Bugs Pay for Days of Steady Reservoir Releases to Reduce Costs to Hydropower Customers and Sustain Funds to Maintain Infrastructure

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Key Points:

- Steady low releases help aquatic invertebrate production, raise costs to hydropower customers, and lower funds to maintain infrastructure.
- To reduce costs, move some days of steady low releases from Summer to Spring/Fall.
- Create an ecosystem fund to compensate hydropower producers for releases that help bugs, mobilize sediment, and control invasive fish.

Abstract

Steady low reservoir releases allow downstream aquatic invertebrates (bugs) to lay and hatch eggs and increase production. These releases also reduce revenue from hydropeaking operations, increase costs to hydropower customers, reduce funds to maintain project infrastructure, repay project loans, and exacerbate hydropower production-ecosystem conflicts. This paper has the purpose to (1) quantify tradeoffs between the number of days of bug flows and hydropower revenue, (2) identify ways to reduce costs to hydropower customers, and (3) inform the design of a financial instrument to increase bug production, compensate hydropower customers for costs, and reduce conflict. A linear program identified tradeoffs between hydropower revenue and number of days of steady low releases per month for different contract and market energy prices and monthly release volumes across March to October months when bugs are most productive. We found that bug flows on 8 weekend days per summer month in 2018 from Glen Canyon Dam, Arizona reduced hydropower revenue by $300,000 (June) to $600,000 (August). Shifting bug flow days to Spring/Fall months reduced costs. To reduce conflict, we suggest creating a new financial instrument funded by the Federal Treasury for ~$300,000 to $600,000 per month. The instrument can give ecosystem managers more flexibility to choose days for steady low releases that advantage bugs and pay hydropower producers for costs. Next steps are to engage federal agencies on the benefits and limitations of the proposed instrument and expand to steady high releases that mobilize sediment, build sandbars, and disadvantage non-native, invasive fish populations.

Plain Language Summary

Reservoir operations that increase daytime releases to increase hydropower revenue desiccate eggs laid by aquatic invertebrates (bugs) and depress bug production. We developed a linear optimization model to identify the tradeoffs between days of steady low flow and hydropower revenue. Results suggested that an increase in release volume will benefit both the objectives (win-win scenario), energy price differential between on- and off-peak periods controls the position and shape of tradeoff curves, and offset release does not have an impact on tradeoffs. Monthly results of the model helped us devise a program where hydropower producers are compensated for the steady low flow days. The program provides funds to ecosystem managers to pay hydropower producers revenue loss from the steady low flow days. Buying steady low-flow days during spring and fall instead of summer months can reduce hydropower revenue loss and it will avoid exhausting basin funds. The summer Bug flow experiment is funded by basin funds which otherwise are spent to support environmental flow experiments (e.g., high flow experiments, trout management flows, etc.) and infrastructure maintenance. Next steps a) Inclusion of GTMax SL model used by the Western Area Power Authority and b) Improve adaptation by increasing outreach of the study.

1 Introduction

Hydropeaking operations ramp up reservoir releases during the daytime and reduce nighttime releases to follow energy demands. These operations have downstream ecological impacts (Poff et al., 2007; Carpenter et al., 2011) that researchers are trying to identify and mitigate (Bunn and Arthington, 2002; Poff and Zimmerman, 2010; Vörösmarty et al., 2010; Liermann et al., 2012). One downstream ecosystem impact is to desiccate eggs that aquatic invertebrates (bugs) lay at or near the water surface as the downstream water level drops (Kennedy et al., 2016). Egg desiccation suppresses bug production, insect diversity, and the availability of food for downstream native, endangered fish (Nakano and Murakami, 2001; Baxter et al., 2005; Kennedy et al., 2016). At the same time, steady low releases to encourage bug production exacerbate conflict between ecosystem managers and hydropower producers because bug flows reduce revenue from hydropeaking operations, increase costs to hydropower customers, reduce funds to maintain project infrastructure, delay repayment of project loans, and limit temporary releases above turbine capacity to mobilize downstream sediment, build sandbars, and/or disadvantage non-native, invasive fish. This paper has the purpose to (1) quantify tradeoffs between hydropower revenues and the number of days of steady low releases, (2) reduce costs of steady low releases, and (3) inform the design of a new financial instrument to increase bug production, pay hydropower producers for associated financial losses, and reduce conflict between hydropower and ecosystem managers.

Herein, we answer four questions about the win-lose tradeoffs between hydropower revenue and number of days of steady low releases at Glen Canyon Dam, Arizona:

a) How is monthly hydropower revenue impacted by number of days of steady low releases on weekends and weekdays?
b) How do the shape and position of tradeoff curves vary with different monthly release volumes and contract and market energy prices across March to October months when bugs are most productive?
c) How to reduce costs of bug flows? and
d) How to use answers to questions a) to c) to design a financial instrument to give ecosystem managers more flexibility to schedule steady low releases, compensate hydropower producers for associated losses, maintain project infrastructure and repay loans?

Section 2 reviews the relevant literature on hydropower generation, impacts to downstream aquatic ecosystems, and management of Glen Canyon dam. Section 3 presents the linear program formulation to quantify tradeoffs. Sections 4, 5, and 6 share results, discussion, limitations and conclusions

2 Literature Review

Typically, a hydropower objective to maximize revenue is a non-linear function (Yoo, 2009) that depends on the power generation release, elevation difference between reservoir water surface and tailwater, turbine efficiency, and release in relation to design efficiencies (e.g., Yakowitz, 1982; Ko et al., 1992; Tilmant et al., 2002). Commonly, dynamic or nonlinear programming has been preferred to solve energy generation problems because multiple sub decisions are required to reach the ultimate optimal decision. Nonlinear optimization problems are computationally intensive (Hochbaum, 2007).

Therefore, researchers have approximated nonlinear objectives with various linearization techniques. Yoo (2009) used successive linear programming to maximize the annual energy production at Yongdam dam in South Korea. To avoid iterations, he considered weighted constant values of the storage water level and the water volume released for hydropower generation in the objective function to linearize the problem. Similarly, Wang et al., (2015) linearized the hydropower objective in their multi-objective mixed integer programming model by assuming a constant reservoir level and hydropower generation as primarily flow dependent.

The assumption of constant reservoir head is case specific and usually applied for large reservoirs (Magilligan and Keith, 2005; Loucks and Beek, 2017). Lee et al. (2008) used a first-order linear approximation for transformation of a non-linear hydropower function into linear objective.

To serve both human and freshwater ecosystem requirements, researchers identified and defined environmental flows—change in quantity, quality and timing of flows to favor ecosystems (Baron et al., 2002; Richter et al., 2003; Tharme, 2003; Arthington; 2012; Null and Lund, 2012; Pegram et al., 2013; Richter, 2014; Hart, 2016). For instance, Postel and Richter (2003) showed that ecological health is dependent on flow quantity and timing instead of constant minimum water flow. Lane and Rosenberg (2020) recommended modifications in water rights law to improve in-stream flow conditions. Many researchers have used mathematical models to better understand and optimize water systems for environmental flows (Horne et al., 2016).

Rheinheimer et al. (2015) developed a linear programming model to maintain downstream cold-water temperatures for Chinook salmon below Lake Spaulding, California. Their model determined the amount of water required from different stratified reservoir layers to maintain downstream river temperature. They modeled the reservoir as two completely mixed thermal layers (i.e., warm and cold pools) and the release decisions were made prior to, and independent from, temperature management decisions. These assumptions converted a non-linear problem with both quality (thermal layer selection) and quantity (release hydrograph) decisions into a linear problem with only the quality decision. Richter and Thomas (2007) described a framework to help evaluate the ecological benefits of dam re-operation. Numerous studies have presented a decision support system which considered both human and ecological objectives (e.g., Young et al. (2000); Xevi and Khan (2005); Shafroth et al. (2010); Alemu et al. (2011); Yin et al. (2011); Yin et al. (2012); Adams et al. (2017), etc.). These optimization models are rarely used by managers (Horne et al., 2016) and there is art to translate ecological knowledge into operations because of limited information about long-term effects of ecological flows (Harman and Stewardson, 2005). To overcome, researchers engaged managers earlier in the process and explored alternatives that balance competing water management and environmental objectives (Kareiva et al., 2000; Langsdale et al., 2013; Acreman et al., 2014; Richter, 2014; Poff et al., 2016; Alafifi and Rosenberg, 2020).

Hydropeaking operations at Glen Canyon Dam, Arizona make high day-time releases and low night-time releases to follow energy demands at a contract price that is fixed between the hydropower producer, Western Area Power Authority (WAPA), and distribution companies over a contract period (Topping et al., 2003). Market price is the price to purchase or sell energy on the open market. WAPA purchases energy at the market price when generated energy is less than the contracted amount.

Glen Canyon dam releases supply the Colorado River through Grand Canyon. The Grand Canyon attracts millions of visitors each year because of its unique geology and spectacular scenery (DOI, 2017). Grand Canyon is one of the most studied geologic landscapes in the world and home to numerous native endemic species (NPS, 2018). Hydropeaking operations created an unsuitable environment for aquatic organisms (Ward and Stanford, 1979; Moog, 1993) that require their eggs to stay wet throughout the incubation period for days to weeks' time (Stevens et al., 1997; Kennedy et al., 2016). Many hydropeaking dams across the Western United States have little downstream insect diversity (Kennedy et al., 2016; Carlisle et al., 2017).

Aquatic invertebrates (e.g., Stoneflies, Mayflies, Caddisflies, and Midges) construct the major part of the Colorado River food web in the Grand Canyon (Kennedy et al., 2016) that varies throughout the canyon (Cross et al., 2013). Just below the dam, the food web is dominated by non-native invertebrates. Rainbow trout are in abundance because release water temperatures are cold. At downstream locations, the river temperature as well as food web variety increase, yielding higher populations of native fish species. Mackey and Marsh (2009) discussed the causes of the degrading population of native fish in various river systems. Human developments -- e.g., dams, canals, diversions, industrialization, and urbanization -- have destroyed native ecosystems and significantly modified natural river systems. The existing river systems have altered river water temperature, flows, sediment transport, and water quality regimes that favor non-native fish over native fish.

Mihalevich et al., (2020) developed a model to estimate water temperature of Colorado River in the Grand Canyon. They found that short-wave radiation dynamics and hydropeaking flows control river temperatures over space and time. Lately, it has been observed that native fish populations in downstream locations of the canyon are increasing. The possible reasons are variable flow regimes, increasing water temperature, the lowering of Lake Mead, and emergence of the Pearce Ferry rapid as a barrier between non-native lake fish and upstream native fish (Ragowski et al., 2018; Kegerries et al., 2020). These changes also favor non-native fish population (Rahel and Olden 2008).

Starting in 1990's, there have been numerous efforts to learn and restore the natural river ecosystem of the Grand Canyon. For instance, since 1996, controlled releases above turbine capacity mimicked natural annual pre-dam flood flows, mobilized sediment, and restored downstream sand bars (Robinson and Uehlinge, 2008; Cross et al., 2011). Those flow experiments are recognized as High-Flow Experiments (HFE). The latest Bug flow experiments preserved the monthly release volume by keeping weekend releases steady and low while increasing hydropeaking releases on weekdays.

The idea for steady low weekend flows was to keep aquatic invertebrate eggs wet. Further, energy demands on weekends are lower (Førsund, 2015) and weekend steady flows reduce impacts on hydropower revenue (USBR, 2016). From 2018 to 2020, weekend steady low flows were implemented during summer months of each year at Glen Canyon dam. Bug flows were included in the preferred alternative of the long-term experimental and monitoring program (LTEMP, 2016). Ploussard and Veselka (2019) used the proprietary GTMax SL model to estimate the overall hydropower revenue loss from 2018 Bug Flow Experiment as approximately $165,000. May and June showed profit while July and August showed losses. In the 2019 Bug flow experiment, Ploussard and Veselka (2020) found that losses increased to $327,000.

Presently, Glen Canyon dam hydropower revenues supply a fund that pays for bug flows, other experimental flows, project maintenance, and repayment of loans. This setup exacerbates conflict between hydropower and ecosystem managers by creating a negative feedback loop wherein steady low flows increase costs to hydropower customers and reduce money available for bug flows, other experimental flows, project maintenance, and replayment of loans. We see a need to

(1) quantify the tradeoff between hydropower revenue and days of steady low releases that advantage downstream aquatic invertebrates, (2) identify how monthly release volumes and market and contract energy prices affect the tradeoff, (3) reduce costs for bug flows, and (4) identify a financial instrument to reduce conflict that compensates hydropower customers for costs of steady low releases. Next, we describe a linear programming model to quantify tradeoffs between hydropower revenues and days of steady releases good for bugs.

3 Materials and Methods

We quantified tradeoffs between hydropower revenue and number of days of steady releases from Glen Canyon dam with a linear optimization model. The model had 12 characteristic flow decisions per month which were Saturday, Sunday, and Weekday during peak- and off-peak energy demand periods for days with hydropeaking and steady low release patterns. One objective function maximized hydropower revenue. A second objective—number of days of steady releases—was programmed as a constraint whose limit varied in scenarios from 0 to 31 days per month. Physical constraints limited releases within infrastructure capacities. Operational constraints limited the rate-of-change of release during successive peak- and off-peak energy demand periods, set releases for both periods to the low release on days of steady low flows, and set Saturday and Sunday high releases on hydropeaking days to match observed high releases on those weekend days. The model was implemented in the General Algebraic Modeling System (GAMS; Hozlar, 1990). The model was solved for scenarios of different monthly release volumes, contract and market energy prices, and flow offsets from Sunday to Weekday low flows during March to October months when aquatic invertebrates are most productive. The structure and formulation for a Saturday-Sunday-Weekday model with high and low energy demand periods and contract prices (Figure 1) are further defined as follows.

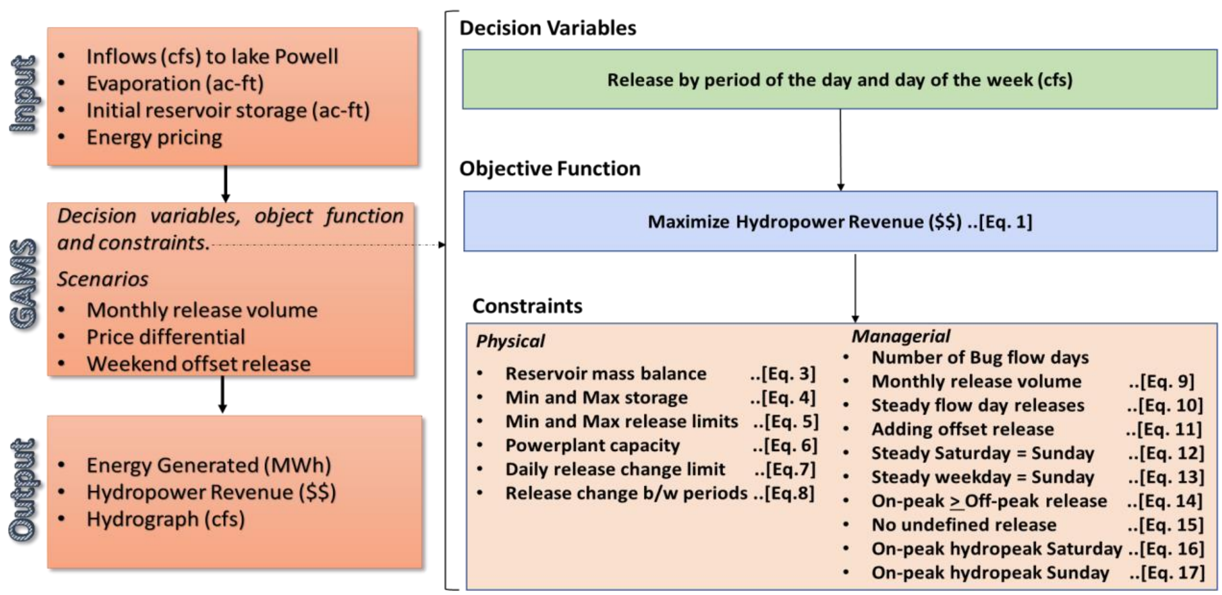

Figure 1. Saturday-Sunday-Weekday model structure.

3.1 Release decisions and Energy generation state variables

We defined 12 characteristic releases per month ($Release_{Flowpattern,d,p}$ [cfs]) for two *flowpatterns* of hydropeaking or steady low releases, 3 day types *d* of Saturday, Sunday, or Weekday, and two periods p per day of high (pHigh) and low (pLow) releases corresponding to peak- and off-peak energy demands. We arrived at these characteristic flows per month by analyzing the monthly hydrograph observed at Lees Ferry gage (station id: USGS 09380000) for months with (e.g., August 2018) and without (e.g., August 2016) weekend steady low flows. For example, in August 2018, the hourly release data (Figure 2, blue line) grouped into 3 day types—Saturday, Sunday, and Weekday—and two flow periods per day: 1) off-peak period (pLow) from midnight to 8 a.m., and 2) on-peak period (pHigh) from 8 a.m. to midnight (Figure 2, red line; Palmer, personal communication, 2019). These periods defined $duration_p$ [hours per period] of 8 for pLow and 16 for pHigh.

The August energy pricing data (Supplemental Information, Figure S1) also showed two periods per day. The groupings reduced 744 hourly flow values for a month (24 hours per day * 31 days per month = 744 hours per month) into 6 sub-daily characteristic flows for a month (2 periods per day * 3 day types = 6 characteristic flows per month). We also compared different number of periods, e.g., three and four, and period lengths against the observed hydrograph. We found monthly estimates of hydropower revenue from two periods per day closely approximated actual hydropower revenue. Finally, the *flow pattern* on any day was either steady and low (flows for peak- and off- peak periods were the same) or hydropeaking (flow for the peak period exceeded flow for the low period).

Moreover, for Saturdays and Sundays with a steady low flow pattern, the peak release equaled the off-peak release (red, Figure 2). In this case, monthly releases were defined by three release decisions (Weekday pLow and pHigh, and Weekend steady release).

The area under the observed and modeled Sunday-Saturday-Weekend characteristic flow hydrographs were the same even though the traces do not overlay perfectly (Figure 2). With Saturday-Sunday-Weekday characteristic flows, there was higher weekday base flow, lower weekday peak flow, and higher Weekend steady releases due to the selected lengths of the peak and off-peak demand periods.

We introduced and calculated the state variable energy generation ($Energy\_Gen_{Flowpattern,d,p}$ [MWh per month]) for each *flow pattern* (hydropeak or steady), day type d (Sunday, Saturday, and Weekday), and period p (pHigh and pLow) as:

$$Energy\_Gen_{\text{Flowpattern,d,p}} = Release_{\text{FlowPattern,d,p}} * Duration_{\text{p}} * 0.03715 \quad (1)$$

where *Release* and *Duration* were defined previously and 0.03715 is typical energy generation [MW-hr] per 1 cfs of release during July 2014 (Palmer, personal communication, 2019). The information we received from WAPA used the same factor for energy generation during each month of 2014.

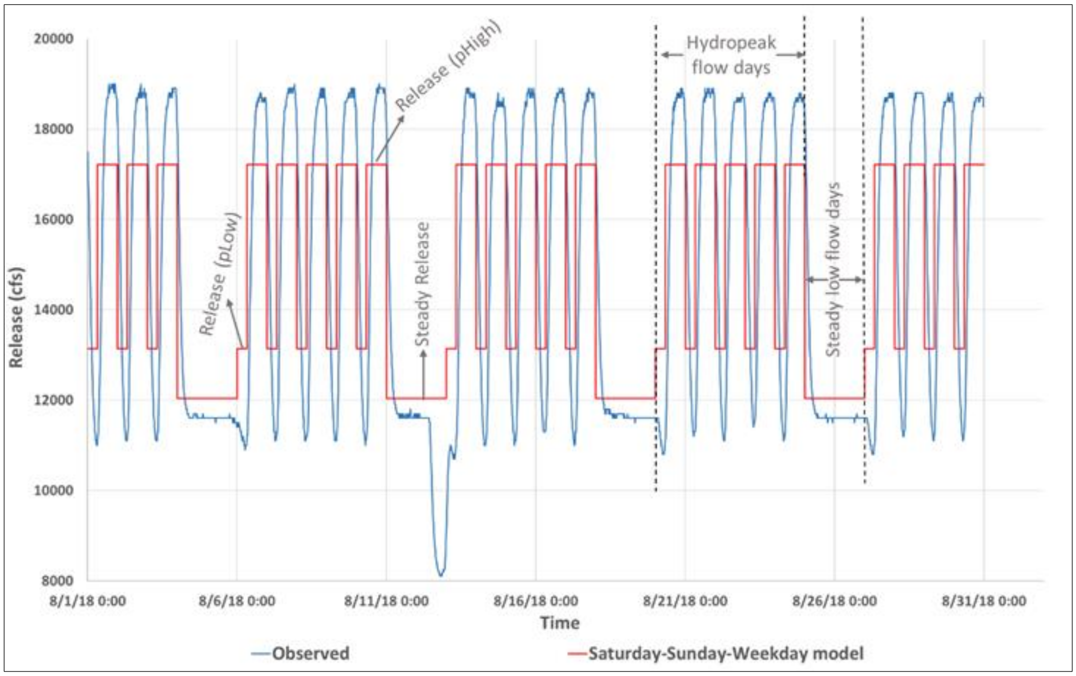

Figure 2. Comparison between hourly hydrograph observed at Lees Ferry gage during August 2018 (blue color) and the modeled hydrograph with two periods per day: pLow and pHigh (red color).

3.2. Objective functions: Hydropower Revenue and Days of Steady Flows

The model has two competing objectives: 1) maximize aquatic invertebrate's suitability represented by the number of days of steady low flow ($Num\_Days_{Flowpattern,d}$), and 2) maximize total monthly hydropower revenue [$]. We quantified the tradeoff between the two objectives by maximizing hydropower revenue while constraining the days of steady low releases to different values.

$$Max.\ hydropower\_Revenue = \sum_{Flowpattern,d,p} Energy\_Gen_{Flowpattern,d,p} * Energy\_Price_{Price,d,p} * Num\_Days_{Flowpattern,d} \quad (2)$$

Here, *Energy_Price* [$/MW-hr] represents energy price type (contract or market) during each day type d and period of the day p. Specifying the number of days ($Num\_Days_{Flowpattern,d}$) for each flow pattern and day type allowed the model to vary the number of steady low flow days per month from 0 to 31 and define the order that day types switched from hydropeak to steady flow (e.g., first Sundays, then Saturdays, then Weekdays). For example, if there are 10 steady flow days in a month (e.g., August) that starts on a Monday, then the model will place 4 steady days on Sundays first because contract energy prices on Sunday are lowest, then 4 steady flow days on Saturdays, and the remaining two steady days on weekdays. In this scenario, all the remaining *hydropeak* days are placed on weekdays. In contrast, a scenario with zero steady low flow days means the model will decide releases for all weekends and weekdays with flow pattern *hydropeak* while all releases for *flow pattern* steady are zero.

WAPA contracted with power companies and rural electric utilities for a long-term and fixed energy price. When demand exceeded electricity generation—either because demand increased, generation dropped from a bug flow release, power generation was disrupted (e.g., turbine maintenance), or droughts that lowered reservoir level—WAPA bought electricity from private companies at the market rate but sold the additional purchased energy at the lower contract price. Thus, there was an $Energy\_Price_{price,d,p}$ ($/MW-hour) for each *price* type (market or contact), each day type *d*, and period *p*.

We estimated contract energy prices for each period of each characteristic day using 15-minute flow records from the Lees Ferry gage and hourly energy prices from 2014—the most recent energy price data available. First, we averaged the 15-minute hydrograph data from the Lees Ferry gage to get hourly release values. We then used the hydropower generation formula (Eq. 1) provided by WAPA (Palmer, personal communication, 2019) to calculate energy generation per hour. We multiplied the estimated hourly energy generation by the hourly energy price (e.g., Supplemental Information, Figure S1) to estimate hydropower revenue generated per hour. Finally, we divided the monthly hydropower revenue for each high and low flow period of each day type by the number of hours for each period of each day type. This division gave an estimated average energy price for each day type and period. For example, for August 2018, the estimated energy prices for off- and on-peak periods on a weekday were $49.7/MWh and $79/MWh, respectively. Sunday peak- and off-peak prices were the same as the price for the weekday low period. We did not know the contract energy price for on-peak Saturday so we averaged prices for on- and off-peak weekday periods i.e., $64.4/MWh. This estimation method assumed contract energy prices for different day types (Weekday, Saturday, Sunday) were the same throughout the month.

3.3. Constraints

The model has physical and managerial constraints. Physical constraints include:

a) Reservoir mass balance. The mass balance was applied at the reservoir and it was applied on monthly time scale.

$$Storage = Initstorage + Inflow - Released\_vol - evap \tag{3}$$

Where, *Initstorage* is initial reservoir storage [ac-ft], *Inflow* is monthly volume inflow to the reservoir [ac-ft]. The inflow volume is the product of average inflow [cfs] converted into [ac-ft/hr] (i.e., 1 cfs = 0.083 ac-ft/hr), duration of periods [hrs], and number of day in a month. *Released_vol* is total volume of water released in the month [ac-ft], and *evap* is volume of water evaporated during the month [ac-ft].

b) Reservoir storage limits. Storage should not go below a minimum storage volume *minstorage* [ac-ft] or exceed maximum storage capacity *maxstorage* [ac-ft].

$$minstorage \leq Storage \leq maxstorage \tag{4}$$

The minimum live storage required for hydropower generation at Glen Canyon Dam was 4 million-acre feet [MAF] (3490 ft msl) and the maximum live storage was 25 MAF (3710 ft msl).

c) Release limits. During any period *p* on any day type *d*, reservoir releases should not go below a minimum release [cfs] or exceed a maximum release [cfs]. The minimum release was

8,000 cfs (approx. minimum required for hydropower generation) and maximum release was the turbine capacity at Glen Canyon Dam i.e., 31,500 cfs.

$$MinRel \leq Release_{\text{FlowPattern,d,p}} \leq maxRel \qquad \forall FlowPattern,d,p \qquad (5)$$

d) Maximum Energy Generation limit. During any time period, the energy generated should not exceed maximum generation capacity [MWh] of the turbines.

$$Energy\_Gen_{\text{FlowPattern, d, p}} \leq 1320 \times Duration_{\text{p}} \qquad \forall FlowPattern,d,p \qquad (6)$$

Where, 1,320 MW is the maximum hydropower generation capacity at Glen Canyon Dam (USBR, 2019).

e) Allowable change in release between periods. The maximum allowable change between periods is defined in the Long Term Experimental Management Plan (LTEMP, 2016) as 8,000 cfs. The change in release between any two periods should not exceed *Daily_RelRange* (i.e., 8000 cfs).

$$Release_{\text{FlowPattern,d, "pHigh"}} - Release_{\text{FlowPattern,d, "pLow"}} \leq Daily\_RelRange \qquad \forall FlowPattern,d \qquad (7)$$

f) Allowable change in release between periods of neighboring days. Release change between on-peak periods of current day and off-peak period of next day should not exceed *Daily_RelRange* (i.e., 8000 cfs).

$$Release_{\text{FlowPattern,d, "pHigh"}} - Release_{\text{FlowPattern,d+1, "pLow"}} \leq Daily\_RelRange \qquad \forall FlowPattern,d \qquad (8)$$

The managerial constraints include:

g) Total monthly release volume. The model is required to make release decisions for each period of day types that sums to the monthly release volume.

$$TotMonth\_volume = \sum_{\text{Flowpattern,d},p} Release_{\text{Flowpattern,d,p}} * Convert * Duration_{\text{p}} * Num\_Days_{\text{Flowpattern,d}} \qquad (9)$$

Convert is a conversion factor from cfs to ac-ft per hour (i.e., 1 cfs = 0.083 ac-ft/hr).

h) Same on- and off-peak release on steady flow days. On a steady flow day, the model should make same releases during both on- and off-peak periods.

$$Release_{\text{"Steady", d, "pHigh"}} = Release_{\text{"Steady", d, "pLow"}} \qquad (10)$$

i) Add offset release as the difference between the steady low Sunday release and weekday low hydropeak release. This offset was added because with zero offset (H0), downstream sites saw progressively smaller benefits because the weekday peak releases converged to a high flow value. Eggs laid on weekdays were still desiccated when the trough of the weekend steady low release passed downstream (Kennedy, personal communication, 2021). The offset release value was based on results of egg laying optimization models that sought to maximize egg laying benefits canyon wide (especially at downstream locations where native fish populations are high). The offset release is still experimental. A 1000 cfs (H1000) offset was tested in 2018, and 750 cfs (H750) during 2019-2020.

$$Release_{\text{“Steady”, “Sunday”, “pLow”}} = Release_{\text{“Hydropeak”, “Weekday”, “pLow”}} + Offset\_Rel \quad (11)$$

Where, *Offset_Rel* [cfs] is pre-defined offset release value.

j) Same flows on steady Saturdays and Sundays.

$$Release_{\text{“Steady”, “Saturday”, p}} = Release_{\text{“Steady”, “Sunday”, p}} \qquad \forall p \quad (12)$$

k) Steady weekday release equals the release on steady Saturday and Sunday.

$$Release_{\text{“Steady”, “Weekday”, p}} = Release_{\text{“Steady”, “Sunday”, p}} \qquad \forall p \quad (13)$$

l) On-peak release on a Hydropeak day should be equal to or greater than off-peak release.

$$Release_{\text{“Hydropeak”, d, “pHigh”}} \geq Release_{\text{“Hydropeak”, d, “pLow”}} \qquad \forall d \quad (14)$$

m) No release during undefined flow pattern. This constraint ensures that when a particular flow pattern and day type (e.g., hydropeak Saturday) is not required in a hydrograph, the flow during that pattern and day type is zero.

$$Release_{\text{FlowPattern, d, p}} = 0 \quad (15)$$

n) On-peak hydropeak Saturday release equals 2000 cfs less than on-peak hydropeak weekday to follow the pre-bug flow hydrograph where there was ~2000 cfs lower release during on-peak Saturday and Sunday in comparison to on-peak weekday. This difference may be that there was lower hydropower demand on weekend.

$$Release_{\text{“Hydropeak”, “Saturday”, “pHigh”}} = Release_{\text{“Hydropeak”, “Weekday”, “pHigh”}} - 2000 \quad (16)$$

o) On-peak hydropeak Sunday release equals 2000 cfs less than on-peak hydropeak weekday.

$$Release_{\text{“Hydropeak”, “Sunday”, “pHigh”}} = Release_{\text{“Hydropeak”, “Weekday”, “pHigh”}} - 2000 \quad (17)$$

Constraints n and o (Eq. 16 and 17) mimic a pre-Bug Flow Experiment hydrograph (Supplemental Information, Figure S2). Without constraints n and o, the model was expected to generate maximum possible hydropower revenue by saving water during *hydropeak* Saturdays and Sundays (minimum release). Nevertheless, the minimum release would have created energy deficit and forced WAPA to purchase energy from market.

3.4. Market-Contract price model variant.

Adding a market price required a different model setup that we call the Market-Contract price model. We introduced a $Nobugflow\_Rel_{d,p}$ (cfs) parameter that specified observed, historical reservoir releases from 2017, 2016, and 2015 (i.e., years before bug flows; Supplemental Information, Figures S2 to S4). The Market-Contract price model had two submodels. In the first submodel, releases and generated energy for zero days of steady low releases are constrained to historical hydropeaking values (*Nobugflow_Rel*$_{d,p}$) and priced at the contract price (Figure 3, black line and yellow fill). In the second submodel, extra or deficit energy generation associated with one or more days of steady low releases above or below historical releases are priced at the market price (Figure 3, red line, blue and pink fill). Section S2 of the Supplemental Information further describes the two submodels. We did not find market prices for August 2018. Thus, we assumed the market price was $5/MWh higher than the contract price.

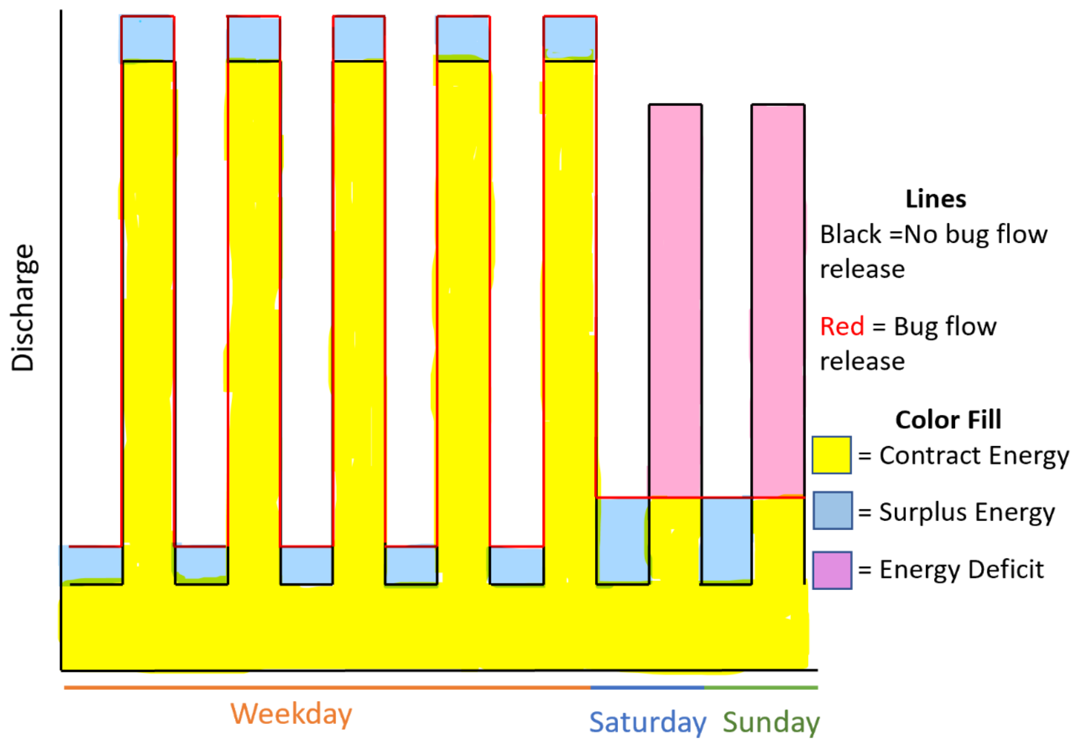

Figure 3. Weekly hydrograph for historical hydropeaking (black line) and steady low flows on Saturdays and Sundays (red line). The yellow filled portion is historical contract energy priced at contract price. Blue fill indicates surplus energy sold at market price with two weekend days of steady low releases. Pink fill is energy deficit purchased at market rate.

3.5. Scenarios

We ran the Saturday-Sunday-Weekday model for the following scenarios:

- Monthly release volume varied from 0.71 to 0.95 MAF,
- On-peak weekday contract energy price decreased from $79 (base case) to $64.4 to $49.7 per MWh,
- Offset release increased from 0 to 1000 cfs (H0 to H1000).
- Contract energy prices, initial reservoir storage, monthly inflows, and reservoir evaporation were varied from values observed in April to September of 2018.

4 Results

4.1 Validation

The Saturday-Sunday-Weekday model releases and energy generation were validated for August 2018 against 15-minute flow data at Lees Ferry (https://www.gcmrc.gov/discharge_qw_sediment/station/GCDAMP/09380000), aggregated hourly flows, and daily Glen Canyon power plant energy generation (https://www.usbr.gov/rsvrWater/HistoricalApp.html). In the model validation runs, flow volume for the observed, hourly, and Saturday-Sunday-Weekday models were identical (Table 1; Supplemental Information, Fig. S5). Energy generation varied by only 4.2% in comparison to observed energy generation (Table 1; Supplemental Information, Fig. S6). The possible reasons for surplus energy generation were an assumption that reservoir head remains constant throughout the month and an outdated energy generation formula (Eq. 1). Validation over different months of 2018 showed that the energy generation error varied from 2.8% (July) to 9% (October; Supplemental Information, Table S2). We did not find monthly revenue generated by WAPA during 2018, so we only validated our model against the observed energy generated.

Table 1. Validation summary statistics for August 2018

Scenario	Flow volume (Ac-ft/ Month)	Energy Generated (MWh)	Revenue generated (Million $)	% Error in Energy generated relative to observed
Observed	914,428	392,938	--	--
Hourly	914,428	409,289	$27.2	4.2%
Saturday-Sunday-Weekday model	914,428	409,289	$27.6	4.2%

4.2 Scenario results

Using the Saturday-Sunday-Weekday model with contract prices, hydropower revenues increased by $56,160 for each added Sunday and by $3,932 for each added Saturday of steady low flow (Figure 4). The counter-intuitive increases in hydropower revenue per added weekend day of steady flow moved tradeoff curves closer to the ideal point of large hydropower revenues and more weekend days of steady low flows (Figure 4, red circle). The counter-intuitive increase in hydropower revenue occurred because constraints n and o (Eq. 16 and 17) were relaxed that describing the load following pre-Bug Flow hydrograph. Above 8 days of steady low weekend flows, hydropower revenues decrease by $64,420 per day for each weekday of steady low flow added. Here, constraints e and f bind that limited change in release between periods. Thus, the Bug Flow hydrograph of 8 weekend days per month of steady low flows maximized hydropower revenue.

Each additional 0.11 MAF of monthly release volume from 0.72 to 0.94 MAF added an extra ~$3.5 million in monthly hydropower revenue (Figure 4, darker blue tradeoff curves pushed right and outward). The slopes on the 0.72 MAF per month tradeoff curve differed because constraints e and f (Eq. 7 and 8) did not bind with the lower monthly flow volume. For the release scenarios of 0.72, 0.83, and 0.94 MAF per month, hydropower revenues with zero steady flow days generated the same breakeven revenue as at 16, 12, and 12 of steady flow days.

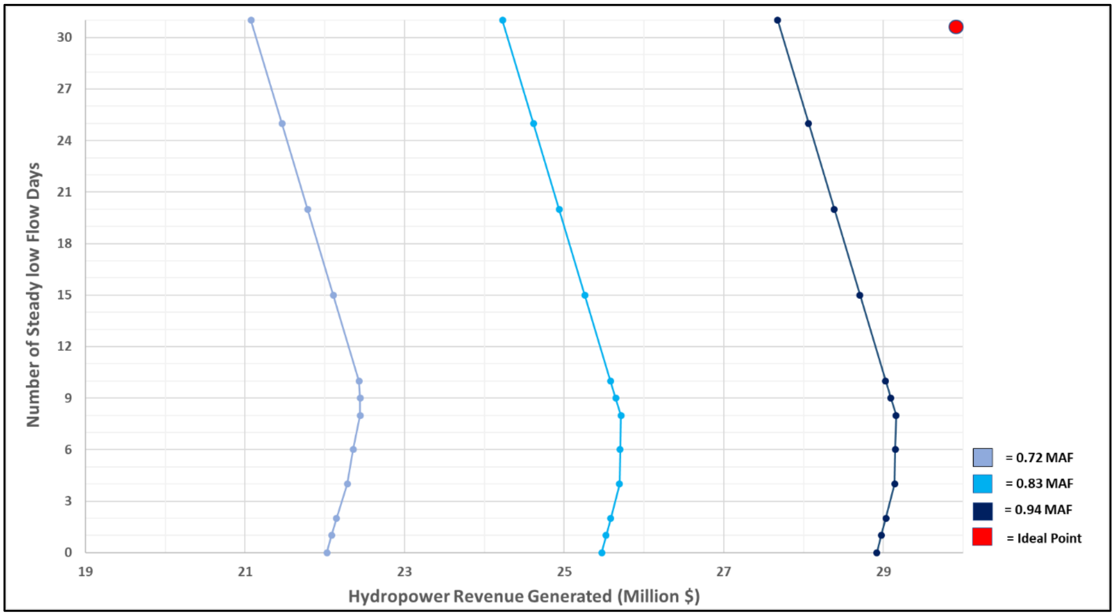

Figure 4. Tradeoffs between number of steady low flow days and Hydropower revenue from Saturday-Sunday-Weekday model in August, with contract prices, and zero offsets. Trace color indicates a specific monthly release volume scenario.

The number of steady low flow days controlled the on- and off- peak releases (Figure 5). Until eight steady low flow days, the model reduced off-peak releases on *hydropeak* days and steady low flow releases. The saved water is released during on-peak weekday periods to maximize overall hydropower revenue (high contract energy price of on-peak weekday). Above eight steady low flow days, the allowable release change between periods constraints becomes binding, hence increased peak and base releases.

A decreasing price difference between weekday on- and off- peak prices moved the tradeoff curves left towards less hydropower revenue (Supplemental Information, Fig. S6). An increase in offset releases slightly decreased hydropower revenue (Supplemental Information, Fig. S7). For the remainder of this analysis, we use only the single offset release of H1000 (1000 cfs differential between off-peak weekday and steady releases).

Adding a market price shifted the tradeoff curves left to lower revenue in comparison to the Saturday-Sunday-Weekday model with contract prices (orange vs blue, Figure 6). Each added day of steady release reduced revenue. There was no breakeven point.

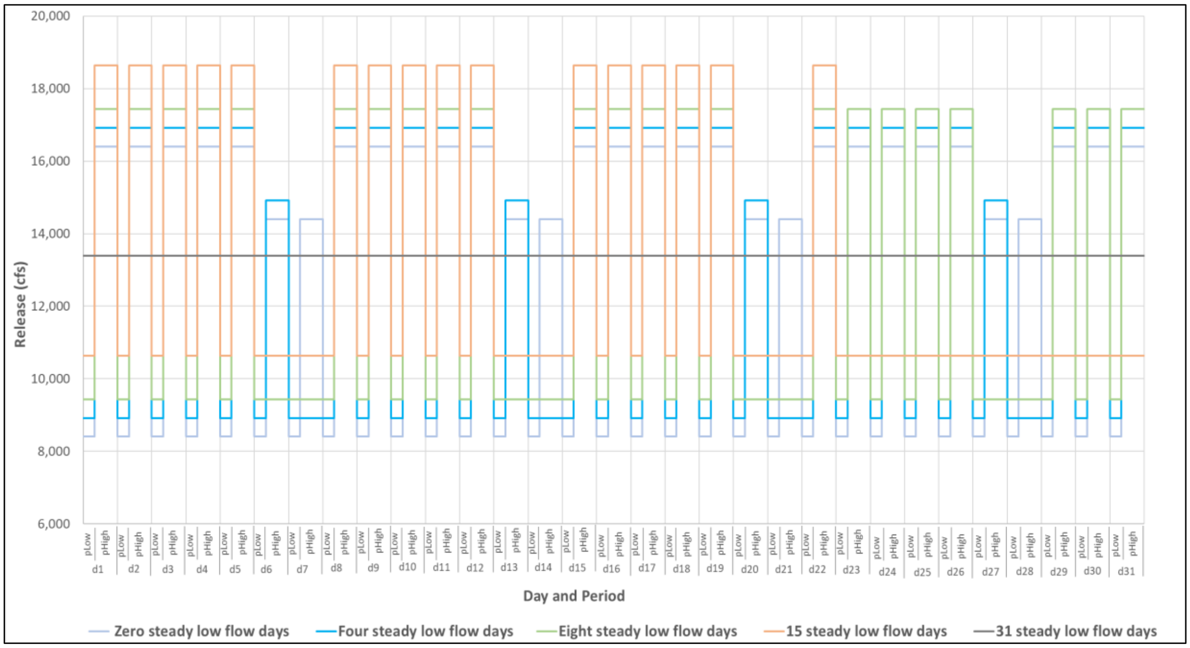

Figure 5. Monthly hydrographs from Saturday-Sunday-Weekday model for different steady low flow day scenarios (color) with 0.83 MAF monthly release volume and zero offset release. d1 is a Monday.

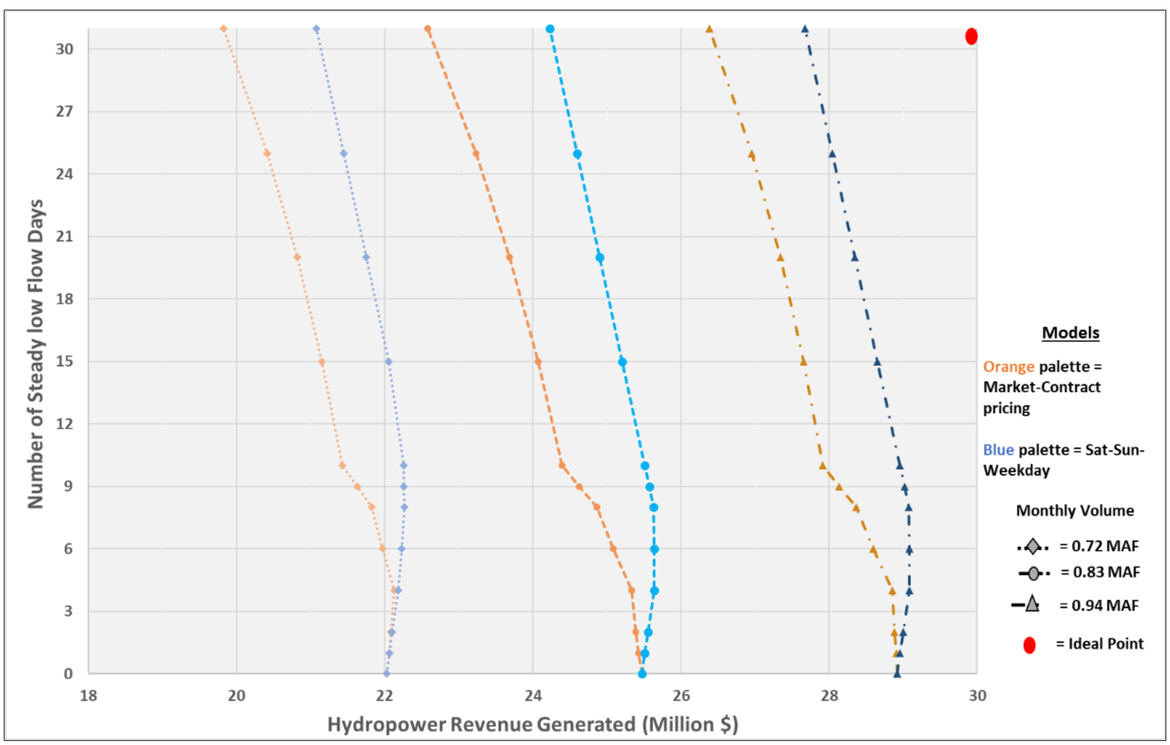

Figure 6. Comparison of tradeoffs with contract (blue) and market (orange) prices for different release volumes (line types and symbols) in August 2018 with 1000 cfs offset.

4.3. Reduce costs for bug flows

Calculating the cumulative hydropower revenue loss for each added day of steady low flow from the Market-Contract tradeoff curves in Figure 6 shows that the current bug flow experiment of 8 steady flow weekend days per month from May to August results in $300,000 (June) to $600,000 (August) per month in lost hydropower revenue (Table 2). The cumulative losses in hydropower revenue also show that ecosystem managers can reduce bug flow costs – or increase the number of days of steady low flows without reducing hydropower revenues – by making:

- Eight days of steady weekend releases in April and 8 days of steady weekend releases in June that cost $600,000.
- Eight days of steady weekend and 7 additional days of steady weekday releases in April for $530,000 or in September for $520,000.
- Six days of steady weekend releases in May and 6 days of steady weekend releases in July that cost $600,000
- And many other combinations.

More generally, ecosystem managers can move days of additional steady low releases from Summer to Spring/Fall months where hydropower revenues are lower and bug flows are not presently implemented (e.g., March, April, September, and October).

4.4. Financial instrument where bugs pay hydropower producers for days of steady low releases

The win-lose Market-Contract tradeoff curves (Figure 6, orange) highlight a conflict between hydropower producers and ecosystem managers. For example, steady low releases on 8 weekend days per month in summer months reduce hydropower revenue by $300,000 to $600,000 per month. Under the current administration program, reduced hydropower revenues increase costs to hydropower customers, decrease money to pay for future Bug Flows, lower money available to maintain project infrastructure, and reduce loan repayment. The negative feedback loop exacerbates conflict between hydropower producers and ecosystem managers and reduces ecosystem manager flexibility to schedule days of steady low releases.

To reduce the conflict, reverse the negative feedback loop, and give ecosystem managers more flexibility to schedule days of steady low releases, we suggest a new financial instrument that gives ecosystem managers a budget of $300,000 to $600,000 per month. This budget corresponds to lost hydropower revenue for the current 8 weekend days per month of Summertime steady low releases. Managers can use the budget and their ecosystem expertise to schedule days of steady low releases during Summer and/or Fall months and pay hydropower producers for costs of days of steady low releases.

Graphically, the payments convert the left-sloping, market-contract tradeoff curves (Figure 6, orange) into vertical lines of constant revenue that intercept the x-axis at the revenue generated in months with zero days of steady low releases (Table 2, Column 2, $Revenue_0$ [$]). Mathematically:

$$Revenue_0 = Hydropower\_Revenue_n + Payment\_for\_SteadyRelease_n \quad (18)$$

Here, *Hydropower_Revenue*$_n$ ($) is the modeled hydropower revenue for *n* days of steady releases (Figure 6, orange line) and *Payment_for_SteadyRelease*$_n$ ($) is the difference in revenue between 0 and n days of steady low releases (Table 2).

The $300,000 to $600,000 monthly budget is almost two orders of magnitude lower than monthly Glen Canyon Dam hydropower revenues. Environmental non-governmental organizations, Reclamation, the National Park Service, or other U.S. Federal agencies can provide the budget for steady low flows rather than the current practice to fund from hydropower revenues.

Table 2 Cumulative hydropower revenue loss ($ Million) per added day of steady release in 2018 with 0.83 MAF release volume, H1000 (offset release), and market and contract energy prices.

Month	**Revenue at Zero Steady days**	**Cumulative revenue loss ($ Mill) for the number of steady Flow Days**						
		4	**6**	**8**	**9**	**15**	**30**	**31**
March	$19.9	$0.19	$0.38	$0.37	$0.41	$0.68	-	$1.81
April	$18.6	$0.03	$0.18	$0.31	$0.36	$0.53	$1.3	-
May	$18.4	$0.09	$0.27	$0.43	$0.6	$1.02	-	$2.09
June	$20.1	$0.03	$0.14	$0.29	$0.47	$0.93	$1.8	-
July	$25.3	$0.09	$0.33	$0.55	$0.8	$1.61	-	$3.11
August	$25.5	$0.14	$0.39	$0.61	$0.85	$1.4	-	$2.89
September	$23.6	$0.1	$0.29	$0.27	$0.3	$0.52	$1.51	-
October	$21.8	$0.18	$0.39	$0.52	$0.56	$0.87	-	$2.12

**Blue color represents profit.*

5 Discussion and Limitations

We found that reducing the number of monthly release decisions from 744 (hourly) down to 12 characteristic flows—3 day types for 2 periods and two flow patterns—resulted in a 2.3 to 7.7% error in monthly energy generation from March to October 2018. Reducing the number of release decisions helped us maintain a linear model formulation, reduce the number of decision variables, and lower computational time. Reducing the number of release decisions also allowed us to explore different scenarios of monthly release volumes, energy price differentials between peak- and off-peak periods, offset releases, and market energy prices for March to October months. These analyses showed ways to reduce costs for steady low releases that advantage aquatic invertebrates—move days of steady low releases from Summer to Spring/Fall months. The analyses also informed the budget for a new financial instrument where ecosystem managers pay hydropower producers for lost revenue on days of steady low releases. With a budget, ecosystem managers get more flexibility to schedule days of steady low releases, compensate hydropower producers for lost revenue, and reduce hydropower-ecosystem conflict.

We found hydropower revenue decreased in all months as days of weekend steady release were added. Ploussard and Veselka (2019) reported smaller financial losses of $210,000 and $135,000 for July and August 2018 and gains of $19,000 and $160,000 for May and June. Our model validated monthly release volume and energy generated so we believe differences were due to different financial assumptions. For example, Ploussard and Veselka (2019) used energy sale (market) and purchase prices from 2019 and 2018 that were 25% and 50% lower than the 2014 prices we used. Our model maximized hydropower revenue by releasing a specified monthly water volume whereas GTMax SL used energy demand, sale price, and purchase price profiles for every hour of a representative week. Our work suggests the monthly budget for ecosystem managers to pay for days of steady releases can be $300,000 to $600,000.

The ecological benefits for an additional day of steady low flow depend on river temperature, sediment transport, and aquatic invertebrate growth. This information is constantly evolving. A financial instrument that gives ecosystem managers a budget to pay for days of steady low releases allows managers more flexibility to adapt the timing and number of days of steady low releases to evolving information. This flexibility also allows ecosystem managers to schedule days of steady low releases and reduce effort to renegotiate changes with hydropower producers.

Lake Powell’s water level will also affect budget amounts and payments for days of steady low releases. The water level is falling because annual releases are larger than inflows. This drawdown lowers energy head, efficiency, energy generation, and hydropower revenue (Arellano at CRWUA, 2022). In response, WAPA introduced the Deliverable Sales Amount (DSA) where each year WAPA sets the energy that they expect to generate and sell. Hydropower customers purchase energy shortfalls from alternative providers at market prices. As DSA energy generation decreases, we expect tradeoff curves for hydropower revenue and days of steady releases to shift left (e.g., as in Fig. S7 for price differential). We also expect the tradeoff curves to have larger revenue lost per day of added steady low release.

If Lake Powell draws down below the elevation of the hydropower penstocks, releases will switch to steadier and longer flows through the lower level river outlets that can increase aquatic invertebrate production. Dam managers may also increase releases through the river outlets if:

1. Non-native fish in Lake Powell get entrained in the existing penstocks, pass through, and threaten native, endangered fish populations in the Grand Canyon. This event may trigger releases through the river outlets before Lake Powell reaches its minimum power pool elevation of 3,490 feet.
2. Summertime Lake Powell levels fall below approximately 3,525 feet. This event could trigger releases through the penstocks with temperature greater than 18 ^{o}C. These high water temperatures make outcomes for native, endangered fish of the Grand Canyon highly uncertain (Wheeler et al, 2021).

The suggested financial instrument that gives ecosystem managers a budget to pay hydropower producers for days of steady low releases can also help reduce conflict and compensate hydropower producers for other releases that benefit ecosystems. For example, steady high releases send water through Glen Canyon Dam's penstocks and lower level river outlets with the purpose to mobilize sediment, build sandbars, and/or disadvantage non-native, invasive fish. Bypass releases reduce hydropower generation and revenue during non-bypass periods. Bypass releases also increase costs to hydropower customers, decrease money to pay for days of future steady low or high releases, lower money available to maintain project infrastructure, and repay loans. To reduce hydropower-ecosystem conflict, give ecosystem managers (i) separate financial budgets for steady low and high releases, or (ii) a single budget and allow managers more flexibly to prioritize steady low, high or other releases to respond to system conditions.

Last, we recommend next steps to:

- Update results with the proprietary GTMax SL model.
- Consider scenarios where Glen Canyon dam releases water through both the hydropower penstocks and lower level river outlets.
- Further engage people at Western Area Power Authority, National Park Serve, Reclamation, and Glen Canyon Dam Adaptive Management program.
- Apply the proposed financial instrument to other flow experiments such as high flows (LTEMP, 2016).

6 Conclusions

For many dams, days of steady low releases allow downstream invertebrates to lay and hatch eggs. These steady low releases also reduce hydropower revenues, increase costs to hydropower customers, lower funds to maintain project infrastructure, delay loan repayment, and exacerbate conflict between hydropower and ecosystem managers. To reduce this conflict, we suggested a new financial instrument for Glen Canyon dam, Arizona that gives ecosystem managers a budget to pay and compensate hydropower producers for days of steady low releases that reduce hydropower revenue. We used a linear optimization model with three day types, two energy demand periods, and two flow patterns to quantify tradeoffs between hydropower revenues and number of days of steady, low releases. We validated the model against energy generation data for August 2018 and ran for scenarios of different monthly release volumes, peak- and off-peak energy price differentials, offset releases, and market energy prices for March through October months.

We found the 2018 experiment of steady releases for 8 weekend days per summer month reduced hydropower revenues by \$300,000 (June) to \$600,000 (August). We found ecosystem managers can reduce costs to hydropower customers by shifting summertime steady low releases to Spring/Fall months. If given a budget, ecosystem managers can use the budget to purchase days of steady releases more flexibly in different summer and Spring/Fall months, compensate hydropower producers, and reduce effort to renegotiate changes in releases.

We see next steps to 1) update program values with the proprietary GTMax SL model used by WAPA, 2) engage more people from WAPA, National Park Serve, Reclamation, and Glen Canyon Dam Adaptive Management program, and 3) expand the financial instrument to include releases for other ecosystem purposes that reduce hydropower revenue such as mobilize sediment, build sand bars, and/or disadvantage non-native, invasive fish. The work will have a larger impact when researchers engage with the Federal employees who have the awesome responsibility to plan and manage Glen Canyon Dam as a large, unique, and critical piece of our nation's infrastructure.

Data Availability Statement

The data, models, and code used in this study are available in the GitHub repository (Rind and Rosenberg, 2022).

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