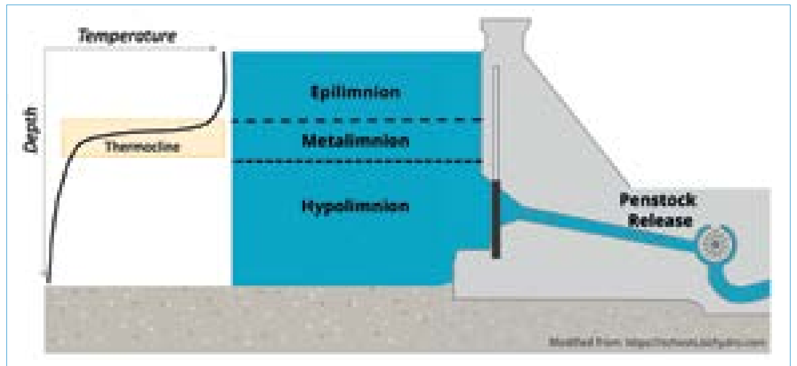
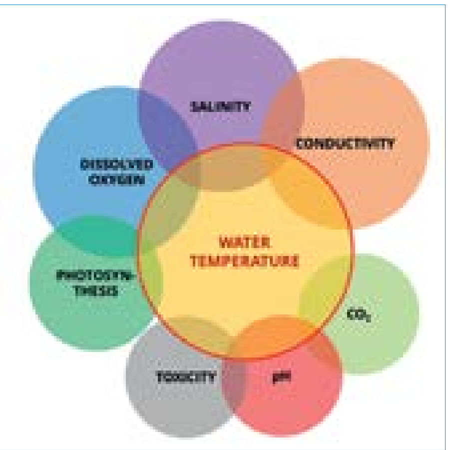
The hot and cold of current and future hydropower dams

Shahryar K. Ahmad and **Faisal Hossain** explain why they believe the thermal pollution of hydropower operations deserves closer attention by the waterpower industry



Above: **Figure 1. Thermal stratification of a reservoir in context of hydropower dam operations**

Below: **Figure 2. The variety of aquatic processes and states that depend on water temperature**



ALTHOUGH LAKES IN MANY places with a sufficiently deep pool have been known to form layers of cooler, under warmer, blankets of water, the global implications for dam operations were never as clear as they are now. We now know that when a reservoir thermally stratifies during summer, hydropower operations can actually cause the downstream rivers to cool significantly below its natural water temperature due to the continued pushing out of water at the deeper pools through the penstocks (Figure 1). Sometimes, an opposite effect can be observed during winter when the same deeper pool of water is warmer than the surface layer due to sub-zero ambient temperatures. This phenomenon of hydropower operations blowing hot and cold during winter and summer seasons, respectively, is called 'thermal pollution', and deserves closer attention by the waterpower industry if more eco-friendly operations for energy generation is desired from the current and future fleet of hydropower dams.

Why is water temperature important?

The first thing to ask for hydropower operations is why should one care if dams are cooling or warming the downstream river waters. Sustained and extensive perturbations in the thermal regime of the river downstream can have significant impacts on the health of the fish population and regional biodiversity. For example, changes in the thermal regime of rivers in the Mekong basin can threaten fish production downstream in the world's largest inland freshwater fisheries, Tonle Sap lake, a source of food and livelihood for millions in Cambodia (Bonnema et al., 2020). Temperature of water also dictates a variety of aquatic processes (Figure 2). If the goal is to be minimally disruptive during hydropower operations, temperature should be added to the current list of impacts for waterpower industry to mitigate.

Where can thermal pollution occur?

Alteration of river temperatures that are significantly cooler or warmer than the ambient temperature or the natural (pre-dam) water temperature do not happen everywhere due to hydropower operations. First of all, the reservoir needs to be deep enough to thermally stratify into distinct layers of cold and heavy water at the bottom, and warm and light water at the top. Shallow reservoirs with large surface area therefore usually do not thermally stratify or the stratification is minimal. Another criterion is location and climate. Reservoirs located in mid or higher latitudes, such as in the US, that experience large air temperature variations due to distinctly cold and warm seasons are more likely to cause thermal pollution than those located in regions with round-the-year steady environmental temperature (such as near the equator). So the overall thermal impact is highly variable and depends on reservoir bathymetry, location and climate as evident from Figure 3.

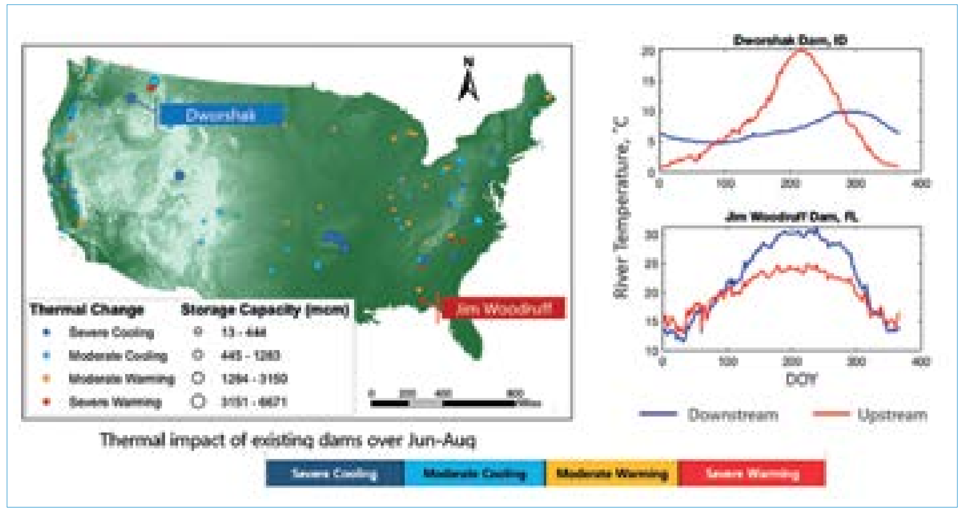
In places where there is no in-situ temperature monitoring, we can now clearly detect thermal changes using remote sensing. Using 30 years of Landsat satellite thermal infrared observations (1988-2018), Bonnema et al. (2020) have recently identified a relationship between dry and winter season (October-April) water temperature cooling trends and dam development in the 3S Basin, a major tributary of the Mekong River. 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 (Figure 4; Bonnema et al., 2020). 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.

How can thermal pollution be managed?

In light of hydropower operation's thermal cooling and warming effect downstream, which we are now able to detect in severely dammed regions, the question we should ask now is if hydropower operations can be managed in a way that mitigates this impact. Recently, we put this idea to a test. We revisited an optimisation strategy for assessing the benefit of weather forecast-based reservoir inflow for the Detroit Dam in Oregon (US) to maximise hydropower production (Ahmad and Hossain, 2020a).

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 applied a hydropower maximisation exercise over Detroit Dam using an additional constraint pertaining to varying levels of biologically allowable thermal cooling or warming downstream (ranging from 2 degrees to 6 degrees Celsius of change).

Our results indicated that the benefit of additional hydropower from 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 thermal stability standpoint, there is still significant benefit overall even at very stringent thermal alteration constraints of 2 degrees Celsius of allowable temperature change (Table 1; Ahmad and Hossain, 2020b).



Left: **Figure 3. Typical thermal alteration of river temperatures downstream of dams in the United States based on USGS in-situ temperature gauges** [After Ahmad et al., 2021, Earth's Future]

How might planned hydropower dams alter river temperature?

Given the pace at which future hydropower dams are being built today in developing regions, it is imperative to identify development pathways where the proposed infrastructure can serve its purpose while maintaining a sustainable and productive river system (Grill et al., 2015). As predicted by Zarfl et al. (2019), the majority of future hydropower development is planned in catchments with a high share of threatened megafauna species. This requires an urgent study of future dams in the context of their potential impacts on the ecosystem.

We recently tried to predict the thermal impact of 216 planned hydropower dams around the world on their likely change to downstream river temperatures. Our predictions are based on a novel framework for planned hydropower dams called 'FUture Temperatures Using River hISTory' (FUTURIST; Ahmad et al., 2021). The FUTURIST framework is based on the key premise that a long record of the past thermal impact is a reasonable representation of the near-future impact due to planned hydropower dams.

We employed a historical record of in-situ river temperature changes from 107 dams in the US to train an artificial neural network (ANN) model. This data-based ANN approach predicted temperature change between upstream and downstream rivers. Satellite remote sensing-based thermal change was used for model training and validation where in-situ monitored values were absent or scarce. The ANN model was then applied at planned hydropower sites worldwide to predict the likely thermal impacts and elucidate the need to include thermal pollution within dam planning to ensure safety and sustainability of the ecosystem.

Our results revealed interesting and varying patterns of 'anticipated' thermal impacts across the selected planned dams. A general trend of lower highs (reduced temperatures during summers) and higher lows (warmer temperatures during winters) is predicted. The predictions reflect homogenised changes in the thermal regime of downstream rivers over a long period of time. Dams with strong thermal stratification tend to cool downstream rivers during warm seasons. The effects of change in thermal regime are not only limited to the local river channel but may also translate into basin-wide impacts, in many cases over longer period of times, as ➜

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). Ahmad and Hossain, 2020

ΔT (˚C) Constraint	Hydropower Benefit (GWh)	Change (%) in Benefits from 'no temperature constraint'
±2	416.9	-13.1
±3	439.0	-8.5
±4	473.0	-1.4
±6	479.1	-0.2
No temperature constraint	479.9	–

References

Ahmad, S.K. & Hossain, F. (2020a). Maximizing Energy Production from Hydropower Dams using Short-Term Weather Forecasts. Renewable Energy, 146, pp.1560-1577. https://doi.org/10.1016/j.renene.2019.07.126

Ahmad, S.K., & Hossain, F. (2020b). Realizing ecosystem-safe hydropower from dams. Renewables: Wind, Water, and Solar, 7(1), pp.1-23. https://doi.org/10.1186/s40807-020-00060-9

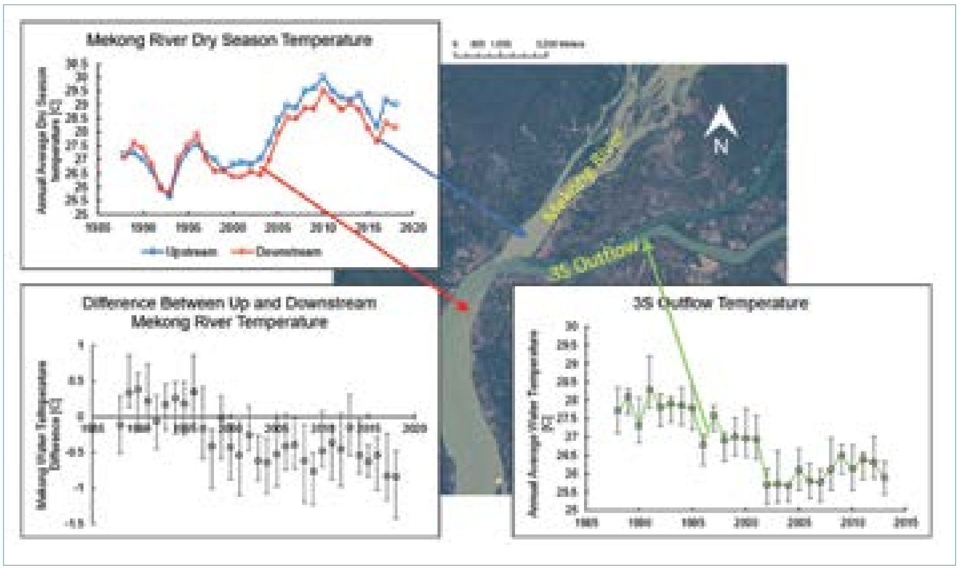
Ahmad, S.K., Hossain, F., Holt, G., Galelli, S., & Pavelsky, T. (2021). How Might Future Dams Modify Temperature of Rivers around the World? Earth's Future (provisionally accepted).

Bonnema, M., Hossain, F., Nijssen, B., & Holtgrieve, G. (2020). Hydropower's hidden transformation of rivers in the Mekong. Environmental Research Letters, 15(4), 044017.

Grill, G., Lehner, B., Lumsdon, A.E., MacDonald, G.K., Zarfl, C., Liermann, C.R. (2015). An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales. Environmental Research Letters, 10(1), 015001.

Zarfl, C., Berlekamp, J., He, F., Jähnig, S.C., Darwall, W., & Tockner, K. (2019). Future large hydropower dams impact global freshwater megafauna. Scientific Reports, 9(1), pp.1-10.

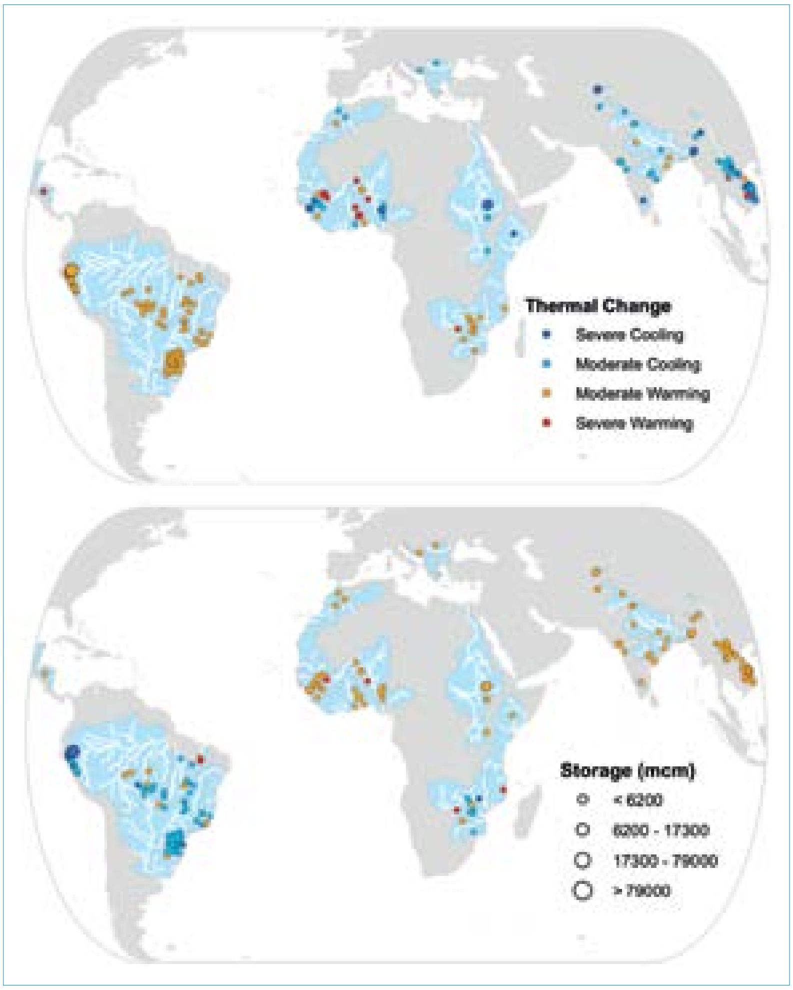
Right: **Figure 4: Landsat based dry season temperature trends of the 3S Basin outflow, and the Mekong River upstream and downstream of the 3S-Mekong confluence. The difference between the upstream and downstream Mekong River temperature is also shown.** [Bonnema et al., 2020, ERL]



Below: **Figure 5. Thermal regime predictions for planned hydropower dams during the months of (a) JJA and (b) DJF. Variability in each class of thermal change is shown as boxplots for the respective seasons.** [Ahmad et al., 2021, Earth's Future]

❮ reported by Bonnema et al. (2020). A number of potential hotspots appear that may lead to severe changes of warming or cooling for the native biodiversity.

Basins like the Amazon which have been labeled as relatively pristine in terms of fragmentation and flow regulation will be experiencing dam development that can lead to moderate cooling and, in some cases, moderate warming (Figure 5). There are also basins such as the Parana in South America and the Niger in Africa that are projected to experience further hydropower dam developments in the near future. While the hydropower dams in the Niger basin will likely be causing a severe warming impact on the tailwaters, those in Parana basin are predicted to cause moderate cooling during summers. This suggests that basins already fragmented due to hydropower dam operations are also susceptible to serious thermal impacts. Such basins demand reconsideration of hydropower generation plans or design of adaptive operation procedures to protect the ecosystem from long-term ecological impacts due to thermal regime change by hydropower operations.



Conclusions

Temperature variation of rivers is a natural phenomenon, and the ecosystem is, in general, resilient to adapt to natural fluctuations. However, the intensive damming due to hydropower operations of those natural river systems has not only also caused net shifting of temperature profiles but also led to the homogenisation of those temperatures over longer periods. Such homogenised changes as predicted by the FUTURIST framework (warmer cool water periods and colder warm water periods) are the drivers of negative biological responses.

Water temperature highlights yet another facet of the environment that will be significantly altered by continued hydropower dam construction. One method to offset such alteration in the face of dam development in the Mekong River Basin is to design hydropower operations that also explicitly include environmental goals such as maximising fishery health. Before this idea can be made operationally feasible, much more research is required into the interconnected environmental systems and societal needs.

What is evident from this study is that hydropower dams can have a significant impact on river temperature in the long-term and can stabilise natural thermal variability to the detriment of survival of indigenous aquatic species. This effect should be taken into account in future attempts to design hydropower operations that mitigate such environmental damages. ●