.*, 1996; *Cioffi and Gallerano*, 2012], maximizing for one or more biologic life stages.

Here we develop a method and theory to optimize the timing and magnitude of seasonal reservoir releases for downstream environmental benefit. The environmental benefit function is defined as the ideal environmental flow regime which could be developed using any of the state of the art environmental flow methodologies. In our case study, we define the benefit function to be the seasonal flow requirements of each life history stage of one keystone species of fish. Operation time steps are discretized by life histories and hydrologic seasons. Consequent reservoir release schedules maximize downstream environmental benefit while considering seasonal trade-offs among hydrologic seasons and life cycle stages for a range of water storage and probabilistic and conditional hydrologic conditions. This method incorporates environmental flow objectives to show when reservoir releases might best be reduced for early life stages in order to improve survival of older life stages. The environmental benefit function, a persistence constraint that remembers environmental benefit over time, and a drought protection constraint, are the constraints on reservoir operations that minimize environmental damage and maximize environmental benefit.

We employ a multistage stochastic mixed-integer nonlinear program for a range of forecasted hydrologic states to produce optimal release schedules. Markov Chains transition forecasts of predicted inflows, as well as the contingencies for errors in these forecasts. We assume some downstream targets for human water supply (i.e., hydropower, municipal/agricultural/industrial water supply, and flood control) have higher priority than environmental demand, so decisions for the environment occur without making other users worse off. The overall result is a general approach to maximize downstream goals: in this case, to balance downstream biological success with seasonal uncertainty and other water demands. The results sometimes involve "environmental hedging" operations which conserve water in dry times by reducing early releases in order to improve success in later times, given future drought probabilities and minimum storage needs for the environment and other uses. Releases avoid flood in wet times with spill. Releases hedge for past conditions by being constrained to not exceed flows for current downstream fish population size, given the "memory" of the earlier fish population size. This strategy may force some early damage (i.e., small fish kills in early life stages, most notably early in the scheduling period), in order to reduce the risk of storage crises and crises (i.e., fish extirpation) during extreme events.

2. Environmental Hedging Method

The timing and magnitude of making strategic environmental release and curtailment decisions are outlined below. An objective function, six constraints, and hydrologic and biologic forecasting are the components of the environmental flow hedge method. With this method, reservoir operations deviate from standard linear operating policy with strategic hedges. A multistage stochastic mixed-integer nonlinear program operationalizes environmental hedging theory into reservoir operations and planning practice.

The model explicitly quantifies downstream environmental impacts of release decisions with the assumption that some environmental damage (e.g., fish mortality) is sometimes inevitable but larger damage levels (i.e., population or species extirpation) should be avoided. The optimized contingent release decisions hedge and adapt as the water year's hydrologic and ecologic uncertainty diminishes with time. In this particular case, the first stage release decision is made (based on expected fall inflow and initial storage) before observing any outcome of random "actualized" inflow for the fall or future time stages. Decisions in later stages are made within system constraints based on the realization of inflow acquired during earlier stages, without observing future inflows. Environmental benefits (e.g., fish populations) from the release decision for each possible hydrologic condition in each time period is carried forward for each time period's state into the following period. The decision tree branches combinatorially based on the number of possible inflow states and stages considered. In our case, the environmental benefit function is based on empirical observation and expert opinion of native anadromous fish (e.g., Chinook salmon) requirements. Native anadromous fish are sensitive indicators of environmental flow needs for reasons that are economic, ecological, practical, genetic, aesthetic, and moral [*Moyle*, 2002]. Native fishes evolved with the native hydrograph. A number of species could have been used for our model. However, we applied the model to predict survival of three freshwater life-history stages of fall-run Chinook salmon in the lower American River of California, because they require high water quality, are a species in decline, and are well studied [*Williams*, 2001]. Although the river flow regime is characterized by a Mediterranean climate, the principles and mathematics of the model can be modified and applied to other species or downstream goals (e.g., groundwater recharge) in other regulated rivers and climates.

2.1. Timing of Releases

Reservoir releases $R_{y_t,t}$ are made to support each discrete life-history stage for each possible hydrologic state y of time duration t, y_t. The number of distinct operational time periods t coincide with the fish's riverine life stages (such as eggs or fry) and the distinct hydrologic seasons (such as fall and spring), for all hydrologic states y (from driest to wettest; Figure 1). Discretizing time by meaningful fish life stages and hydrologic seasons gives flexibility in scheduling bulk water releases to account for seasonal and ecological variability. Time is aggregated by months because most water supply operations are planned with a monthly time scale. Decisions are made for all time steps and contingent conditions to maximize fish populations.

Model Decision Stage	1	2	3.1		3.2	Minimum Carryover Storage Requirement		
Time Discretization	1	2	3	4	5	6	7	8
Months	Oct, Nov, Dec	Jan, Feb, Mar, Apr	May, Jun	Jul, Aug, Sept	Oct, Nov, Dec	Jan, Feb, Mar, Apr	May, Jun	Jul, Aug, Sept
Fish year class g	A					B		
Water year h	1					2		
Hydrologic Season	Wet Season		Dry Season		Wet Season		Dry Season	
			Snowmelt	Baseflow			Snowmelt	Baseflow
Fish Development Period	Egg	Fry	Smolt	None	Egg	Fry	Smolt	None
Fish Release Decision $R_{y_t,t}$	$R_{y_1,1}$	$R_{y_2,2}$	$R_{y_3,3}$	$R_{y_4,4}$	$R_{y_5,5}$			

Figure 1. Example discretization of time periods *t* used to develop a release schedule to support two cohorts of anadromous fish downstream of a reservoir under uncertain hydrologic conditions. Release decisions vary with hydrologic states *y* (e.g., very wet, median, or abnormally dry).

2.2. Magnitude of Releases

2.2.1. Objective Function

The operator is responsible for maximizing environmental benefit below the dam. For this example, in maximizing the survival of anadromous fish, the dam operator is responsible for two cohorts over all hydrologic conditions: one developing cohort (e.g., salmon that survive growing from eggs laid to smolts migrating to the ocean; (cohort A) and a second cohort of adults returning after several years at sea to spawn (cohort B). The objective (equation (1)) is to maximize the average weighted sum of both cohorts (N^A and N^B), across the range of seasonal hydrologic conditions (y) which occur with probability (p). The second fish cohort ($g=B$) is weighted with a constant ($\propto$) to capture trade-offs between cohorts. Maximizing final water storage at the end of the final period of the model (S^F) is included as added value to the objective function with weighting constant (β) to penalize present releases lacking fish benefit and to save water for fish and other water uses in the future. In another system dominated by nonmigratory fish, the objective function could be rewritten as the sum of the probability of fish survival for every fish life history stage over the full range of hydrologic states.

$$\max(z)=\left[\sum_{y} p_{y_{T-1},T-1} N^{A}_{y_{f-1},T-1}+\alpha\sum_{y} p_{y_T,T} N^{B}_{y_T,T}\right]+\beta\sum_{y} p_{y_T,T} S^{F}_{y_T,T} \tag{1}$$

where z is the net expected downstream fish population; y_t is the hydrologic/inflow state (i.e., wet, dry, or very dry) of inflow for each time period t; g is the fish cohort (i.e., fish cohort A or B); T is the final time step t for future fish population (i.e., time period 5 for cohort B); t is the indexed time step expressed in aggregated months. (Time step durations can differ for each fish development and hydrologic stage.) $p_{y_t,t}$ is the probability of predicted hydrologic state y for time period t; $N^{g}_{y_t,t}$ is the fish surviving population in each predicted hydrologic state y of time duration t for fish cohort g; $\propto$ is the relative weighting of cohorts; β is the relative weighting of final storage; and $S^{F}_{y_T,T}$ is the final storage volume for final time period t = T.

2.2.2. Hydrologic Forecasting

Each season's release decision is the sum of a base release decision and an incidental spill decision (equation (3d)). The base release decision is determined before the period has begun, for planning, based on the period's predicted inflow state $p^{q'}_{y_t,t}q'_{y_t,t}$ (supporting information Text S1 and S2). Base release decisions hedge releases based on expected inflow to guarantee water storage during drought. Each period's spill release is made after the period has begun, based on a range of expected period inflow states $p^{q}_{y_t,t}q_{y_t,t}$ (supporting information Text S1 and S2) that represent a range of actualized inflow states that could happen given the inflow of the previous stage. Spill decisions are made every period to avoid overtopping the reservoir; like hedging for drought, sometimes spill is hedged between time periods to avoid environmental damage. A range of modeled seasonal hydrologic conditions y adjusts releases to forecast and actual inflow so the release schedule has interannual variability. Conditional probabilities forecast seasonal predicted inflow (supporting information Text S1). A Markov Chain based on exceedance probabilities of the historical inflow record forecast seasonal actualized inflow. Depending on the statistical relationship between seasonal inflows (supporting information Text S2), predicted inflow for each hydrologic state y in each time period t can be conditional (e.g., between wet seasons), dependent (e.g., snowmelt following a wet season), or independent (e.g., at the beginning of the water year) of the previous season inflow. Building a model that forecasts both predicted (before the release) and future actualized (after the release) inflow allows for error and regret analysis for adaptive operations, explicitly modeling the likely probability that a seasonal forecast is wrong. Uncertainty narrows as the water year develops and more inflow information is known.

2.2.3. Decision Tree

The objective function is written in terms of $N^{g}_{y_t,t}$ and $S^{F}_{y_t,t}$ as this seems the most direct model conceptualization. The decision variables, reservoir releases $R_{y_t,t}$, (including the base release decision $R^{\min}_{y_t,t}$ to avoid a fish kill and a spill decision $P_{y_t,t}$) do not appear in the objective function but enter via constraints. The outcome of the release decisions is measured in terms of fish survival $N^{g}_{y_t,t}$ at each stage t (Figure 2).

2.2.4. Constraints

Six constraints support reservoir releases for each time step t. Releases are physically constrained to fall within (a) water availability, (b) dam infrastructure capacities, and (c) minimum streamflow requirements. Releases also are guided by (d) environmental benefit functions, (e) a persistence constraint, and (f) a drought protection constraint.

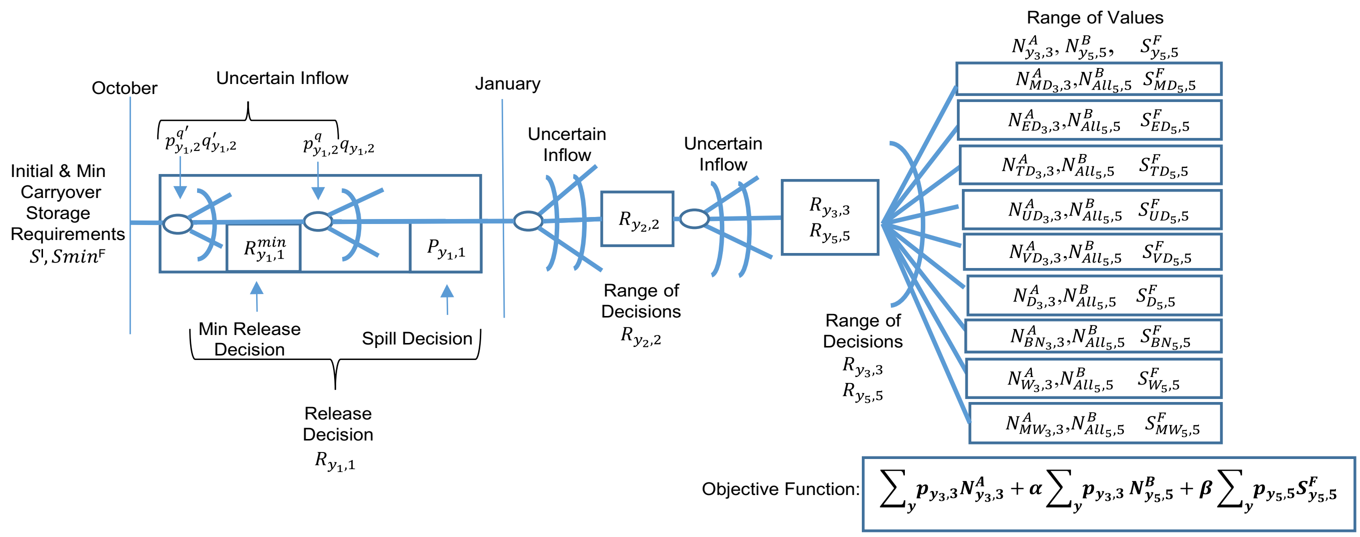

Figure 2. Decision tree for a three-stage optimization model for maximizing fish survival. Each release decision $R_{y_t,t}$ includes a drought management decision $R^{\min}_{y_t,t}$ and a flood management decision $P_{y_t,t}$.

2.2.4.1. Water Availability

Releases cannot exceed available water at any time (equation (2)). Water availability includes the period's initial storage plus expected inflow minus higher priority diversions.

$$R_{y_t,t} \leq a_{y_t,t} \ \ \forall \ y \in t \tag{2}$$

$$a_{y_t,t} = S^I_{y_t,t} + q'_{y_t,t} - d_t \ \ \forall \ y \in t \tag{2a}$$

where $R_{y_t,t}$ is the reservoir release for each hydrologic state y of time period t; $a_{y_t,t}$ is the water availability each hydrologic state y of time period t; $S^I_{y_t,t}$ is the incoming stored water for each hydrologic state y of time period t; $q'_{y_t,t}$ is the predicted reservoir inflow for each hydrologic state y of time period t; and d_t is diversions with higher priority than fishes, such as domestic water use, for each time period t.

2.2.4.2. Reservoir Infrastructure Limitations

Water storage must always equal or exceed deadpool storage dp but cannot exceed reservoir storage capacity rc (equations (3a) and (3b)). Releases also cannot exceed the maximum reservoir outlet capacity moc. Releases are the total of the base required release $R^{\min}$ and the reservoir spill release P.

$$S^F_{y_t,t} \geq dp \quad \forall \ y_t \in t \tag{3a}$$

$$S^F_{y_t,t} \leq \ rc \ \forall \ y_t \in t \tag{3b}$$

$$R_{y_t,t} \leq moc \ \forall \ y_t, t \ = \ f \tag{3c}$$

$$R_{y_t,t} = \ R^{\min}_{y_t,t} + P_{y_t,t} \ \forall \ y_t, t \ = \ f \tag{3d}$$

where dp is the deadpool storage requirement for the reservoir; rc is the reservoir capacity; moc is the maximum reservoir outlet capacity; $R^{\min}_{y_t,t}$ is the base release planned for each hydrologic state y of each time period t given the period and hydrologic state's expected water availability a; and $P_{y_t,t}$ is the spill release for each hydrologic state y of time period t.

2.2.4.3. Minimum Streamflow Requirement

Releases must meet a minimum streamflow threshold (e.g., the flow required to save at least 10% of the target fish population during the juvenile stage). Beyond this threshold the ecosystem has been pushed to the limits of resiliency and will shift to an undesirable new ecological state.

$$R^{\min}_{y_t, \ t} \geq emin_t \ \forall \ y \ \text{in} \ t \tag{4}$$

where $emin_t$ is the minimum downstream streamflow requirement for the months of time period t).

2.2.4.4. Stored Water

Water stored for the future offers the ability to hedge for dry times. Actualized inflow plus water storage from the previous period (less last period's diversions and releases) determine the incoming storage for the next time period (equation (5)).

$$S^F_{y_t,t} = \left(\left(S^I_{y_t,t} = S^F_{y_{t-1},t-1} \right) - R_{y_{t-1},t-1} + q_{y_{t-1},t} - d_{t-1} \right) \ \forall \ y \ \in \ t \tag{5}$$

where $q_{y_t,t}$ is the actualized inflow to the reservoir for each hydrologic state y of time period t.

2.2.4.5. Environmental Benefit Function

This equation links streamflow to environmental benefit for each hydrologic state of each time period. The linkage can be based on any environmental flow methodology (e.g., expert interviews and/or mechanistic models that index environmental need based on hydraulic, hydrologic, water quality, and ecological indicators). In using fish species as indicators of environmental health, for example, fish population size (N) is limited by spawning and rearing area, such as the flow required to keep temperatures below the maximum at which the fish species can survive.

$$N_{y_t,t} \le f\left(R_{y_t,t}\right) \ \forall \ y \in t \tag{6}$$

2.2.4.6. Population Dynamics and Persistence Constraint

Current period ecological and biological abundance is based on natural mortality and curtailments from the environmental support capacity of the previous period. For example, the fish population (*N*) for any life stage during any time period *t* has been reduced by the fish's natural mortality rate (*k*) and fish death in the previous period from releasing spill or curtailing the environmental benefit function (equation 3), i.e., if the natural mortality rate (*k*) of eggs to fry is 30%, and egg incubation period releases are curtailed to 50% of ideal, then the largest population possible in the current period is only 35% of the target. This population dynamics constraint carries the memory of environmental conditions from one time period to the next. Strategic releases are hedged, when necessary, to meet but not exceed the requirements of the current population size rather than that for ideal population size.

$$N_{y_t,t} \le (1-k) N_{y_t,t-1} \ \forall \ y \in t \tag{7}$$

where *k* is the expected mortality occurring between time step t − 1 and t.

2.2.4.7. Drought Storage Protection

Stored water at the end of the modeled period $S^F_{y_T,T}$ provides some drought protection for future years. This end of modeled period storage must exceed the sum of deadpool storage *dp*, minimum carryover storage requirements $Smin^F$, and the storage to meet the high priority diversions and minimum streamflow requirements for each season's driest hydrologic state y_D.

$$S^F_{y_T,T} \ge Smin^F_{y_T,T} + dp + d_T + emin_T - \forall \ t \in (\mathrm{y{=}D}) \tag{8}$$

where $S^F_{y_T,T}$ is stored water for each hydrologic state *y* in the final modeled period *T*; $S^f min^F_{y_T,T}$ is the minimum carryover storage requirement for the reservoir after the final modeled period; D_t is the driest expected (D) hydrologic state y of time period t; and is expected future actualized inflow for each time period t of the driest hydrologic state D.

3. Environmental Hedging Theory

Environmental hedging helps to manage uncertain water supply availability for downstream release and to balance near-term environmental benefit with long-term environmental resilience. The hedging selects whether or not to kill a small number of fish now in order to reduce the likelihood of killing more later if supply is limited or will cause a damaging flood. Environmental hedging applies the same logic as water supply hedging [*Draper and Lund*, 2004; *You and Cai*, 2008a, 2008b; *Hui and Lund*, 2015] for which "it is sometimes economical to accept a small current deficit in output so as to decrease the probability of a more severe water or energy shortage [or flood] later in the drawdown-refill cycle" [*Bower et al.*, 1962]. As water availability increases (from A → F in Figure 3a) six types of hedges bind each period's release decision based on current, future and past biologic and water availability (displayed alphabetically in Figure 3a). The hedging effects (e.g., diminished fish populations and flow needs) of decisions in one time period persist into future time periods. Releases can be further hedged

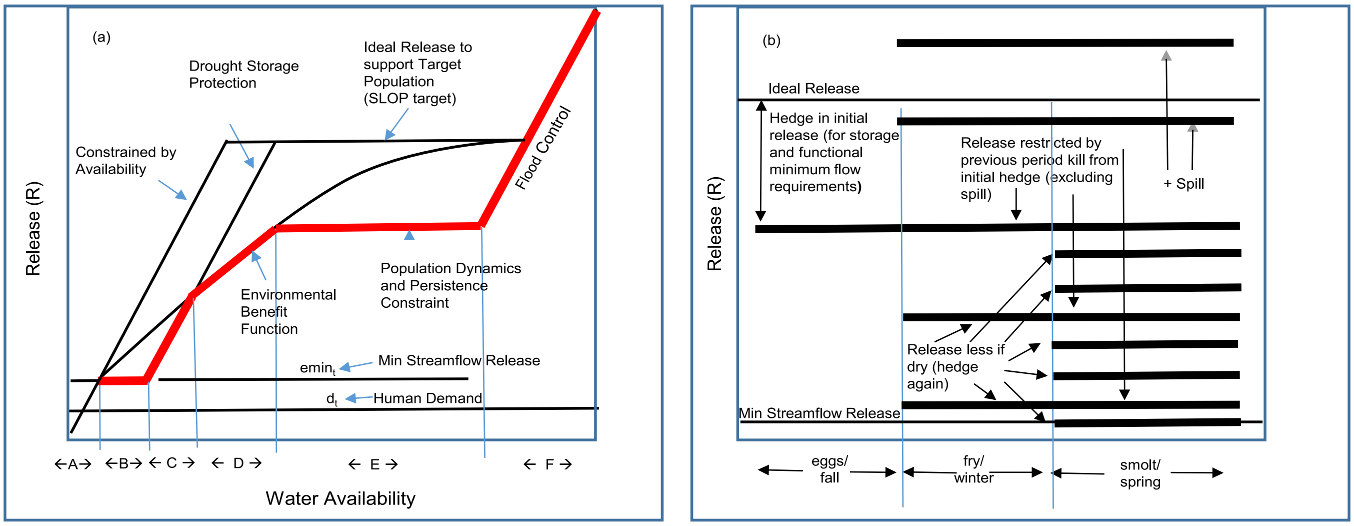

Figure 3. (a) Environmental hedging for one time period. The optimal release policy (environmental hedging) follows the thick red line for time period t. Dashed lines are release constraints. (b) Environmental hedging across time periods. Each line is the optimal decision per stage for each possible hydrologic condition.

over time (Figure 3b) under drier conditions, or greater releases and spill can occur in anticipation of, or after, wetter conditions.

Environmental hedging method hedges along the standard linear operating policy for seven reasons. Within one time period, six reasons make up the hedge (and are displayed alphabetically in Figure 3a). Depending on the system, the order of the hedge could change. (A) Water Availability, equation (2): Water is not released beyond current water availability. (B) Minimum Streamflow Requirement, equation (4): A lower bound restricts a lower release by the minimum streamflow requirement. (C) Drought Storage Protection, equation (8): Releases are hedged to meet both water availability and drought storage constraints for the driest expected current and future seasons. (D) Environmental Benefit Function, equation (6): Releases are hedged along the slope of the environmental benefit (E) Population Dynamics Persistence Constraint, equation (7): Releases are constrained to not exceed the water needs of the current population (considering population losses from the previous period). (F) Spill, equations (3b) and (3d): Releases are made to avoid overtopping the reservoir, even if the spill inflicts major environmental damage downstream. Hydrologic forecasting is the reason for hedging over time (Figure 3b). The model will hedge with predicted inflow in anticipation of extreme events at each time period.

4. Environmental Operation of California's Folsom Dam

Environmental hedging was applied to Folsom Dam in central California to maximize the downstream Chinook salmon population that can be supported by releases to the lower American River. Environmental conditions for the 48 km downstream from Folsom Dam to the Sacramento River confluence are determined largely by Folsom releases. Fall-run Chinook salmon are a key species for the lower American River. The hydrologic needs of the fall-run Chinook track the natural hydrograph.

Time is discretized by hydrologic season and the three distinct periods for which cohort A is in the stream: egg, fry, and smolt ($t = 1, 2, 3$, respectively), followed by the spawning and egg period of cohort B ($t = 5$) (see Figure 1). October through December is the period when fall-run Chinook salmon return from the ocean to spawn and lay eggs, January through April is the period when eggs mature to fry, and May through June is when young salmon, or "smolts" migrate to the ocean where they stay for 2–5 years before returning to spawn. Each fish life stage has different instream water needs. For fall-run Chinook the hydrology and fish life cycle stages are synchronized. Cohort B is included to represent the value of flows and storage toward the end of the water year.

Hydrologic forecasting for Folsom reservoir considers the region's two distinct hydrologic periods: wet season precipitation (October–April) and dry (May–September). Wet season inflow is highly variable, so operations must consider both droughts and floods. Seasonal inflows were estimated for each time period from the river's 113 years of historical record of unimpaired from the California Data Exchange Center's Full Natural Flow at Fair Oaks station. Wet season inflow is modeled by two fish development periods: the egg stage (October–December) and fry stage (January–April; Figure 1). Egg and fry period inflows correlate weakly with a correlation coefficient of 0.35 (p value of 0.12×10^{-6}). The egg stage includes adult migration to spawn the eggs. The May and June spring snowmelt season coincides with smolt out-migration and with inflows correlated with wet season snowpack ($r = 0.6$ with a p value of 0.75×10^{-11}); wet egg (winter) and fry (fall) seasons tend to beget wet smolt (spring) seasons. Dry season base flow between July through September correlate strongly with the next period's wet season inflow ($r = 0.83$ and a p value of 0.22×10^{-15}) and is modeled here as deterministic, so streamflow is modeled with conditional probabilities. Predicted and actualized future inflow events and the transition probability matrix between inflows for the lower American River are in supporting information Tables S1 and S2. Here, the egg (fall) season inflow lacks prior inflow information at the beginning of the water year so it is predicted initially to be 919 cfs, median historical seasonal inflow. Fry (winter) and smolt (spring snowmelt) predictions and future inflow are conditional on inflow of previous wet and dry season inflow. Snowmelt and dry season inflow at the end of the water year are determined by inflow (precipitation) received earlier in the year.

Hydrologic states y_t are discretized by the quantiles of the cumulative distribution function of each state's historical record (supporting information Text S2). The range of selected exceedance probabilities for the lower American River, $w = \{0.01, 0.025, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5 \text{ and } 0.75, 1\}$, includes floods, but emphasizes dry times for drought operations planning [*California State Water Resources Control Board*, 2015]. More fish suffer and die during drought, although some life-history stages (e.g., egg incubation) suffer from floods.

The water availability and infrastructure constraints are bound by Folsom reservoir's 1 million acre-foot storage capacity, 90 TAF deadpool storage requirement and 115,000 cfs outlet capacity [*Bureau of Reclamation*, 2016]. The 325 TAF/year released [*NOAA*, 2011] for downstream human diversion is always met. The minimum streamflow requirement allocates water to support 5% of fish from each of the two cohorts, thereby avoiding extirpation.

The environmental benefit function is modeled with fish survival $N^{g}_{y_t,t}$ as a function of reservoir releases $p_{y_t,t}R_{y_t,t}$ for each stage (combined fish life-stage and hydrologic season). The magnitude of the fall-run Chinook-streamflow functions may have error, but the shape of the function describing the need of each fish flow, is correct. The fall-run Chinook egg survival-flow relationship is an inverse quadratic survival function (Figure 4). Survival greatly increases with flow initially, and then less so, until finally high flows scour gravel bars and redds where eggs are laid [*USFWS*, 2003; *Jager and Rose*, 2003; *Jager et al.*, 1997; *Null and Lund*, 2011]. More flow creates more fry habitat [*Jager and Rose*, 2003; *Jager et al.*, 1997] until the river's carrying

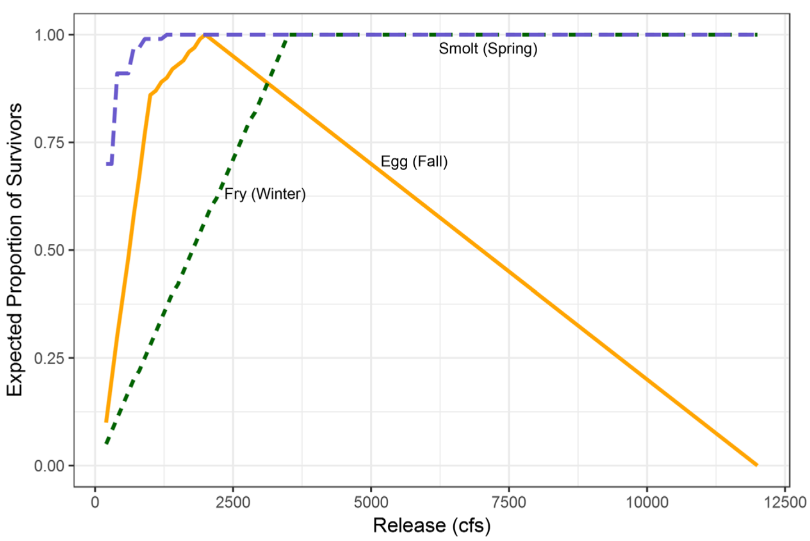

Figure 4. Maximum survival of fall-run Chinook for different releases to the lower American River. Survival rates from authors *Bradford* [1995], *SWRI* [2001], and *Williams* [2006]. Fish population size-streamflow curves developed from authors *Jager et al.* [1997], *Jones and Stokes Associates* [1997], *Jager and Rose* [2003], *USFWS* [2003], *U.S. Department of Interior* [2008], *Sykes et al.* [2009], *Null and Lund* [2011], and *Jager* [2014].

capacity is reached. Therefore, the fry survival-flow function is the linear slope-intercept between the fry minimum and maximum fish flow requirements. Smolts need pulse flows, so the smolt-flow relationship for the lower American River is pulsed [*Jager and Rose*, 2003; *Sykes et al*., 2009; *Jager*, 2014] to simulate spring snowmelt peaks that cue smolts to migrate downstream to the ocean. One pulse of 1,500 cfs is assumed to initiate outmigration for at least 75% of smolts. Releases that mimic base flow between pulses are assumed to maintain cold temperatures. Fish population optimization results in at least two, but no more than five "snowmelt pulses" because five pulses that each move 70% of the smolts out, will save roughly 100% of the smolt population. Pulses are modeled as mixed-integer variables in the model. The exact timing of pulse releases within the smolt period is not allocated so the operator can flexibly synchronize American River pulse releases with Sacramento River pulses. Pulse water is not allocated in the winter because it is assumed that fish will out-migrate with the natural pulse they receive from overland flood flow. Flow of 300 cfs in May and 600 cfs in June are released between pulses to ensure minimum fall-run Chinook temperature requirements of 65°F [*Jones and Stokes Associates*, 1997; *U.S. Department of Interior*, 2008].

Minimum fish flow requirements for eggs and fry are 190 cfs [*California State Water Resources Control Board*, 1958], the flow assumed to save 10% of eggs and 5% of fry. Smolts have a minimum release requirement of 123 cfs, or 33 TAF, the storage volume required to support two May pulses of 1,500 cfs with 5 days of 300 cfs and base flow in between, which is assumed to save at least 70% of smolt. Below these minimum fish flow requirements the population is considered extirpated because current fragmentation of the Sacramento River system prohibits fish from coping with the drought naturally by moving to another river or finding refuge in cold pools. Maximum flow requirements are assumed to support the ideal target fish population, set in the 1992 Central Valley Project Improvement Act's Anadromous Fish Restoration Plan for the wettest water year type (2,500 cfs between September and February and 4,500 cfs between March and June) which are currently used for Folsom operations [*Williams*, 2001].

The persistence of the Chinook salmon population under ideal conditions results in an average returning adult population of 160,000 [*USFWS*, 2001]. We assume female fall-run Chinook salmon (approximately 50% of the population) lay an average of 4,300 eggs [*Bradford*, 1995], about 15% of which successfully bank into redds, resulting in about 51,600,000 eggs, on average. We then assume about 10% of these eggs survive to become fry and about 70% of juveniles survive to become smolt [*Bradford*, 1995]. Including hatchery releases, about 5% of smolts survive the ocean and return to spawn [*Williams*, 2006]; even with ideal river conditions only about 7% of young salmon survive from egg to smolt.

Folsom reservoir was operated with environmental hedging for 28 combinations of initializing (i.e., at start of the model) and minimum carryover storage conditions. For these cases, minimum carryover storage requirements were discretized to 0, 50, 100, 150, 200, 250, and 300 TAF and initial storage conditions at the beginning of water year 1 are 250, 500 (Folsom average), 750, and 1,000 TAF.

The Pareto frontier of optimal release schedules were found for each storage case by running the environmental hedging model with a range of weights between 0 and 1 for the α penalty for allocating water to cohort B and β, the penalty for allocating water to final storage. This set of efficient solutions was then plotted to analyze the trade-offs in expected fish survival resulting from optimal allocation between the two cohorts (Figure 6a) as well as between releasing water for fish survival or storing it for the future over the range of α and β (Figure 6b). Expected fish survival for each case is the surviving percentage of the total population. These percentages exclude natural mortality to isolate the effect of water scarcity (and the consequent effects of water scarcity like habitat loss and warm temperatures).

Finding the globally optimal release schedule for each storage case required producing a subset of each case's set of efficient solutions four times. The first subset retains only solutions that produce the maximum average survival of cohorts. Maximum average survival is considered the globally optimal solution because both cohorts are equally important. Maximum average survival was normalized as the proportion of the sum of the target population supported by the release decision of each hydrologic condition weighted by the probability of that hydrologic condition. The second subset

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retained solutions that produced the largest final stored water volume, a less, but still important, goal. The third subset retained solutions with the smallest alpha and of those, the smallest beta to minimize computation time. For all storage cases, the optimal beta is 0.25. The optimal alpha is always 0.1 except when available stored water (initial less minimum carryover storage requirements) exceeds 600 TAF, in which case alpha is 0.05.

5. Results

5.1. Trade-offs Between Cohorts and Final Storage

A Pareto curve highlights trade-offs between allocating water for cohort A or B (Figures 6a and 6b), found by selecting different values of alpha and beta, the objective function priority weights for cohort B and final storage (equation (1)). Each line in Figure 6a is an interpolation of all model runs with a range of weights for each of the initial stored water volume and carryover storage requirements. Total population maximizing solutions (displayed as circles in Figure 6a) produce the maximum average allocation to cohort A and cohort B across all water year types.

Because of spill, the small human demand below Folsom, and the small probability of drought, expected survival of cohort A is often quite high. Because of the hedge in the first period for drought protection and the population dynamics constraint, cohort A has an upper bound cap, regardless of the choice of alpha or beta. After supporting the cohort A population, surplus water is available to support cohort B and final storage requirements. Depending on the choice of alpha and beta penalties, a wide range of cohort B survival is possible.

5.2. Trade-offs Between Storing Water or Releasing It for Fish Survival

The relationship between salmon survival and stored water is both complimentary and competitive, particularly with environmental hedging. Depleting water reserves is needed to save fish but because fish later depend on stored water (particularly in drought), depletion is not in the best interest of later life stages. Likewise, with greater initial storage and/or inflow is greater, both stored water and releases (and consequently fish survival for both cohorts) is also greater because more initial storage can increase releases for cohort A eggs in the first stage with greater impact on improving the objective function than other life stages. However, some competition between releases and storage also exists—minimum carryover storage requirements increase at expense of the fish population (Figure 5).

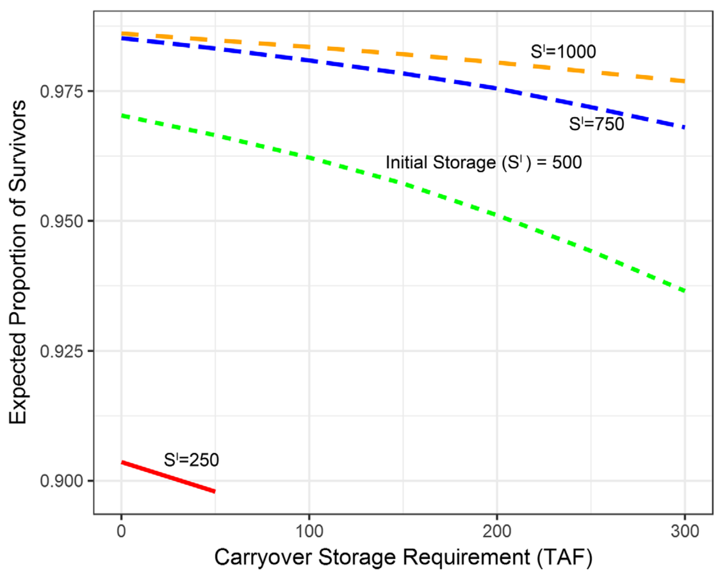

Figure 5. Maximum fish cohort survival for the range of minimum carryover and initial storage (start of model) requirements.

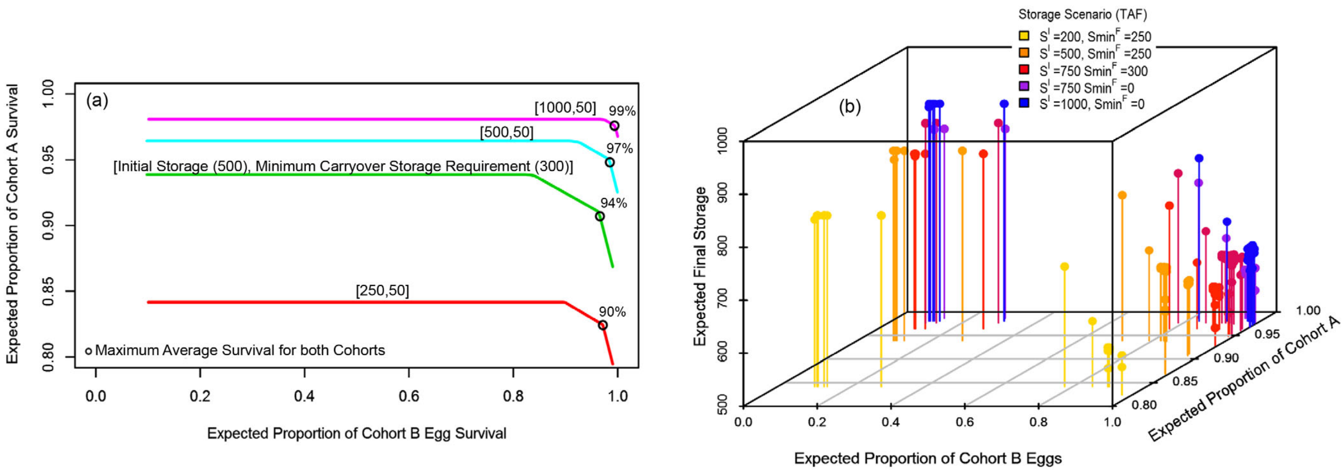

Figure 6. (a) Average fish survival of cohorts A and B for a range of initial and minimum carryover storage requirements. (b) Expected water in final storage and cohort A and B survival fish survival for a range of alpha, beta, minimum carryover storage requirements and initial water in storage conditions.

Within the set of efficient solutions, solutions vary negligibly with final storage penalty beta unless beta imposes a strong final storage penalty (of approximately 0). Final trade-offs among releasing water for cohort A or cohort B, or saving water in storage for the final time period, are more influenced by the choice of alpha. Strong alpha penalties (i.e., less than 0.01) tend to curtail a greater proportion of ideal releases to cohort B. In those cases, not enough water is available to improve cohort A, resulting in more fish death than is hydrologically necessary. Alpha choices above 0.01 produce the curve in the Pareto front between cohort A and B (Figure 6a). These choices exaggeratedly curtail ideal allocation to cohort A and instead save water for cohort B until all of cohort B is supported.

To meet all constraints, initial storage conditions at the beginning of the model at Folsom must exceed 194 TAF and the minimum carryover storage requirement be at least 194 TAF less than initial water storage conditions. Within these boundary conditions, enough stored water is available to support the minimum fish population (5%) of cohort A and B (equation (5)), as well as meet minimum carryover storage requirements—therefore avoiding the crises of fish extirpation and draining the reservoir.

5.3. Operating Rule Curves

Planning rule curves (Figure 7), a rule tableau (supporting information Text S3), and operations rule curves (Figure 8) communicate guidance for optimal release decision choices for each hydrologic condition for each time period. Planning rule curves are generated by running the model to exclude spill decisions. Operational curves include spill and communicate total releases to operators for each hydrologic condition and time period.

In Figure 7, each line (or for t = 1, each point) of each time period's planning rule curve follows the recommended base release per expected water availability for each stage and water storage condition. Second and third period releases are constrained by forecasted water availability, fish losses from the previous period, and stored water requirements for future releases. First and fifth period releases are similarly constrained, although because these periods occur at the start of new water years, forecast water availability is independent of the previous period. Third and fourth period inflows are known snowmelt quantities distinguished only in that the third period is when the fall-run Chinook out-migrate and the fourth period has little to no fall-run Chinook activity. Therefore, only third period releases are modeled although third period releases are required to meet third and fourth period human requirements. The infrequent nonmonotonic relationship between seasons (i.e., a wetter egg season is infrequently followed by a drier fry season), are smoothed in the rule curve with nonparametric local regression (LOESS curve fitting) using the LOESS R package.

Each row of the rule table (supporting information Table S3) provides guidance for release decisions for each of the four time periods for which environmental release decisions are needed, for each of the 28 storage cases. Release rules are made for the range of expected inflow and incoming stored water for each time period. As the water year develops more inflow information is known so the branches of the release decisions increase (Figure 2). When plotted (Figure 7), each expected inflow (column $q_{y,t}$ of supporting information Table S3) for

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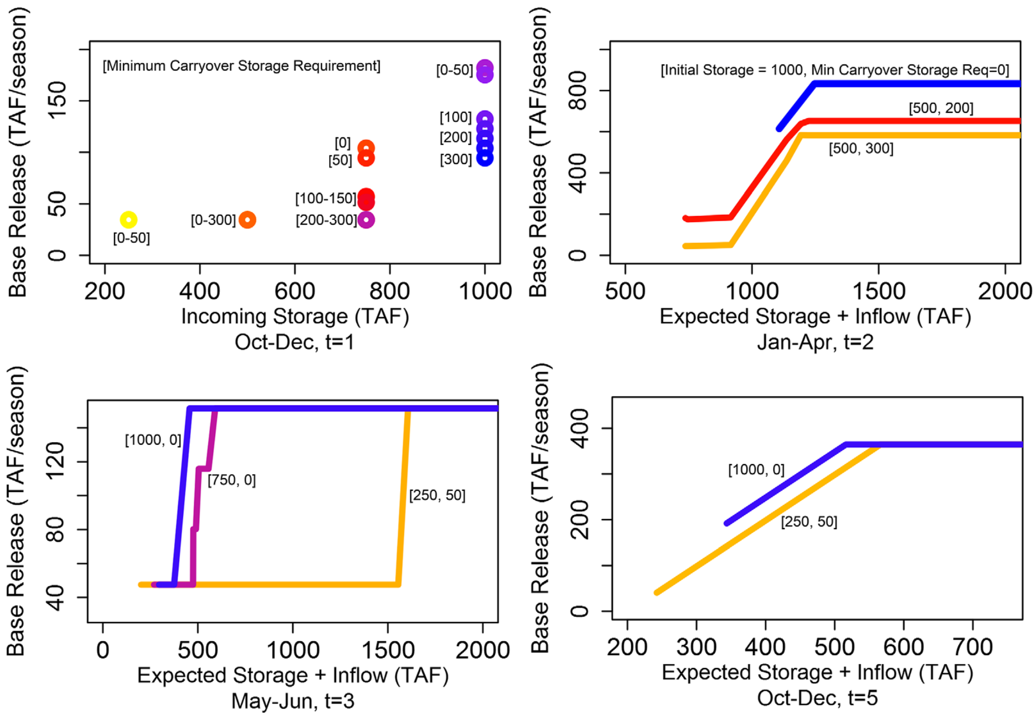


Figure 7. Each line (or point as in the case of t = 1) is a base release planning schedule with the optimized release policy given each period's water availability (equation (2)) for each of 28 initial and carryover storage cases.

each storage case is plotted as a line guiding the operating rule curve. Figure 8c plots the range of recommended releases for the full range of expected inflow for each modeled time period for specific initial storage conditions and minimum carryover storage requirements. Curtailments and augmentations to the environmental benefit function occur strategically. For example, releases, above 364 TAF are avoided during the egg stage because of damage to redds (i.e., the inverse quadratic fish-streamflow relationship). There are either positive or no consequences of additional water during juvenile and smolt stages, so flood releases are made during juvenile and smolt stages, when possible, instead of the egg stages.

Each line of Figures 8a, 8b, and 8c represents a possible water year. Figure 8c plots the same information as Figure 8a, but releases are normalized as a proportion of the target release achieved over time. Figure 8b is with Figure 8c is without including flood releases. Figures 8b and 8c show the effect of the hedging: the first period is hedged when needed. The second period is hedged again as needed. The third period is also hedged, but because of the discrete releases options from the smolt pulse releases sometimes the magnitude of the release appears larger than is needed. The fifth period starts a new water year and is not hedged.

6. Discussion

Expected survival over time of fall-run Chinook salmon was compared (Figure 9a) with several alternative operating approaches: (1) this environmental hedging model, (2) standard linear operating reservoir policy (SLOP) with and without minimum carryover storage and minimum streamflow requirements, (3) a simulation that mimics the natural flow regime, (4) an incomplete environmental hedging that omits the persistence and population dynamics constraint, and (5) historical annual fall-run Chinook production (average of 134,753 adult salmon/year) measured below Folsom Dam [*Azat*, 2016]. System performance [*Hashimoto et al.*, 1982; *Bayazit and Ünal*, 1990] for each approach was assessed (Figure 9b) in terms of (a) the fish population expected value; (b) the frequency of meeting minimum streamflow requirements and avoiding a fish kill; the probability of system failure, e.g., (c) draining or (d) overtopping the reservoir; (e) the frequency of failing to meet the minimum carryover storage requirement; and (f) the frequency of time water storage exceeds Folsom flood storage capacity (610 TAF).

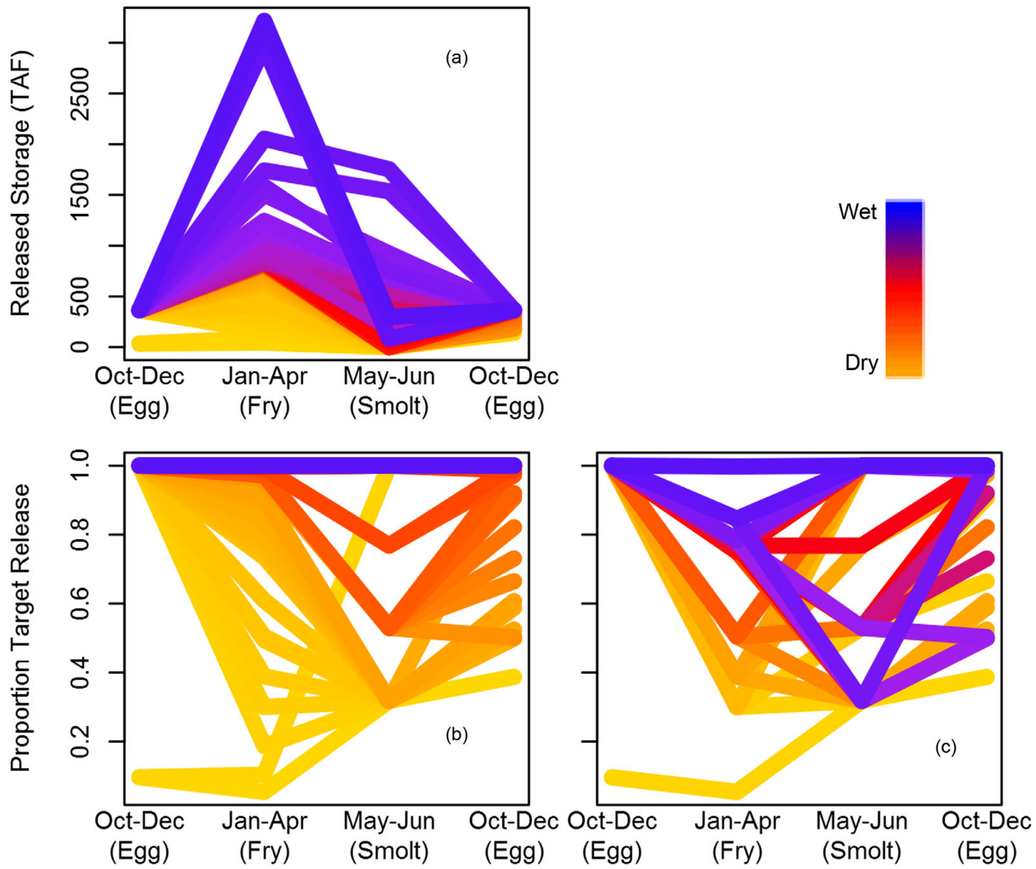


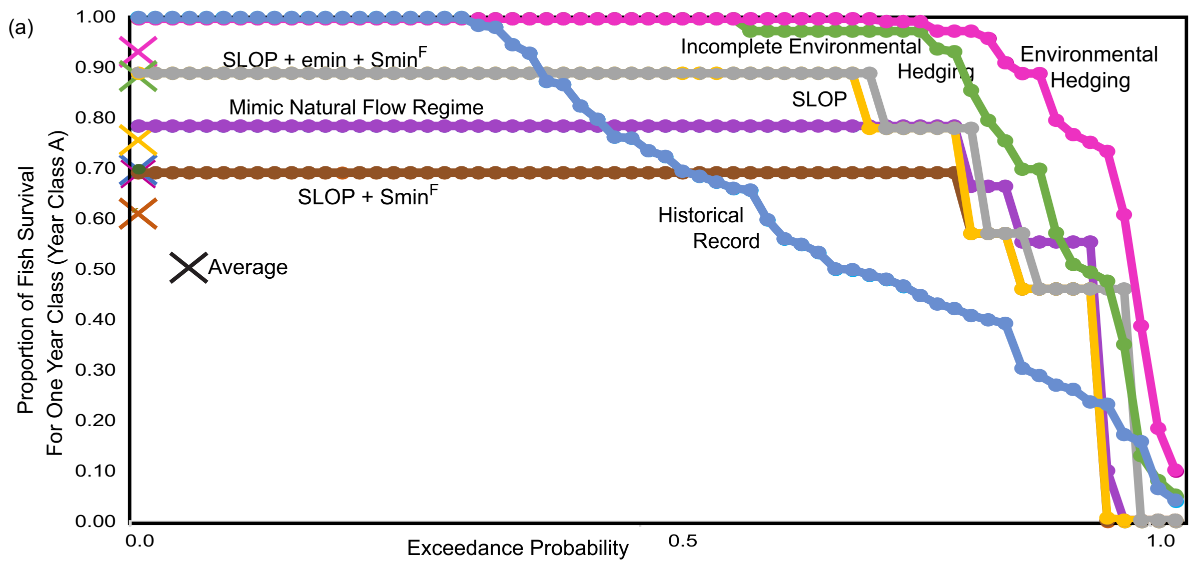
Figure 8. Each line represents expected releases over time for a range of inflow states (a) as a proportion of the release target (b) with and (c) without spill, over time, with initializing model storage conditions of 500 TAF and minimum carryover storage requirements of 200 TAF. Planning release schedules exclude spill.

The cumulative distribution function plots of fish survival (Figure 9a) were created for each reservoir operation policy for the range of hydrologic states. Since historical data was measured only for out-migrant smolts, only survival of out-migrating smolts (cohort A) were compared.

In general, fish survival is higher in wet years and lower in dry years. In wet and normal years (i.e., low and middle exceedance probabilities) all the reservoir operation approaches performed well. In near-dry and dry years all the operating approaches had more performance variation. Historical Folsom reservoir operations have the most variable success, performing well in wet years, but poorly in normal and most dry years. Perhaps most importantly, only historical Folsom operations and modeling strategies that employ optimization did not fail in very dry years. Optimization models leverage the Markov Chains and specific constraints so proposed releases best fit overall fish needs. Notable improvements in fish survival result with environmental hedging when stored water is not unnecessarily released without considering water demand from the current period's fish population size.

Nonoptimized rule-based simulations (operating with SLOP or mimicking natural flow) did not consider the future. Water is allocated less efficiently and consequently saves less fish and storage than optimization models, particularly in dry times. Were fish-flow relationships strictly increasing, including the egg period, then simulation models of SLOP and the natural flow regime approach would have outperformed the optimization models in wet conditions. Environmental hedging saves all fish in wet years even though it hedges because of spill. Simulation models do not leverage past and future information and therefore just implement specified release rules over time. The advantages of SLOP in wet times are outweighed by fish kills and draining the reservoir in dry times, without hedging.

Environmental hedging had the highest average modeled survival of cohort A (86%) compared with other methods (Figure 9b). Environmental hedging also always avoided reservoir drainage and overtopping, met



(b) Initial Storage = 500 TAF, Minimum Carryover Storage Req = 200 TAF	Frequency of… Fish Survival	Fish Extirpation	Draining the Reservoir	Failing to Meet Minimum Carryover Storage	Water Storage in exceedance of Flood Capacity	Overtopping the Reservoir
Environmental Hedging *	86	0	0	0	67	0
Incomplete Environmental Hedging	77	0	0	0	36	0
SLOP + Min Eco Release (emin)+ Min Carryover Req ($Smin^F$)*	83	7	0	0	95	87
Mimic Natural Flow Regime *	72	6	12	2	87	65
Historical Data	72	0	0	n/a	50	0
SLOP	48	8	51	100	0	69
SLOP + Min Carryover Req ($Smin^F$)	40	70	13	1	0	61

* Pareto efficient

Excellent

Poor

Figure 9. (a) Fish survival probability for each of six modeled operating strategies and historical operating strategy with initial model storage of 500 TAF and minimum carryover storage requirement of 200 TAF. (b) Reservoir operations performance for cohort A with six reoperation policies and historical operating policy with initial water in storage of 500 TAF and minimum carryover storage requirements of 200 TAF.

minimum carryover storage requirements, and performed well with respect to fish survival while meeting water supply requirements and leaving enough water in final storage for future human and fish uses.

Environmental hedging also has limitations. The current model could be improved to include evaporative losses, bed load movement and other factors affecting fish development stage survival, climate change, fish-ocean dynamics, and ecological uncertainty. For the lower American River, environmental hedging also could include flow requirements of the Sacramento-San Joaquin Delta, flow requirements of the diverse fish assemblage in the Lower American River, including the summer streamflow requirements of steelhead. The model could also include groundwater interaction and banking opportunities, and multireservoir operation to hedge among several reservoirs to improve water supply efficiency. Extending the model to include a multiyear extreme event could provide insight into the intensity of hedging needed to maximize environmental benefits during extreme drought and flood. In short, a more comprehensive definition of lower American River environmental benefits could also result in hedging with different timing and intensity.

Implementing environmental hedging in practice can have barriers. If environmental flow laws are more stringent than the minimum streamflow needs of the fish population, or are inflexible and prevent hedging, releases will be forced to meet regulatory requirements, even if they tend to cause fish kills in late dry years. Without hedging, forced early releases can deplete available storage and harm overall fish survival in dry years. Sufficient water is available in Folsom to meet high priority human demand and environmental demand without violating the minimum streamflow constraint. However, in a more constrained system, or at a daily time step, water availability may be insufficient for environmental hedging and a multiobjective framework that curtails both economic and environmental goals is needed [e.g., *Yang and Cai*, 2011].

7. Conclusions

Sometimes the ideal is the enemy of the good. Developing an environmental benefit function and using this environmental hedging optimization approach provides a support tool with which to set and curtail environmental releases optimally in drier periods. Killing some fish early to preserve water in storage for later use effectively "hedges bets" for the worst-case low hydrologic conditions and can help to avoid later and larger fish kills. Curtailing releases in early stages can enhance survival of future life stages by increasing water in storage and lessening fish-water demand for the future by diminishing current fish population size. Both functions can be particularly important in drought.

Compared to other operating policies, environmental hedging can help improve environmental performance without draining the reservoir while still meeting minimum carryover storage requirements and producing additional storage. The fish survival-streamflow environmental benefit function enables operational decisions to consider releases to support biological objectives, and to weigh trade-offs among storing or releasing water for different cohorts for different water year types and different storage limits. The hydrologic forecasting in the model can allow for realistic decisions based on long-term planning of an unknown future and short-term planning with adaptation as inflow information becomes known.

Environmental hedging provides an adaptable framework for optimizing downstream releases for environmental benefits. The environmental benefit function could be based on different environmental flow methodologies using different biological or downstream targets such as habitat, insect and bird survival, groundwater recharge, or even a multiobjective model to benefit multiple species and/or ecological goals. However, the environmental hedging principles and mathematics would remain the same.

Because any initial hedging reduces releases for all later seasons, augmenting releases during the first period (which for fall-run Chinook in the lower American River is during the egg season (better redd than dead!)) has the greatest potential for saving more fish and water in storage than later seasons. Furthermore, since water storage is in effect hedged for the driest year, which has a low probability, excess water in storage often is available at the end of wet and even normal hydrologic seasons. Banking wet season surplus water in groundwater could offer additional reserves for human demand and free water supply to augment first period environmental releases.

This paper quantifies the potential benefits and trade-offs of hedging reservoir operations for fish and other downstream environmental objectives. Environmental hedging has the potential to outperform other operating strategies for a range of cases using diverse fish population and water supply performance metrics. It is highly likely that it would outperform traditional reservoir operating policy, such as historical operation of Folsom Reservoir. For example, saving stored water for later and releasing less when it is known that some of the fish population has already suffered mortality can ultimately result in water allocations that save more fish and increase storage over an operating year cycle.

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