SPECIAL ISSUE

CSIRO PUBLISHING

Marine and Freshwater Research, 2018, **69**, 1805–1813
https://doi.org/10.1071/MF18088

Perspective

Addressing fish-passage issues at hydropower and irrigation infrastructure projects in Indonesia

Lee J. Baumgartner[A,D] *and Arif Wibowo*[B,C]

[A]Institute of Land, Water and Society, Charles Sturt University, PO Box 789, Albury, NSW 2640, Australia.
[B]Research Institute for Inland Fisheries and Fisheries Extension, Ministry of Marine Affairs and Fisheries, Jalan Gub H Bastari number 8, 8 Ulu, Seberang Ulu I, Kota Palembang, Sumatera Selatan 30111, Indonesia.
[C]Southeast Asia Fisheries Development Centre, Inland Fisheries Resources Development and Management Department, Palembang 30252, Indonesia.
[D]Corresponding author. Email: lbaumgartner@csu.edu.au

Abstract. Development activities threaten the long-term sustainability of tropical floodplain systems. The construction of dams, weirs, irrigation infrastructure and regulators affect connectivity among habitats and can facilitate rapid declines in riverine biota, especially fish. Indonesia is a tropical island country with an abundance of monsoonal rivers. Massive expansions in hydropower and irrigation infrastructure are planned over the next two decades and mitigation measures will be needed to protect migratory fish. Most Indonesian freshwater fish need to migrate among habitats to complete essential life-history stages. So, strategies are urgently needed to mitigate the barrier effects of river infrastructure to ensure the long-term sustainability of river fishes. A common tool used worldwide is the construction of upstream and downstream fish passes. Only two fish passes exist in Indonesia. One at Perjaya Irrigation Dam on the Komering River (Sumatra island) and another on Poso Dam on the Poso River (Sulawesi island). Neither of these structures has been assessed and many other projects are proceeding without considering potential impacts on fisheries. The proposed infrastructure upgrades over the next two decades provide a once-in-a-generation opportunity to ensure that migratory fish are adequately protected into the future.

Additional keywords: freshwater, sustainable development, tropical systems.

Received 8 March 2018, accepted 27 July 2018, published online 9 October 2018

Introduction

Large tropical river-floodplain systems, being increasingly developed for irrigation and energy requirements, are experiencing rapid fishery declines (Oldani and Baigún 2002; Ziv *et al.* 2012). Tropical river-floodplain systems have productive and diverse fish communities that provide environmental, social and economic benefits to humans (Dudgeon 2000). However, the extensive construction of water-management structures prevents fish from accessing spawning, feeding and nursery habitat, which can affect multiple life-history stages (Rosenberg *et al.* 2000; Dugan *et al.* 2010) and reduce spawning and recruitment (Pringle *et al.* 1988). Over time, fishery productivity falls, and development-project benefits may become negatively offset (Baumgartner *et al.* 2012).

Indonesia is an oceanic nation comprising 10 individual islands in the southern hemisphere and is situated north of Australia (Fig. 1). Like all tropical rivers, waterways in Indonesia face challenges from increasing populations and urbanisation (Amri *et al.* 2014). The current population of Indonesia exceeds 250 million people and is placing increasing pressure on water resources and local aquatic fauna. Furthermore, significant land-use changes arising from increased cropping, deforestation and urbanisation have two significant impacts (Remondi *et al.* 2016). First, they increase overland runoff in the wet season, leading to increased flooding frequency. Second, they draw down groundwater reserves in the dry season, leading to significantly decreased flows. Thus, human expansion is significantly affecting river hydrology across many parts of Indonesia. Floodplain Rivers in Indonesia are typical monsoonal streams characterised by high wet-season flows and low-discharge dry seasons. All rivers in Indonesia flow from headwaters to the sea.

Diversity and behaviour of Indonesian fisheries

The inland-fishery sector is valued at US$266 million and supports thousands of jobs in subsequent supply chains (Coates 2002); protecting the fishery resource base from the impacts of irrigation infrastructure is of paramount importance in Indonesia. Inland capture fisheries in Indonesia deliver food

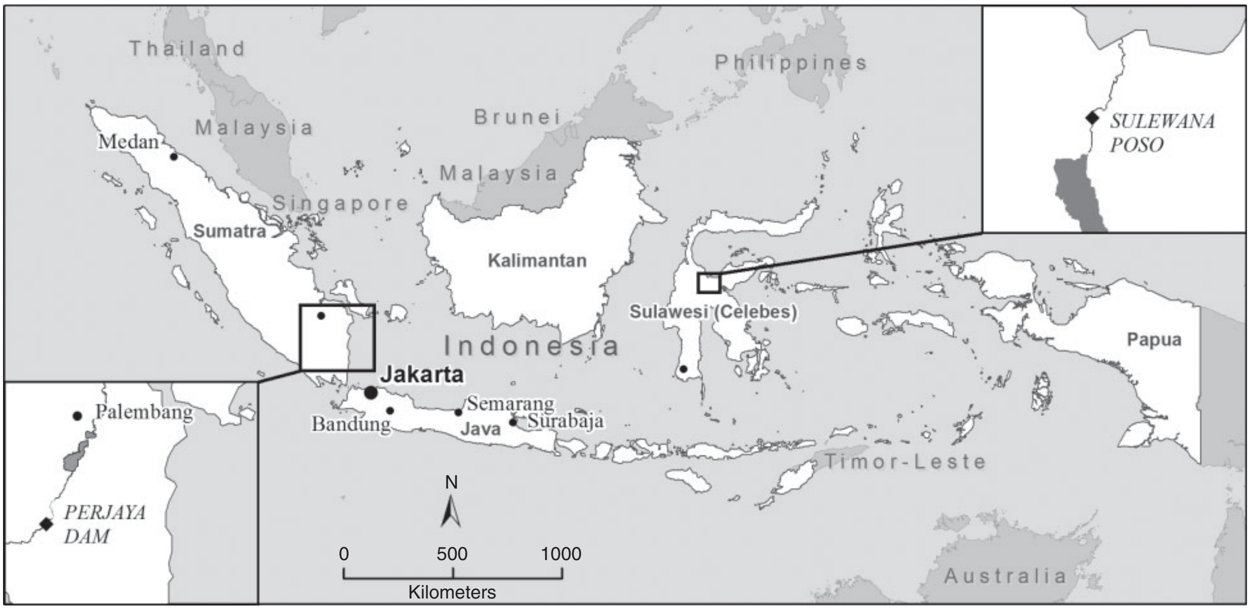

Fig. 1. Map of Indonesia. Locations of the two only operating fishways at Perjaya Dam (Sumatra Island) and Poso Dam (Sulawesi Island) are shown. All Indonesian rivers flow to the ocean and diadromy is a dominant life-history trait.

security and income for rural households and also serve as a valuable source of protein and important micro-nutrients (Kottelat *et al.* 1993). In all, 1218 species belonging to 84 families have been reported from Indonesian rivers, including 1172 native species from 79 families; 630 species are endemic and 28 are exotic species (Wirjoatmadjo 1987; Christensen 1992). Exotic species are present and, in the context of fish passage, it is important to ensure that fish-passage solutions do not expand distributions and transfer additional stresses on native fish (Hubert *et al.* 2015). With a density of 0.6 species per 1000 km^2, Indonesia hosts one of the world's highest density of fish species, ahead of Brazil (0.37 species per 1000 km^2) and the Democratic Republic of Congo (0.48 species per 1000 km^2), which are two countries that host some of the world largest and speciose tropical rivers.

Indonesian freshwater fish fauna are either obligate freshwater species (potamodromous) or diadromous species. Potamodromous fishes can complete all aspects of their life history in freshwater. These species generally do not require fish-passage solutions to maintain distributions, but they may be affected if barriers block migrations to important spawning sites or alter habitat to the point where species may no longer be supported. Very little data exist on potamodromous species in Indonesia. There is an urgent need to categorise these species, and understand habitat preferences and distribution to determine the potential impacts of river development.

Diadromous fish spend portions of their life histories in the ocean and are further categorised as anadromous, i.e. fish that migrate from the sea to freshwater to spawn, and catadromous, i.e. those that migrate from freshwater to the ocean (Augspurger *et al.* 2017). Examples of important anadromous fish in Indonesia include species of Polynemidae (e.g. *Polynemus melanochir*), Pangasiidae (eq. *Pangasius krempti*), Ariidae (e.q *Arius sumatranus*) and Sciaenidae (*Boesemania microlepis*). Common catadromous fishes include Anguillidae (e.g. *Anguilla bengalensis*, *A. bicolor*, *A. marmorata*, *A. interioris*, *A. celebesensis*, *A. borneensis*). The strong need for these species to connect between freshwater and ocean environments demands that any river development occurs in a way which preserves these important migrations (Miles *et al.* 2013).

Catadromous fish, such as eels, have important commercial and cultural values in Indonesia. In 2009, the international trade for eels exceeded 270 000 tonnes (Mg) (Bruinsma 2003). These were dominated by glass eel exports, which can fetch up to US\$5000 kg^{-1}. However, resources of temperate anguillid eels are declining globally. The numbers of species such as Japanese eel (*Anguilla japonica*), European eel (*A. anguilla*) and American eel (*A. rostrata*) have decreased rapidly in recent years, and these species are now listed on IUCN red List (Jacoby and Gollock 2014). Compensating for losses in temperate eel fisheries, the harvest of tropical eel species has increased significantly. Trade statistics (see http://unstats.un.org/unsd/trade/, accessed 28 August 2018) noted that ~3593 Mg of tropical eel harvest originates from Indonesia, with an estimated market value of US\$194 million (Brasor and Tsubuku 2012). Increasing fishing pressure on these species will require strict management.

Irrespective of the migration strategy, it is important that both future and existing riverine development projects consider potential impacts on fish. Construction of cross-river obstacles, such as dams, weirs and roads, as means for rapid development in response to increasing population and demand for agriculture products, hydropower generation or urbanisation, are major threats to the long-term sustainability of inland fisheries as any changes in migration, reproduction and biodiversity of aquatic populations has the potential to decrease productivity. Management interventions may be required to protect these important fisheries.

Hydropower development and impacts

The energy sector of Indonesia is undergoing significant changes that are creating both challenges and opportunities (Hasan *et al.* 2012). Energy demand continues to expand with the nation's economic growth. The energy industry is undergoing a profound change and more than 86 million people in Indonesia still lack basic access to electricity (Erinofiardi *et al.* 2017). Total energy demand in Indonesia is expected to increase by 8.7% each year up to 2024 (Erinofiardi *et al.* 2017). The challenge is to meet increasing demand while progressing towards sustainable energy systems, including the use of new technologies, renewable sources and increased efficiency. Many Indonesian rivers are high gradient with abundant water, so hydropower is becoming an increasingly attractive option as a major future energy source.

Hydropower constitutes ~10.2% of the total energy production of the country (Anonymous 2014). Indonesia's technical hydropower potential is estimated to be at ~75 000 MW, with untapped resources being concentrated on the islands of Sumatra, Java and Sulawesi (Darmawi and Firdaus 2011). It is estimated that there is currently ~8 GW of undeveloped hydropower potential, which would provide almost 33 TWh of electricity per year. According to the national strategic plan, up to 1 GW of new hydropower capacity has already been developed or is planned in the next decade (Darmawi and Firdaus 2011). Seven hydropower stations totalling 1559 MW are currently operating and a further 10 projects totalling 1819 MW are subject to power purchase-agreement (PPA) negotiations. An additional 19 projects totalling 2131 MW are in the study or design phase (Anonymous 2016).

Globally, hydropower projects have affected fishery production (Williams 2008). In most cases, impacts can be separated into direct and indirect (Bilotta *et al.* 2016). Direct impacts are where fish are killed, injured or physically blocked by the dam or turbine operation. Fish can experience significant welfare issues during downstream migration, either from blade strike (Deng *et al.* 2007), shear stress (Cada *et al.* 1999) or pressure changes (Brown *et al.* 2014) experienced during turbine or spillway passage. Fish can be physically excluded from upstream habitat simply by the barrier effect of the dam (Dugan *et al.* 2010) and can often require costly mitigation measures to be implemented (Williams 2008). But hydropower dams also affect downstream flow regimes (through hydropeaking; Gostner *et al.* 2011) and also alter upstream habitat, changing it from fast-flowing lotic habitat to slow-flowing lentic habitat (Kanehl *et al.* 1997). So, following hydropower dam construction, fish are faced with two challenges. First, the dam and turbine operation creates physical issues for up- and downstream migrations. Second, the dam significantly alters flow regimes and habitat availability. Both can be somewhat mitigated, but need to be addressed during the early stages of the planning process.

Irrigation development and impacts

The rapid and widespread expansion of the irrigation sector in Indonesia has placed substantial pressure on fishery resources, on which many people depend for food security and income. Between 1969 and 1989, extensive investment in irrigation and agricultural infrastructure (several thousand dams, weirs and diversion channels) supported a 4.8% increase in rice production per year, which led to a reduction in rural poverty from 40% in 1970 to 16.5% in 1997 (Booth 1977; Vermillion *et al.* 2000). But despite this increase in rice production, malnutrition (of children 2–5 years old) from a lack of micronutrients normally provided by fish is high. This is the case partly because inland fisheries form the main source of protein and income for many rural families (Melse-Boonstra *et al.* 2000; Kawarazuka and Béné 2011). But irrigation infrastructure has blocked important migration routes and led to declines in the resource base. For instance, the completion of the irrigation diversion at Perjaya Dam on the Komering River led to the localised extinction of 55 species in the upstream impoundment (Nizar *et al.* 2014).

Irrigation expansion was rapid in Indonesia and occurred at a time where impacts on inland fisheries were largely unknown. Infrastructure was essential to secure rice production, but has blocked fish seeking to access critical nursery and feeding habitat. In coastal streams, maintaining unimpeded access between freshwater and saltwater is critical for both inland and coastal species to complete their life cycles. Fish cannot access critical upstream habitat unless functional fishways are constructed. Thus, as seen at Perjaya Dam, any barrier that interrupts natural processes can lead to substantial, and rapid, fishery declines, which affects nutrition, jobs and income.

Impacts of existing infrastructure projects

Many tropical rivers in Indonesia are still free-flowing but many are proposed for extensive dam development in the future (Pringle *et al.* 2000). However, the present understanding of dam-related impacts in Indonesian ecosystems is severely limited (March *et al.* 2003). Although future tropical dam construction may be limited by social, economic and environmental concerns (McCully 1996), increasing demand for electricity, water and flood control are leading to continued tropical dam construction (Olivas 2004; Sierra *et al.* 2004), especially given that most suitable sites for dams in temperate regions have already been developed.

Dam and regulator design and operation significantly affect fish history patterns in temperate systems (Poff and Hart 2002). Barriers to fish passage can effectively stop many fish species from breeding and re-populating waterways by restricting their ability to access spawning grounds (Lucas and Baras 2001). Fish attempting to negotiate barriers are also forced to use up precious energy reserves. If this occurs during a breeding event, fish may actually re-absorb reproductive tissue and effectively lose a breeding season. Long-term effects will be supressed population size. For instance, the construction of Tallowa Dam on the Shoalhaven River (Australia) led to the localised extinction of many catadromous species from upstream reaches (Gehrke *et al.* 2002). Only species with strong climbing abilities were able to maintain populations. In tropical regions, migratory species such as barramundi (*Lates calcarifer*) are unable to access impounded reaches and experience population declines (Gehrke *et al.* 2002). Further, migratory catfish has experienced significant declines, following damming, in tropical rivers in Brazil (Agostinho *et al.* 2008). A common mechanism to mitigate the impact of dam on fish is to provide technical fish-passage solutions (Godinho and Kynard 2009). In developed rivers, provision of bidirectional fish passage will be critical to the long-term persistence of many migratory Indonesian native fish.

Fishways are often used to offset negative effects caused by infrastructure in large tropical rivers (Baumgartner *et al.* 2012). These structures are effectively channels around or through a migration barrier that promote upstream passage. Commonly used designs include vertical slot, pool and weir and Denil passes (Stuart and Berghuis 1999; Baumgartner *et al.* 2012). However, despite many designs being available, including fish locks, nature-like bypasses and bypass channels, determining effectiveness, especially in tropical systems, is often overlooked (Schwalme and Mackay 1985; Foulds and Lucas 2013). Much existing knowledge exists mainly for temperate species either from laboratory-based trials (Mallen-Cooper 1992) or *in situ* field-based experiments (Baumgartner *et al.* 2012).

Fishways are best addressed during the design phase (Clay 1995). Once a hydropower site has been determined, a fishway design should be progressed alongside plans for civil works. Technical fishways designed for upstream passage must take into consideration local hydrology, local fish ecology, swimming capabilities, hydraulic preferences and physical characteristics of the dam wall (Clay 1995). Further, the entrance location must be situated at the upstream migration limit and internal fishway hydraulics must suit the swimming ability of the target species (Bunt 2001). Developing robust solutions requires that fish ecologists, dam operators and engineers should work collaboratively to design effective solutions (Baumgartner *et al.* 2014*a*).

Passing fish downstream is also a challenge at hydropower and irrigation infrastructure (Cada *et al.* 1999). Indonesia has an abundance of diadromous fish. So any fish that move upstream into the dam reservoir must be provided the opportunity to return to the ocean to complete essential life-history stages. Fish generally move downstream via the spillway or turbine, or specially constructed downstream facilities can be provided for fish (Baumgartner *et al.* 2014*b*). Passage via the turbine can be associated with increased injury and mortality arising from blade strike, barotrauma or shear stress (Deng *et al.* 2005; Brown *et al.* 2012*a*, 2012*b*). In many instances, passing fish upstream can be pointless unless functional downstream facilities are also constructed (Williams 2008; Pelicice *et al.* 2015).

Should fish passage be considered in Indonesia?

Establishing that both hydropower and irrigation development can have fishery-related impacts, the following key question remains: when should fish passage be considered as a fishery-mitigation option? Many factors influence the appropriate answer.

First, can an efficient fish pass be constructed? There is mounting global evidence suggesting that, in some instances, providing fish passage may do more harm than good especially if it works suboptimally (Agostinho *et al.* 2002). Not passing enough fish, or only passing certain size classes may not yield the anticipated results. On the Atlantic coast of the USA, inappropriate application of inadequate technology has not yielded the required fishery outcomes (Brown *et al.* 2013). In Indonesia, it is extremely important to ensure that appropriate fish-passage designs (both upstream and downstream) are based on criteria suitable for local species. Furthermore, it is very important that the best solution is found for each site. Fish-passage construction is a very precise science. Even a small, seemingly insignificant, design change can lead to significant decreases in efficiency. Compromising too much on design specifications, to save costs or otherwise, can lead to suboptimal fishery outcomes.

The second question is whether the quality of the upstream habitat is suitable? For instance, in Neotropical rivers of South America, it has been suggested that passing fish upstream into unsuitable habitat actually has a negative effect on populations (Pelicice and Agostinho 2008). For instance, many species that have abundant spawning habitat downstream of barriers are disadvantaged when moved upstream into slow-flowing reservoir environments where spawning habitat is limited (Pelicice *et al.* 2015). In some instances, where fish passes have been constructed, and fish are recorded moving through, there is simply no evidence of overall fishery recovery (Oldani *et al.* 2007).

The third question is whether the downstream passage is possible? A main argument is that fish migration is often cyclic. An upstream migration may require a subsequent downstream movement (Baumgartner *et al.* 2014*b*). Fish may move upstream as adults, spawn and then both adults and larvae may undertake a subsequent return migration (Agostinho *et al.* 2011). The critical point is that, in progressing a suitable fish-passage solution, the complete life-history strategies must be known and understood for the target species (Kraabøl *et al.* 2009). A challenge in Indonesia will be sourcing this critical life-history information and then applying it to river-development works through effective designs that are proven in the local context.

The fourth question is whether it is acceptable to decide not to proceed with fish passage? If it is determined that a suitable design is not available, or if upstream habitat is unsuitable or if mechanisms to provide for downstream passage cannot be found, then an appropriate decision may be to not proceed with a fish-passage solution at all. Indeed this occurred in Australia when the government considered the construction of Traveston Dam (Mary River, Queensland; Walker 2008). It was determined that no adequate fish-passage solution could be found for local species and the dam was not approved to proceed. In the USA, areas where inadequate passage has failed to rehabilitate fishery populations has led to significant efforts to decommission and remove dams altogether (Bednarek 2001; Poff and Hart 2002). Such decisions have yielded far better fishery rehabilitation outcomes than have fish-passage programs. However, these are extreme cases, although extremely relevant to Indonesian river development. Hydropower and irrigation construction should be accompanied by environmental-impact considerations and fishery-related impacts should be considered during the design stages of planned projects. Such planning is the only way to ensure that the adequate solutions are found.

Progress on fish passage

Assuming that due diligence has taken place and a need for fish passage is agreed, then it is essential that appropriate mitigation measures are developed and implemented in the local context. Fishways have been constructed worldwide; however, knowledge of the importance and effectiveness of these structures is very limited. It is now accepted that fish-passage solutions

Fig. 2. Aerial view of Perjaya Dam, showing location of (*a*) fishway entrance too far down from dam face, (*b*) fishway exit too close to irrigation scheme intake (image sourced from Google Earth Pro).

should consider local species and conditions (Baumgartner *et al.* 2012), and not be adopted from studies conducted elsewhere (Mallen-Cooper and Brand 2007).

The Indonesian government has emphasised infrastructure development and modernisation as a major priority. In 1987, the Indonesian government adopted an irrigation operations and maintenance (O&M) policy (Bruns 2004). This included efforts to ensure adequate funding for O&M and the introduction of irrigation service fees. Inadequate uptake of the policy led to unsatisfactory maintenance of existing infrastructure. Although Indonesia achieved self-sufficiency in rice production in 1984, this is presently declining because of inadequate maintenance, rapid deterioration and loss of productivity of irrigation systems (Mears 1984). Thus, irrigation policy is presently being reformed and the majority of irrigation infrastructure is due for urgent upgrade over the next 15 years. These proposed works offer substantial opportunities to provide for fish because improved fishery outcomes (e.g. through the facilitation of fish passage) can be factored into upgrade works.

Because of a scarcity of information about the effectiveness and importance of fishways, only two have ever been built in Indonesia, these being Perjaya Irrigation Dam, on the Komering River, Sumatra Island) and an eel fishway (Poso Hydroelectric Scheme, Sulawesi Island; Fig. 1). However, these were based on solutions developed in North America and were potentially not suitable in the local context. The effectiveness of Perjaya Dam fishway was limited to a single study seeking to quantify species passage (Nizar *et al.* 2014). Very few species were captured and it was reported that the local fishway, a pool and weir design, was trapped on a daily basis, by local fishermen. No fish are, subsequently, gaining passage to the upstream reservoir. Nevertheless, there are several design flaws in the existing facilities. First, the entrance is located a significant distance downstream from the weir face and would be difficult for fish to locate (Fig. 2, 3). Second, the internal baffle design was based on those for salmonids and no current information is available on fish swimming abilities in the Komering River. Third, the fishway exit is directly adjacent to a large, unscreened irrigation diversion (Fig. 2). It is highly likely that fish exiting the fishway would be diverted into the irrigation canal and be effectively 'lost' from the system.

Fig. 3. Close up view of Perjaya fishway, demonstrating that both fishing nets located downstream of the fishway exit and the location of the entrance significantly downstream of the regulator gates.

Fig. 4. Aerial view of Poso Hydroelectric Dam, demonstrating how the fishway passes fish into the former Poso River. Most flow now passes through the hydropower plant and no downstream passage facilities were included in the scheme construction (image sourced from Google Earth Pro).

The fishway at Poso Dam is far more complex (Fig. 4). There was concern that Poso Dam would have significant impacts on local eel populations. Eels fetch a high price for local villagers who export them to a lucrative Japanese market (Honda *et al.* 2016). Provision was, therefore, made for a short fishway connecting the lower tailrace to the former Poso River, which was diverted to make provision for the Poso hydroelectric project. Conceptually, the fishway is sound. It represents a short section of the channel to allow elvers to pass a major barrier and recolonise upstream habitat. However, from an ecological perspective, the main issue is related to downstream passage. Eels generally migrate long distances to spawn in deep ocean trenches and would return seaward after spending many adult years in the Upper Poso catchment (Honda *et al.* 2016). However, there are no downstream migration facilities included into the Poso Hydroelectric design. So seaward-migrating broodfish risk injury or mortality when passing through the turbine blades. Therefore, best efforts to provide upstream migration could significantly affect the eel fishery through impacts on breeding individuals.

In light of design deficiencies at both Poso and Perjaya Dams, the Indonesian government is urgently seeking advice on the importance of fishways to increase the sustainability of fishery resources and guide the irrigation modernisation program. It is expected that each new irrigation structure will include a fishway, but there are presently no formal criteria for fish passage in Indonesia. Thus, there is substantial concern that a one-in-a-generation opportunity will be lost if thousands of irrigation structures are upgraded without considering potential fishery-productivity benefits. The political and industry climate is perfect to boost fishery productivity through the application of fish-passage technology; however, targeted research and development are needed to ensure that sustainable opportunities are developed and implemented within the next 5 years.

Future approaches and opportunities for fish-passage advancement

A stepwise approach is recommended to further fish-passage advancements in Indonesia. A detailed understanding of the existing two fishways is required to determine applicability to other sites in Indonesia. Specifically, a detailed monitoring plan should be implemented, with the objectives of defining which species are migratory, how well the existing fishways perform, whether any modifications can be made to improve performance, implementing local fishery management plans to prevent exploitation from within the fishways and a concerted effort should be made to identify the ecological life-history traits of target species. Understanding which species have potamodromous or diadromous life-history requirements is important, to determine the impacts of broader river development.

A concerted effort should be made to understand swimming abilities of local fish species. Swimming ability is a critical factor that governs effective fishway design (Castro-Santos 2005). It is specifically important to understand critical swimming speeds and the impact of turbulence on passage success. These two factors can be controlled by effective design specifications and, if known, could be developed into a set of national standards to govern future fishway construction.

Ensuring that fish-passage provision is captured in national policy is essential for effective fishery-recovery programs. There are many global examples where policy changes have been implemented to ensure that riverine development effectively provides for fish passage (Odeh 1999; Calles and Greenberg 2009; Godinho and Kynard 2009; Kemp and O'Hanley 2010; Baumgartner *et al.* 2014). Specifically, fishery-management policy should recognise obstruction of migration routes as a key threatening process. Further, ensuring that fish passage is mandated in irrigation and hydropower policy is essential to ensure that fish are considered early in the planning stages of infrastructure projects (Larinier 2008). Often, fish are included as an afterthought, usually after a decline has occurred. However, it is always less costly to consider fish during the design phase and ensure that fishery considerations are integrated into scheme operation over the long term.

Finally, fish passage is a two-directional phenomenon. Whereas substantial effort is usually made to ensure that fish are able to migrate upstream at barriers, it is just as important to move fish downstream. This is particularly relevant for diadromous species such as eel, which has an obligate requirement to migrate downstream to spawning grounds. Understanding how the operation of hydropower and irrigation schemes affects downstream migrants is paramount to developing effective solutions. In areas where mortality or injury rates may be high, such as through undershot sluice gates (Baumgartner *et al.* 2006) or in hydropower turbines (Ferguson *et al.* 2006), it may be worthwhile considering physical barriers such as screens to divert fish away from areas of welfare concern (Baumgartner and Boys 2012).

Conflicts of interest

Dr Baumgartner is an Associate Editor for *Marine and Freshwater Research* and is the Handling Editor for this special issue. Despite this relationship, he did not at any stage have Associate Editor-level access to this manuscript while in peer review, as is the standard practice when handling manuscripts submitted by an editor to this journal. *Marine and Freshwater Research* encourages its editors to publish in the journal and they are kept totally separate from the decision-making processes for their manuscripts. Dr Wibowo declares that he has no conflicts of interest.

Acknowledgements

The work has made possible through a collaboration grant obtained from the Australian National University. The authors thank the staff at Poso Energy and Perjaya Dam for sharing their thoughts and experiences from those respective sites. Two anonymous reviewers greatly enhanced an earlier draft of this work.

References

Agostinho, A. A., Carlos, G. L., Rodriguez, F. D., and Irene, S. H. (2002). Efficiency of fish ladders for Neotropical ichthyofauna. *River Research and Applications* **18**(3), 299–306. doi:10.1002/RRA.674

Agostinho, A., Pelicice, F., and Gomes, L. (2008). Dams and the fish fauna of the Neotropical region: impacts and management related to diversity and fisheries. *Brazilian Journal of Biology* **68**, 1119–1132. doi:10.1590/S1519-69842008000500019

Agostinho, C. S., Pelicice, F. M., Marques, E. E., Soares, A. B., and de Almeida, D. A. A. (2011). All that goes up must come down? Absence of downstream passage through a fish ladder in a large Amazonian river. *Hydrobiologia* **675**(1), 1. doi:10.1007/S10750-011-0787-0

Amri, K., Halim, A., Ngudiantoro, and Barchia, M. F. (2014). Criticality analysis of recharge area and land in the catchment area of Musi hydropower Bengkulu Indonesia. *APCBEE Procedia* **10**, 235–240. doi:10.1016/J.APCBEE.2014.10.045

Anonymous (2014). 'Outlook Energi Indonesia.' (Dewan Energi, Nasional Republik: Jakarta, Indonesia.)

Anonymous (2016). Hydropower status report. International Hydropower Association, London, UK.

Augspurger, J. M., Warburton, M., and Closs, G. P. (2017). Life-history plasticity in amphidromous and catadromous fishes: a continuum of strategies. *Reviews in Fish Biology and Fisheries* **27**(1), 177–192. doi:10.1007/S11160-016-9463-9

Baumgartner, L. J., and Boys, C. (2012). Reducing the perversion of diversion: applying world standard fish screening practices to the Murray–Darling Basin. *Ecological Management & Restoration* **13**(2), 135–143. doi:10.1111/J.1442-8903.2012.00655.X

Baumgartner, L. J., Reynoldson, N., and Gilligan, D. M. (2006). Mortality of larval Murray cod (*Maccullochella peelii peelii*) and golden perch (*Macquaria ambigua*) associated with passage through two types of low-head weirs. *Marine and Freshwater Research* **57**(2), 187–191. doi:10.1071/MF05098

Baumgartner, L. J., Marsden, T., Singhanouvong, D., Phonekhampheng, O., Stuart, I. G., and Thorncraft, G. (2012). Using an experimental in situ fishway to provide key design criteria for lateral fish passage in tropical rivers: a case study from the Mekong River, central Lao PDR. *River Research and Applications* **28**(8), 1217–1229. doi:10.1002/RRA.1513

Baumgartner, L. J., Daniel Deng, Z., Thorncraft, G., Boys, C. A., Brown, R. S., Singhanouvong, D., and Phonekhampeng, O. (2014*a*). Perspective: towards environmentally acceptable criteria for downstream fish passage through mini hydro and irrigation infrastructure in the Lower Mekong River Basin. *Journal of Renewable and Sustainable Energy* **6**(1) 012301. doi:10.1063/1.4867101

Baumgartner, L., Zampatti, B., Jones, M., Stuart, I., and Mallen-Cooper, M. (2014*b*). Fish passage in the Murray–Darling Basin, Australia: not just an upstream battle. *Ecological Management & Restoration* **15**, 28–39. doi:10.1111/EMR.12093

Bednarek, A. T. (2001). Undamming rivers: a review of the ecological impacts of dam removal. *Environmental Management* **27**(6), 803–814. doi:10.1007/S002670010189

Bilotta, G. S., Burnside, N. G., Gray, J. C., and Orr, H. G. (2016). The effects of fun-of-river hydroelectric power schemes on fish community composition in temperate streams and rivers. *PLoS One* **11**(5), e0154271. doi:10.1371/JOURNAL.PONE.0154271

Booth, A. (1977). Irrigation in Indonesia part. *Bulletin of Indonesian Economic Studies* **13**(1), 33–74. doi:10.1080/00074917712331333034

Brasor, P., and Tsubuku, M. (2012). How much money do rice farmers need to make from farming? *Japan Times Online* **April 3**, 2012.

Brown, J. J., Limburg, K. E., Waldman, J. R., Stephenson, K., Glenn, E. P., Juanes, F., and Jordaan, A. (2013). Fish and hydropower on the US Atlantic coast: failed fisheries policies from half-way technologies. *Conservation Letters* **6**(4), 280–286. doi:10.1111/CONL.12000

Brown, R. S., Ahmann, M. L., Trumbo, B. A., and Foust, J. (2012*a*). Cooperative research advances fish-friendly turbine design. *Hydro Review* **December**, 48–53.

Brown, R. S., Pflugrath, B. D., Colotelo, A. H., Brauner, C. J., Carlson, T. J., Deng, Z. D., and Seaburg, A. G. (2012*b*). Pathways of barotrauma in juvenile salmonids exposed to simulated hydroturbine passage: Boyle's law vs. Henry's law. *Fisheries Research* **121–122**, 43–50. doi:10.1016/J.FISHRES.2012.01.006

Brown, R. S., Colotelo, A. H., Pflugrath, B. D., Boys, C. A., Baumgartner, L. J., Deng, Z. D., Silva, L. G. M., Brauner, C. J., Mallen-Cooper, M., Phonekhampeng, O., Thorncraft, G., and Singhanouvong, D. (2014). Understanding barotrauma in fish passing hydro structures: a global strategy for sustainable development of water resources. *Fisheries* **39**(3), 108–122. doi:10.1080/03632415.2014.883570

Bruinsma, J. (2003). 'World Agriculture: Towards 2015/2030: an FAO Perspective.' (Earthscan: Rome, Italy.)

Bruns, B. (2004). 'From Voice to Empowerment: Rerouting Irrigation Reform in Indonesia. The Politics of Irrigation Reform: Contested Policy Formulation and Implementation in Asia, Africa, and Latin America.' (Ashgate: Hans, UK.)

Bunt, C. (2001). Fishway entrance modifications enhance fish attraction. *Fisheries Management and Ecology* **8**(2), 95–105. doi:10.1046/J.1365-2400.2001.00238.X

Cada, G., Carlson, T., Ferguson, J., Richmond, M., and Sale, M. (1999). 'Exploring the Role of Shear Stress and Severe Turbulence in Downstream Fish Passage.' (American Society of Civil Engineers: Las Vegas, NV, USA.)

Calles, O., and Greenberg, L. (2009). Connectivity is a two-way street: the need for a holistic approach to fish passage problems in regulated rivers. *River Research and Applications* **25**(10), 1268–1286. doi:10.1002/RRA.1228

Castro-Santos, T. (2005). Optimal swim speeds for traversing velocity barriers: an analysis of volitional high-speed swimming behavior of migratory fishes. *The Journal of Experimental Biology* **208**(3), 421–432. doi:10.1242/JEB.01380

Christensen, M. S. (1992). Investigations on the ecology and fish fauna of the Mahakam River in East Kalimantan (Borneo), Indonesia. *Internationale Revue der Gesamten Hydrobiologie und Hydrographie* **77**(4), 593–608. doi:10.1002/IROH.19920770405

Clay, C. H. (1995). 'Design of Fishways and Other Fish Facilities', 2nd edn. (Lewis Publishers: Boca Raton, FL, USA.)

Coates, D. (2002). Inland capture fishery statistics of Southeast Asia: current status and information needs. *RAP publication* **11**, 114.

Darmawi, P., and Firdaus, P. (2011). Hydro energy and its significant role in the future of Indonesian energy. In 'The 4th Sriwijaya International Seminar on Energy Science and Technology 2011', 5–6 October 2011, Palembang. Indonesia. (Ed. D Bayin.) p. 8. (Pasca Sarjana Sriwijaya University: Palembang, Indonesia.)

Deng, Z., Guensch, G. R., McKinstry, C. A., Mueller, R. P., Dauble, D. D., and Richmond, M. C. (2005). Evaluation of fish-injury mechanisms during exposure to turbulent shear flow. *Canadian Journal of Fisheries and Aquatic Sciences* **62**(7), 1513–1522. doi:10.1139/F05-091

Deng, Z., Carlson, T. J., Ploskey, G. R., Richmond, M. C., and Dauble, D. D. (2007). Evaluation of blade-strike models for estimating the biological performance of Kaplan turbines. *Ecological Modelling* **208**(2–4), 165–176. doi:10.1016/J.ECOLMODEL.2007.05.019

Dudgeon, D. (2000). Large-scale hydrological changes in tropical Asia: prospects for riverine biodiversity. *BioScience* **50**(9), 793–806. doi:10.1641/0006-3568(2000)050[0793:LSHCIT]2.0.CO;2

Dugan, P. J., Barlow, C., Agostinho, A. A., Baran, E., Cada, G. F., Chen, D., Cowx, I. G., Ferguson, J. W., Jutagate, T., Mallen-Cooper, M., Marmulla, G., Nestler, J., Pierre, M., Welcomme, R. L., and Winemiller, K. O. (2010). Fish migration, dams, and loss of ecosystem services in the Mekong Basin. *Ambio* **39**, 344–348. doi:10.1007/S13280-010-0036-1

Erinofiardi, Gokhale, P., Date, A., Akbarzadeh, A., Bismantolo, P., Suryono, A. F., Mainil, A. K., and Nuramal, A. (2017). A review on micro hydropower in Indonesia. *Energy Procedia* **110**, 316–321. doi:10.1016/J.EGYPRO.2017.03.146

Ferguson, J. W., Absolon, R. F., Carlson, T. J., and Sandford, B. P. (2006). Evidence of delayed mortality on juvenile Pacific salmon passing through turbines at Columbia River dams. *Transactions of the American Fisheries Society* **135**, 139–150. doi:10.1577/T05-080.1

Foulds, W. L., and Lucas, M. C. (2013). Extreme inefficiency of two conventional, technical fishways used by European river lamprey (*Lampetra fluviatilis*). *Ecological Engineering* **58**, 423–433. doi:10.1016/J.ECOLENG.2013.06.038

Gehrke, P. C., Gilligan, D. M., and Barwick, M. (2002). Changes in fish communities of the Shoalhaven River 20 years after construction of Tallowa Dam, Australia. *River Research and Applications* **18**(3), 265–286. doi:10.1002/RRA.669

Godinho, A., and Kynard, B. (2009). Migratory fishes of Brazil: life history and fish passage needs. *River Research and Applications* **25**, 702–712. doi:10.1002/RRA.1180

Gostner, W., Lucarelli, C., Theiner, D., Kager, A., Premstaller, G., and Schleiss, A. J. (2011). A holistic approach to reduce negative impacts of hydropeaking. *Dams and Reservoirs under Changing Challenges* **1**, 1–10.

Hasan, M. H., Mahlia, T. M. I., and Nur, H. (2012). A review on energy scenario and sustainable energy in Indonesia. *Renewable & Sustainable Energy Reviews* **16**(4), 2316–2328. doi:10.1016/J.RSER.2011.12.007

Honda, S., Muthmainnah, D., Suryati, N. K., Oktaviani, D., Siriraksophon, S., Amornpiyakrit, T., and Prisantoso, B. I. (2016). Current status and problems of the catch statistics on aguillid eel fishery in Indonesia. *Marine Research in Indonesia* **41**(1), 1–14. doi:10.14203/MRI.V41I1.94

Hubert, N., Kadarusman, , Wibowo, A., Busson, F., Caruso, D., Sulandari, S., Nafiqoh, N., Pouyaud, L., Rüber, L., Avarre, J.-C., Herder, F., Hanner, R., Keith, P., and Hadiaty Renny, K. (2015). DNA Barcoding Indonesian freshwater fishes: challenges and prospects. *DNA Barcodes* **3**, 144–169. doi:10.1515/DNA-2015-0018

Jacoby, D., and Gollock, M. (2014). *Anguilla Anguilla* (European eel). In 'The IUCN Red List of Threatened Species 2014', e.T60344A45833138. (International Union for Conservation of Nature and Natural Resources.) Available at http://www.iucnredlist.org/details/60344/0 [Verified 18 September 2018].

Kanehl, P. D., Lyons, J., and Nelson, J. E. (1997). Changes in the habitat and fish community of the Milwaukee River, Wisconsin, following removal of the Woolen Mills Dam. *North American Journal of Fisheries Management* **17**(2), 387–400. doi:10.1577/1548-8675(1997)017<0387:CITHAF>2.3.CO;2

Kawarazuka, N., and Béné, C. (2011). The potential role of small fish species in improving micronutrient deficiencies in developing countries: building evidence. *Public Health Nutrition* **14**(11), 1927–1938. doi:10.1017/S1368980011000814

Kemp, P. S., and O'Hanley, J. R. (2010). Procedures for evaluating and prioritising the removal of fish passage barriers: a synthesis. *Fisheries Management and Ecology* **17**(4), 297–322.

Kottelat, M., Whitten, A. J., Kartikasari, S. N., and Wirjoatmodjo, S. (1993). 'Freshwater Fishes of Western Indonesia and Sulawesi.' (Periplus Editions: Jakarta, Indonesia.)

Kraabøl, M., Johnsen, S. I., Museth, J., and Sandlund, O. T. (2009). Conserving iteroparous fish stocks in regulated rivers: the need for a broader perspective! *Fisheries Management and Ecology* **16**(4), 337–340. doi:10.1111/J.1365-2400.2009.00666.X

Larinier, M. (2008). Fish passage experience at small-scale hydro-electric power plants in France. *Hydrobiologia* **609**(1), 97–108. doi:10.1007/S10750-008-9398-9

Lucas, M., and Baras, E. (2001). 'Migration of Freshwater Fishes', 1 edn. (Wiley-Blackwell: Oxford, UK.)

Mallen-Cooper, M. (1992). Swimming ability of juvenile Australian bass, *Macquaria novemaculeata* (Steindachner), and juvenile barramundi, *Lates calcarifer* (Bloch), in an experimental vertical-slot fishway. *Marine and Freshwater Research* **43**(4), 823–833. doi:10.1071/MF9920823

Mallen-Cooper, M., and Brand, D. M. (2007). Non-salmonids in a salmonid fishway: what do 50 years of data tell us about past and future fish passage? *Fisheries Management and Ecology* **14**(5), 319–332. doi:10.1111/J.1365-2400.2007.00557.X

March, J. G., Benstead, J. P., Pringle, C. M., and Scatena, F. N. (2003). Damming tropical island streams: problems, solutions, and alternatives. *AIBS Bulletin* **53**(11), 1069–1078.

McCully, P. (1996). 'Silenced Rivers. The Ecology and Politics of Dams.' (ZED Books: London, UK.)

Mears, L. A. (1984). Rice and food self-sufficiency in Indonesia. *Bulletin of Indonesian Economic Studies* **20**(2), 122–138. doi:10.1080/00074918412331334642

Melse-Boonstra, A., De Pee, S., Martini, E., Halati, S., Sari, M., Kosen, S., and Bloem, M. (2000). The potential of various foods to serve as a carrier for micronutrient fortification, data from remote areas in Indonesia. *European Journal of Clinical Nutrition* **54**(11), 822. doi:10.1038/SJ.EJCN.1601094

Miles, N. G., Walsh, C. T., Butler, G., Ueda, H., and West, R. J. (2013). Australian diadromous fishes: challenges and solutions for

understanding migrations in the 21st century. *Marine and Freshwater Research* **65**(1), 12–24.
Nizar, M., Kamal, M. M., and Adiwilaga, E. M. (2014). Composition and community structure of migrating fish passed the fish ladder at Perjaya Weir, Komering River, South Sumatera. *Depik* **3**(1), 27–35.
Odeh, M. (1999) 'Innovations in Fish Passage Technology.' (American Fisheries Society: Bethesda, MD, USA.)
Oldani, N. O., and Baigún, C. R. (2002). Performance of a fishway system in a major South American dam on the Parana River (Argentina–Paraguay). *River Research and Applications* **18**(2), 171–183. doi:10.1002/RRA.640
Oldani, N. O., Baigún, C. R. M., Nestler, J. M., and Goodwin, R. A. (2007). Is fish passage technology saving fish resources in the lower La Plata River basin? *Neotropical Ichthyology* **5**, 89–102. doi:10.1590/S1679-62252007000200002
Olivas, E. A. (2004). Ecological and social implications of hydropower development on a Neotropical river system, Costa Rica. Ph.D. Thesis, University of Georgia, Athens, GA, USA.
Pelicice, F. M., and Agostinho, A. A. (2008). Fish-Passage Facilities as Ecological Traps in Large Neotropical Rivers. *Conservation Biology* **22** (1), 180–188. doi:10.1111/J.1523-1739.2007.00849.X
Pelicice, F. M., Pompeu, P. S., and Agostinho, A. A. (2015). Large reservoirs as ecological barriers to downstream movements of Neotropical migratory fish. *Fish and Fisheries* **16**(4), 697–715. doi:10.1111/FAF.12089
Poff, N. L., and Hart, D. D. (2002). How dams vary and why it matters for the emerging science of dam removal: an ecological classification of dams is needed to characterize how the tremendous variation in the size, operational mode, age, and number of dams in a river basin influences the potential for restoring regulated rivers via dam removal. *Bioscience* **52**(8), 659–668. doi:10.1641/0006-3568(2002)052[0659:HDVAWI]2.0.CO;2
Pringle, C. M., Naiman, R. J., Bretschko, G., Karr, J. R., Oswood, M. W., Webster, J. R., Welcomme, R. L., and Winterbourne, M. J. (1988). Patch dynamics in lotic systems: the stream as a mosaic. *Journal of the North American Benthological Society* **7**, 503–524. doi:10.2307/1467303
Pringle, C. M., Freeman, M. C., and Freeman, B. J. (2000). Regional effects of hydrologic alterations on riverine macrobiota in the new world: tropical-temperate comparisons. *AIBS Bulletin* **50**(9), 807–823.
Remondi, F., Burlando, P., and Vollmer, D. (2016). Exploring the hydrological impact of increasing urbanisation on a tropical river catchment of the metropolitan Jakarta, Indonesia. *Sustainable Cities and Society* **20**, 210–221. doi:10.1016/J.SCS.2015.10.001
Rosenberg, D. M., McCully, P., and Pringle, C. M. (2000). Global-scale environmental effects of hydrological alterations: introduction *Bioscience* **50**(9), 746–751. doi:10.1641/0006-3568(2000)050[0746:GSEEOH]2.0.CO;2
Schwalme, K., and Mackay, W. C. (1985). Suitability of vertical slot and Denil fishways for passing north-temperate, nonsalmonid fish. *Canadian Journal of Fisheries and Aquatic Sciences* **42**, 1815–1822. doi:10.1139/F85-227
Sierra, J., Sánchez-Arcilla, A., Figueras, P., Gonzalez Del Rio, J., Rassmussen, E., and Mösso, C. (2004). Effects of discharge reductions on salt wedge dynamics of the Ebro River. *River Research and Applications* **20** (1), 61–77. doi:10.1002/RRA.721
Stuart, I. G., and Berghuis, A. P. (1999). Passage of native fish in a modified vertical-slot fishway on the Burnett River barrage, South-Eastern Queensland. Number 0727-6281, Department of Primary Industries, Rockhampton, Qld, Australia.
Vermillion, D. L., Samad, M., Pusposutardjo, S., Arif, S. S., and Rochdyanto, S. (2000). An assessment of the small-scale irrigation management turnover program in Indonesia. IWMI Research Report 038, International Water Management Institute (IWMI), Colombo, Sri Lanka. . doi:10.3910/2009.043
Walker, K. (2008). Environmental impact statement for Traveston Crossing dam (Mary River, Queensland): a review with regard for species of concern under the EPBC Act 1999. Environmental Defenders Office, Canberra, ACT, Australia.
Williams, J. G. (2008). Mitigating the effects of high-head dams on the Columbia River, USA: experience from the trenches. *Hydrobiologia* **609**, 241–251. doi:10.1007/S10750-008-9411-3
Wirjoatmadjo, S. (1987). The river ecosystem in the forest area at Ketambe, Gunung Lueser National Park, Aceh, Indonesia. *Archiv für Hydrobiologie* **28**, 239–246.
Ziv, G., Baran, E., Nam, S., Rodríguez-Iturbe, I., and Levin, S. A. (2012). Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin. *Proceedings of the National Academy of Sciences of the United States of America* **109**(15), 5609–5614. doi:10.1073/PNAS.1201423109

Handling Editor: Colin Finlayson