| Research

Generating more hydropower with less dams and better ecosystem outcomes: is it possible?

An aspect of the eco-system that is significantly altered by continued hydropower dam construction, particularly in the developing world where construction is picking up pace, is river cooling. One method to offset these negative thermal (ecosystem) changes in the face of dam development is to design reservoir operations that explicitly include environmental goals such as maintaining thermal regimes. The latest research suggests that it is possible to operate fewer dams at higher levels of efficiency using weather forecasts to generate more power with better ecosystem outcomes.

The unique benefits of hydropower as a non-fossil energy option

Hydropower generation facilities have a unique and complementary role to play in the portfolio of other renewable energy options such as wind, solar and tidal energy. Hydropower is a stable and renewable source of electricity that can reliably provide baseload power (i.e., minimum power needed at a steady rate). Unlike thermal power plants, hydropower can supply power to a grid or be stopped almost instantaneously to address unexpected power demand or the lack of it (US EIA, 2018). Features unique to hydropower over other renewable energy sources are significant operational flexibility with the ability to store energy, low operating and maintenance costs, and integration capabilities with other intermittent renewables in the electric grid (Hamlet and Lettenmaier, 2002; Liu et al., 2019; Ahmad and Hossain, 2020).

Numerical weather forecasts can make hydropower dams more efficient

The current management of most hydropower dams in the world is based on rule curves that outline the reservoir storage targets to be met at specific times of the year. These rule curves are designed based on existing storage volumes using a climatology of historical flow observations. Operating strictly based on these rules, without considering recent or near-future changes in inflow patterns, can result in high inefficiency in operating the dam, at least from a hydropower standpoint (Miao et al. 2016). Recently, significant research has been carried out on hydropower generation based on short-term inflow forecasts derived from publicly available numerical weather prediction (NWP) models (Ahmad and Hossain, 2020, 2019a, 2019b). In these studies, forecast fields from the NWP model of the Global Forecast System (GFS) were used to force a hydrologic model to forecast reservoir inflow for 1-16 days lead-time. The optimization of reservoir operations was performed based on the forecast of inflow. This concept was demonstrated over Detroit dam in Oregon (US) (Figure 1), showing that an additional 9270MWh of hydropower can be gained during two-year return period storm events. Optimization over a longer ten-month period raised the total energy production by 5.6% over the traditional rule-curve scenario (Ahmad and Hossain, 2020). Such optimization of hydropower dam operations based on weather forecast data can not only increase hydropower generation, but also satisfy the goals of flood control and dam safety. Our research on weather forecast-informed hydropower operations clearly reveals that the current and future inventory of hydropower dams can operate at much higher efficiency levels, thereby requiring less dams to be in operation in order to meet growing energy demands (Zarfl et al., 2014).

Authors

Shahryar Ahmad[1], Matthew Bonnema[2] and Faisal Hossain[1*]

[1] Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington, USA.

[2] NASA Jet Propulsion Laboratory, Pasadena, California, USA.

[*] Corresponding author: fhossain@uw.edu

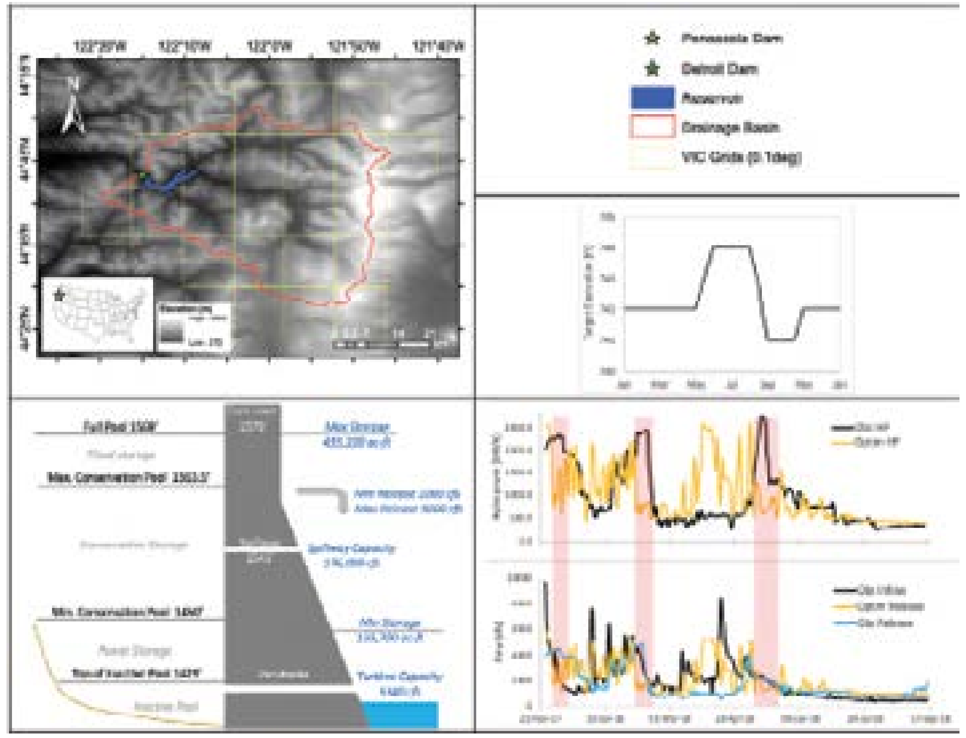
The hidden cost of efficient hydropower generation

However, dams come with a cost to the environment. This cost can be multi-faceted. For example, dams can damage the freshwater eco-system, restrict the flow of sediments downstream and often reduce the livelihood and cultural identity of local inhabitants who live in the region that the dam inundates permanently. Such environmental costs are well documented and several measures have now been recommended to mitigate these negative effects (see for example, Olden et al., 2010). There is one critical impact of hydropower dams that has usually gone undetected - the aggregate effect of hydropower operations on downstream water temperature and the negative consequences on ecosystem services (Bonnema et al., 2019).

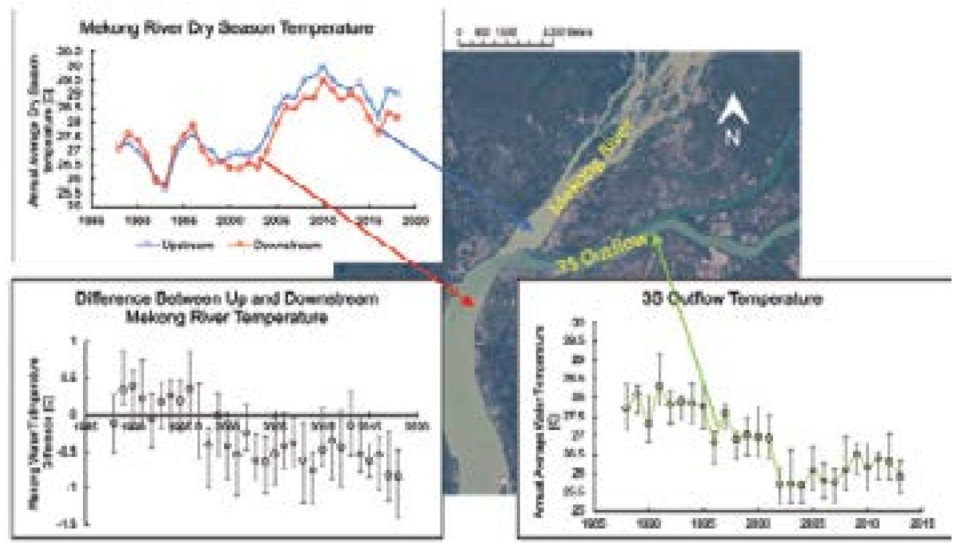
Hydropower dams tend to cool the downstream water temperature by releasing water from the penstock located at deeper levels of thermally stratified reservoirs. If there is enough powered release taking place from a deep and thermally stratified reservoir, then the eco-system downstream becomes an easy casualty. Sustained and extensive perturbations in the thermal regime of the river by the hydropower dam has impacts on the health of the fish population (Ficke et al., 2007) and regional biodiversity (Liermann et al., 2012).

The fact that we can now clearly detect such changes using remote sensing has been demonstrated in recent research reported by Bonnema et al. (2019). Using 30 years of Landsat satellite thermal infrared observations (1988-2018), Bonnema et al (2019) identified a relationship between dry season water temperature cooling trends and dam development in the 3S Basin, a major tributary of the Mekong River that is home to the world's largest inland fisheries system.

Within a year of the beginning of operations of major dams in the 3S River Basin, rapid decreases in annual average dry season river temperature were observed. These temperature changes ranged from 0.7° C to 2° C



Left: **Figure 1:**
Upper left panel **shows the location of the Detroit Dam in Oregon (US) and its topography.**
Upper right panel **is the rule curve currently used by Detroit Dam**
Lower left panel **shows the physical feature of the dam.**
Lower right panel **shows the comparison between hydropower generation using weather forecast-based inflow (orange line) and static rule curve and nowcast inflow (black line). Red shaded bars indicate the few times when weather forecast-informed operations result in less hydropower due to poor forecast skill. However, the aggregate benefit over the 10 month period is found to be consistent and around 5.6% more hydropower using weather forecasts**
After Ahmad and Hossain, 2020, 2019a



Left: **Figure 2:**
Landsat based dry season temperature trends of the 3S Basin outflow, and the Mekong River upstream and downstream of the 3S-Mekong confluence. The difference between the upstream and downstream Mekong River temperature is also shown
After Bonnema et al., 2019

Table 1. The hydropower benefits for Detroit Dam in Oregon (US) for weather forecast-based inflow operations using temperature change as a constraint (during one year - 2017). *Unpublished data by Shahryar Ahmad.*

ΔT (˚C) Constraint	Hydropower Benefit (MWh)	Change (%) in Benefits from 'no temperature constraint'
±2	416856	-13.1
±3	439023	-8.5
±4	473044	-1.4
±6	479092	-0.2
No temperature constraint	479909	–

(Figure 2; Bonnema et al., 2019). Furthermore, in-situ water temperature observations confirmed decreasing river temperature for two major dam development events in the same region.

Evidence was found that the 3S outflow has cooled the Mekong River downstream of the confluence by as much as 0.8° C in recent years.

So how valuable are weather forecasts from an eco-sensitive stand-point?

In light of hydropower operation's thermal cooling effect downstream, which we are able to detect in highly dammed regions, the question we should now ask is if the use of weather forecast-informed operations to generate more hydropower can be made eco-safe?

Recently, we put this idea to a test. We revisited our optimization strategy for assessing the benefit of weather forecast-based reservoir inflow for the same Detroit dam in Oregon (US). We added a constraint for maximum allowable temperature change between upstream and downstream waters. By using a long record of in-situ temperature observations, we developed a regression equation for temperature change in downstream waters as a function of decision variables for hydropower operation (i.e., reservoir level, powered release, spillway release, storage) and weather forecast variables (e.g. air temperature). We repeated our hydropower maximization exercise over Detroit dam shown in Figure 1 using an additional constraint pertaining to varying levels of allowable thermal cooling or warming downstream (ranging from 2 degrees to 6 degrees Celsius of change).

Our results indicate that the benefit of additional hydropower from the optimal reservoir operations is noticeably diminished when compared with a case where temperature is not a constraint. However, if we want hydropower operation to be eco-safe from a thermally stable regime change standpoint, we observe clearly that there is still significant benefit overall even at very stringent thermal constraints of 2 degrees Celsius of temperature change (Table 1).

Conclusion

It is clear that there is another facet of the eco-system that will be significantly altered by continued hydropower dam construction, particularly in the developing world where construction is picking up pace (Zarfl et al., 2015). This facet is the thermal cooling of downstream waters leading to negative ecosystem consequences due to the aggregate effect of many hydropower dams coming online.

As shown in this article, one method to offset these negative thermal (ecosystem) changes in the face of increasing dam development is to design reservoir operations that explicitly include environmental goals such as maintaining thermal regimes.

Before this idea can be made operationally feasible, much more research is required into the interconnected environmental systems and societal needs (Holtgrieve et al., 2018). The hydropower community has some ways to go towards developing operational, sustainable and eco-safe strategies for generating more power using weather forecasts with less number of dams. Our research however shows clearly that it is indeed possible to operate fewer dams at higher levels of efficiency to generate more power with better ecosystem outcomes. ●

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