Glen Canyon Dam releases to promote bugs and generate hydropower

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ABSTRACT

Stoneflies, Mayflies, Caddisflies, and Midges (affectionately "bugs") are food for the endangered native and non-native fishes of the Colorado River between Glen Canyon dam and Lake Mead, Nevada. These bugs lay their eggs at dusk on rocks and other strata just below the water surface and require at least 48 hours of inundation to hatch. Hydropeaking operations--the daily fluctuations in dam releases by up to 8000 cfs to generate more energy during afternoons when energy demand and prices are high--desiccates bug eggs. The U.S. Geological Survey's Grand Canyon Monitoring and Research Center (GCMRC) and Western Area Power Authority (WAPA) are still evaluating the effects of summer 2018 experimental steady weekend releases to encourage bug egg hatching. Here we share results from a non-linear multi-objective optimization model that recommends Glen Canyon dam releases to maximize energy revenues and minimize a bug objective that is quantified as the standard deviation of releases. The model runs for one month with two sub-daily timesteps and is subject to daily release limits, maximum energy generation, storage limits, and an exogenously specified monthly release volume. We used the constraint method to identify the tradeoff between the energy generation and bug objectives. We tested scenarios that vary the month of the year, monthly flow volume, number of consecutive days of bug flows, and the steady bug flow release value. Preliminary results show: 1) Increasing the monthly release volume simultaneously improves the bug and energy generation objectives. 2) Increasing the number of steady bug flow days from 2 to 4 increases the standard deviation of flows; standard deviation of flows is not a good metric for bugs. This is a working document and materials will be updated over time based on work with GCMRC, WAPA, and others.

INTRODUCTION

Aquatic eco-system is one of the major components of the environmental life cycle. It is home to unique species, and provides food, pleasure, and sustainability to the related systems including humans. However, due to uncertainty in inflows and growing water demand (municipal, industrial, agricultural, hydropower etc.), the majority of Earth's rivers are now dammed (Nilsson et al. 2005). This anthropogenic development has drastically altered the ecosystems (Carpenter et al. 2011), and the natural flow regimes are engineered to meet the societal needs (Poff et al. 2007). The upshot of those hydrologic modifications on downstream ecology is yet to be quantified and mitigated (Kareiva et al. 2000, Dugan et al. 2010).

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~~Traditionally~~Elsewhere, water resources are managed for multiple and competing uses, such as water supply, hydropower, flood control, recreation and environmental protection (Null and Lund, 2012). In particular, the world's largest dams, including the Three Gorges Dam on the Yangtze River in China, the Itaipu Dam on the Paraná River in Brazil and Paraguay, and the Hoover Dam on the Colorado River in the United States are built and operated as storages of water supply and an immense sources of hydropower generation (World Commission on Dams, 2000). Until recently, the impacts of these artificial storages on downstream eco-system has been ignored. There is growing interest and wide recognition of the problem; with environmental objectives put before the hydropower (Richter, 2014; Pegram et al., 2013; Hart, 2015). Some studies also claim the precedence of rivers increasingly managed to support aquatic ecosystems and fisheries, in addition to traditional human water demands (Null and Lund, 2012). Still, for easy implementation, the concept of environmental flows needs further elaboration regarding measurable ecological objectives and methods to achieve those objectives (Alafifi and Rosenberg, 2016).

In the modeling world, the environmental flow operations are normally mimicked by simulation or optimization methods (Adams et al., 2017). For the reason, numerous studies have been carried out and number of methods have been developed to determine environmental flow requirements (Tharme, 2003; Arthington, 2012). On the contrary, translating that acquired ecological knowledge into operational paradigms is yet another challenging task (Harman and Stewardson, 2005). Hence, there is an urgency for water managers to find ways that can trade off and balance the competing environmental watering objectives (Acreman et al., 2014; Richter, 2014; Poff et al., 2015).

~~For instance, the case study of Grand Canyon, Arizona, USA.~~ In total, the Grand Canyon is home to five different eco-systems (National park service, 2011-12). However, the presented study will only focus on the aquatic eco-system and related species. Aquatic eco-system in the Grand Canyon is managed by releases from the Glen Canyon Dam- second highest concrete-arch dam in the United States with storage capacity of 26.2 million acre-ft. Besides, the Glen Canyon Powerplant is huge source of hydropower generation with an annual total of five billion kilowatt-hours. Which is distributed by the Western Area Power Administration (WAPA) to Wyoming, Utah, Colorado, New Mexico, Arizona, Nevada, and Nebraska (USBR, 2019).

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One of the upshots from hydropower dams, to meet daily energy demand variation, is hourly timescale fluctuation in release amount known as load following or hydropeaking (Kennedy et al., 2016). Under hydropeaking, the river flows are increased during the daytime and decreased at night; chasing the energy demand (Førsund, 2015). In some cases, the required variation in flow can be substantial, and the release value varies by factor of 10 or more within a day (Moog, 1993, Topping et al., 2003). ~~The instability in release amount impose additional~~These changing releases stress~~es on~~ rivers, including water temperature, flow velocity, sediment transport, and water depth (Poff et al. 2007, Schmidt and Wilcock 2008, Olden and Naiman 2010). These stressors adversely affect the aquatic life, and often extirpate organisms that rely on nearshore environments during one or more stages of life cycle (Kennedy et al., 2016).

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For example, aquatic insects (bugs) are amongst worst affectees of hydropeaking phenomenon. Bugs lay their eggs at dusk time, when the water level is fairly high, ~~around~~ on the river edges. ~~While at the~~During nighttime, due to hydropeaking, the water level drops, ~~and~~ the river width shrinks and ~~leaving~~ th~~os~~e river edges ~~to~~ dry out. ~~Due to desiccation most of th~~When the river edges dry oute, the bug eggs ~~die~~desiccate, and the population of bugs drops. These ~~,~~ ~~which~~bugs are the primary ~~prey~~food for myriad species of fish, birds, bats, and other wildlife living in and along the river (Nakano and Murakami 2001, Baxter et al. 2005)~~, suffer adversely~~. ~~In support to the discussed idea,~~ Kennedy et al., 2016 found ~~a relationship between hydropeaking index and insect diversity (EPT %) at 16 rivers across the western United States. The results of the study show~~ that insect diversity is strongly and negatively related to the degree of hydropeaking index in 16 rivers below 16 dams across the western United States.

~~In addition, the findings from~~ Kennedy et al., 2016 also found ~~shows~~ that Glen Canyon Dam has the ~~worst~~lowest invertebrate richness in comparison to other dams. There are reports blaming cold releases from dams responsible for invertebrate community assembly in tailwaters (Olden and Naiman 2010), including for the Colorado River ecosystem downstream of the Glen Canyon Dam (Stevens et al. 1997). However, Kennedy et al., 2016 modifies that notion by presenting a strong inverse relationship between hydropeaking index and invertebrate diversity.

~~The study~~Kennedy et al (2016) further suggested an innovative solution to the problem by recommending Glen Canyon Dam release stable low flows on weekends. Since ~~the~~ electricity demands are low on weekends (Førsund 2015), ~~therefore, escaping hydropeaking on weekends will be the minimal hydropower generation~~weekend hydropower revenue losses will be small (USBR, 2016). ~~Nevertheless, t~~The stable low flow conditions will ~~be favorable for~~allow eggs to incubate for 48 hours and hatch~~ing~~. Eggs laid on weekends remained wetted and never subject to desiccation prior to hatching, which typically occurs after days to weeks of incubation (Merritt et al., 2008, Statzner and Beche, 2010). Thus, the suggested environmental flows will substantially help aquatic-insect egg laying and rearing life stages.

To test the hypothesis of steady low weekend flows put forward by Kennedy et al., 2016, the first bug flow experiment was conducted ~~in 2018~~ between May~~-~~ and August, 2018 (GCDAMP, 2019). The experiment was included in the Preferred Alternative of the long term experimental and monitoring program (LTEMP DEIS) and has been repeated in 2019. ~~There are few studies~~Several researchers are trying to quantify the impacts of bug flow experiment~~ on various indicators such as report by~~. Ploussard & Veselka, 2019 explore~~s~~ the financial implication caused by the experiment. Although the study has quantified the financial difference due to hydropower generation variability from hydropeaking but, no one ~~till date~~ has ~~calculated~~ shown the tradeoffs between hydropeaking index and hydropower revenue generation.

~~Therefore, the presented~~This study will calculate the tradeoffs using optimization model developed in general algebraic modeling system (GAMS). If low steady flows are favorable for bugs population, the developed model has capability to devise dam releases (decision variable) corresponding to maximization of hydropower revenue and minimization of hydropeaking index. The model runs for one month with two sub-daily timesteps ~~and was~~ subject~~ed~~ to daily release limits, maximum energy generation, storage limits, and an exogenously specified monthly release volume. To deal with multiple objectives problem, the constraint method was used to identify the tradeoff between the energy generation and bug objectives. The model ~~tests~~ shows how the bug-

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Objectives:
Hydropower revenues
Bug population immediately downstream of the dam.

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hydropower revenue tradeoff changes for scenarios that vary month of the year, monthly flow volume, number of consecutive days of bug flows, and the steady bug flow release value. ~~The outcome of the study are tradeoff curves under variable scenarios, and the release schedule at each of the tradeoff points. Besides, the model calculates the energy plot for each of the release schedule. Overall, the study can be helpful to decide release schedule and its implications on both environmental (bugs population downstream) and financial (hydropower revenue generation) aspects~~.

METHODS

A multi-objective optimization model for Glen Canyon Dam, Arizona was setup in GAMS; having daily inflow volume, estimated daily evaporation, and initial reservoir storage (datasets were acquired from USBR website: https://www.usbr.gov/rsvrWater/HistoricalApp.html). Also, for simulation purpose, 15 mins flow data observed at Lees ferry was acquired from GCMRC website (https://www.gcmrc.gov/discharge_qw_sediment/station/GCDAMP/09380000) and feed in the model. For energy comparison, the observed daily megawatt hour (MWh) values (from USBR website) was compared with the modeled daily MWh values. The hourly power (MWh) prices used in the model were provided by WAPA official.

~~With parameters defined and indexed over daily and sub-daily timesteps, constraint method was used to setup the model and find the tradeoff between following two competing objectives:~~The model has two objectives:

~~a)~~ *Minimize hydropeaking index (Bugs Objective)*

$$\text{ObjectiveVal}(f_{HydropeakingIndex}) = \text{Obj\_dir}(f_{\text{HydropeakingIndex}}) \times (\text{standarddev}(d)/\text{Avgrelease}(d)); \qquad \forall\, d \in D$$

~~b)~~ *Maximize Revenue from energy generation (Hydropower Objective)*

$$\text{ObjectiveVal}(f_{\text{EnergyRevenue}}) = \text{Obj\_dir}(f_{\text{EnergyRevenue}}) \times \sum_d \sum_p \text{Energy\_Gen}(d,p) \times \text{EnergyRate}(p); \qquad \forall\, d \in D,\, p \in P$$

Where: Obj_dir is controlling the direction of the equation i.e. whether to maximize or minimize the objective.

The model has opportunity to devise releases and was subjected to number of constraints, including reservoir mass balance, storage limits, minimum and maximum release limits, ramp up and ramp down limits, maximum energy generation, and total monthly release volume.

Within the developed modeling code, two sub models were embedded and executed simultaneously. Each of the sub model has its specific importance in the overall framework and were interdependent. Initially, the extreme points model (one of the sub model) was solved and the extreme values for objectives were acquired. Later, while applying constraint method, various intermediate hydropeaking index values were ~~linearly interpolated~~ between the extreme values, and each of the intermediate value was made constraint for the run. The model was solved for hydropower revenue generation value corresponding to that constraint hydropeaking index value. In total, the pareto optimal curve amongst objectives under each of the total monthly volume values was prepared (refer results sections for further details).

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Look at Ayman Alafifi's or Omar Alminagorta's dissertation for examples.

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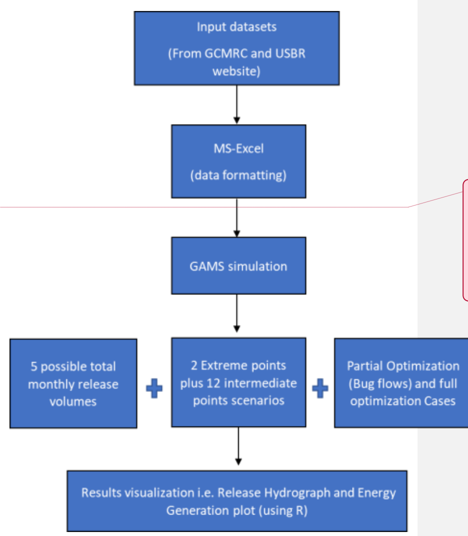
For validation, ~~the model was simulated with~~ observed release data on hourly timestep for April and June 2018 were used to calculate hydropeaking index, energy generation, and hydropower revenue generation results (Eqs. 1 and 2). ~~In addition, to select the suitable~~ Several sub-daily timesteps of different start times and durations were tested to determine ~~duration, various scenarios were developed and tested~~ (Table 1). The ~~introduction of~~use of 2 or 4 sub-daily timesteps ~~instead of using hourly timestep simulation simplifies the model calculation~~reduces the computational burden by a factor of 12 or 6 over and hourly timestep and helps reservoir operators and stakeholders focus on ~~, and the implementation will also be easier for the reservoir operator~~key attributes of the release hydrograph. ~~Nevertheless, all the scenarios were developed based on understanding of the favorable conditions for bugs population as well as the power price variation within the day. Table 1 provides details of the scenarios tested, and the outcome from each can be found in results and discussion section of the paper. Overall, the model was validated with two months of data from April and June 2018.~~

Table 1 Details of the scenarios tested under validation of the model

Scenario	Period	Start Time	End Time	Description
Scenario 1	Period 1 (PHigh)	9:00 AM	10:00 PM	Each day is divided into two periods. With the first period "pHigh" lasts for 13 hours and second "PLow" 11 hours
	Period 2 (PLow)	10:00 PM	9:00 AM	
Scenario 2	Period 1 (PLow)	4:00 AM	9:00 AM	Each day is divided into two periods. With the first period "pLow" lasts for 5 hours and second "PHigh" 19 hours
	Period 2 (PHigh)	9:00 AM	4:00 AM	
Scenario 3	Period 1 (PLow)	12:00 AM	8:00 AM	Each day is divided into two periods. With the first period "pLow" lasts for 8 hours and second "PHigh" 16 hours
	Period 2 (PHigh)	8:00 AM	12:00 AM	
Scenario 4	Period 1	12:00 AM	5:00 AM	Each day is divided into 4 periods. With the first period lasts for 5 hours, second 5 hours, third 4 hours and fourth 10 hours.
	Period 2	5:00 AM	10:00 AM	
	Period 3	10:00 AM	2:00 PM	
	Period 4	2:00 PM	12:00 AM	

Additonally, the model was run for X scenarios that test 5 monthly release values, Y durations of steady flows, and Z ----------- (Table 2 or Figure 1).~~Likewise, for model simulation, monthly model was setup with two periods per day, validation scenario 3 was selected based on validation results, and release within each period for the day was considered constant. Next, the application of constraint method. The method works by first identifying the range of feasible hydropeaking values (extreme values). This range is linearly segmented into 12 intermediary values. At each intermediary hydropeaking index value, the model was solved to maximize the energy generation objective subjected to the base model constraints and an additional constraint that require the hydropeaking index equal to the intermediary value. The model was run for scenarios that vary by the month of the year, monthly flow volume, number of consecutive days of bug flows, and~~



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The validation results are shown below in the results section. Show them here.

~~the steady bug flow release values. Each run generates results describing the hydropower generated, generated energy revenue, hydropeaking index value, releases hydrograph, and reservoir storage time series. Figure 1 provides a schematic of the model setup and the resources used to carry out a simulation run.~~

RESULTS AND DISCUSSION

Model Validation

For all sub-periods tested, modeled energy revenue is close to the observed revenues calculated at an hourly timestep (Tables 2 and 3).

For hydropeaking index calculation, two different approaches were considered: Monthly co-efficient of variance (CV) and daily co-efficient of variance averaged over the month. Under monthly CV approach, the model was given opportunity to calculate a single best CV value for the month benefiting both the objectives. While in the second approach, a daily co-efficient of variance value was calculated and averaged over the month. In both approaches the values found for CV were quite different (Table 2~~Table 2~~ and Table 3~~Table 3~~), however, the daily co-efficient of variance averaged over the month approach was considered for further simulation. The selection of approach was influenced by prior work by Kennedy et al., 2016.

Next was the consideration of the daily CV values and revenue generated under different scenarios (Table 2~~Table 2~~ and Table 3~~Table 3~~) to finalize the day's division in periods, and the duration of those periods. Hourly power price provided by WAPA was also considered while setting the periods duration. Overall, scenario 3 (Table 1~~Table 1~~) was found most feasible for the analysis.

~~In general, while comparing the observed energy generated amount with the modeled energy amount under different scenarios (Table 2 and Table 3), it can be found that the modeled amount is greater than the observed amount. The deviation is an offshoot of the hydropower~~

~~**Figure 1 Model schematic showing steps and**~~

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Delete this figure. It does not add anything new beyond the text. "Partial Optimization" is not explained in the text. What are the 5 possible release volumes?

Instead, create a figure or table that lists the scenarios tested.

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~~generation formula provided by WAPA. Also, the hydropower revenue generated value is dependent on the hourly power information provided by WAPA. Since this is an ongoing study, hence, materials will be updated over time based on work with GCMRC, WAPA, and others. Still, the numbers found from validation runs (presented in Table 2 and Table 3) are convincing since they are near to the observed values; proving the authenticity of the methodology used.~~

Table 2 Validation results April-2018

S.No:	Scenario	Flow volume (Ac-ft/ Month)	Energy Generated (MWh)	Hydropeaking Index (Monthly Cv)	Hydropeaking Index (Daily Average CV)	Revenue generated ($)	% Error in Revenue w.r.t to hourly result
1	Observed	7.49E+05	318194	0.157	0.139		
2	Model Simulated (1 Hr Time step)	7.49E+05	331452.8	0.156	0.141	$15,548,174	
3	Model Simulated (2 Time steps- 9:00 to 22:00 & 22:00 to 9:00)	7.49E+05	331452.8	0.102	0.085	$15,295,675	1.62%
4	Model Simulated (2 Time steps- 04:00 to 09:00 & 09:00 to 04:00)	7.49E+05	331452.8	0.133	0.138	$15,471,397	0.49%
5	Model Simulated (2 Time steps- 00:00 to 08:00 & 08:00 to 00:00)	7.49E+05	331452.8	0.114	0.114	$15,556,918	-0.06%
6	Model Simulated (4 Timesteps -00:00 to 5:00, 5:00 to 10:00, 10:00 to 14:00 & 14:00 to 00:00)	7.49E+05	331452.8	0.136	0.128	$15,487,948	0.39%

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Commented [DR31]: Which numbers?

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Rename the other scenarios as:

Two period (start 9 am and 10 pm)
Two period (start 4 am and 9 am)
Two period (start midnight and 8 am)
Four period (start, midnight, 5 am, 10 am, and 2 pm)

Table 3 Validation results June 2018

S.No:	Senario	Flow volume(Ac-ft/ Month)	Energy Generated (MWh)	Hydropeaking Index (Monthly Cv)	Hydropeaking Index (Avg daily Cv)	Revenue generated ($)	% Error in Revenue w.r.t to hourly result
1	Observed	7.94E+05	343202.0	0.228			
2	Model Simulated (1 Hr Time step	7.94E+05	351092.8	0.228	0.161	$18,308,079	
3	Model Simulated (2 Time steps- 9:00 to 22:00 & 22:00 to 9:00)	7.94E+05	351092.8	0.187	0.118	$17,471,339	4.57%
4	Model Simulated (2 Time steps- 04:00 to 09:00 & 09:00 to 04:00)	7.94E+05	351092.8	0.204	0.151	$17,884,520	2.31%
5	Model Simulated (2 Time steps- 00:00 to 08:00 & 08:00 to 00:00)	7.94E+05	351092.8	0.194	0.163	$18,051,497	1.40%
6	Model Simulated (4 Timesteps -00:00 to 5:00, 5:00 to 10:00, 10:00 to 14:00 & 14:00 to 00:00)	7.94E+05	351092.8	0.219	0.169	$18,246,971	0.33%

Figures ~~2~~ and ~~Figure 3~~ 3 ~~are presenting~~show the time series of observed and simulated energy generated ~~time series plot under different scenarios for~~in April and June 2018. ~~While, Figure 4 and Figure 5 are illustrating the observed and simulated hydrographs for the same cases~~.

~~As previously mentioned, overall, t~~The modeled energy values are greater than the observed values ~~(Figure 2); because of the provided WAPA's power generation formula used. While looking at the modeled energy values and their trends, it can be found that all the validation scenarios are overlapping at most of the times. Which means the~~However, the total energy generated ~~amount is almost insensitive to period's duration~~is nearly identical across the different test periods. The reason behind this insensitivity is the same volume of release under all the scenarios. ~~Nevertheless, small fluctuations can be observed in the modeled values curves (Figure 2 and Figure 3) suggesting that period's duration and number of periods can be impactful factor while deciding the total hydropower revenue generated i.e. if more energy produced in the high value period means more money generated and vice versa.~~

Error! Reference source not found.~~Figure 4~~ and Figure 5~~Figure 5~~ compare the observed and simulated reservoir release hydrographs~~Figure 4 and Figure 5 depicts the impacts of modifying the period's duration on hydrograph and its comparison with the observed hydrograph~~. ~~It can be witnessed that v~~Varying the period~~s durations~~ start times ~~can~~ modif~~y~~ies the ~~peaks~~ high and low flow periods ~~(Figure 4 and Figure 5)~~. ~~Moreover, t~~The scenario with low flow from 0:00 to 8:00 and high flow from 8:00 to 0:00 fits the observed hydrograph better than other scenarios. Hence, the scenario was selected for ~~further simulations~~tradeoff analysis.

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Figure 1~~2~~ Energy plot for different validation runs (April 2018)

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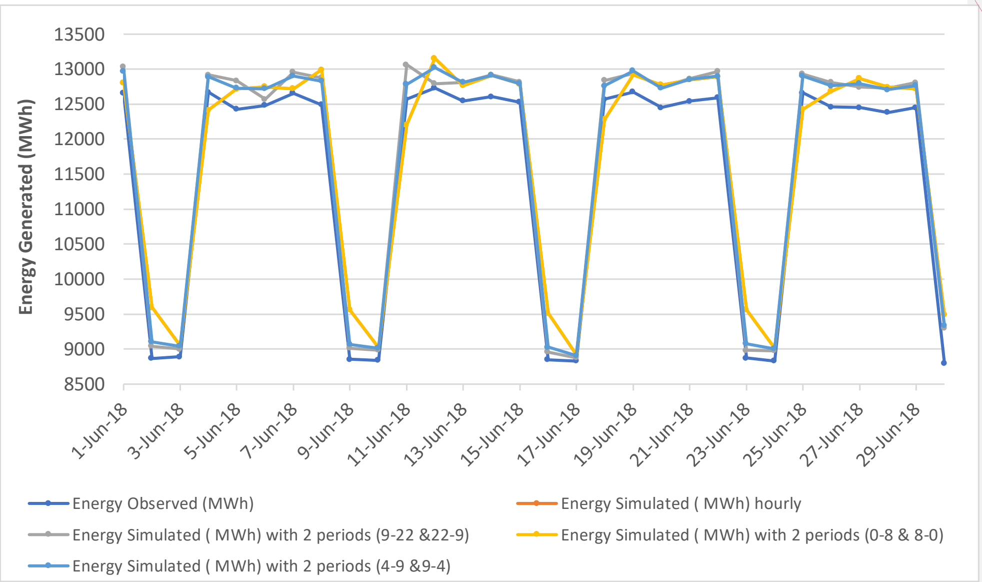

Figure 2~~3~~ Energy plot for different validation runs (June 2018)

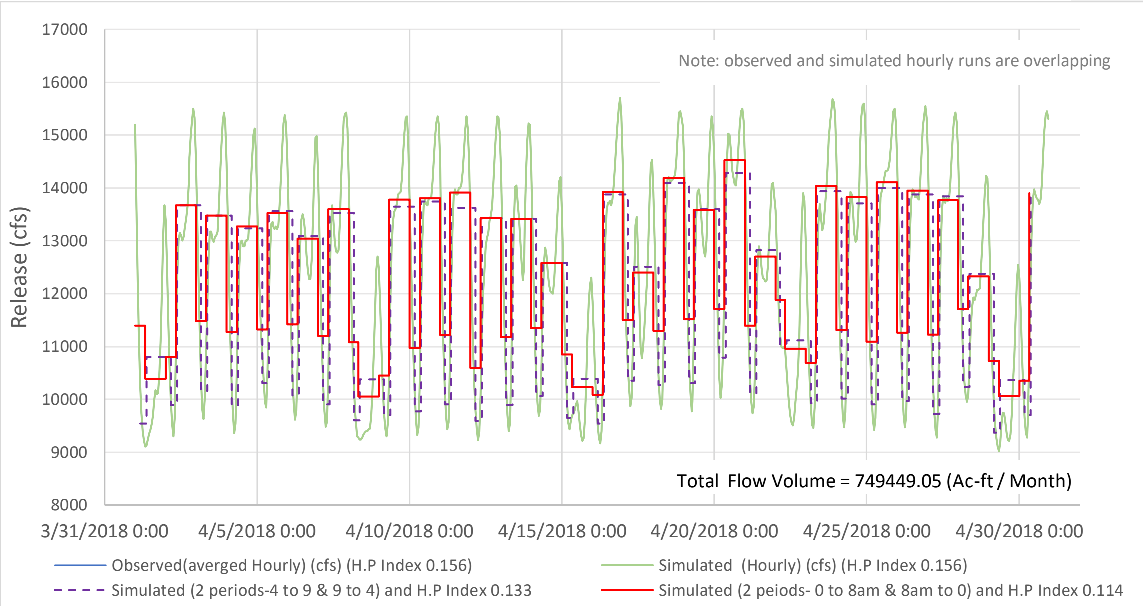

Figure ~~3~~4. Hydrographs for different validation runs with monthly flow of 0.75 Mill acre-feet (April 2018)

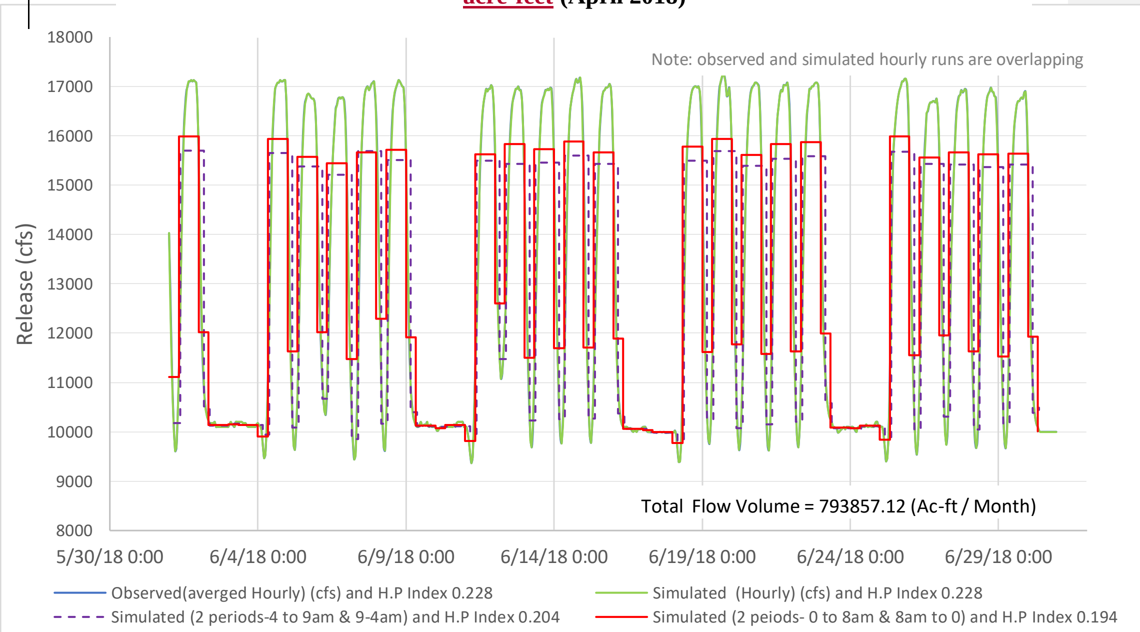

Figure ~~4~~5 Hydrograph for different validation runs (June 2018)

The ~~results from the monthly averaged CV model~~tradeoff analysis ~~(Figure 6)~~ shows that there are many~~is significant window of~~ opportunit~~y~~ies ~~available to benefit both the~~to improve ~~objective~~the hydropower revenue and bug objectives (Figure ??). By moving from 2 days bug flow practice (solid line) to optimize release pattern suggested by the model without any specified constant bug flow days (dashed line) can improve both the objectives significantly. And the size of window increases as the total monthly release volume increases. The black square in Figure 6 mimics the observed release pattern of June 2018. While comparing the observed case with the min point on the optimization curve with the same total volume (sky blue dashed line below the black square) it can be safely concluded that even by having zero hydropeaking -flat constant flow throughout the month- the loss in energy revenue generation will be only half a million under the observed release volume.

Conversely, the results from the daily CV averaged over the month (Figure 7~~Figure 7~~) illustrates that curves from both the scenarios (i.e. run with 2 days bug flow and optimization without bug flow) overlaps. Which means almost no window of improvement between 2 days bug flow and optimization cases. Still, comparing the observed case with the min point on modeled curves with the same total volume (sky blue line below the black square) concludes the same point that by having zero hydropeaking -flat constant flow throughout the month- the loss in energy revenue generation will be only half a million under the observed release volume. However, the presented study focuses on the daily CV averaged over the month approach.

The model has capability to produce releases and energy generated values at each of the location along the curve. For example, Figure 8~~Figure 8~~ and Figure 9~~Figure 9~~ presents the release hydrograph and energy plot for the middle points of both curves under the observed total monthly release volume of June 2018. ~~Likewise, at any required hydropeaking index value or hydro-power revenue value the model can suggest the release hydrograph and calculate the energy plot; unless the required values are outside the extreme points of the curve.~~

In addition, the model was simulated with increased number of bug flows days (Figure 10~~Figure 10~~) as well as increased bug flow release value (Figure 11). While increasing the number of bug flow days the model becomes infeasible for greater release volumes. Hence, the infeasible outcomes were ignored in Figure 10. The reason behind the infeasibility was the constrained monthly total release volume to achieve. With the increased number of bug flow days, the model was unable to spit the required volume while keeping the other constraints. Nevertheless, it can be observed in Figure 10~~Figure 10~~ that the feasible 3 and 4 days bug flow curves are also overlapping the optimization and 2 days bug flow curves. It is worth notice that increasing the number of bug flow days decreases the range of the curve. Which means with increase number of constant bug flow days, the model is left with only few possible options to choose amongst.

On the other hand, results shown in Figure 11 suggests that increasing the bug flow release values significantly cuts the hydropower revenue generation objective. In case of higher total release volumes, same limitation occurs i.e. increasing the bug flow share hijacks the model outputs and the model have only limited or no solution to the question asked with other constraints also in action.

Commented [DR37]: Figures 4 and 5. Remove all text annotations (add to figure caption). Simplify legend entries –
- -Observed hourly
- Simulated hourly
- -Simulated 2-period (start 4 am and 9 am)
- Simulated 2 period (start midnight and 8 am)

Use the following rendering (so people who are red-green color deficient can differentiate).
- Solid dark blue
- Dashed light blue
- Dash-dot purple
- Dot-do red

Commented [DR38]: The tradeoff figure is insanely complex. The text first needs to describe what is happening on the plot – how the plot is organized. Describe each plot aesthetic.

Then identify the three (or maybe 4) main take away points from the figure. Go back to your last "major points" sheet. We identified the main point in their order of importance.

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Commented [DR39]: Hard to follow. What is the point here?

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Commented [DR40]: Where? I don't see the figures.

Is there something in particular you want to show about these release hydrographs? Choose release hydrographs that have a compelling message and describe that message in one sentence.

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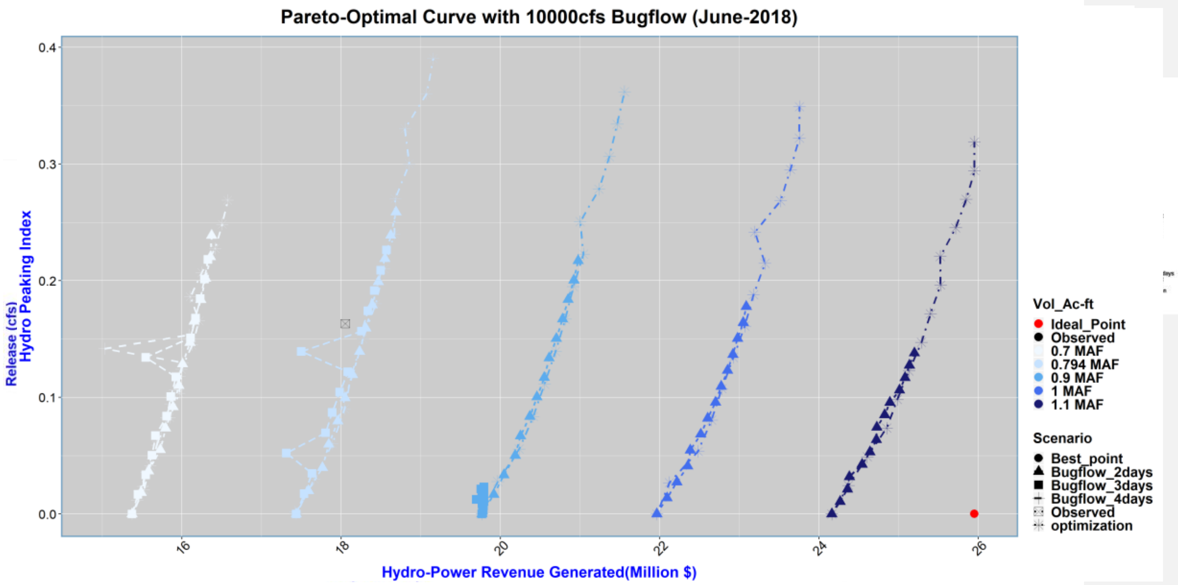
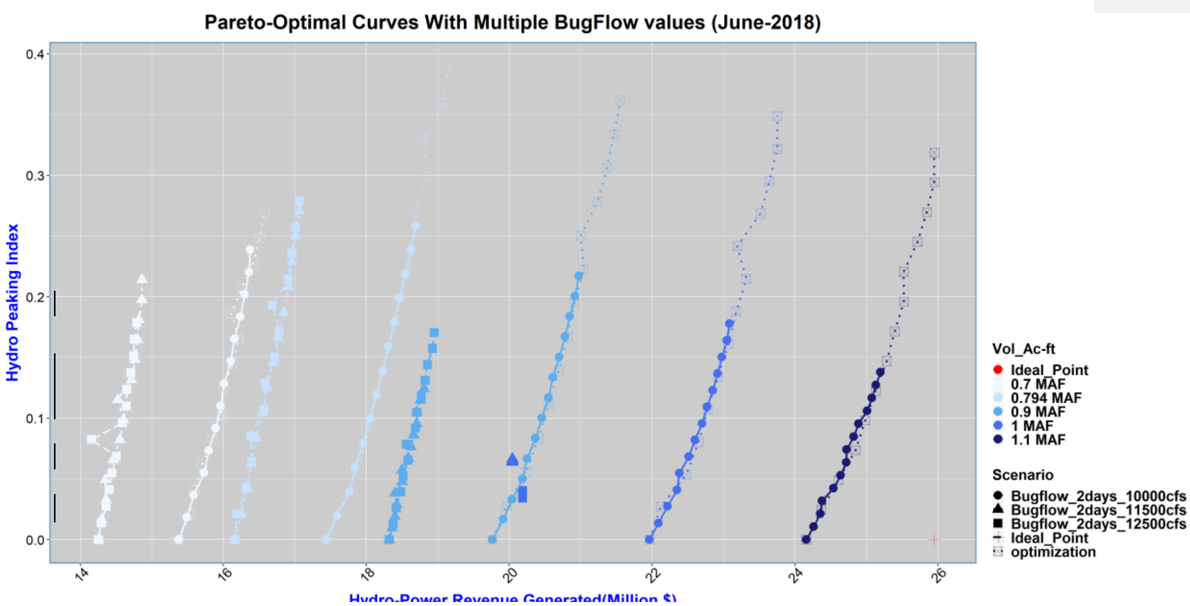
Commented [DR41]: Where are these results?

Commented [DR42]: The figures and figure captions overlap. Instead, use a 1 column x 2 row table. Paste the figure into the first row and figure caption into the second row.

Commented [DR43]: Next figure. Let's simplify. Remove the 3-day traces. Also need to censor (remove) the points that deviate from the trade-off curves. They are artifacts of the solver not reaching an optimal solution. It is misleading to show them on the figure. Add a sentence in the methods to describe the criteria for which points were not shown.



CONCLUSION



[11] **Figure 11 Trade-off curves for different total monthly volumes under different Bugflow release value scenarios.** ~~**In case of 1.1 MAF volume, the 12500 Bugflow release value run was found infeasible, and ignored. While, the model found either feasible or optimal solution for all the other cases. However, by increasing the Bugflow release value the model is predicting a significant cut in the hydro-power revenue objective.**~~

The objective of the study was to develop an optimization model that can ~~calculate~~ show the trade-off between hydropeaking index and hydro-power revenue generation. ~~The model can test the findings from Kennedy et al., (2016) and simulate some additional scenarios. In addition, to verify the notion that hydropeaking index is a suitable metric to quantify the bugs population suitability.~~

Commented [DR44]: Overview the model in 1-2 sentences.

The model was initially tested with both the monthly averaged CV and daily CV averaged over the month approaches. The results from the monthly averaged CV approach (Figure 6~~Figure 6~~) shows a significant window of opportunity to improve both the objectives by adopting the suggested optimized release pattern instead of following 2 days Bugflow practice (stable flows on weekends).

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On the contrary, the results from the daily CV averaged over the month approach (Figure 7~~Figure 7~~) doesn't show any window between optimization and 2 days Bugflow scenario. However, the major takeaway from Figure 7~~Figure 7~~ is that the difference in revenue generated between the observed point and the min point on the curve -having zero hydropeaking index- is almost insignificant (half a million $ only). Overall, the results from both approaches concludes that by increasing the total release volume the model simultaneously generates more revenue and reduces the hydropeaking index value (win-win trade-off).

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In addition, the results from the runs with increased Bugflow days doesn't show any significant difference as the curves are either overlapping or the solution becomes infeasible (Figure 10~~Figure 10~~). However, the results from the runs with increased Bugflow release value show a significant decrease in hydropower revenue generation objective (Figure 11). Hence, the increase in Bugflow release value can be a serious concern for hydropower sector.

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Commented [DR45]: Difficult to follow. The text all runs together.

Go back to the bullet points of major findings in our prior draft. List these point by point.

~~To sum up, the presented study provides a mechanism which can be used to predict the tradeoff curve, and calculate the releases corresponding to points on the curve. The findings of the study~~ challenge the idea that hydropeaking index is a suitable metric to quantify bugs suitability. Hence, further research is required to define a better bug suitability metric.

Commented [DR46]: This is probably one of the major findings to list above.

~~Lastly, as mentioned earlier, this is an on-going study and the results presented are not the final products. The results will be updated over time based on work with GCMRC and WAPA, and the~~ updated model along with results will be publicly available in near future at: https://github.com/moazzamalirind/-Bug-flow-

Commented [DR47]: You can only list if they are available! Move to a new section titled Data Availability.

ACKNOWLEDGEMENT

This work is funded by center for Colorado River studies, Utah State university under the future of the Colorado River project. In addition, we are thankful to the staff of GCMRC and WAPA; especially Clayton Palmer (WAPA), Craig Ellsworth (WAPA), and Charles Yackulic (GCMRC) for their continuous support and suggestions.

Commented [DR48]: You can also acknowledge your US-Pakistan scholarship.

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