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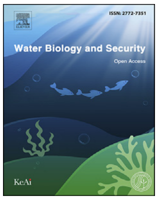

Bright spots for inland fish and fisheries to guide future hydropower development

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ABSTRACT

Hydropower production is one of the greatest threats to fluvial ecosystems and freshwater biodiversity. Now that we have entered the Anthropocene, there is an opportunity to reflect on what might constitute a 'sustainable' Anthropocene in the context of hydropower and riverine fish populations. Considering elements of existing practices that promote favorable social-ecological outcomes (i.e., 'bright spots') is timely given that there are plans to expand hydropower capacity in previously undammed rivers, intensify dam development in some of the world's largest river systems, and re-license existing facilities. We approach this from a pragmatic perspective: for the foreseeable future, hydropower will likely remain an important source of renewable electricity. To offer support for moving toward a more 'sustainable' Anthropocene, we provide syntheses of best practices during the siting, design, construction, operation, and compensation phases of hydropower development to minimize impacts on inland fish. For each phase, we offer positive examples (or what might be considered 'bright spots') pertaining to some of the approaches described within our syntheses, acknowledging that these projects may not be viewed as without ecological and (or) societal detriment by all stakeholders. Our findings underscore the importance of protecting critical habitat and free-flowing river reaches through careful site selection and basin-scale planning, infrastructure designs that minimize reservoir effects and facilitate safe passage of fish, construction of hydropower plants using best practices that minimize long-term damage, operating guidelines that mimic natural flow conditions, and compensation that is lasting, effective, inclusive, and locally relevant. Learning from these 'bright spots' may require engagement of diverse stakeholders, professionals, and governments at scales that extend well beyond a given site, river, or even basin. Indeed, environmental planning that

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integrates hydropower development into broader discussions of conserving regional biodiversity and ecosystem services will be of utmost importance.

1. Introduction

Humans have engineered the planet to the point that the current epoch has been labeled by some as the Anthropocene (The Anthropocene currently has no formal status in the Divisions of Geologic Time (https://pubs.usgs.gov/fs/2018/3054/fs20183054.pdf) and is not recognized by the USGS.) (Steffen et al., 2007). Although the connotations of the Anthropocene might appear to be largely negative (Dalby, 2016), this label signifies that humans have an urgent opportunity to be good stewards of the environment through managing resources in ways that ensure sustainable use into the future, both locally and globally (Steffen et al., 2011). The apparent acceleration of ecosystem changes arising from human activities (Steffen et al., 2015) requires that humanity decide what Earth system conditions are desirable for present and future generations, and then work toward that goal. Bennett et al. (2016) presented an overview of 'bright spots'—hopeful elements of existing practices that promote favorable social-ecological outcomes—in an effort to identify examples of initiatives that benefit both humans and the environment. The value of the 'bright spot' approach is to offer models that could be adopted widely (Cinner et al., 2018; Frei et al., 2018; Jeanson et al., 2021). This framework is timely but has yet to be widely applied to protecting the functioning of imperiled freshwater ecosystems (but see Tickner et al., 2020).

Rivers meander through the landscape from headwaters to lakes and oceans, transferring water, nutrients, and materials that form a downstream gradient of ecological communities (Hynes, 1970; Vannote et al., 1980). They also serve as a movement corridor for many animal species (e.g., fish, crustaceans, freshwater mammals). Humans have long appreciated the many provisioning and cultural ecosystem services derived from rivers, including potable water, irrigation, transportation, tourism, religious interaction, and food (Aylward et al., 2005). Human populations have favored sites along rivers for the aforementioned reasons, as well as for the potential to harness flowing water as a source of mechanical energy to support demands along the river (e.g., historic flour, cotton and timber mills) and now throughout electrical distribution grids (Postel and Richter, 2012). Although these and other anthropogenic activities within basins lead to many benefits for humans, these activities also have resulted in degradation of physical, chemical, and biological conditions in river networks worldwide (Vörösmarty et al., 2010).

Hydropower projects and their associated infrastructure constitute one of the most significant threats to freshwater biodiversity (Dudgeon et al., 2006; Reid et al., 2019). Over the last several decades, freshwater vertebrate populations have fallen 84% (including freshwater migratory fish; 76%), and river ecosystem fragmentation is among the leading causes of these declines (Deinet et al., 2020; WWF, 2020). Fish and fisheries worldwide have been impacted by dams and hydropower turbines, which block migration routes, alter flows and flood pulses, modify thermal regimes, damage or kill small fish moving downstream, and convert lotic habitats into lentic ones (WCD, 2000). Despite severe declines, freshwater fishes provide many ecosystem services (Cowx and Portocarrero 2011; Holmlund and Hammer, 1999) such as supporting food security and livelihoods in economically-depressed regions (Cooke et al., 2015; Lynch et al., 2016; McIntyre et al., 2016; Smith et al., 2005). Inland waters contribute 14% of total capture fisheries worldwide, which in turn support an estimated 21 million fishers and 36 million associated jobs (FAO and WorldFish Center, 2008; FAO, 2014).

As the global population and average standard of living continue to grow, demand for energy—and pressure to tap renewable energy sources—is rising even faster (Fronk et al., 2010; Mischke and Karlsson, 2014). For the foreseeable future, hydropower will likely serve a pivotal role in renewable energy production in many parts of the world (Kaygusuz, 2004; Yüksel, 2009, 2010), including developing countries and emerging economies (Goldemberg, 1995; Yüksel, 2007). Hydropower has been critiqued for both environmental and social impacts (e.g., Azarpour et al., 2013), but it is still regarded as an essential part of global energy production portfolios (Frey and Linke, 2002). Its continuing appeal stems from being one of the few globally-applicable means of generating substantial electricity without burning fossil fuels (though reservoir greenhouse gas (GHG) emissions can be substantial; Almeida et al., 2019), and is augmented by being relatively inexpensive, renewable, and offering 'black-start' capability (i.e., requiring no power input before producing new electricity). The technically feasible global hydropower potential is nearly 15 000 TW h/yr, with much of the potential in countries or regions where safe and reliable energy supplies are most needed (Zarfl et al., 2015). Thus, new hydropower facilities are under development throughout Asia, South America, and Africa (Bartle, 2002; Winemiller et al., 2016), regions of the world where people are reliant on inland fisheries for food, income, and livelihoods (Winemiller et al., 2016), while expanded production capacity is also sought in Europe and North America via a mixture of new dams and modernization of existing facilities (e.g., Pimentel et al., 2002; Uria-Martinez et al., 2018; Wagner et al., 2019). Although world energy supplies are sufficient to satisfy basic human needs (Gleick, 1996; Krugmann and Goldemberg, 1983), the uneven geographic distribution of energy production inhibits economic development in many regions (Zarfl et al., 2015). Proposals for new hydropower can invoke attempts to level the opportunities that accompany access to reliable electricity.

The purpose of this paper is to identify 'bright spots' among existing hydropower operations that may serve as models for achieving a more sustainable Anthropocene (Bennett et al., 2016). We focus on examples from around the world where evidence-based steps have been taken during hydropower development to minimize effects on fish and fisheries (Fig. 1). We provide a synthesis of best practices during the siting, design, construction, operation, and compensation phases of hydropower development to minimize impacts on inland fish, which also has implications for decommissioning and relicensing. For each phase, we offer examples of 'bright spots' that exemplify some of the practices described within our synthesis. We conclude by providing suggestions for operationalizing the ideas presented herein through the collaborative efforts of biologists, engineers, power companies, policy makers, and community stakeholders. Most of our case studies are oriented toward Canada and the United States, which are global leaders in hydropower production (IHA, 2019), but our key messages often parallel those developed for a global audience within the International Hydropower Sustainability Guidelines on Good Industry Practice (IHA, 2020). We refer readers to that resource for a perspective on hydropower sustainability from the viewpoint of the power industry.

We focus on inland fish and riverine fisheries because they have enormous value for food security, livelihoods, culture, recreation, and ecosystem functioning (Funge-Smith and Bennett, 2019). Hydropower development often interacts with other stressors that degrade rivers and their basins (e.g., flood control, or irrigation dams; Dudgeon et al., 2006; Richter et al., 2010; Vörösmarty et al., 2010), but those interactions are beyond the scope of this synthesis. We also acknowledge that inland fisheries can themselves threaten fish diversity; for instance, the most intensive harvests of river fisheries generally occur in the most biodiverse rivers (McIntyre et al., 2016). 'Bright spots' are useful as models for responsible hydropower and embracing them could foster partnership rather than conflict among stakeholders. More generally, we believe that responsible hydropower development can complement, rather than replace, efforts to reduce energy demand and embrace more sustainable energy sources. We also recognize that dams serve many other purposes for society, including irrigation, flood control, and navigation enhancement (ICOLD, 2019), but many of the practices that we suggest for hydropower dams are equally applicable to other types of dams.

2. Site selection

2.1. Criteria

The choice of where to site a project will depend on economic, social (many dams are multi-purpose), political, cultural, geographical, hydrological, geological, and environmental considerations (Jager et al., 2015; Wang et al., 2021). First and foremost, there will be limited sites where the hydrological and geological factors (e.g., head, water flow, and substrate) are conducive to siting a facility (Wang et al., 2021). Once candidate sites are identified from an engineering and geomorphological perspective, environmental impacts across these sites may be considered and prioritized through a robust project-level environmental assessment which could include consultation with the local community (e.g. Netherlands Commission for Environmental Assessment 2018). Certain areas may be more prone to severe socio-ecological impacts based on the available habitat upstream and laterally, sedimentary processes, presence and locality of critical habitat types, level of biodiversity and endemic species, implications on downstream, upstream, and floodplain ecosystem functioning, as well as presence of culturally or economically important fisheries. These impacts should be evaluated during planning, keeping the broader goals of ecological connectivity and ecosystem functioning in mind.

We envision hydropower planning that is undertaken at the basin scale. Determination of sites should consider the locations of existing and proposed hydropower projects within the basin, their respective lifespans (including plans for removal), their energy-producing capacities, as well as the cumulative effects of multiple dams on the same river system (Haney and Plummer, 2008; Jager et al., 2015). In some cases, a subset of hydropower projects in a basin may produce a disproportionately small amount of energy relative to the ecological impacts. Models have been developed to prioritize removal of the least productive and most damaging dams, while constructing new dams, to not only benefit inland fish, but also increase power generation (O'Hanley et al., 2016; 2020). A recent synthesis on the topic of hydropower siting suggested that dams should be concentrated in tributaries (avoiding mainstems and protecting other tributaries as free-flowing), that sufficient space is left between dams to allow species to complete their lifecycles, and that spatial planning of dams is undertaken at the scale of large river basins (Jager et al., 2015). Further, to reduce GHG emissions dams should generally be placed in higher elevations and smaller streams (Almeida et al., 2019). Siting a hydropower project in the vicinity of an existing project minimizes the free-flowing habitat lost between dams and can take advantage of the hydraulic potential of the nearby dam (and thereby potentially reduce the reservoir size needed at the downstream dam; Shen et al., 2018). In some cases, it may be least environmentally damaging to site a

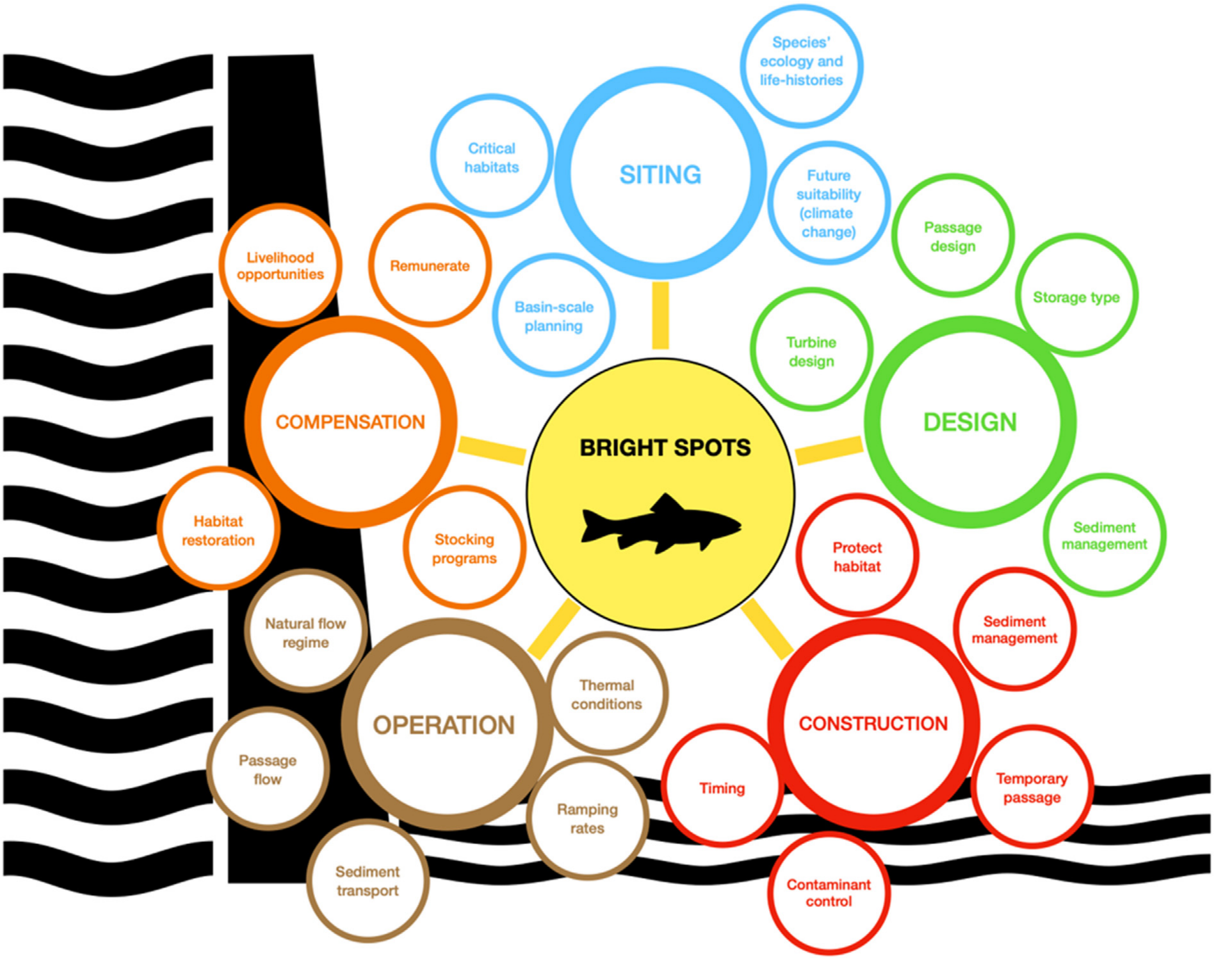

Fig. 1. 'Bright spots' constitute examples from around the world where decisions have been made during hydropower development to minimize impacts on inland fish and fisheries (both directly and indirectly). We consider 'bright spots' related to the siting (blue), design (green), construction (red), operation (brown), and compensation (orange) stages of hydropower, and highlight some of the many aspects (smaller circles) of these stages that 'bright spots' may relate to. As the adoption and body of knowledge surrounding various 'bright spot' concepts increases, the opportunity for collaboration and innovation of new 'bright spot' ideas may also increase.

dam on a previously impounded river that has already lost certain ecological functions of the system (e.g., migration of diadromous species) rather than losing that ecological function in a separate river system (i.e., trading multiple hydropower projects in one area for setting aside other rivers/basins).

The species present and their life-history strategies should be taken into account during site selection. New hydropower projects should aim to avoid most critical habitats of all species present in the river network, particularly reproductive habitats needed to complete life cycles. Communicating with local Indigenous people and other community members can provide important information on the local environment (Folke, 2004). When baseline biological information is not available, a precautionary approach to decision-making could be required (i.e., assume a habitat is of importance; Black, 2020). Migratory fish are typically the most vulnerable to barriers that prevent them from accessing habitats that support a critical life history stage, such as rearing, feeding, or spawning. For diadromous species that are dependent on longitudinal connectivity, dams could be sited such that the majority of the river is free-flowing to the marine environment (i.e., the dam would be placed high up in the river system so that most or all spawning or feeding habitats can be accessed). In the case of in-river potamodromous migrants (e.g., golden perch, *Macquaria ambigua* or Mekong giant catfish, *Pangasianodon gigas*) and resident species (e.g., European grayling, *Thymallus thymallus*) it is important to understand the spatial extent of movements and whether dams can be built outside of these areas or at least in a non-critical portion of their home range (Cooke et al., 2016). In some rivers, there may be opportunities to place dams on one of many anabranches to ensure alternative passage routes exist, or to ensure minimum river pathways (e.g., Hawkins et al., 2018), although sites with anabranches that are also suitable for hydropower are rather uncommon. Alternatively, nature-like fishways could be engineered to facilitate passage and provide compensatory habitat (Tamario et al., 2018). Similar thinking (providing alternative passage routes) could help to ensure lateral connectivity is maintained between river systems and floodplains used for spawning and rearing (e.g. *Henicorhynchus* spp., *Labiobarbus* spp., Baumgartner et al., 2012). Trade-offs will exist for a proposed dam location such that siting a dam in one location may minimize the impacts to one species, while increasing the impacts on another. Questions may arise, such as: how might we prioritize the species to be impacted least in terms of socio-ecological and economic considerations, conservation status, and vulnerability to barriers? Winemiller et al. (2016) recommend that basin-scale biodiversity be considered in hydropower site selection.

Siting of dams also influences geomorphological and hydrological characteristics of the associated reservoirs, including depth, area, complexity of bottom topography, seasonal drawdown and water retention rate. Siting dams to minimize the extent that the lotic system is transformed to lentic for a given amount of power production is one option to consider (e.g., Pelicice et al., 2015). That said, the characteristics of reservoirs have important implications for the potential productivity of reservoir fisheries and degree to which reservoirs impact riverine fish migrations. For instance, shallower reservoirs tend to support higher fisheries production and habitats more similar to natural river-floodplain systems than deep reservoirs (Bernacsek, 1984; Petrere, 1996).

The issues associated with hydropower production extend beyond the footprint of the dam to include the complementary civil works that support the dam and post-impoundment settlement around the reservoir. Hydropower projects require constant monitoring, service, and operational changes that result in the need for humans to access the associated structures. Depending on the placement of the project (e.g., outside urban centres), roads may need to be built to allow people access to the facility. Roads have a number of ecological consequences stemming from the fragmentation of terrestrial habitats that ultimately alter flow and sediment transfer into nearby waterbodies (Forman and Alexander, 1998). Although it may be ecologically beneficial to have a dam in the headwaters of a river system (discussed above), the consequences of accessing the site may be overly damaging. At remote sites, longer power transmission lines are also needed to reach the energy users, which can further fragment natural landscapes, adversely impact migratory pathways for birds (Bevanger, 1998; Hyde et al., 2018) and reduce the efficiency of energy transfer.

The costs associated with constructing (and decommissioning) dams are high, so it may be beneficial to site hydropower projects where they provide long-term delivery of services. Environmental assessment processes that evaluate and account for hydrological changes expected at a site over the lifespan of a proposed facility will likely be beneficial (Castello and Macedo, 2016) to assess whether the site will remain a viable location. Climate-change projections suggest river flows may be altered such that streams at higher latitudes will generally experience increased annual flows due to increased winter precipitation, while streams and rivers in mid-latitude and tropical areas may tend to experience reduced annual flows (Nijssen et al., 2001). These expected changes may be particularly important for arid parts of the world that are already finding it difficult to provide sufficient water for both hydropower and fish (Clarke, 2013). As such, a site that is suitable for hydropower production now (economically, socially, ecologically) may not be so in the future. Models predicting hydrological changes under various climate change scenarios can be used to make informed, robust decisions regarding future developments (Fowler et al., 2007). All this is to say, there is no one rule to follow that will apply to the siting of every hydropower project and river system, but the following general principles could help to guide the hydropower siting decision-making process (Fig. 2).

2.2. *'Bright spots'*

2.2.1. *Siting at a natural barrier – Churchill Falls, Canada*

The Churchill Falls Generating Facility was constructed in 1974 and is currently the second largest power facility in Canada, with the capacity to generate up to 5428 MW (Kirby, 2015). The facility lies on the Churchill River, Newfoundland, which flows 856 km from the Smallwood Reservoir to the Atlantic Ocean. The power station harnesses energy from Churchill Falls, a 75 m high natural waterfall. This waterfall posed a complete barrier to fish movements, so no further obstructions were created by the construction of the generating facility. The power station was carved out of granite approximately 300 m underground and minimizes the ecological footprint associated with an above ground hydropower facility. The Churchill River also did not support productive, anadromous Atlantic salmon (*Salmo salar*) populations at the time of construction unlike several other rivers within the province (Ryan 1980), reducing impacts on this culturally-valuable fish species. Siting at a natural barrier may be most valuable at northern latitudes where fewer endemic species live in the areas directly surrounding the falls whereas the opposite is likely to be true (i.e. avoiding falls) in areas with high species richness and endemism (Winemiller et al., 2016). The siting of the Churchill Falls Generating Facility achieves two principles outlined above: that facilities be constructed near existing barriers, and in rivers that have lower fish productivity.

2.2.2. *Siting to improve ecosystem productivity—Blönduvirkjun Hydropower Project, Iceland*

The Blanda River is one of the longest rivers in Iceland at 125 km. It hosts anadromous runs of Atlantic salmon and Arctic charr (*Salvelinus alpinus*) which are popular targets for recreational anglers. The Blanda River is partially glacier-fed which leads to high turbidity (570 000 t/year) and unstable flows that peak in the summer (300–500 m^3/s) and are lowest during the winter (20 m^3/s; Jónsson et al., 2017). The high turbidity, fluctuating flows, and corresponding channel instability may have resulted in overall low fish productivity in the river prior to establishment of the Blönduvirkjun Hydropower Project off Iceland's central highland plateau in 1991 (Antonsson, 1984; Jónsson et al., 2017).

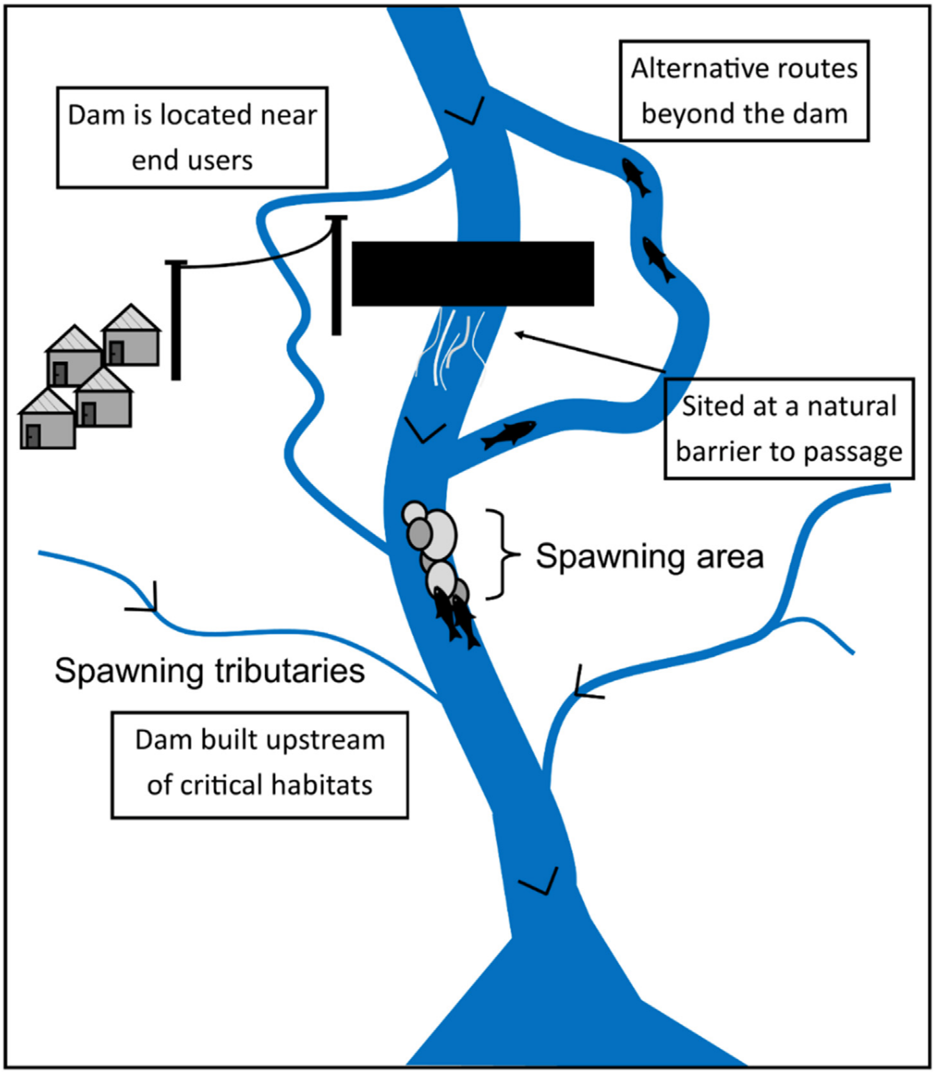

Fig. 2. Hydropower siting considerations to minimize impacts to inland fish and fisheries. This idealized example for a new dam on a previously free-flowing river indicates four site selection guidelines. Though many projects may be unable to adhere to all four factors, it can be important to examine these (along with other preferred characteristics related to design, construction, and operation) during the planning process.

Blönduvirkjun has the capacity to produce 150 MW and has reservoir areas of 56 km^2 and 5 km^2. Water is moved from the upper reservoir to an intake reservoir 9.8 km downstream, the water is then passed through canals and ultimately drops vertically through a 236 m penstock to an underground power station and is subsequently returned to the Blanda River. Regulation of the river from Blönduvirkjun has since changed the dynamic nature of the low productivity, glacial-fed river. Sediment retention in the upstream dam has reduced silt in the river from 570 000 t/year to 63 000 t/year (Jónsson et al., 2017). Bathymetric surveys have since been completed to monitor sediment accumulation within the reservoir (The International Hydropower Association [IHA] 2017). Similarly, water levels now fluctuate less throughout the year, and the channel has become stable. The overall result has been higher light penetration and primary productivity, and improved conditions for migratory fish. Salmon and charr population sizes have increased after construction of the hydropower project (Jónsson et al., 2008, 2017). This has led to an increase in angler catches from <100/year prior to construction of the facility to over 500 salmon in 2016 (Jónsson et al., 2017) benefiting the angling tourism industry (Sæþórsdóttir and Hall, 2018). A significant environmental impact resulting from this project was the flooding of fertile lands used for sheep-grazing (IHA, 2017). In response, a large-scale ongoing revegetation programme has been carried out by the power corporation, the Soil Conservation Service of Iceland, and a farmers' cooperative to improve grazing lands around the reservoir. The International Hydropower Association (2017) claims that social impacts were low, and that the impact of the hydropower project on sedimentation and erosion are generally perceived as beneficial by the local population. As such, the Blönduvirkjun Hydropower Project was awarded with the Blue Planet Prize by the IHA in 2017 (demonstrating excellence in sustainable development). The Blönduvirkjun Hydropower Project provides an example of how hydropower plants can be positioned to minimize impacts to (and in some cases improve) inland fish and fisheries by siting projects in lower productivity rivers away from critical habitat. Contrary to the goal of maintaining the natural flow regime (which is desired in most hydropower contexts), the modification of flows in this river appears to have had a positive impact on inland fish and fisheries.

3. Design

3.1. Criteria

The selection of a site will impart certain engineering constraints, which can then influence the design of the structure. Therefore, it is important to consider the design alternatives that could be implemented at proposed locations, and their potential ecological impacts. Although certain ecological impacts may be unavoidable, the design of the facility can be such that impacts on surrounding aquatic and terrestrial habitats, and animals that use them, are minimized (Egré and Milewski, 2002). For instance, the footprint of a hydropower facility can vary extensively for the same level of energy production (Gleick, 1992).

Reservoir size can be an important consideration as it influences the level of flow alteration and associated bio-physical-chemical processes. The impounded water can result in modified flows and altered downstream temperature regimes, water quality issues, and modified erosion and sedimentation processes (Ledec and Quintero, 2003; Petts, 1984). Designs exist to minimize reservoir size that may be applicable for different hydropower projects. Run-of-river plants use the water flows in a river but tend not to have large upstream reservoirs and thus do not alter river flows substantially, although exceptions exist such as the large run-of-river hydropower schemes on the main stem of the Mekong River (e.g., Xayaburi Hydropower Plant has a 93-km impoundment, but low water retention time of 2–3 days). Run-of-river systems are sometimes implemented downstream of impoundment-type dams so they can 're-use' the reservoir's hydraulic potential. Very-low head (or ultra-low head) turbine designs are generally considered run-of-river and usually have no dam or a small dam and turbines with wide blade passages and slow rotating speeds that reduce collisions (Tuononen et al., 2020; Zhou and Deng, 2017). Other design alternatives exist to minimize reservoir sizes including river diversion projects, pumped storage, and smaller hydropower projects. River diversion projects (either in-stream or across basins) pose the risk of altering natural flow regimes in both the receiving and donor systems and may shift hydrological regimes, water quality, and aquatic community compositions (Habit et al., 2007). For example, the diversion of water from the Nam Theun River to Xe Bangfai River under the Nam Theun 2 project changed the hydrological regime in the receiving river to a continuous high flow and subsequently altered the fish community with severe impacts on local fishing communities and their food security (Phouthavong, 2015). Increasing interest has been put towards smaller hydropower projects <100 MW in size. This includes concepts such as 'standard modular hydropower' that rethinks small hydropower projects by framing them in terms of their functional units such as fish and sediment passage, generation, and water passage, with the goal of preserving stream functionality while optimizing costs (Witt et al., 2017). Mini (<1 MW) and micro-hydro (<100 kW) are other designs that can produce small quantities of electricity (5–100 kW) but can still have an impoundment. Although the impacts of an individual plant are typically smaller, the cumulative barrier effect and impounded area for many small facilities can be greater than that of one large facility (Gleick, 1992; Goodland, 1995). Another means of reducing reservoir size is to install more energy-efficient turbines that compensate for hydropower designs with less water storage potential (e.g., run-of-river). The choice of turbine, however, has important implications for fish survival.

Fish can move downstream beyond a dam via different routes such as fish bypasses and spillways, although some fish inevitably move downstream through the turbines given that much of a river's discharge is diverted through them. This can lead to high levels of fish injury and mortality (Algera et al., 2020; Davies, 1988) stemming from blade strikes, pressure changes (barotrauma), sheer forces, turbulence, and cavitation (Čada, 2001; Coutant and Whitney, 2000). Fish responses to turbine entrainment can be species-specific (Pracheil et al., 2016) and little is known about the impact of turbines on fish and fisheries in highly speciose systems like the Amazon or Mekong (Algera et al., 2020; but see Colotelo et al., 2018). A number of modifications (e.g., blade gaps, runner speeds) to existing designs have been proposed to try and minimize the sources of mortality outlined above while maintaining or improving energy efficiency (Hogan et al., 2014). Designs such as the Archimedes screw (Bracken and Lucas, 2013; Spah, 2001), DIVE turbine, and Alden turbine have shown promise and may be useful for smaller scale systems (Winbeck and Winkler, 2018), although their adoption may be contingent on evidence demonstrating they can be cost efficient (e.g., Kumar et al., 2020). Additionally, Clay (1995) highlighted that providing alternative means of moving fish around hydropower facilities (i.e., fish passage) and away from harmful passage routes (ie., screening) can be important for mitigating impacts from turbines.

A perfectly implemented fish passage strategy would allow fish to move freely both up and downstream with no delays, recognizing that structures should not enhance passage at natural barriers or shift community assemblages (Baras and Lucas, 2001; Castro-Santos et al., 2009; Perônico et al., 2019). This goal of 'free movement' is idealistic and has yet to be achieved (Bunt et al., 2012; Noonan et al., 2012; Roscoe and Hinch, 2010). Consequently, it is important for fish passage initiatives to focus on supporting long term self-sustaining migratory fish populations (Pompeu et al., 2012; Wilkes et al., 2019). Relatively high fish passage connectivity can be achieved in the downstream direction via turbines, spillways, or bypass structures (Noonan et al., 2012), but this is for a limited number of species and facilities and is often dependent on the size of the reservoir as these low flow areas can discourage downstream movement (Pelicice et al., 2015). Bypass routes can also allow fish to pass a barrier, taking advantage of the orientation (surface or bottom) of a species by providing a route at that depth of the water column. Spillways can also be an effective passage route if they allow fish to pass without succumbing to injury (Bell and Delacy, 1972; Larinier, 2001). Diversion structures can guide fish with physical (e.g., screens, deflectors) or behavioural (e.g., lights, bubbles, electricity) barriers towards less destructive passage routes (Katopodis, 2005).

Many measures exist to facilitate upstream fish passage at hydropower facilities, including multiple designs of fish passes and derivations such as fish lifts and locks (Larinier, 2001), as well as trap and transport. Fish passage structures can also be an important means of restoring lateral connectivity to floodplains (Baumgartner et al., 2014). Fish passes are by far the most commonly used passage strategy, although these structures tend to pass less than half of all fish approaching these structures (Noonan et al., 2012). Issues can arise when fish passes have hydraulic conditions that do not match the swimming ability, size, or behaviour of local fish species (Petts, 1984). Furthermore, it is unlikely fish passes are capable of coping with the high volumes of fish typically found migrating upstream in large river systems in the tropics (e.g., the Mekong or Irrawaddy). In these areas, other approaches to passage may prove useful such as the opening of sluice gates during certain periods of the year, as was done at the Pak Mun Dam (Baird et al., 2020). The design of a successful fish pass will vary on a species-specific basis, but generally pool-and-weir/slot and natural fish passes have been found to have the highest passage efficiencies across temperate species (Noonan et al., 2012). Fish passes that are built close to the obstruction with the entrance positioned on the river bank or at the foot of the dam with appropriate attraction flow, slope, rest stops, and flow for target species may be the most effective at attracting and passing fish (Larinier, 2001). Nonetheless, the successful performance of a fish pass cannot be guaranteed, so a flexible design may need to be considered so it can be changed adaptively if performance is low (e.g., gabion baskets with welded steel mesh walls filled with rocks to allow temporary placement of structures). It is also important to consider situations where greater passage efficiency is not always optimal for every species in a system. Fish passes can act as 'ecological traps' when fish are attracted to use a unidirectional fish pass that leads them to low quality habitat upstream (e.g., lentic reservoir habitat for a lotic species), having left suitable conditions downstream (Pelicice and Agostinho, 2008). Similarly, fish passes can provide invasive species access to habitat that may have been previously inaccessible. For these passes, design features (e.g., velocity barriers, jump screens) may be installed to prevent passage of certain species (Rahel and McLaughlin, 2018). Multi-attribute sorting systems (similar to that used in recycling programs) may prove useful to restricting some species from passing barriers (Zielinski et al., 2020). Fish may also be vulnerable to predation before or after fish passage. High levels of predation on downstream migrating fish have been reported at hydropower dams both in temperate and tropical ecosystems (Agostinho et al., 2012; McLaughlin et al., 2013). To minimize predation on adult salmonids, predator-avoidance measures including barred-exclusion devices in fishways and non-lethal pinniped deterrence programs have been implemented on the Columbia River with some success (Stansell et al., 2010). Barriers can also attract high densities of fishers, and regulations and enforcement may be needed to curtail human harvest in these areas.

Similar to the passage of fish, is the passage of water and abiotic components of the environment. The passage method of releasing water from stratified reservoirs can influence downstream water conditions. Temperatures downstream can be warmer for surface water draw-off dams and the converse for bottom-draw-off dams, which can shift the community composition downstream (Lugg and Copeland, 2014). Selective withdrawal and mixing from different depths are strategies to minimize this impact. Similarly, water released downstream through turbines may be hypoxic while water released through the spillway may become supersaturated, which can lead to gas bubble disease in fish (Weitkamp and Katz, 1980). Air injection facilities or aerating turbines can assist in the recovery of water oxygenation and various spillway designs and stilling basins can help to reduce supersaturation of total dissolved gases from spillways (Feng et al., 2018a). Erosion and deposition processes of sediments can also be affected when flooded areas upstream of dams shift from lotic to lentic. Reduced flow rates in reservoirs can lead to high coarse sediment retention, particularly if arrangements for flushing are not built into the design, leaving a coarse sediment-depleted area downstream that is prone to erosion and habitat loss. Designs exist to facilitate sediment transfer, including low-level gates to support drawdown flushing of sediments and sediment bypass tunnels that move sediments from upstream river reaches beyond the reservoir and dam (Boes et al., 2014; Kondolf et al., 2014). This can minimize sediment starvation downstream and therefore erosion and channel incision downstream. However, it should be noted that even if sediment flushing is adopted, it can rarely enable 100% movement of sediment in large impoundments due to reduced flows. Flushing is also unlikely to facilitate the passage of larger materials such as coarse woody debris (important fish habitat) that can become trapped in the reservoir (Moulin and Piégay, 2004). Although no hydropower design will be perfect, an effectively designed facility will reduce its overall footprint, while ensuring it is flexible and robust to potential changes that are predicted throughout its lifecycle (e.g., several turbine sizes responsive to flow alterations with climate change; IHA, 2020).

3.2. *'Bright spots'*

3.2.1. *Minimizing turbine mortality for downstream-migrants with Kaplan designs*

Reviews on turbine mortality have provided insight into the relative survival rates of various fish species across certain turbine designs (Algera et al., 2020; Davies, 1988). There is substantial evidence that Kaplan turbines allow fish to move downstream with relatively low mortality rates (~8%; Pracheil et al., 2016). For many families of fish (e.g., Centrarchidae, Clupeidae, Cyprinidae, Percidae, and Salmonidae), survival through Kaplan turbines can be greater than 90% (Pracheil et al., 2016). It should be noted that survival is lower (>74%), but still high for other families of fish (e.g., Ictaluridae, Esocidae, and Anguillidae). Compared to Francis turbines which generally incur higher mortality rates (~25%; Pracheil et al., 2016), Kaplan turbines usually have fewer runner blades and have axial (rather than radial) water entry. There are also a number of modifications to Kaplan turbines that offer environmental improvements. Minimum gap runner (modified Kaplan design) turbines have been installed at Bonneville dam, Wanapum dam, and the Box Canyon hydroelectric project in the United States. Although this turbine design did not increase survival of juvenile fish compared with conventional Kaplan turbines (>96.5%), the electrical output of the modified design is 30% greater (Hogan et al., 2014). In theory, this means less water (and therefore fish; Jansen et al., 2007) can be diverted to the turbines to produce a given amount of energy. Similarly, very low head turbines (modified Kaplan) have demonstrated high survival (>95%) for Atlantic salmon smolts, adult, silver, and yellow phase American eels (*Anguilla rostrata*), and both juvenile and adult carp (*Cyprinus carpio*) and tench (*Tinca tinca*, Lagarrigue et al., 2008; Lagarrigue, 2013; Leclerc, 2008). In the Kinzig River, Germany, a movable Kaplan Bulb turbine with a curved rack over the intake allowed fish opportunities to move both below and above the turbine depending on its operation. This design showed high levels of survival for Atlantic salmon smolts moving through the hydropower facility, seemingly because smolts could pass over top of turbines (94–97%; Thorstad et al., 2017). Thus far, most research evaluating Kaplan turbines has focused on fish species from the northern hemisphere (particularly juvenile salmonids; Algera et al., 2020). More work is needed to determine whether Kaplan-style turbines are similarly effective for species in the southern hemisphere and at all life stages of fish from egg to adult (Wilkes et al., 2018).

3.2.2. *Maintaining the natural thermal regime—Flaming Gorge Dam, USA*

Releases of water from reservoirs can be either warmer or colder than ambient water temperatures depending on the depth of the water column from which the water is drawn. Selective withdrawal systems and temperature control devices have been implemented at hydropower projects to modify water temperatures downstream of dams, often with the aim of restoring temperatures to pre-dam conditions. At the Flaming Gorge Dam, Utah, USA, a water intake structure is operated to abstract water from different levels (and thus different water temperatures). This structure was operated to increase summer water temperature below the dam from 6 to 12 °C and annual degree days warmed to values similar to pre-dam conditions (Vinson, 2011). These systems can also be used to reduce warm summer temperatures. Rheinheimer et al. (2015) modeled how selective withdrawal systems could be used to decrease summer temperatures below the Lake Spaulding reservoir in California, USA, for the benefit of Chinook salmon (*Oncorhynchus tshawytscha*). Further, in alpine systems, thermopeaking (i.e., frequent and sudden changes in water temperature) linked to reservoir releases decreased water temperatures during heatwaves and thus provided more suitable thermal habitats for brown trout (*Salmo trutta*, Feng et al., 2018b). Although further studies to quantify biotic responses to these temperature modifications are needed, these approaches show promise that hydropower operations may be modified to better meet the water temperature preferences for a given species. These systems can also allow hydropower operations to adapt to seasonal/annual changes in water temperature, potentially providing some resilience to climate change (as recommended by IHA, 2020).

4. Construction

4.1. *Criteria*

The construction phase for hydropower facilities can constitute a period of upheaval between two relatively stable states, and activities during this period can result in lasting harm if caution is not exercised. There are specific opportunities and challenges for minimizing the effects of hydropower development on freshwater ecosystems and fisheries during construction, but this phase can be underemphasized perhaps due to the relatively short duration of this stage in the life of a hydropower project. Regulatory, management, and planning frameworks can help to ensure that best practices are implemented during the construction phase. The International Hydropower Association *Guidelines for Sustainable Hydropower* advises that construction-related consequences (e.g., air, noise, and water pollution, land contamination, land disturbance, water management, waste management, introduced species) be accounted for in environmental impact assessments to ensure affected areas can be rehabilitated efficiently (IHA, 2020). Where impacts are identified, construction management plans may be produced that outline steps to be taken to avoid and mitigate harm during the construction phase (Gómez-Balandra et al., 2015). Following stepwise procedures to assess and rank the outcomes of construction and mitigation alternatives can help proponents quickly identify preferred options (Koutsos et al., 2016). Monitoring and auditing of construction activities may then be conducted to ensure compliance with avoidance and mitigation requirements. Bonds or bail may be required to ensure that proponents can be penalized if they fail to comply with mitigation measures (Gómez-Balandra et al., 2015).

Various stages of construction can sometimes be timed to avoid acute impacts on fish, such that work is completed outside of sensitive periods of a species' life cycle (e.g., reproductive periods). For example, if explosives must be used in aquatic environments, effects on aquatic organisms could be considered and mitigated (i.e. blast during seasons when migratory fish are absent). When work is completed during these periods, impacts may be mitigated by permitting flow for migratory fish during the spawning season or filling the reservoir after fry have emerged. If a river is to be diverted during construction, the diversion channel may be designed to permit fish passage. When fish passage cannot be maintained during construction, mitigation may involve physically transporting individuals around the barrier. For example, during construction of the Whitehorse Hydro Plant in 1958, 224 Chinook salmon (~25% of the run) were captured and transported upstream of the dam by truck as a compensatory measure prior to construction of the fishway (Brown et al., 1976).

Construction activities can also affect aquatic habitat and water quality, but harm may be avoided, mitigated, and compensated as necessary. Waste and contaminants from construction activities such as solid waste, hazardous substances and materials, and waste water may need to be managed (Gómez-Balandra et al., 2015). Sediment and erosion management strategies can also be implemented during the construction phase (Dewals et al., 2012). Sediment traps and silt fences can help prevent sediment from entering the water (Chapman et al., 2014) among other erosion control efforts like slope protection and bank restoration (Gómez-Balandra et al., 2015). Contaminated sites in the area to be flooded, such as municipal dumps, tailing ponds, and sewage pits, can be remediated before the reservoir is filled. Flooding of terrestrial areas promotes the decomposition of vegetation over time, which may create anoxic conditions that can make heavy metals (e.g., Hg, Mn, Mg, and Fe compounds) soluble in the water column where they can then be passed downstream (discussed in Munger et al., 2017) and ultimately bioaccumulate in fish (Mailman et al., 2006). One option is to clear lands to minimize bioaccumulation of heavy metals in fish and therefore humans (Mailman et al., 2006), though reducing organic inputs to the reservoir can also lead to trophic depression as internal nutrient inputs decrease over time (Kennedy and Walker, 1990). It may be better to selectively clear hard wood materials to allow some woody structure, as the surface area of the wood provides an opportunity for the growth of aufwuchs, which are a rich source of food for fish in the impoundment. Although partially a siting consideration, effort could be made to limit ancillary roads, settlements, and infrastructure development during the construction phase to reduce effects (e.g., of increased impervious surface) on the aquatic environment (Cooke et al., 2020; Quintero, 2012), or be remediated once the construction is complete. One approach to reducing the impacts of roads is to build them below the flood zone.

Consideration has been given to relocating animals from areas to be flooded, but this has often been unsuccessful due to a paucity of suitable relocation sites (WCD, 2000). Focusing on rare or endangered species may be more fruitful, provided that suitable unoccupied habitat or captive breeding programmes exist. Although we focused here on fish and aquatic ecosystems, it is important to consider cultural impacts. Human communities can face displacement, loss of livelihoods, promises of jobs that never materialize, disruption of community cohesion, and settlement on inferior land. Cultural artifacts and sacred spaces may need to be salvaged and relocated along with communities (WCD, 2000), and new temples constructed at relocation villages. Compensation is discussed further in the 'compensation/offsetting' section.

4.2. *'Bright spots'*

4.2.1. *Best practices handbook for construction practices—hydropower in Ontario, Canada*

The Ontario Waterpower Association (OWA) is an industry association that represents hydropower producers in Ontario. They have developed a series of evidence-based, best management practices (BMPs) guides for their members and practitioners, including a guide for mitigating the effects of constructing waterpower facilities (OWA, 2013). The hydropower construction guide was created under the guidance of a steering committee that included industry and regulators, although did not include other stakeholders or rights holders such as Indigenous groups, non-governmental organizations, or researchers. It was developed to support environmentally responsible waterpower construction activities and accompanies other species-specific BMPs developed by the OWA. The guide provides detailed recommendations for construction activities and rehabilitation of hydropower facilities. This includes 42 separate BMPs for activities such as dewatering, fish removal, vegetation clearing, invasive species management, rare species management, drilling and blasting, among many others. Many activities are split into distinct elements, each of which has specific BMPs. For example, for the activity of dewatering, BMPs are provided for treating discharged water, dissipating energy of discharged water, and removing suspended solids using filter bags with fractionation tanks and settling ponds. Each of these BMPs summarizes the potential effects of the activity, recommends mitigation options, and provides references. The BMPs were completed in 2012, and provide a useful starting point for practitioners in any jurisdiction to plan environmentally responsible construction activities.

4.2.2. *Providing temporary fish passage during construction—Xayaburi Hydropower Plant, Lao*

During the construction phase of hydropower, river flows may be diverted, and there may be periods where auxiliary structures such as fish passes are not yet functional. For instance, construction of the Xayaburi Hydropower Plant in northern Lao PDR, saw the navigation lock, spillway, and intermediate block wall built over 2012–2014, with the intermediate block, powerhouse, and fishway constructed from 2015 to 2019 (Poomchaivej and Supachokepanich, 2018). To provide fish passage prior to the construction of the fishway, the navigation lock was modified to encourage upstream movement. The primary changes made to the lock included roughening the bottom, creating an auxiliary water feeding system, and providing up and downstream bypass valves in the lock's gates to create flow through different sections of the lock. The fish were driven up through the lock by a herding boat with a net that covered the width of the lock forcing fish to move upstream. Monitoring suggested much higher use of the lock when fish were herded by pontoon through the lock structure. Although the efficiency of the system was likely low, over the course of 3.5 years, millions of fish across 54 different species were found to use the modified lock and it was even used by one Mekong giant catfish (*Pangasianodon gigas*), a critically endangered species in the Mekong River. While the approach used at Xayaburi to accommodate fish passage may not be applicable across all contexts, this example demonstrates the importance of creative thinking when looking to limit the consequences to fish populations during the transient construction phase of hydropower development.

5. Operation

5.1. *Criteria*

Operation of a hydropower plant may depend on previous siting and design decisions and the timing of demand for power. Storage dams have the basic function of holding water in an upstream reservoir so that water is available to meet changing energy demands. In contrast, run-of river systems hold sufficient water in the impoundment to meet more immediate (diel) energy demands. Power demands can vary greatly over both diel and seasonal cycles, resulting in altered flow regimes that affect fish communities downstream of the facility (Cushman, 1985). Of particular concern is hydropeaking, which describes the regulated release of water through turbines related to peaks in energy demand, typically during the day, causing rapid fluctuations in flow and water level downstream of hydropower facilities. Flows downstream will typically be greatest during periods of peak demand, and less during low demand, but the downstream hydrology is also influenced by the annual flood cycle and precipitation levels across the catchment area. Loss of the natural flow regime (characteristic patterns of a river's flow, discharge, timing, and variability in duration, timing, and amplitude of floods and droughts; Poff et al., 1997) through flow regulation may alter downstream physical habitat, strand fishes in backwaters or channel margins (Irvine et al., 2009), alter fish movements (Bunt et al., 1999; Jeffries et al., 2005; Scruton et al., 2005), and disrupt spawning migrations, nest sites, and recruitment (Poff and Zimmerman, 2010). The flood pulse is a primary driver of river-floodplain system productivity (Junk et al., 1989). Flow regulation that alters the timing and reduces the amplitude of floods can compromise lateral connectivity (discussed in Arantes et al.) to the point that floodplain lakes may be permanently isolated (Lorenzen et al., 2007). Species have different responses to flow change that should be considered when establishing thresholds for hydropeaking (Moreira et al., 2019), as well as regulated flows associated with seasonal energy requirements.

Similarly, flow regulation can lead to fluctuations in reservoir levels (i.e., draw down), though these changes may be less pronounced than those experienced downstream. In some cases, reservoir fisheries can be highly productive (Miranda, 1999; Sugunan, 1995) and operational decisions can strongly influence the productivity of these inundated areas (Bernacsek, 1984; Lorenzen et al., 2007). Annual patterns in drawdown can lead to the destruction of marginal vegetation and erosion of the reservoir bed, making this habitat barren and unproductive (Hellsten, 1997). Fish species may experience a loss of habitat, food inputs, desiccation of eggs, and stranding, particularly those dependent on the littoral zone (Benoît and Legault, 2002; Carmignani and Roy, 2017).

Restoring the natural flow regime may be the ultimate goal of ecologists and managers, but it can be important to consider other societal needs and timing of energy demands. Kennedy et al. (2016) suggested that modifying hydropeaking by simply reducing hourly discharge variation at critical stages of animal reproduction could provide substantial increases in offspring production. This can be captured through regulations on ramping rates (rate of flow changes) that are outlined in most hydropower guidelines (IHA, 2020). Further, it was suggested that providing more stable, low flows during a short time period when electricity demands are lower (weekends) could provide food web benefits while minimizing the economic costs to the hydropower facility (Kennedy et al., 2016). There is now increasing attention being given towards environmental or ecological flows (EFlows) that are defined as the quantity, timing, and quality of water flows necessary to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems (Brisbane Declaration, 2007). The criteria for effective EFlows may need to be based on the ecology of the fish assemblages and their functional responses to flow alterations. A number of analytical approaches have been developed (e.g., ELOHA, building block, DRIFT) to quantify EFlow requirements, but a common thread is a shift towards basin-scale and regional assessments of flow needs (Arthington, 2012, 2020). On a seasonal scale, storing water in aquifers during high flow seasons can make water available for power generation during the low flow season and ensure there is sufficient water for EFlows year-round (Karimov et al., 2012). Establishing minimum flow criteria downstream of dams and providing variation to simulate natural flood dynamics is becoming more common place, although the concept of EFlows needs to be expanded to include other processes and properties such as sediment dynamics and water temperature, that help form the habitats supporting fluvial communities (Arthington, 2020; De Jalón et al., 2017; Olden and Naiman, 2010). What is clear is the need for flow releases to move from minimum flows to optimal flow releases that focus on ecosystem responses as an outcome (Jager and Smith, 2008). Strategic water operation will be needed to achieve optimal flows, while balancing against other societal demands for water.

Flow is also an important consideration for effective fish passage. Sufficient directed flows are needed to attract fish to fish pass entrances (Gisen et al., 2017). This may be achieved through auxiliary attraction flows that enter through gates at the fish pass entrance. These flows may differ based on the characteristics of the species and their navigational cues. For example, rheotactic species like salmon have increased attraction to fish passes with higher attraction flows (Aarestrup et al., 2003). Sufficient flow should be allocated to fish passage facilities to ensure they operate at all times (for all species and life stages). As a rule of thumb, 10% of Q95 (i.e., the discharge surpassed at a location 95% of the time) should be provided. However, hydropower business models are based on maximizing flows through turbines and diversion of flows through the fish pass can be seen as loss of energy. In some instances, flows allocated to fish passes are inadequate for them to function effectively. This was the case for the ZTB dam fish pass on the Daduhe River, China, that lacked sufficient water to permit passage through the fish pass (Bao et al., 2019). This may lead fish to be attracted elsewhere in the tailrace where flows are higher such as the turbines. In South America, for instance, fish agglomerations can be common in the tailrace (Godinho and Kynard, 2009), and fish attempting to move upstream can be trapped and killed in turbines during turbine stop/startup, when the fish in the tailrace have free access to the draft tube (Andrade et al., 2012). Impingement of several tons of fish in a single turbine have been reported for some Brazilian Hydropower plants (Godinho and Loures, 2017) resulting in lesions caused by decompression and/or mechanical impact (Andrade et al., 2012). Fish also require flow cues to orient themselves during downstream passage (Pelicice et al., 2015). The lack of flow in reservoirs may lead to mortality in downstream drifting eggs that sink to the bottom of the impounded area and increase rates of predation and starvation of larvae. One potential solution is to alter flows in the reservoir at certain points in the day or year to increase successful movement beyond a facility. Planned turbine shutdowns during key migration periods can also help improve connectivity. Across five dams in the Shenandoah River, planned turbine shutdowns overnight between September to December decreased adult American eel mortality from 63% to 37% (Eyler et al., 2016).

Maintaining the physicochemical conditions of the river may also aid native fish conservation and management. Dams and reservoirs can allow sediments and other materials to settle in upstream reaches, thus starving the river of these materials downstream which in turn can alter fish habitat (Rollet et al., 2014; Waters, 1995). However, techniques exist to allow for passage of sediment through impounding structures, including sluicing (moving sediment rapidly through reservoirs) and turbidity current venting (Kondolf et al., 2014). Sediment flushing may need to be done frequently, as infrequent flushing of large quantities of sediment downstream can impact fish (Chapman et al., 2014; Crosa et al., 2010). Similar thinking is needed to identify strategies for the passage of large wood (Ruiz-Villanueva et al., 2016) and other fish habitat features that can be retained in reservoirs. High retention times, minimal flows, and stratification in the reservoir can increase accumulation and bioavailability of heavy metals, impacting the fish community and fisheries (Munger et al., 2017). When reservoirs are well-mixed and oxic (e.g., spring) heavy metals may remain stable and insoluble reducing their presence in the water column. Artificial mixing may be used to limit stratification and anoxic conditions throughout the year (Visser et al., 2016). This could have downstream benefits as the passage of high concentrations of soluble heavy metals and anoxic water is minimized.

Flexibility in hydropower operations will be critical to effectively respond to changing environmental, social, and economic interactions over time. Adaptive management approaches should be considered that seek to optimize the balance between the many different environmental, economic, social, and cultural values of the entire river system (Rheinheimer et al., 2016; Richter and Thomas, 2007). This will require setting clear objectives (defined by multidisciplinary teams and stakeholder groups) and implementing rigorous ecological monitoring to inform adaptive management decisions. Many existing hydropower projects may require a 're-operation' plan that incorporates an adaptive management framework.

5.2. 'Bright spots'

5.2.1. Mitigating hydropeaking—Aare River, Switzerland

One of the more obvious operational changes to minimize the consequences of hydropower generation on aquatic biota is to modify water releases to better meet the needs of fish and other aquatic organisms. The difficulty is that there are often tradeoffs between the provision of ecological flows and energy production (Suen and Eheart, 2006). Hydropeaking (i.e., rapid starting and stopping of turbines to meet energy demand) can be particularly problematic for river systems as flows are altered throughout the day (Petts, 1984). In Switzerland, hydropeaking has resulted in major hydrological alterations to alpine streams, impacting fish and their habitat (Fette et al., 2007). Given the high extraction of water and increased concern for water protection, Switzerland's parliament passed the *Law on Water Protection* in 2009, providing political pressure to reduce hydropeaking, among other water related issues. Efforts to this effect were undertaken on the River Aare, one of the largest rivers in Switzerland and home to several species of fish targeted by recreational fisheries. Research was conducted to evaluate various hydropeaking mitigation measures and it was found that compensation basins had the greatest cost-benefit ratio with respect to ecological and economic outcomes (Person et al., 2014). Compensation basins are constructed downstream of dams and can be operated to retain water during periods of high flow and release water during periods of low flow (or match other flow regimes based on ecological criteria). By moderating flow changes, compensation basins have the effect of dissipating the consequences of hydropeaking, decreasing the likelihood that habitat will be dewatered and fish will be left stranded. Modeling of the Aare River suggested that suitable habitat ratios for spawning brown trout could be increased two-fold or more in braided channel habitats for production loss of less than 4% of annual revenue (Person et al., 2014). In 2015 this compensation basin was completed, in line with the construction of a new powerhouse (Müller et al., 2016). Despite concern that this upgrade may compromise the ability for the compensation basin to attenuate hydropeaking impacts, modeling indicated that down- and up-surge gradients would comply with identified ecological thresholds (Meier et al., 2016). This example illustrates how a combination of both effective design features (compensation basin) and operational procedures may lead to measured benefits for inland fish and fisheries with minor compromises to overall energy production.

5.2.2. Diminishing fish kills in turbines—Três Marias dam, Brazil

Turbine operation may lead to the death of tons of fish, affecting downstream communities of fish and people. The Três Marias Hydroelectric Dam is located in the São Francisco River basin, the third largest basin in Brazil. The dam is 75 m high and 2700 m long and started operating in 1962. Três Marias dam has changed the São Francisco River flow regime (Santos et al., 2012). However, largely unregulated tributaries are able to provide flood pulses along its 1000 km long free-flowing segment downstream of the dam, which sustains plentiful migratory fish populations (Nestler et al., 2012). In response to an environmental accident at Três Marias Dam that killed about 7 tons of fish in 2007, the power company (CEMIG) made efforts to better protect fish (Godinho and Loures, 2017). The drivers of temporal and spatial variations in fish abundance and density in the tailrace (Andrade et al., 2017; Loures and Pompeu, 2012, 2015), and their relationship with the number of fish trapped in the turbines were investigated (Rêgo et al., 2017). Fish movements and aggregation patterns downstream of the dam were also studied (Suzuki et al., 2017). Finally, techniques to protect fish in the tailrace were implemented and tested, including fish screening (Andrade et al., 2012), and manipulation of dam flow before turbine dewatering and stop/startup (Andrade et al., 2017). In some situations, such maneuvers have been aborted when fish densities at the tailrace were high. Following these changes, the proportion of biomass affected has been reduced by 77% (Godinho and Loures, 2017). It is unfortunate that it took an accident of this magnitude to spur change, though the opportunity to learn and apply these lessons to other hydropower contexts is nonetheless valuable.

6. COMPENSATION/OFF-SETTING

6.1. Criteria

When infrastructure or operations cause ecosystem change (including direct impacts on humans such as displacement) that cannot be avoided or mitigated, appropriate off-setting or compensation may be needed. In an ideal scenario, the design and operations could be such that all issues had been avoided or mitigated so neither off-sets nor compensation were needed. With hydropower projects, especially those involving dams, footprint effects may be impossible to avoid such that some level of compensation is almost always needed. Off-setting can be done to account for any barrier effects, entrainment- and turbine-related losses that cannot be mitigated or due to alterations in the upstream or downstream productivity of the system (e.g., loss of riverine spawning habitat in reservoirs, downstream stranding, changes in nutrient dynamics or thermal properties, changes in habitat from lotic to lentic systems). Off-setting is most well developed in terms of biodiversity (McKenney and Kiesecker, 2010) and habitat (Moilanen et al., 2009; Taylor et al., 2019), with the idea that damage to biodiversity and/or habitat associated with development are off-set by providing gains in biodiversity of habitat elsewhere. Not surprisingly, the concept is not without controversy and there are key ethical, social, governance, and technical issues that need to be considered (Maron et al., 2016). Ideally off-sets should require little ongoing maintenance, mimic nature's form and function to the greatest extent possible (as opposed to overly-engineered solutions; Bradshaw, 1996), represent a true gain (that is, the ratio of the off-set to the loss is well above 1:1—the target should be 2:1 or greater; Bull et al., 2013; Bull and Brownlie, 2016; Gardner et al., 2013; Quigley and Harper, 2006), and be as close to the affected sites as possible unless deemed to be best delivered off-site. It is also important, however, to consider the consequences of hydropower impacts throughout the entire basin and to appropriately spread offsetting/compensation to all people affected. For example, a dam sited in the lower reaches of a mainstem river that blocks migratory fish, will not only affect local fisheries, but also fisheries located upstream and downstream. Off-sets may be designed to address loss of ecosystem services (e.g., maintenance of self-sustaining fish populations and biodiversity), providing benefits on a more continual (permanent or long-term—until additional off-setting is explored) basis than is often considered for the longevity of off-sets. Off-setting (and compensation) alternatives may be compared using a cost-benefit analysis (Yu and Xu, 2016) which should incorporate preferences identified by the local community, and corresponding Traditional Knowledge (Griffiths et al., 2020). Inherent in any off-setting program is the need to use evidence to guide decision-making (recognizing that habitat restoration and ecosystem management are imperfect and the evidence base to support actions is fractured and weak; but see Angelopoulos et al., 2017). Once off-sets have been implemented, monitoring is essential to ensure the off-set is functioning as expected, and if deficiencies are identified, a regulatory apparatus is necessary to force refinements.

Efforts to off-set impacts should extend beyond simply thinking about biomass to include consideration of fish species that are of relevance to local stakeholders (see Lees et al., 2016), particularly those whose livelihoods, nutritional security and culture can be dependent on riverine fish (Fearnside, 2001; Hall and Branford, 2012). This may not mean appropriate resettlement but may mean enhanced livelihood opportunities, food security, and poverty alleviation. Reservoir fisheries can provide the most direct offsetting for lost productivity of river fisheries. Traditional river-floodplain fishers have been shown to expand their activities into reservoirs, particularly where reservoir fisheries can be exploited using familiar techniques (Nguyen Khoa et al., 2005). However, large reservoirs often support different fish species (lacustrine vs. riverine species) and require different and more capital-intensive fishing methods, while providing fishing opportunities that are less seasonal than those in rivers (Lorenzen et al., 2007; Petrere, 1996). Yields from reservoir fisheries can be low at the outset as the reservoir is colonized by lacustrine species and fishers learn how to exploit them. This is usually followed by a surge in yield due to high nutrient availability after inundation and increases in fishing effort, before stabilizing at a lower level of yield and sustained effort.

Stocking of hatchery-reared fish is carried out on a very large scale in many countries (e.g., Halverson, 2008). Stocking can play an important role in mitigating or offsetting anthropogenic impacts, including those of hydropower projects, on fish and fisheries. Hatchery fish may also be stocked for different purposes and in different situations (Cowx, 1994; Lorenzen et al., 2012). Hatcheries may be used to support conservation or restoration goals for endangered or locally extinct fish populations. For instance, hatchery fish may be stocked to enhance the abundance of native fish stocks that reproduce naturally but do so at a reduced level due to the impact of hydropower dams. Many of the salmon enhancement programs in the Pacific Northwest of the USA are of this type (Barnett-Johnson et al., 2008; Naish et al., 2007). In some cases, non-native species may be stocked. Culture-based fisheries and ranching programs for non-native species can involve intensive stocking and harvesting to achieve high production (or availability for recreational fishing) and account for some of the most successful hatchery programs. Since wild conspecifics are absent, so are many ecological and genetic risks except for interspecific interactions. Hatchery fish may also be stocked to support fisheries for species that cannot reproduce naturally for lack of spawning and nursery habitat but can utilize the modified habitats as late juveniles and adults. Examples of such culture-based fisheries or ranching systems are Chinese reservoir fisheries stocked with riverine major carps (Li and Xu, 1995), or the creation of trout fisheries in the fast flowing and cold tailwaters of dams in the warmer continental USA (Weiland and Hayward, 1997). Hatchery programs run for such different purposes necessarily have different design criteria and vary in types and levels of risk they pose to wild fish (Cowx, 1994; Lorenzen et al., 2012).

Hatchery fish can be genetically different from, and less fit in the wild than their wild conspecifics (Araki et al., 2007; Miller et al., 2004; Twardek et al., 2021). As such, stock enhancement programs in which hatchery fish are stocked into existing wild stocks can lead to negative ecological and genetic interactions between the stock components that can limit the overall effectiveness of such programs and pose risks to the wild stock components (Levin et al., 2001; Lorenzen, 2005). Managing stock enhancements well is complex and can require careful consideration of population dynamics. It is sometimes possible, particularly with salmonids, to separate the wild and hatchery components genetically and at harvest to reduce risks to wild stocks (Naish et al., 2007). In conservation and restoration-oriented hatchery programs, wild stocks tend to be small and are often protected from intentional harvest (George et al., 2009; Johnson and Jensen, 1991). Hatchery releases tend to be of moderate magnitude, and genetic resource management can be focused on preserving the characteristics of the wild stocks (Lorenzen et al., 2012; Waples, 1999). It is therefore important that hatchery programs are designed carefully with respect to their objectives and the situation and design criteria outlines. Further guidance on the design of such programs can be found in Cowx (1994), Lorenzen et al. (2010), and Naish et al. (2007).

When losses to fisheries resources important for food security or livelihoods cannot be avoided, mitigated, or offset with fish or habitat, compensation should be considered. Compensation measures may strive to support cultural values and avoid conflict rather than providing short-term remuneration. For example, it may be necessary to provide affected peoples with replacement opportunities for alternative proteins that they can raise or purchase or to assist with re-training programs for alternative employment relevant to the local context (see Orr et al., 2012). It is fair to say that this type of compensation is rarely embraced by affected peoples with long-standing conflict arising (Trussart et al., 2002). Although beyond the scope of this article, we also recognize that compensation may be needed for displaced peoples or individuals for which the facilities or its operations either directly or indirectly influence their ability to derive the same benefits from the aquatic ecosystem as prior to development (see Brown et al., 2008; Trussart et al., 2002). For example, if fisheries resources or a specific site were of cultural significance, appropriate compensation should be provided. This is unlikely to be a like-for-like in terms of ecology but may mean creating ways of celebrating cultural history and providing an alternative site of worship or reflection.

Appropriate governance structures and policy to guide and enforce these activities is critical. Indeed, even where such structures and policy are deemed to be robust, there is evidence that net gains are rarely achieved as few resources are devoted to inspection and monitoring (Harper and Quigley, 2005), or such efforts fail to focus on the best metrics or monitoring design (Smokorowski et al., 2015). Mitigation, off-sets, and compensation should ideally be the financial responsibility of those responsible for creating environmental damages. An appropriate financial model is necessary to ensure that there is adequate long-term funding for off-setting and compensation, beyond the life of the project. This should include support for long term monitoring and contingencies to account for potential refinements or redesign that are inherent in an adaptive management framework. Implementation of 'environmental/restoration bonds' that remain active for the entire lifecycle of the structure could be a useful approach to facilitate these long-term changes (Shogren et al., 1993). It is also important to highlight the possibility for barrier removal as a viable off-set option. Barrier removal can be an effective means of restoring fish passage, sediment transport, and habitat in rivers (Bednarek, 2001). Hydropower companies could off-set their impact at one facility by removing other obsolete barriers (Opperman et al., 2011).

6.2. 'Bright spots'

6.2.1. Creating fish habitat - Bay d'Espoir, Canada

The Granite Canal Hydroelectric Generating Station (40 MW capacity, 220 GWh annual average production) has been operated by Newfoundland and Labrador Hydro since 2003 and is located within the Bay d'Espoir Hydroelectric System. The hydropower development resulted in a loss of salmonid spawning and rearing habitat. A Fish Habitat Compensation Agreement was therefore developed where the hydropower utility committed to the Canadian Department of Fisheries and Oceans to ensure proper construction, utilization and long-term viability of the habitat compensation. The agreement included a surety bond such that if demonstrated that the habitat compensation worked fully, the proponent may be released from the monitoring requirement. A core part of the compensation plan was a 1:1, ~45 000 m^2 fish habitat compensation facility known as 'Compensation Creek.' The main channel (designed for Atlantic salmon spawning and rearing) is 15 m wide and 1.6 km long with two smaller side channels (designed for brook trout *Salvelinus fontinalis*). Importantly, compensation plans were informed by extensive pre-development surveys, and there was also an extensive program of post-implementation assessment and research (summarized in Clarke, 2016) to evaluate effectiveness—one of the first such projects in Canada to do so from a 'function' perspective. Monitoring indicated that a large proportion of the salmonid population (>48%) entered the constructed habitat to spawn (Enders et al., 2007; Loughlin et al., 2016) and that the habitat was colonized by benthic macroinvertebrates (needed to support fish populations; Gabriel et al., 2010). This project benefits from ongoing assessment and refinement (including investment) as needed. A particularly 'bright' aspect of this offset was the holistic approach that extended beyond a single species.

6.2.2. Removing barriers—Penobscot river, USA

The Penobscot River is the largest river in Maine, USA, with a drainage area of 22 300 km^2 and a length of 363 km (including West Branch) as it flows downstream to the Atlantic Ocean. The river supports 12 species of anadromous fish (e.g., American shad *Alosa alosa*, Atlantic salmon, sea lamprey *Petromyzon marinus*, alewife *Alosa pseudoharengus*, striped bass *Morone saxatilis*, sea run brook trout, among others) that require access to various riverine habitats throughout their lifecycle. The Penobscot River is highly regulated, with over 100 hydropower projects located throughout the basin (Hall et al., 2011). The presence of these dams restricted access of anadromous fish to historic spawning habitat upstream (Hall et al., 2011), and installed fish passes were unsuccessful at facilitating passage (Holbrook et al., 2009). Dams on this river have been the subject of strong debate over the last several decades as hydropower compromised native fisheries (Day, 2006). Recognizing a need to maintain or increase hydropower production in the area, while improving the conditions for anadromous fish, the Penobscot River Restoration Trust was formed (comprised of the Penobscot Indian Nation, and several non-profit organizations). The trust partnered with hydropower companies and various government departments to undertake the Penobscot River Restoration Project. This project had the goal of restoring access to historic habitats for inland fish, providing recreation opportunities and supporting the Penobscot Indian Nation's cultural traditions without compromising energy production. The project was a public-private partnership, and approximately US$55 million was raised to restore connectivity at four priority dams in the lower reaches of the Penobscot River (Opperman et al., 2011). This was achieved by removal of the Great Works Dam (~rkm 60) in 2012 and the Veazie Dam (~rkm 48) in 2013, and through the construction of a new fish lift at Milford Dam (~rkm 62) in 2014 and a natural fish bypass around the recently decommissioned Howland Dam (~rkm 100) in 2016. These restoration works provided access to more than 1600 km of river and stream habitat that was previously inaccessible to anadromous fish (Lovett, 2014). Index sampling of newly connected reaches of river (above and below removed dams) indicated a 31% increase in fish assemblage similarity, in large part driven by increased abundance of anadromous fish and decreased abundance of slow-water and introduced species (Watson et al., 2018). Overall, a three-fold increase in mean fish abundance was observed in post-dam removal years (Scherelis et al., 2020). As part of the agreement, the capacity of six other hydropower projects in the Penobscot basin were increased to meet production levels (NRCM, 2019). Overall, this constituted a highly progressive example of a restoration effort (and offset) that engaged many organizations, benefited the environment, and did not compromise energy output, making it a valuable 'bright spot' for others to learn from.

6.2.3. Hatchery reform—Columbia River Basin

The Columbia River Basin in the Pacific Northwest of the United States supports major commercial, tribal and recreational salmon and steelhead fisheries. The Columbia River and its tributaries are intersected by multiple hydropower projects and are home to some large-scale and long-running hatchery programs aimed at compensating for lost spawning habitat and fish passage mortality. Recognizing that the effectiveness of hatchery programs was variable and that some hatchery programs may have detrimental impacts on remaining wild stocks, a process of Hatchery Reform was instituted in the early 2000s (Paquet et al., 2011). Working cooperatively with fisheries and hatchery managers, a team of scientists reviewed hundreds of salmonid hatchery programs. Modelling was used to determine the best system design for each program, using an approach based on best available science, goal identification, scientific defensibility, and adaptive management to transition from an aquaculture focus to a renewable natural resource paradigm. In a recent application to the Columbia River basin, hatchery reform solutions were projected to increase the abundance of natural origin spawners across many salmonid populations (25% of steelhead populations, and more than 70% for Chinook and Coho salmon) while also providing increased harvest (Paquet et al., 2011).

7. Toward more 'bright spots' in hydropower for inland fish and fisheries

The production of hydropower can come with inherent ecological costs (often very large, under accounted costs), but there are opportunities to minimize these costs as presented in the 'bright spots' above (Table 1). It is important to note that the case studies presented generally only had one aspect of the facility that was considered 'bright'. Further, the characteristics leading to 'bright spots' currently, may not continue to be 'bright' for the lifespan of the hydropower project in the face of climate uncertainty. The question remains: is it possible to produce hydropower with multiple dimensions of 'brightness' and if so, how can this be facilitated? In short, we believe it is possible, but this may need to be done such that hydropower projects remain economically viable and continue to produce energy, while accounting for the true economic value of the ecosystem services delivered by the (pre)impacted river against the economic performance of the hydropower scheme. Comprehensive cost-benefit analyses will be necessary to ensure that the tradeoffs associated with various siting, design, construction, operation, and compensation alternatives are accounted for during decision-making processes. We also envision planning that occurs on the basin scale but is more regional, with water resource management across adjacent basins rather than only within a basin (e.g., Danube and Mekong River Commission and the São Francisco River basin, Brazil; O'Hanley et al., 2020), thinking that is rarely implemented currently. This concept of transboundary river management is challenging but can be overcome by promoting shared sovereignty and fair water sharing (Zeitoun et al., 2013). In many cases, this will require a paradigm shift where society puts freshwater ecosystems and their long-term sustainability first (Tickner et al., 2020). This may entail short-term economic costs, but this investment should reduce offset and compensation costs and reduce stakeholder conflict (and for developers, this could increase future development opportunities). These shifts may require public pressure upon leaders and industries. To enhance this dimension of the conservation ethic in cultures around the world, outreach events like World Fish Migration Day (Twardek et al., 2020) or World Rivers Day can play an essential role in underscoring the natural wonder and utilitarian value of protecting free-flowing rivers wherever possible.

Having collaborative, multi-stakeholder teams (including the local community) engaged in decision making is highly desirable (Glucker et al., 2013; Hasan et al., 2018; IHA, 2020). Extensive consultation with the local community can help to identify potential social impacts of proposed projects. However, it is important to recognize that multi-stakeholder, collaborative decision processes (MSP) are challenging and complex. As stated by Asmal (2000) who chaired the World Commission on Dams, *'doing so [conducting an MSP] is never a neat, organized, tidy concerto. More often, the process becomes a messy, loose-knit, exasperating, sprawling cacophony. Like pluralist democracy, it is the absolute worst form of consensus-building except for all the others.'* Hemmati et al. (2002) suggested that multi-stakeholder processes may need to transition from debate to dialogue and from listening to hearing, to truly achieve sustainable development. An essential first step is for all stakeholders to adopt a 'win-win' approach wherein all parties recognize the validity of the goals of other parties. Success is by no means assured, but it is at least possible. In addition to stakeholder involvement, experts on aquatic biodiversity and fisheries could be included from the very beginning, rather than being consulted after siting and operations decisions have

Table 1
Various high-level aspects and considerations related to inland fish and fisheries during the siting, design, construction, operation, and compensation stages of hydropower production that could be deliberated by decision-makers. We recognize that this list is by no means inclusive and readers may need to consult the text and additional resources (e.g., IHA, 2020) for more information. We acknowledge that for many hydropower projects there will be inherent tradeoffs between various considerations listed below and, in some cases, certain considerations may exclude others (e.g., in some tropical areas siting at an impassable natural barrier may coincide with an area of high biodiversity). Given the context-specific nature of this topic, it is important to integrate local expertise and perspectives with science to inform decision-making.

Aspect	Consideration	Outcome
SITING		
River selection	- Take a basin-scale approach	- Accounts for cumulative impacts of barriers and maximizes extent of free-flowing river
	- Consider climate projections	- Considers long-term viability of a site
Within river selection	- Avoid critical habitat and fisheries	- Protects biodiversity and livelihoods
	- Site close to headwaters	- Maximizes the length of free-flowing river
	- Site where anabranches exist	- Provides alternative migratory routes
	- Site at impassible natural barriers	- Limits additional barrier construction
	- Site near end users	- Decreases transmission losses
DESIGN		
Storage type	- Consider designs that minimize reservoir size (e.g., run-of-river)	- Limits loss of aquatic habitat and minimizes the impact on the floodpulse
Passage facilities	- Design fish passes and bypass systems to be species and context specific	- Ensures passage facilities are optimized for local fish community
Turbine design	- Install deterrents near turbine intakes (e.g., screens) and install turbines that minimize mortality (ideally without compromising energy production)	- Minimizes the injury and mortality of fish migrating downstream
Sediment management	- Implement design features that allow sediments to be transferred downstream (e.g., low level gates, sediment tunnels)	- Allows sediments and associated nutrients to reach downstream habitats and increases reservoir longevity
CONSTRUCTION		
Timing	- Avoid construction during ecologically-sensitive seasons	- Minimizes impact to reproductive fish
Temporary connectivity	- Provide minimum flows and temporary passage (e.g., locks, trap and transport)	- Helps ensure various life-history stages can be completed
Habitat protection	- Limit use of explosives where necessary	- Avoids unnecessary damage to aquatic habitat
Water quality management	- Restrict use of harmful chemicals and remediate contaminated areas before flooding. Clear land to avoid methylmercury accumulation.	- Decreases long-term contamination of fish and the fisheries they support
Sediment management	- Control the input of sediment into the waterbody (e.g., sediment traps)	- Limits sedimentation of the waterbody
OPERATION		
Flow regulation	- Limit hydropeaking by adjusting ramping rates, through off-site storage, or compensation basins	- Reduces severe flow changes downstream of the facility
	- Provide ecological flows that mimic the natural flow regime.	- Supports the signaling of important life-history processes, increases suitable habitat
	- Adjust flows during migratory windows, and ensure constant minimum flows available for passage.	- Facilitates passage during key periods of the year and ensures passage is always possible.
Transport of sediment and other materials	- Undertake transport procedures (e.g., sluicing, flushing, venting) that pass sediment and other materials (e.g., wood)	- Supports the movement of nutrients and habitat features downstream and increases reservoir longevity
Thermal regulation	- Control reservoir releases (e.g., top and bottom releases)	- Matches thermal conditions of reservoir releases to that of the ecosystem
Adaptive management	- Monitor ecological conditions and adapt operations over time	- Helps balance the different environmental, economic, social, and cultural values of the entire river system
COMPENSATION		
Habitat restoration	- Provide a net-benefit from the off-set (e.g. create more habitat than that lost)	- Prevents a net loss in habitat availability
Stocking	- Identify the goals of stocking. In most cases the aim is to create self-sustaining populations with long-term viability	- Supports sustainability of a socio-ecological system and persistence of native species
Compensation	- Compensate all parties involved and design compensation collaboratively with those affected	- Ensures groups are not left out and reduces long-term disagreements by helping to maintain cultural values

been made based on engineering and financial factors. As much as possible, decision-making should align with fisheries and biodiversity objectives, in which the non-monetary value of the biota is recognized and honored. Granting fish and fisheries a seat at the table during planning, design, and implementation of hydropower development requires having a transparent and effective environmental impact assessment process as well as functional governance and regulatory systems that seek to ensure compliance with agreements.

To facilitate these changes, we believe environmental laws and the environmental impact assessment (EIA) processes may need to be strengthened and the outcomes of review adhered to, rather than being shelved. We picture a robust EIA process that assesses the entire suite of effects that extend upstream and downstream of the project over both short- and long-term time scales. This includes monitoring effects using a before-after-control-impact design (Kilgour et al., 2007). Many emerging techniques exist to contribute to monitoring at hydropower facilities such as remote sensing to evaluate landscape changes (Lin and Qi, 2019) and eDNA to monitor biodiversity (Muha et al., 2021). Unfortunately, it is all too common for changes to be implemented without monitoring the consequences (Pullin and Knight, 2001). This restricts our ability to learn from, refine, and adopt various ‘best practices’ for use at other facilities. The EIA process could be followed by proper permitting, continued monitoring, and strict enforcement. Dams should also be inspected to ensure they remain structurally-sound and are not prone to collapse – a scenario that can have devastating consequences on aquatic and human communities (Cionek et al., 2019). It seems likely this might only be achieved through ‘environmental bonds’ that remain active for the entire life cycle of the structure (Shogren et al., 1993; i.e., until it is decommissioned and removed). Dams are not permanent, and it is important that feasibility studies outline how dams will be decommissioned once they become redundant and economically inviable. These plans could stipulate how to bring the ecosystem back to its expected current state had hydropower not been installed. Currently, some dams are abandoned after this period, resulting in environmental, economic, and safety issues (Pohl, 2002; Workman, 2007). To overcome dam abandonment, the conditions leading to dam decommissioning and removal may be considered in a relicensing policy, recognizing that it is the owner's responsibility to remove the infrastructure. The Federal Energy Regulatory Commission (FERC) relicensing process in the United States exemplifies how legislation can be used to facilitate dam removal (Chaffin and

Gosnell, 2017). Essentially, hydropower dams are relicensed after a fixed period of time (30–50 years), at which point an environmental assessment is undertaken and FERC considers whether relicensing is in the public interest, providing equal consideration to power production in contrast to other uses of the river (Bowman, 2002). If the dam is not relicensed or if a power corporation plans to cease generation, they could apply for a non-power license from FERC, who may order that the dam be removed. FERC may alternatively require that a fish pass be constructed for the hydropower dam to be relicensed (fish passes may also be mandated under the Endangered Species Act (ESA)). Facilitating fish passage can be costly, prompting some owners to opt for dam removal as a cheaper alternative. The majority of legally-driven dam removals are related to safety inspections (both by the state or federally under FERC), where it is deemed that removal is more cost-effective than repairs (Emery, 2001). Like FERC, the energy regulatory commission of a country could develop policy to implement similar relicensing processes for dams. This could be paired with modeling approaches to identify those hydropower dams that would benefit inland fish and potentially energy production if removed or relocated (O'Hanley et al., 2020).

Moving forward, more research is needed from the areas of the world where hydropower development is occurring most rapidly. Many of these areas are highly biodiverse (Winemiller et al., 2016), though comprehensive biodiversity assessments are uncommon, and information on the ecology of local species is lacking. Further, studies evaluating the relationship between fish and hydropower are scant compared to other parts of the world where hydropower is more developed. Of particular concern is the lack of evidence demonstrating effective fishway design in the Southern hemisphere (Wilkes et al., 2018). As such, passage principles developed in North America (for salmonids) have been incorrectly applied for fish passages in the global South (Mallen-Cooper and Brand, 2007). Improving our knowledge on these complex, biodiverse systems may help to mitigate impacts of hydropower on fish and fisheries in these regions of the world where people are typically most dependent on fisheries resources.

8. Conclusions

By raising awareness of ‘bright spots’ we are hopeful we can create a sense of optimism that it is possible to move towards more sustainable hydropower practices (Cvitanovic and Hobday, 2018). Operationalizing the ideas presented in this paper will require interdisciplinary collaboration between scientists, practitioners, engineers, policy-makers, and stakeholders and transparent dialogue and engagement at all stages of development. It may also require a strong legal underpinning to mandate these changes and ensure good practices are adopted. Continuous monitoring, control, and surveillance of hydropower projects throughout their life cycle will be needed to ensure there are no deviations from best practice and that adaptive management actions are undertaken to reduce or mitigate impacts on fish, fisheries, and human communities should they arise. Important lessons gleaned from these case studies and a synthesis of the literature include protecting critical habitat and stretches of free-flowing river through careful siting of facilities, implementing design features that minimize reservoir effects and facilitate safe passage, constructing the hydropower plant using best practices that avoid long-term damage, operating the facility to mimic natural conditions as closely as possible, and providing compensation that is lasting, inclusive, and locally-relevant. While we are hopeful that the case studies presented here provide valuable information to those involved with hydropower, there is a need for a more coordinated approach to share ‘bright spots’ (particularly from emerging economies where most hydropower development is happening). Indeed, the IHA has made an effort to highlight ‘bright spots’ in hydropower through their annual ‘Blue Planet Prize’ (for sustainable development; https://www.hydropower.org/iha/what-we-do-iha-blue-planet-prize) and their Better Hydro: Compendium of Case Studies 2017 (https://www.hydropower.org/publications/better-hydro-compendium-of-case-studies-2017) but more attention is needed. ‘Bright spots’ may be gleaned through systematic, participatory planning processes, best management practice handbooks, and continued knowledge exchange at professional conferences, the scientific literature, and through awareness campaigns (e.g., World Fish Migration Day; Twardek et al., 2020). Knowledge sharing is not exclusive to scientists, and many exceptional resources exist for hydropower practitioners to share information (e.g., https://www.conservationevidence.com). Requiring the release of monitoring reports associated with various aspects of the environmental assessment (EA) process would help improve the transparency of hydropower development decision-making. Such information could allow optimization of the siting, design, construction, operation, compensation, and decommissioning of hydropower structures to help ensure the sustainability of fisheries and continued delivery of ecosystem services are put first. Among the challenges of lesson sharing is that fish vary widely in their needs, so what works for some species may fail for others. The community must also recognize that river biota include far more than just fish (Pringle, 2003). Finally, we encourage other researchers to implement similar environmental ‘bright spot’ thinking related to other energy sectors (e.g., minimizing wind turbine impacts on birds, Bohrer et al., 2013; minimizing the loss of productive habitat from solar, Stoms et al., 2013) and support greater integration of clean energy sources into the energy portfolio of regions and countries.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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