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REVIEWS

Mitigating the cumulative effects of hydropower and climate change on riverine fishes

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Abstract Human-induced climate change is already apparent through warming temperatures, altered precipitation, and greater prevalence of extreme weather events (e.g., droughts and floods) all of which are anticipated to be exacerbated in the foreseeable future. Meanwhile, demand for hydropower generation is expected to increase and future hydropower developments will be important for mitigating climate change. Yet, climate change will affect the natural flow regimes, which will undoubtedly impact hydropower operations (e.g., storages and releases), and in turn the impact of altered hydropower operations on the discharge and consequence to fish that live in these regulated systems. Here, we synthesize the current knowledge of climate-induced alterations to hydropower operations and the expected impacts of altered hydropower operations on riverine fishes. We also consider what is needed to adapt to the way environmental threats will change over the typical 50–100 year lifespan of such facilities. Based on our synthesis, we anticipate the impact on native riverine fishes will increase in severity moving forward. Fortunately, we can take proactive measures to mitigate the adverse, yet synergistic, impacts of hydropower and climate change on aquatic ecosystems. Doing so will require extensive foresight, planning, and incorporating novel mitigation strategies into hydropower development. We also call for greater involvement of fisheries professionals in such processes to ensure that fish are not an afterthought. Failure to better consider how to future-proof hydropower in the context of climate change threatens not only fish populations but also the humans that depend on them for livelihoods, nutrition, and socio-cultural benefits.

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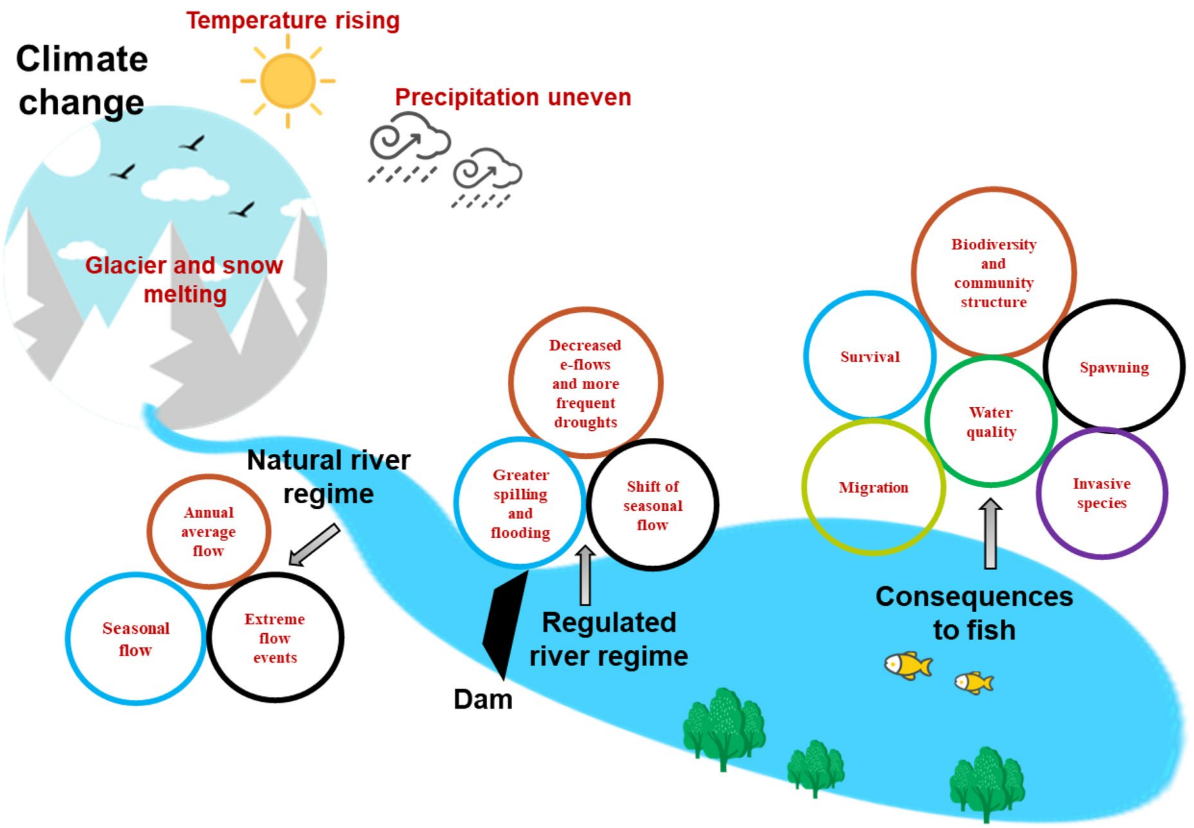
Graphical abstract



Keywords Climate change · Hydropower operations · Flow regimes · Riverine fishes · Management measures

Introduction

Climate change is increasingly altering air temperature and precipitation intensity and frequency (Li et al. 2021). To date, human activities are estimated to have caused approximately 1.0 °C of global warming above pre-industrial levels, and this will almost certainly reach at least 1.5 °C in the next two decades (IPCC 2018). Climate change will also have dramatic impacts on the hydrological cycle and the distribution of water on Earth (Ma et al. 2020). It is predicted that the tendency will be for wet areas to become wetter and dry areas to become drier, though regional sub-basin differences are expected (Donat et al. 2017). Changes in temperature and precipitation levels may also increase the frequency and magnitude of natural disasters such as droughts and floods in the future (Garner et al. 2015). Moreover, changes are projected to continue (at potentially faster rates) during the next century (Bao et al. 2017; Knouft and Ficklin 2017). Given previous reliance on coal and gas-fired generation and its contribution to climate change, "clean" energy sources are in increasing demand.

Hydroelectric dams are seen by governments as a method to mitigate climate change through the provision of "clean," renewable energy, as well as a host of other benefits including floods control, economic growth and water supply for agriculture and industry (ICOLD 2020). There are currently over 50,000 large hydropower dams (> 15 m height) with thousands of additional dams (> 1 MW installed capacity) that are under construction or planned worldwide (Zarfl et al. 2015; ICOLD 2020). Hydropower energy, which accounts for 85% of global renewable electricity energy, is experiencing a boom fostered by international investment mainly in developing countries (Centre for Climate and Energy Solutions 2018). In order to meet the goal of climate change

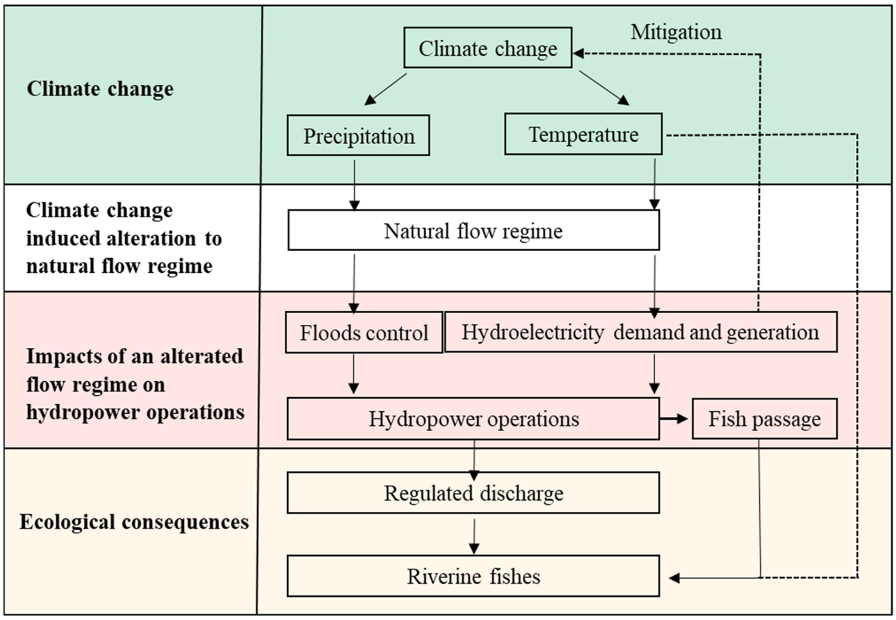


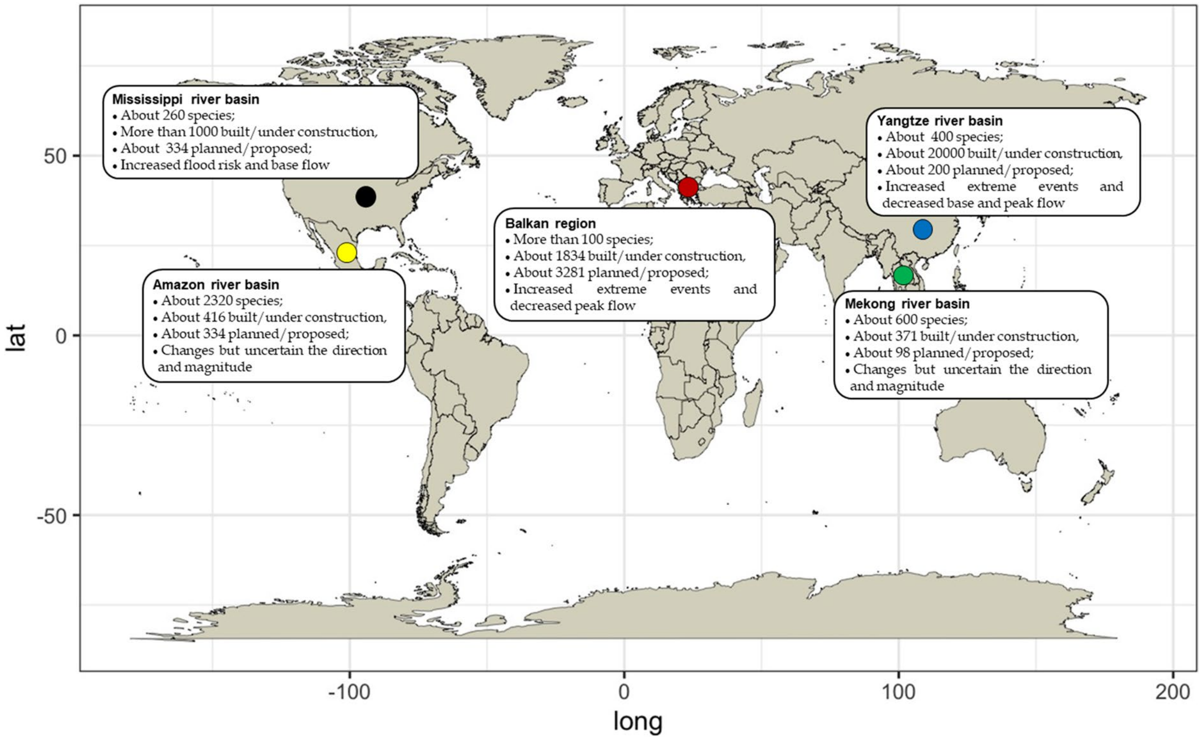
Fig. 1 Schematic diagram showing the relationships between climate change, hydropower operation and riverine fishes. Solid lines indicate the process effect of climate change on hydropower operation and subsequently riverine fishes; Dashed lines indicate direct effects of climate change or hydropower operation on riverine fishes

commitments set in the Paris Agreement in 2015, it seems likely hydropower will have a growing role in the global energy portfolio (Hermoso 2017). The International Renewable Energy Agency (IRENA)'s Global Renewables Outlook 2020 has highlighted that total installed capacity will need to reach 2,150 GW by 2050, while around 850 GW of existing capacity will need to be upgraded to help limit the rise in global temperature to less than 2 °C.

However, climate change is affecting not only the demand (e.g., plant inflow) for hydropower generation but also the water supply and safety of facilities, by changing flow regimes (annual average flow, seasonal flow and extreme flow events) in river systems (Tarroja et al. 2016; Chang et al. 2018). Around the world, faster glacier retreat and snowpack melt, shifting annual and seasonal precipitation patterns, and increased frequency and severity of extreme events (IPCC 2018) will continue to dramatically alter the inflow of the dam, limit the capacity for energy generation and floods control in some regions, and consequently, lead to fundamental changes in the way hydropower operations (López-Moreno et al. 2014; Maran et al. 2014; Spalding-Fecher et al. 2016).

Climate-induced alterations of hydropower operation may offset or exacerbate the effect on discharge and flow in associated structures such as fish passage facilities. Fish species are sensitive to changes in river flow regimes (i.e. Poff and Allan 1995), and changed discharge may negatively affect the fish that live in or migrate through these regulated systems (Kingsford 2000; Bunn and Arthington 2002). Thus far, however, most studies have focused on the direct effects of climate change or hydropower on riverine fishes separately (Ficke et al. 2007). For example, researchers have evaluated the potential impacts of global climate change on freshwater fish (Myers et al. 2017; Paukert et al. 2017) and the implications of dam obstruction on global freshwater fish (Liermann et al. 2012; Zeng et al. 2019). A gap in our knowledge remains as to how climate change will influence hydropower operations by altered natural inflow of dams and what the ultimate consequences of altered hydropower operations will be to riverine fishes that live in or migrate through these regulated systems by altered discharge (Fig. 1).

We know that there is considerable variability among regions, depending largely on local hydrological processes (Döll and Zhang 2010; Schneider et al. 2013). Therefore, we mainly focus on the countries and regions where has largest number of hydropower or hydropower will be concentrated in the next few decades. Meanwhile, these regions are hotspots of fish biodiversity, including the upper Yangtze river basin, Amazon river basin, Mekong river basin, Mississippi river basin and Balkan region (Fig. 2) (Lehner et al. 2011; Schneider



Mississippi river basin
- About 260 species;
- More than 1000 built/under construction,
- About 334 planned/proposed;
- Increased flood risk and base flow

Amazon river basin
- About 2320 species;
- About 416 built/under construction,
- About 334 planned/proposed;
- Changes but uncertain the direction and magnitude

Balkan region
- More than 100 species;
- About 1834 built/under construction,
- About 3281 planned/proposed;
- Increased extreme events and decreased peak flow

Yangtze river basin
- About 400 species;
- About 20000 built/under construction,
- About 200 planned/proposed;
- Increased extreme events and decreased base and peak flow

Mekong river basin
- About 600 species;
- About 371 built/under construction,
- About 98 planned/proposed;
- Changes but uncertain the direction and magnitude

Fig. 2 Representative key regions or watersheds

et al. 2013; Winemiller et al. 2016; Zarfl et al. 2019; Wchwarz 2022). Moreover, we acknowledge that there are other interactive factors (i.e. irrigation expansion, inter-basin water transfers and so on) also impact on the hydrological alterations in those basins, but the climate change and hydropower operation are often seen as the most important factors. The main objectives of this synthesis are to consider (1) the alterations of climate change to the natural flow regime; (2) the effect of altered natural flow regimes on hydropower operations and discharge; (3) the expected threats of hydropower operations and discharge to riverine fishes; and (4) proactive management actions for mitigating the impacts of flow regulation on riverine fishes. By forecasting potential impacts, mitigation measures can be incorporated into hydropower development. Such foresight is necessary to ensure that technological innovations (such as those that are inevitable in the hydropower industry) are responsive to change (Martin 1995; including policy changes; Rapport 1999) and consider diverse outcomes including fish. The goal of this paper is to provide a proactive approach to improve the balance between power generation and the conservation of riverine fishes in a changing world.

Overview of climate-induced alterations to the natural flow regime

Currently, climate change is affecting the flow regimes, in part because of the variability in timing and magnitude of precipitation, accelerated evaporation rates, and accelerated glacier and snow melting rates (i.e. Sorg et al. 2012). Here, we briefly summarize how climate change will influence the natural flow regime by focusing on three representative flow alteration metrics: annual average flow, seasonal flow and extreme flow events.

Annual average flow

There is considerable variability of annual average flow among regions by the middle of the twenty-first century, depending largely on local hydrological processes (Döll and Zhang 2010; Schneider et al. 2013). In Amazon and Mekong River Basins, all studies agree on the changes in the natural annual of flow regime, but the direction and magnitude of change is uncertain in some of the regions due to climate change (da Silva Soito and Freitas, 2011; Lauri et al. 2012). In Yangtze River basin, the results indicated that the streamflow volumes are projected to moderately increase in the upper reach (hydropower is mainly distributed areas) (Zhao et al. 2017). In Balkan region and upper Mississippi River Basin, most climate model scenarios indicate that there will be substantial declines in runoff (Schneider et al. 2011).

Seasonal flow

A modified seasonal pattern of flow regime in rivers has been observed in these basins (Savelsberg et al. 2018), and its estimated the timing of flood peaks will be shifted more often towards earlier month (Döll and Zhang 2010; Arnell and Gosling 2013; Chalise et al. 2021). The main reason is that, due to climate change, the peak spring snow and glacial melt are happening earlier in the year, and winter precipitation may be shifting from snow to rain. As such, augmented flows early in winter and spring will produce flow reductions in summer (i.e. Eum et al. 2017). For example, in the upper Yangtze rivers are characterized by minimum flow values in winter and maximum flows in spring and summer, with earlier glacial and snow melt, upper Yangtze rivers will show higher winter low flow and earlier monthly peak flows and less streamflow during subsequent summer months (Eisner et al. 2017). Projected changes in streamflow seasonality in the upper Mississippi and upper Amazon basin are generally small based on the multi-model ensemble median. Unfortunately, the shifted magnitude still remain unknow (Eisner et al. 2017).

Extreme flow events

All the studies agree on the direction that climate-induced extreme flow events (e.g., floods and droughts) have become more frequent and severe in the past century, and this trend is anticipated to continue to become more prevalent (IPCC 2018). Alfieri et al. (2015) indicated that on average, in Balkan area will be characterized by higher frequency and intensity of droughts due to increased evapotranspiration (Bond et al. 2008; Chessman 2015; Mosley 2015). While precipitation mainly occurs in the winter half-year, extensive low or even zero flow patterns can appear during the dry summer months. In addition, Guan et al. (2017) explored trends of extremes in the Yangtze River Basin and found extremely wet day precipitation, extremely heavy precipitation days, maximum 1-day precipitation, maximum 5-day precipitation and maximum consecutive dry days all increased significantly during 1960–2012. With similarly situation was projected in Amazon and other basins (da Silva Soito and Freitas 2011).

Overview of the effect of altered natural flow regime on hydropower operations and discharge

Alterations to the natural flow regime will directly affect the available flows for power generation in hydroelectric plants, and therefore the way that facilities are operated (Majone et al. 2016; Savelsberg et al. 2018). Here, we consider the potential impacts of altered hydrological metrics on hydropower operations, focusing on generation, but recognize that there will also be operational changes required to ensure infrastructure safety. Given that most reservoirs (especially for run-of-river plants with limited reservoir capacity) will lack ample storage capacity to accommodate high flows during floods, it is unlikely hydropower dams will restrict the increased frequency, longer durations, and severity of flood discharges expected with climate change (Abera et al. 2018; Haun and Olsen 2012).

Hydropower generation

Some hydropower plants (61–74%) are currently situated in regions where there are expected declines in mean annual streamflow (van Vliet et al. 2016a), declining streamflow could undermine hydropower productivity, estimated reductions in the global annual hydropower capacities are 0.4–6.1% (2080s) based on general circulation models (GCM) (van Vliet et al. 2016a). This will lead to unavoidable tradeoffs between storing more water to create a hydraulic “head” for hydropower generation and downstream flow releases (Payne et al. 2004). This may be particularly problematic during dry years, when inflows may not be sufficient to meet

Table 1 Overview of climate-induced alteration to hydropower operations by altering natural flow regime

Climate changes		Changes of dam infow	Alterations of dam operations
Temperature rising	Increased evaporation and other water extractions	Changed annual average inflow	Reduced discharge and droughts for generation
	Earlier glacial and snow melt	Changed seasonal inflow	Shifted flow regime
	Winter snow shift to rain		
Precipitation	Changed frequency, magnitude and increased variability of precipitation	Increased extreme flow events (floods and droughts)	Reduced discharge and droughts Increased discharge and floods for infrastructure safety

both power demands and ecological baselines. For instance, in the next 60 years, the Balkan River basin may experience a gradual reduction in hydropower production potential and the mean annual reservoir pool level will need to increase substantially to store enough water for hydropower generation (Schneider et al. 2011).

It is clear from this synthesis (see Table 1) that climate change is already altering hydropower generation and increasing the uncertainties of operations (and are usually approached from an economic perspective; e.g., Gaudard and Romerio 2014), all of which point toward increased conflicts between sharing water for hydropower production and maintenance of functional aquatic ecosystems. Next, we consider what this means for riverine fishes.

Expected threats of future hydropower operations and discharge on to riverine fishes

The uncertainties of hydropower operations in response to hydroelectric production and climate change will further increase the uncertainties of discharged flow which is regarded as the key driver of river ecosystem structure and function (Bunn and Arthington 2002). Accumulative alterations to flow regimes may offset or aggravate the effects on riverine fishes that live in regulated rivers or migrate in associated fish passage structures (Bunn and Arthington 2002; Poff and Zimmermann 2010), but consequences ultimately depend on flow variability. Here, we anticipate that primary impacts will be related to species composition and diversity, life history processes, (e.g. migration, reproduction, survival), and

Table 2 Impacts of altered hydropower operations on inland fish populations by altering dam discharge flow

Alterations of dam operations	Consequences to inland fish populations	
Reduced discharge and droughts Increased discharge and floods Shifted flow regime	Species composition and diversity	Influenced species composition Reduced abundance
	Survival	Decreased survival rates at all life stages
	Migration	Lost connectivity Energy depletion within migration passage Mistimed arrival in spawning sites
	Spawning	Mismatch between hydrodynamic condition and spawning time Decreased spawning abundance
	Accelerated rate of water quality issues	Increased toxicity of pollutants Increased parasitism and disease Decreased or supersaturated level of oxygen

behaviour (Dudgeon et al. 2006; Magalhães et al. 2007; Costa et al. 2017; Lennox et al. 2019) (Table 2).

Reduced discharge and droughts

In arid regions, reduced discharge and more frequent and severe streamflow droughts may compromise the provisioning of adequate downstream environmental flow (e-flow) (Hirji and Davis 2009), reducing fish habitat availability and connectivity (Matthews and Marsh-Matthews 2003; Webb et al. 2013), and ultimately leading to population declines (e.g., Poff 2018). For example, amphidromous species with semi-buoyant eggs must remain suspended in the water (via turbulence) until they hatch and develop the ability to swim. At low flows, velocities may not be high enough to suspend eggs and fry leading to mortality (Murphy and Jackson 2013). Additionally, complete dewatering of waterbodies is possible, but restoration of connectivity is crucial to sustain diversity (Driver and Hoeinghaus 2016). Jaeger et al. (2014, 2016) predicted a higher frequency of zero-flow days in an intermittent stream in Arizona, United States, which would inevitably reduce hydrological connectivity and even endanger fish that require migratory conditions at a certain period (Larimore et al. 1959). Some global scenarios are catastrophic, proposing that 75% of global freshwater fish will become extinct before the end of the twenty-first century due to a reduction in river discharge (Xenopoulos et al. 2005). Indeed, we are already seeing alarming declines in many of the world's migratory freshwater fish species in large part due to dam construction and climate change (Deinet et al. 2020).

Increased discharge and floods

Moderate increases in annual mean discharge and the frequency and magnitude of floods could improve access to downstream tributaries and effectively increase habitat availability on floodplains (Naus and Adams 2018), which tend to increase fish species richness, abundance, biomass, recruitment, and productivity (Agostinho et al. 2004). O'Keeffe et al. (2018) reported a projected increase in high-flow frequency in the Vistula and Odra basins in Poland, which could be beneficial for northern pike due to more frequent floodplain inundation and better river-floodplain connectivity. Bailly et al. (2008) showed that floods were positively related with gonadal development of species that participate in long-distance migration and parental care in South America. However, increasing in severity of flood peaks often has negative consequences on fish. Spilling floods may undermine the morphology of banks and scour eggs from nests or wash away newly emerged fry and negatively impact egg-to-fry survival rates, which may lead to the failure of fish to establish and recruit populations (Grelsson 1985; Wenger et al. 2011). Fish may also be stranded on shore when flood waters subside, leading to mass mortality events (Nagrodski et al. 2012). Moreover, the severe flood would expose migrants to high flows during migration, which may lead to energy depletion, physiological stress, loss of migratory motivation, lost feeding opportunities, mistimed migrations, and even migration failure (Rand et al. 2006; Nadeau et al. 2010; Whitney et al. 2016).

Shift in the timing of seasonal discharge

There is synchrony between flood pulses and the timing of spawning that may be altered by the combined effects of climate change and hydropower operation. For example, many upper Yangtze fish species are dependent on high-elevation snowmelt streams for spawning during a certain time. If flood pulses in these streams change significantly due to earlier snowmelt, the environmental cues to trigger life cycle events may not be present during normal migratory periods (Battin et al. 2007). This is likely to influence fish recruitment (Agostinho et al. 2004), particularly if fish lack the phenotypic plasticity to adjust migration timing (Crozier et al. 2008) or if there are mismatches in prey availability at key life stages.

Fish passage

Fish passage facilities are constructed to enable fish to pass anthropogenic barriers, and modified operation patterns may influence passage success. If the discharge is below a minimum velocity (e.g., rheotactic speed), it may not provide the orientation cues necessary for fluvial fish to find a fish passage entrance (Aldven et al. 2015; Xu et al. 2017). Further to this, increased water temperatures due to low flows during the migration are likely to influence fish physiology and condition during passage, making the impacts of migration delays more severe (Haraldstad et al.

2019). Moreover, limited water availability may leave fishways disconnected, making passage impossible and injury/death likely (Bao et al. 2019). However, increased discharge (and flood events) could cause flow within fishways to exceed the swimming ability of fish and form a velocity barrier or increase fish attraction to other structures (e.g., spillways) where passage is not possible (Godinho and Kynard 2009). Even if the fish pass the fish passage, the habitats quality located above the larger reservoirs is inferior, fish either cannot spawn or their young cannot reach adequate habitats for development, and the passages may work as ecological traps (Pelicice and Agostinho 2008).

Water quality issues

Water quality could be affected by altered hydropower operations, the most prominent effects of which include accumulated pollutants, changed dissolved oxygen levels, sediment trapping within the impoundment (van Cappellen and Maavara 2016), and high greenhouse gas (GHG) emissions from reservoirs (Räsänen et al. 2018; Almeida et al. 2019). Storage water and declining release flow may influence the transport and dilution capacity of pollutants, resulting in increased concentrations of pollutants in the reservoir, including metals, pesticides, nutrients, endocrine disruptors, and atmospheric ozone, all of which have the potential to influence fish health (Staudt et al. 2013). Although, the hydropower is regard as a "green" energy and could lessen the emission of carbon dioxide (CO_2), it may also release GHG, especially for new dams and placing dams in higher elevations, because the impoundment will make organic matter decomposition and produce GHG (Räsänen et al. 2018; Almeida et al. 2019). In addition, reduced flow has been linked to altered salinity of freshwater ecosystems and increased disease in fish (Hiner and Moffitt 2001; Necker et al. 2019). Elevated magnitude and frequency of spill processes may enhance the chance of supersaturated total dissolved gas (TDG) surrounding hydropower facilities (Pleizier et al. 2020). Flood discharge through dams, especially high dams, results in large amounts of air and bubbles being entrained in the water and transported to deep parts of the water basin downstream of the dam (e.g., super-saturation), causing supersaturated TDG (Weitkamp et al. 1980; Ma et al. 2018), which can persist throughout large areas of the reach downstream of the dam for a long period (Feng et al. 2013; Witt et al. 2017). If fish stay at downstream of a dam with high TDG saturation levels for a long time, they are more likely to succumb to gas bubble disease and ultimately mortality (Witt et al. 2017; Pleizier et al. 2020).

Above, we mainly document how the dams together with climate change may influence more severely downstream flow conditions for fish. Meanwhile, we understand that climate change and dam are great threats in their own way and we would like to have an overall review. For example, climate change is likely to increase the frequency and extent of nuisance algal blooms, thereby posing potential survival problems to fish (Bassar et al. 2016). In addition, climate change may alter species distribution (Parmesan 2006), facilitate biological invasions (Azzurro et al. 2019) and disease outbreaks (Hermoso 2017), has an adverse effect on biological communities (Krabbenhoft et al. 2014). Fragmentation and modified flow regime both caused by hydropower dams. Dams create physical obstructions to fish migration routes, which result in the genetic isolation, fish impingement, injury or mortality and loss of biodiversity. Impoundments change water depths, currents, and deposition patterns, leading to decreasing of habitats number and size, and then has effects on fish growth and reproduction or promote the biological invasions. Discharge would lead to fluctuation downstream, desiccation of eggs, and stranding, spawning activity may been delayed and reduced due to changed water temperature downstream of the dams (Reid et al. 2019).

Proactive management actions for mitigating impacts of flow regulation on riverine fishes under future climates

An anticipatory approach is needed now to ensure we minimize impacts on riverine fishes. Maybe the industry itself may be designed to consider the climate-induced reduction of water availability (Majone et al. 2016; Anghileri et al. 2018). There is also need for ecological researchers to demand forward thinking so that hydropower plans do not just consider the climate change and hydropower plans but how this will consequence to fish populations. Therefore, we highlight five positive steps that can be taken now to help minimize the impacts of future hydropower production on riverine fishes.

Engage in basin-wide planning and siting

As outlined previously, it is anticipated that demand on hydropower production will increase in the future. Meanwhile, we may see the production potential of hydropower plants deteriorate over time with climate change, leading some dams to be considered 'obsolete' or 'dead beat' (Agoramoorthy 2015). What will clearly be important is the location where these dams are sited, especially in some alpine areas where hydropower production is more vulnerable to climate change (Winemiller et al. 2016). There are important questions to consider, such as whether rivers currently suitable for hydropower production will remain viable during the entirety of their lifecycle given predicted climate models (as was done on the Zambezi River; Spalding-Fecher et al. 2016). Improper siting is a lose-lose scenario, and forethought will be needed to ensure hydropower locations remain viable over multiple decades in light of climate change. As such, if climate models indicate there is insufficient water in a system for energy demands and the ecosystem, a hydropower facility should not be sited there. Basin-wide planning is needed that considers the current location of hydropower facilities (Ziv et al. 2012) and the hydropower potential of various locations throughout a watershed.

Adopt operational and structural changes to provide adequate release flows

The management of downstream flows by adjusting hydropower operations is a critical measure for mitigating the unpredictability and intensity of flow change on riverine fishes as a consequence of climate change and hydropower facilities. If inflows are no longer sufficient to meet power generation needs during dry seasons or years, water must first be prioritized for e-flow and secondarily for power generation to ensure downstream reaches can support fish and other aquatic life (Zhang et al. 2016). Introducing a constant base flow or re-operating dams for environmental flows (e.g., using transparency and translucency rules) may significantly increase habitat suitability for riverine fishes in climate-induced arid regions (Renofalt et al. 2010; Owusu et al. 2020). Furthermore, the major objective for improvements should be to make downstream releases similar to the variability of natural discharge patterns (Renofalt et al. 2010). To meet energy demand, society can adopt other renewable energy sources (e.g., solar and wind energy) that can compensate for reduced hydropower production during some periods or years. It will be critical to think about how these energy sources impact the environment and what energy source may be most suitable at a given location. Alternatively, there may be opportunities for improving hydropower generation efficiencies from a technical perspective to compensate for reduced generation. Some previous analyses showed that a 10% increase in the efficiency of hydropower plants was able to completely offset the mean annual impacts of decreased water availability under a changing climate for most regions (North America, Europe, Africa and Asia) (van Vliet et al. 2016a).

As for fish passage, sufficient flow at dams should be allocated to fish passage facilities to ensure they remain functional. Harris (2000) identified a general guideline whereby 10% of dry season flow should be allocated to fish passage facilities. It will be prudent to design fishways that can be quickly adapted to changing river conditions on a seasonal or yearly basis, such as designing fishways with multiple exits and entrances at different water levels that can be adjusted season to season as conditions change. For an already built fishway, minimum flow releases are often combined with weirs and pools as a means of wetting the channel at low discharge (Fjellheim and Raddum 1996; Rørslett and Johansen 1996), preventing migrating fish from being stranded and dried up due to a lack of connectivity within the fishway. In some cases, it may be best to prevent entry into the fishway during low flow, or to provide high flow provisions to the fishway over short periods to trigger migration in a large proportion of fish aggregated below the fishway (Lopes et al. 2018).

Similarly, management strategies are needed to reduce the risks of extremely high flow events posed to fish habitats. The creation of off-channel storage basins or wetlands may be a way to absorb water during high flows (Poff et al. 2002) and provide for e-flow provisions during the dry season. Structural measures (e.g., compensation basins and caverns) can be constructed at the outlet of a hydropower dam to retain water after passing through the turbines (Premstaller et al. 2017). Water flow can then be released from these basins to attenuate ramping rates associated with hydropeaking such that impacts on the aquatic ecosystem are minimized (Person et al. 2014; Tonolla et al. 2017). Hydropeaking can be mitigated through operational or structural measures (Bruder et al. 2016). An appropriate and effective operational measure is modifying the downstream flow regime, by increasing the base flow in the river, either by increasing residual flow releases from the reservoir or by releasing water through the power plant (Person et al. 2014).

Develop parallel conservation and restoration projects

Implementing conservation and restoration projects now to protect existing resources and recover close-to-natural ecosystems will be key to building ecological resilience in the face of future change. Current efforts should focus on assessing species and habitats most vulnerable to future threats and establishment of protected areas. For example, some recent studies have shown the importance of tailrace areas downstream of dams as well as downstream tributaries for fish reproduction (Antonio et al. 2007; Weber et al. 2013). Therefore, protection of tributaries and other existing habitats should be prioritized while also considering how habitats created by the dam (e.g., unique tailrace habitats can be enhanced for fish). Predicting shifts in the distribution of freshwater species will be critical to ensuring both current and future habitats are protected (i.e. Bond et al. 2011). Finally, habitat restoration measures (e.g., placing gravel in channels where it has previously been scoured or constructing artificial fish habitat) can be useful (Taylor et al. 2019).

Engage in efforts to improve water quality

Greater consideration should be given to addressing water quality issues both in the reservoir and downstream of barriers. Reducing river pollution now by preventing domestic water pollution and agricultural pollution is probably the most viable approach to maintaining water quality in the future. In addition, reservoirs should be flushed intermittently to reduce the accumulation of pollutants (e.g., through sediment bypass tunnels or flushing). To address supersaturated TDG, Politano et al. (2012) suggested the installation of spillway flow deflectors that redirect spilt water horizontally and form a surface jet that prevents bubbles from plunging to depth in the stilling basin. It was also found that adoption of bottom orifices could decrease the TDG oversaturation level (Ma et al. 2019). Moreover, a discontinuous discharge pattern instead of a continuous pattern minimized the maximum duration of the high TDG level (Ma et al. 2019). For cascaded dams of rivers, it is worth noting that single operation mode is better for fish than joint operation of both stations as supersaturated TDG generated at the upstream cascade can carry over to the downstream power station and result in cumulative TDG supersaturation (Ma et al. 2018). Finally, we advocate for long-term monitoring of flow, water quality, and responses of vulnerable fish species, combined with developing models that quantify and predict future conditions at a watershed scale to help support decision-making.

Revise hydropower policy and governance processes to prioritize fish

Many of the approaches outlined above require a combination of relevant legal and funding structures to coordinate water rights allocations and ensure the implementation of conservation measures at the local scale (Twardek et al. 2021). First, all stakeholders and rightsholders, ecosystem managers, policymakers, resource users, indigenous communities and citizens should collaborate to prioritize trade-offs between hydropower generation and effects on aquatic systems (Li et al. 2018). E-flow provisions will need to be mandated where they are not through legislative changes that are resilient to changes in political leadership, such as how e-flow has been incorporated into high-level policies for river management in accordance with the European Water Framework Directive (European Commission 2015). Many countries now formally protect and manage environmental water through national laws and regulations, as well as at the basin scale. In some cases, costs associated with greater flow provisions to support fish habitat and fish migrations may be compensated through government funding and optimizing revenue for future climate scenarios. Alternatively, state ownership of hydropower facilities can help to ensure the many ecosystem services provided by the river for the general public are taken into account.

Conclusions

Climate-induced changes to precipitation, evaporation, and ice (including glaciers) and snow melting has and will continue to drastically alter the natural flow regime in rivers worldwide. These changes include variation in annual average flow, shift in the timing of seasonal flow, and increased intensity of extreme flow, which will modify hydropower operations and consequences to fish populations in these regulated systems. We need to think proactively to optimize hydropower site selection, design sites to be flexible and adaptive, restore natural flow regime, to implement conservation and restoration projects, and to improve water quality to support the resiliency of riverine fishes that face synergistic effects. Environmental assessments and other important processes in hydropower planning and licensing must transition towards a long-term view and explicitly consider how altered hydropower operations due to climate change will modify environmental impacts in the future. We are hopeful this synthesis piece will provoke greater thought into hydropower development in the many regions of the world where it is rapidly expanding (Zarfl et al. 2015). Doing so will be critical if we are to meet the call to action to save riverine fishes (Tickner et al. 2020).

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