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Speaking the same language: can the sustainable development goals translate the needs of inland fisheries into irrigation decisions?

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Abstract. Irrigated agriculture and inland fisheries both make important contributions to food security, nutrition, livelihoods and wellbeing. Typically, in modern irrigation systems, these components operate independently. Some

[1]The first two coauthors cofacilitated the workshop that forms the basis of this piece. The next sixteen authors were workshop participants, contributed equally and are listed alphabetically by family name.

practices, commonly associated with water use and intensification of crop production can be in direct conflict with and have adverse effects on fisheries. Food security objectives may be compromised if fish are not considered in the design phases of irrigation systems. The 2030 Agenda for Sustainable Development provides a framework that can serve as a backdrop to help integrate both sectors in policy discussions and optimise their contributions to achieving the Sustainable Development Goals (SDGs). Inland fisheries systems do play an important role in supporting many SDG objectives, but these contributions can sometimes be at odds with irrigated agriculture. Using case studies of two globally important river catchments, namely the Lower Mekong and Murray–Darling basins, we highlight the conflicts and opportunities for improved outcomes between irrigated agriculture and inland fisheries. We explore SDG 2 (Zero Hunger) as a path to advance our irrigation systems as a means to benefit both agriculture and inland fisheries, preserving biodiversity and enhancing the economic, environmental and social benefits they both provide to people.[2]

Additional keywords: food security, integrated management, Mekong River, Murray–Darling Basin, SDGs.

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Kantri bigis blanga Gamilaraay balugirbang. Baga – thalaa guya gambaal, baraa, gaygay, guduu – bajimap leif, thanbarran Gamilaraay. Ngunnhu, 40 000 bigis yuul ngiyani Ngemba. Wanada barraay jeinjim bagaay; thalaa balu-gi. Ngiyani guya maranirra baga.

Indigenous Australians are intrinsically connected to their country. This connection includes our lifeblood, the rivers and the animals they contain. We exist in a symbiotic relationship with our cultural landscapes. Migratory fish have totemic status and relationships with First Nations peoples and were a major food source for my ancestors and some of the fish traps they constructed date back 40 000 years. These cultural sites are being significantly affected by irrigation development and many sites of significance have already been lost. We must do all we can to protect these sites, and our fish, because any truly 'modernised' river management system would consider maintenance of cultural significance as an essential outcome [Uncle Phil Duncan, World Fish Migration Day Ambassador and Cultural Training Coordinator, Macquarie University, Australia; quotation in the language of the Gomeroi Nation translated into English by P. Duncan and L. Baumgartner].

Speaking a common language

In 2015, 193 countries adopted Transforming Our World: The 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs; United Nations 2015). The SDGs differ from the previous Millennium Development Goals (Millennium Ecosystem Assessment 2005) in that they apply to all countries and deliberately strive to balance the economic, social and environmental dimensions of sustainable development (United Nations 2015). The pursuit of integrated outcomes of these critical elements in parallel presents several timely opportunities to accelerate a shift in investment priorities holistically across key development systems. Here, we highlight the fundamental balancing act of managing water as a natural resource and a provider of other aquatic ecosystem services (Fig. 1). Typically, these water services are managed separately and the resulting unintended consequences can be deleterious. For example, irrigation practitioners have traditionally been incentivised to increase land and water productivity in terms of crop production (e.g. rice) and, as a consequence, previously productive fisheries and harvesting of other aquatic animals (OAAs) have mostly declined in irrigation systems as a result of a lack of awareness or motivation regarding effects on fish and aquatic fauna (Falkenmark *et al.* 2007; Welcomme *et al.* 2010).

The SDGs attempt to foster development by sustainable means that also end hunger and poverty. However, such an ambitious aspiration requires a holistic approach that explicitly recognises both the positive and negative effects that pursuance of one goal (e.g. irrigation) can have on another (e.g. fisheries production; Fader *et al.* 2018). Successful implementation of the SDGs requires an appreciation that there are multiple uses for, and users of, water (Renault *et al.* 2013). Furthermore, the SDGs are not achievable independently; there are intrinsic interactions across SDGs that need to be captured in order to integrate holistic, cross-sectoral management approaches into new investments (Neely *et al.* 2017).

Our objective is to discuss the important sectors of irrigation and inland fisheries by showcasing two different, but globally important, river systems, namely the Lower Mekong and Murray–Darling basins, as case studies of conflict and opportunity between these sectors. We discuss development in these systems in the context of the SDGs. There is a need to ensure that global initiatives to expand irrigation systems for agriculture also consider inland fisheries and harvesting of OAAs while balancing the environmental, economic and social benefits irrigation provides to people. Water is life, but equally so are the aquatic resources depending on the water.

Importance of irrigation

Irrigation (the application of water to crops) has been a key component of agriculture for millennia, and many ancient civilisations (e.g. in Mesopotamia, Egypt, Sudan, India, South-east Asia, China, Sri Lanka and tropical America) depended on irrigation for their development (Dooge 2004 and references therein). Irrigation development has been cited as a significant factor in the formation of the centralised political

[2]Any use of trade, firm or product names is for descriptive purposes only and does not imply endorsement by the US Government.

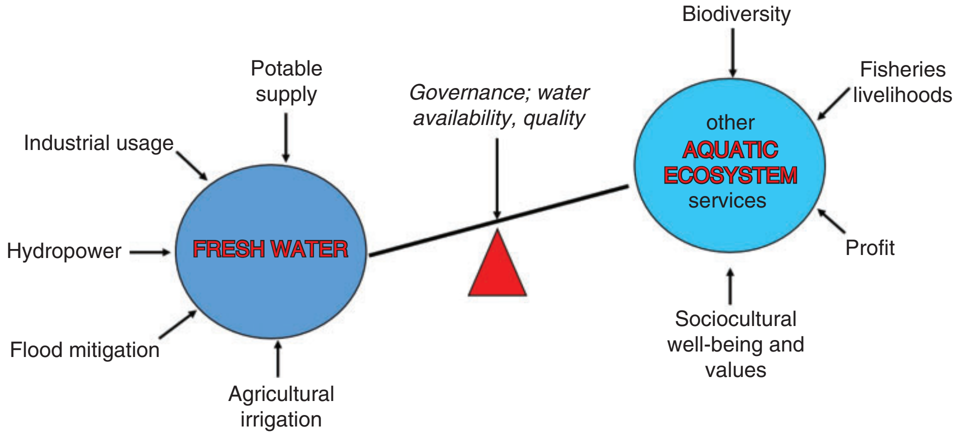

Fig. 1. Water resources development (e.g. hydropower or irrigation) derives huge economic and social benefits, but it is a balancing act with other freshwater ecosystem services, including fisheries.

structures and bureaucracies underpinning these civilisations (Dooge 2004). The ability to make water available and distribute it in suitable systems to enable irrigation has been a prerequisite for agricultural intensification, food security and population growth in many parts of the world (Fitzgerald-Moore and Parai 1996).

Irrigation is currently the largest user of freshwater globally, accounting for more than 70% of human water withdrawals (Siebert and Döll 2010). Facilitated by technological advances, the Green Revolution of the 1950s–1970s transformed farming practices in many regions of the tropics and subtropics where the principal food crops are rice, wheat and maize. The introduction of high-yielding varieties of these staple crops resulted in very substantial production increases (e.g. total grain production in India doubled between 1960 and 1993; Fitzgerald-Moore and Parai 1996), but with substantial increased irrigation and fertiliser use. Globally, the irrigated area has roughly doubled in the past 50 years (Foley *et al.* 2011). Irrigated agriculture represents 21% of the total cultivated land, but contributes 40% of the total food produced worldwide (Food and Agriculture Organization of the United Nations 2018).

Irrigation is relevant not just for food security (SDG 2 Zero Hunger), but importantly also prevents the slide of the poor into deeper permanent or temporary poverty (SDG 1 No Poverty) through provision of other economic benefits from food crops, fodder and non-food crops, such as cotton. There are strong direct and indirect links between irrigation and poverty (Hussain and Hanjra 2004). Irrigation directly benefits the poor who own land through higher production, higher yields, lower risk of crop failure with higher and year-round farm and non-farm employment. Irrigation enables smallholders to adopt more diversified cropping patterns, and to switch from low-value subsistence production to high-value market-orientated production. Increased production makes food available and affordable for the poor. Indirect benefits of irrigation accrue via regional, national and economy-wide means. Allocation of water often tends to be land based, so, in the short-term, the relative benefits to the landless, rural poor and most marginalised may be small. However, irrigation investments can have a strong positive effect on economic growth, benefiting even the poorest in the long term (Hussain and Hanjra 2004). For example, Ethiopia has emerged as an engine of economic growth in Africa in recent years, with gross domestic product (GDP) increasing by 10% a year between 2004 and 2014, in part, because the area irrigated increased by almost 52% during the same period (Ejeta 2019).

Many governments continue to view irrigation as critical to meeting the demands of growing populations and a key contributor to achieving SDGs 1 and 2 and other development goals. Under a business-as-usual scenario, total irrigated area is expected to increase to 394 million ha by 2030 (Ringler 2017). Approximately 90% (39×10^6 ha) of the total increase in irrigation by 2030 is expected to be in developing countries, particularly in Sub-Saharan Africa (Ringler 2017). How this expansion occurs will affect the other services provided by water systems and how these countries can meet SDG 1 and 2 targets as well as other development goals. Negative externalities, particularly associated with large and medium-scale irrigation systems, their dams and reservoirs, are now recognised. In addition, changes in river flow regimes and the widespread use of agricultural chemicals, typically associated with irrigation and high-yielding crop varieties, have led to environmental degradation and increases in pollution with, among other things, negative effects on fisheries (Falkenmark *et al.* 2007). Increasingly, future irrigation must contribute not only to productive agriculture, but also to increased returns on investment, improved livelihoods and environmental conservation for sustainable development (McCartney *et al.* 2019).

Importance of inland fisheries

Inland fisheries contribute to global food security, are a main protein source for many communities in developed and developing countries and provide essential nutrients to humans worldwide, especially in rural and low-income areas (Fig. 2; see also Youn *et al.* 2014). The inland fisheries catch exceeded 11.47 million tonnes (11.47 Tg) in 2015, representing 12.2% of total global capture fishery production (Funge-Smith 2018). Over 90% of global inland fisheries production is used for human consumption, and low-income food-deficit (LIFD)

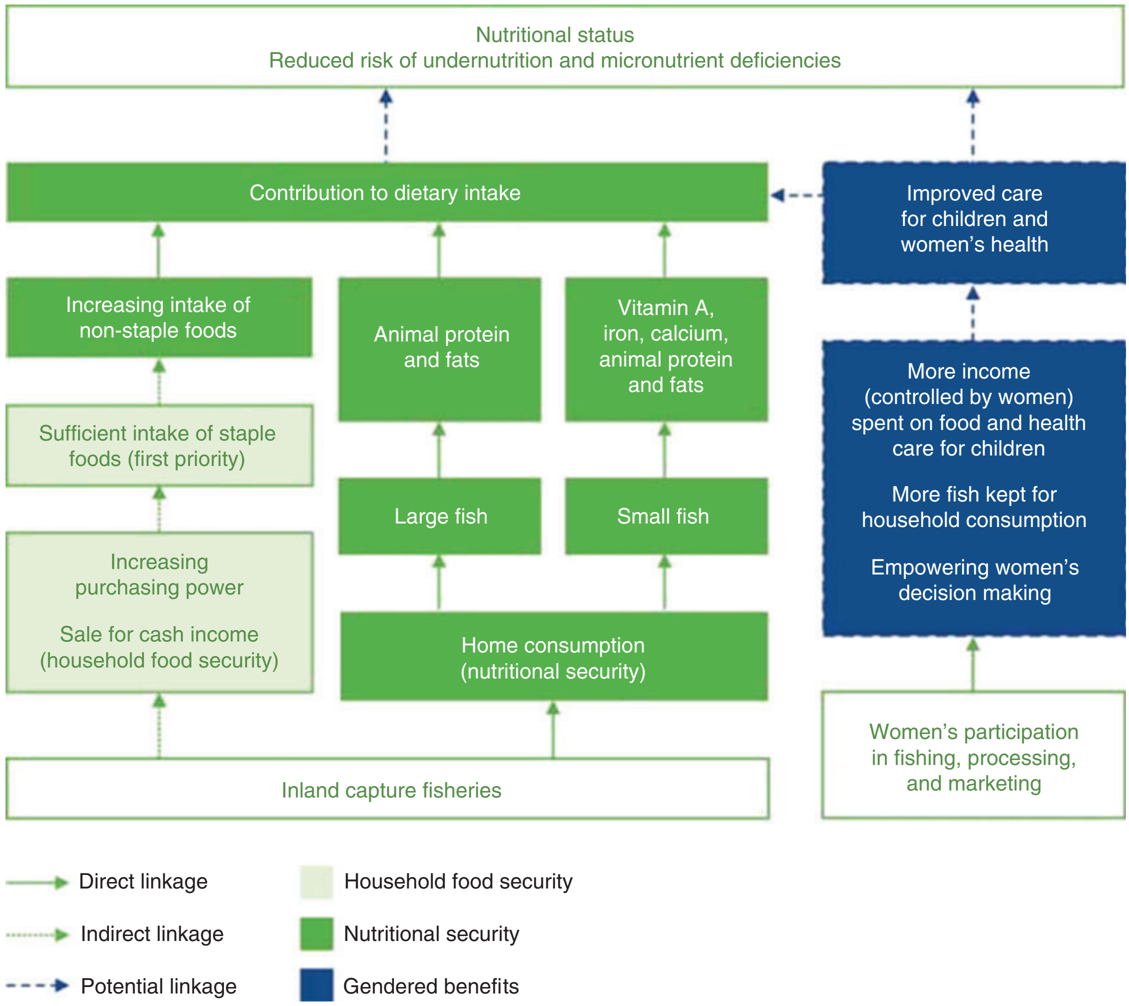

Fig. 2. Importance of inland capture fisheries to the nutritional status of vulnerable populations.

countries contribute more than 40% of this total (Lynch *et al.* 2016; Simmance and Funge-Smith 2018). In addition to being a major source of protein, fish from inland fisheries provide essential micronutrients (e.g. vitamin A, calcium, iron and zinc) and amino acids (e.g. lysine and methionine), which may not be otherwise readily available in certain communities (Roos *et al.* 2007; Kawarazuka and Béné 2010; Béné *et al.* 2015).

Inland fisheries also contribute substantially to livelihoods. The majority of inland waters provide reasonably open access to all population groups, and fishing can require minimal capital investment and gear. Consequently, inland fisheries can be an important natural resource supporting livelihoods (SDG 8 Decent Work and Economic Growth), including for women (SDG 5 Gender Equity), and food security (SDG 2 Zero Hunger), especially for poor and rural people (SDG 1 No Poverty). Livelihood functions can range from an activity of last resort through part of a traditional and diversified subsistence strategy (usually integrated with farming and the collection of other wild foods, including OAAs) to a full-time and market-oriented occupation (Allison and Ellis 2001; Béné 2003; Welcomme *et al.* 2010). Although often a part-time activity, inland fisheries employ as many as 20.7 million people globally, with up to an additional 38 million employed in post-harvest (Funge-Smith 2018). However, this does not include associated sectors, such as tourism, and the full food supply chain.

Despite this demonstrable importance, inland fisheries are often neglected by water resource developers, policy makers and planners (Finlayson *et al.* 2013). These groups regard fisheries as a supplementary activity for the economically and socially marginalised, with full-time fishing an activity for only the poorest and most deprived (Allison and Ellis 2001; Béné 2003). This is far from the truth, and the contribution of inland fisheries to society is only recently being recognised (Lynch *et al.* 2016). This is because inland fisheries are highly dispersed and the catch is often consumed by the fisher households, rather than passing through formal market channels.

Beyond food and livelihoods, inland fisheries also contribute considerably to a diverse array of ecosystem services. They are important culturally and educationally, and are represented in many religious ceremonies and archaeological artefacts. They are also of considerable importance as a leisure activity, with millions of people participating in recreational and sport fishing

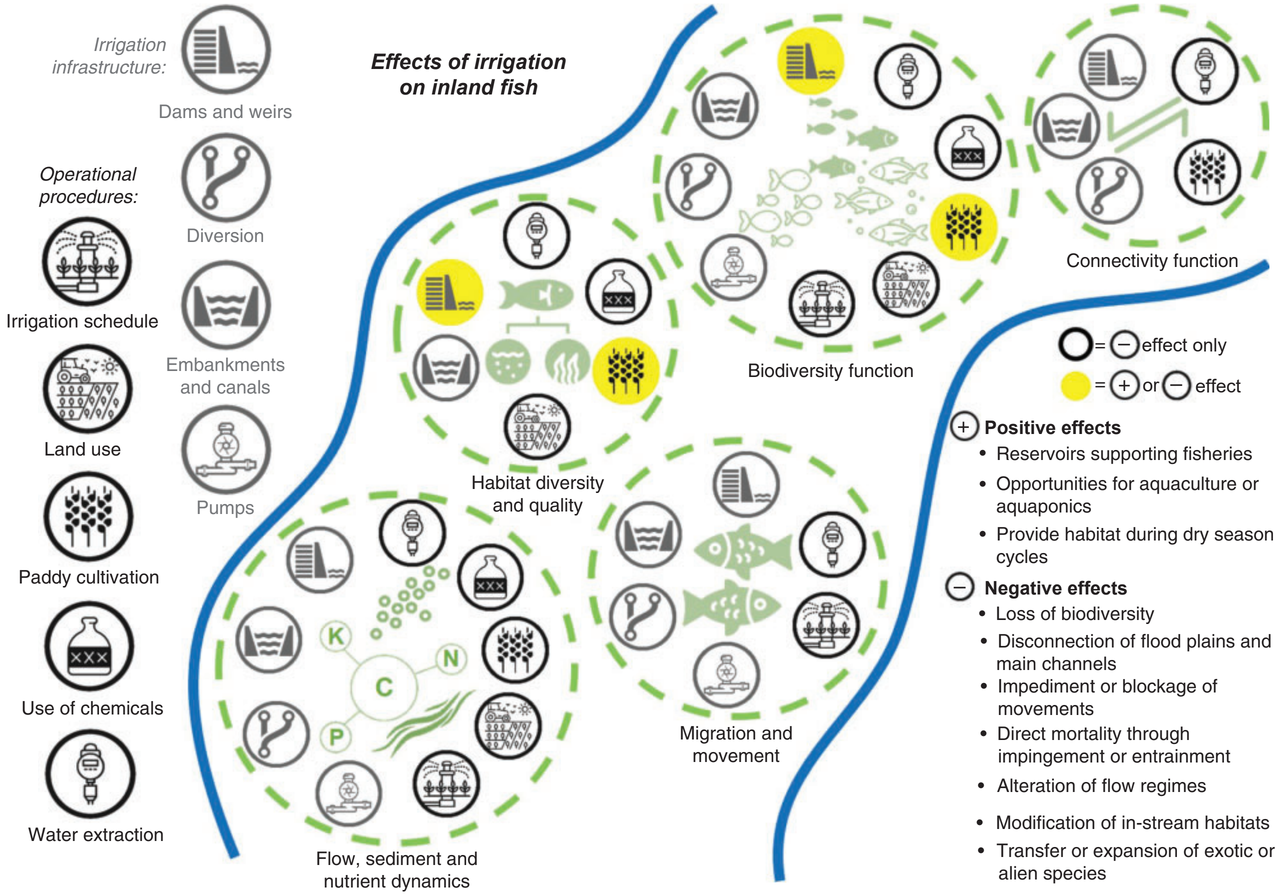

Fig. 3. Multiple effects of operational procedures (black icons) and irrigation infrastructure (grey icons) on inland ecological processes (dashed circles). Ecological processes that sustain inland fisheries include: flow, sediment and nutrient dynamics; migration and movement of organisms; habitat diversity and quality (e.g. spawning, nursery, feeding, refuge); biodiversity function; and connectivity functions. All irrigation components have the potential to affect multiple ecological processes. Irrigation operational procedures and infrastructure can all have a negative effect (icons with outline only) on inland fish but some irrigation components can also have both positive and negative effects (icons with background). See Table 1 for the full suite of potential impacts.

globally (Cooke and Cowx 2004; Arlinghaus *et al.* 2016), creating massive influxes to local economies (e.g. the aggregate annual net value of recreational fishing in the Laurentian Great Lakes is estimated up to US$1.47 billion; Poe *et al.* 2013).

Translating the effects of irrigation on inland fisheries

The expansion of irrigated lands is occurring across the globe (Döll 2002). An often-overlooked parameter is the potential interaction that irrigated agriculture can have on inland fisheries. There is a risk that some objectives of sustainable development may not be met if irrigation expansion adversely affects fisheries production (Baumgartner *et al.* 2019*a*). Thus, although food security is achieved in one sense (i.e. cropping and production), it may be offset in another (i.e. decreases in fisheries productivity). It is important to optimise the outcomes of both sectors by considering fisheries and irrigated agriculture simultaneously in development programs (Finlayson *et al.* 2013).

The development of irrigated agriculture has substantial potential to affect inland fisheries by altering aquatic ecosystem structure and function (Nguyen-Khoa and Smith 2004). However, the impact pathways and mechanisms by which this occurs are complex and varied, and often manifest over time in either negative or positive ways (Fig. 3). Nevertheless, the detrimental effects of irrigation on fisheries are more numerous than those that are favourable (Table 1), stressing the need for strong policies aiming to reduce this inequality and promote both irrigation and inland fisheries in harmony (Finlayson *et al.* 2013).

Irrigation infrastructure (e.g. dams, levees, diversion structures and intakes) can impede or block the movement of organisms, preventing them from accessing critical habitats (Liermann *et al.* 2012; Baumgartner *et al.* 2019*a*), completing critical life stages or cause direct mortality through impingement and entrainment (Baumgartner *et al.* 2009; Piper *et al.* 2013). Impoundment of water alters flow regimes (Petts 1984), in-stream and floodplain habitats (Mueller *et al.* 2011; Pelicice *et al.* 2015; Birnie-Gauvin *et al.* 2017), sediment transport dynamics (Vörösmarty *et al.* 2003) and water quality (Nilsson and Renöfält 2008). Diversion of water modifies catchment

Table 1. Range of impacts to ecological and social processes posed by irrigated agriculture, with potential solutions
For a schematic of these impacts, see Fig. 3

Processes affected	Irrigation drivers	Impact	Potential solutions
Ecological processes			
Biodiversity	Flow alteration; habitat change; migration barriers; direct abstraction	Reduced species richness and abundance	Fish assemblage and aquatic community friendly management (i.e. not single species)
Productivity, nutrient dynamics, food webs	Altered flow regimes; reduced carbon flow	Reduced riverine and flood plain productivity and nutrient dynamics; altered food webs; reduced recruitment	Provision of environmental flows; allowing flows to reach flood plains and return to the river
Spawning and recruitment	Flow regulation; migration barriers; habitat change	Loss of flow volume, variation and seasonality; loss of low to medium floods; extended periods of no and low flows; some permanent flooding	Provision of environmental flows; replicate natural seasonal cues through all water delivery; maintain source populations of species
Connectivity, movement and migration (longitudinal and latitudinal)	Infrastructure barriers (e.g. dams, weirs, levees, culverts)	Barriers or impediments to fish movements; loss of flow dynamics and cues; reduced access to spawning areas and reduced dispersal; reduced spawning and recruitment; loss of population connectivity	Remove unused structures; build fishways; provision of environmental flows; protect and replicate natural seasonal cues
Flow dynamics	Water extraction; altered flows; flow component changes	Loss of flow volume, variation and seasonality; loss of low to medium floods; permanent flooding; extended periods of no and low flows; regulation of water quantity; loss of flow cues; reduced flow variability; change in seasonality; change in habitats; change in salinity and nutrients; impacts on food webs	Provision of environmental flows; increased water-use efficiency with savings returned to the environment; deliver consumptive flows in more fish friendly manner
Provision of habitat	High-volume flows; channelisation and channel clearing; low or no flows; hydraulics	Habitat degradation; removal of in-stream woody habitats; sedimentation; conversion of lotic to lentic habitats; loss of aquatic vegetation; loss of hydraulic diversity	Habitat protection and restoration; periodic sediment flushing; weir removal
Water quality	Altered flows; agricultural run-off pollutants (e.g. nutrients and pesticides)	Reduced water quality causing fish kills and loss of spawning and recruitment; cold water pollution from low-level dam releases; blackwater and algal events	Provision of environmental and flushing flows; variable level off-takes; improved river and catchment management
Fish community	Flow alteration; habitat change; migration barriers; direct abstraction	Encouragement of alien species; stocking of impoundments; conversion of lotic to lentic habitats that favour alien species; fragmented populations	Alien species management; resilient native fish populations; improve flow delivery for fish
Mortality and population processes	Weirs; turbines; water extraction and diversion	Loss of fish diverted into irrigation channels; damage and mortality when passing fish over, under, through weirs and passing through pumps and turbines	Remove unused structures; revised weir design; refurbishment of existing weirs and fish screens
Social processes			
Recreational	Flow alteration; habitat change; migration barriers; direct abstraction	Reduced fish populations resulting in loss of social aspects and tourism; poor impression of environmental conditions	Revised governance structures with the inclusion of recreational and social values and voices in management processes
Cultural	Flow alteration; habitat change; migration barriers; direct abstraction	Reduced fish populations resulting in loss of culture and totems and provision of traditional foods	Revised governance structures with the inclusion of Indigenous values and voices in management processes

water balances (Zhuang 2016) and can act as a vector for the transfer and expansion of exotic or alien species (Jackson and Pringle 2010; Rahel 2013), as well as facilitating disease and parasite infestation in human populations. Furthermore, water diverted to irrigation is largely consumed by crop evapotranspiration, meaning that return flows are depleted and water is removed from the catchment (Lorenzen *et al.* 2007). Land use changes resulting from the expansion of irrigated agriculture often result in the loss of natural wetlands (Kingsford 2000; Finlayson and D'Cruz 2005), development of associated flood management schemes that isolate the flood plain from the main channel (Hein *et al.* 2016) and simplification of natural drainage networks (Blann *et al.* 2009). Intensification of agriculture is also frequently associated with increased use of artificial fertilisers and pesticides, resulting in elevated discharges of nutrients, sediment and other contaminants to receiving waterways (Blann *et al.* 2009; Gramlich *et al.* 2018).

This multiplicity and complexity of impact pathways means that outcomes for fisheries can be varied and difficult to anticipate (Schlüter *et al.* 2009). However, more importantly, linking the impacts back to irrigation and then aligning to achievement of the SDGs is challenging. This is largely because the development of an irrigation system is a physical, measurable, visual outcome, whereas the long, slow deterioration of aquatic ecosystems (targeted in SDG 15 Life on Land) is not. Changes to the natural flow regime, modification of instream and wetland habitats and degradation of water quality are widely reported to have caused disruptions to ecosystem function and loss of native biodiversity where irrigation systems are developed (Dudgeon *et al.* 2006; Poff and Zimmerman 2010; Mims and Olden 2013). Where communities are reliant on the persistence of native fish populations, these losses can have negative effects on food availability (Thompson *et al.* 2002; Belton *et al.* 2014), economic opportunities (Welcomme *et al.* 2010; Lynch *et al.* 2016) and cultural practices (McDowall 2011; Maxwell *et al.* 2018; Whaanga *et al.* 2018), but often these are not captured in the design of new irrigation systems or modernisation of old ones, and many of these impacts can manifest over time. In the Lao People's Democratic Republic (PDR), for example, fish harvest has been projected to decline by up to 20% because of the effects of river development (Nguyen-Khoa *et al.* 2005).

However, even when irrigation systems have negative effects on natural ecosystems, they can, in some cases, have positive implications for some fisheries (Fig. 3). There are examples of highly productive and valued capture fisheries located in reservoirs associated with irrigation infrastructure (e.g. Sarkar *et al.* 2018), as well as the potential for aquaculture expansion in some irrigation reservoirs. Reservoirs, canals and paddy fields can also provide refugia habitats that allow for increased dry season resilience for wild fisheries (Gregory *et al.* 2018). For example, under climate change scenarios or during 'normal' dry season cycles, irrigation systems can provide a year-round source of permanent water. This can create areas for fish spawning, growth and refuge that would otherwise not exist, provided the fish can access these habitats. These can be important areas for fisheries productivity and are exploited by locals dependent upon fish. In South-east Asia, the creation of rice paddies can also be an important source of fisheries and OAA productivity (Meusch *et al.* 2003; Halwart 2006), which can increase fish yields without compromising rice production (Dubois *et al.* 2019). However, it is important to ensure that these fisheries are managed sustainably to ensure access for those dependent upon them and that they are considered as important components of ending poverty and hunger alongside irrigation and cropping.

Case studies

Lower Mekong Basin

The Mekong River Basin covers 795 000 km^2 in six countries in South-east Asia (China, Myanmar, Thailand, Lao PDR, Cambodia and Vietnam) and plays a major role for food security and employment for ~60 million people living in the basin. The Lower Mekong Basin (LMB) produces 4.4 Tg of fish products per year, with more than half the production (2.3 Tg), valued at over US$11 billion, coming from inland capture fisheries (Nam *et al.* 2015). The majority of households participate in fishing in the LMB and their fishing products are often consumed locally; in Lao PDR, for example, 71% of rural households (2.9 million people) depend on fishing to varying degrees (Bishop *et al.* 2003).

Fisheries supply 47–80% of the animal protein consumed in the LMB (Hortle 2007). Average per capita consumption in the LMB is estimated at 45.4 kg year^{-1}, with Cambodia having the highest level at 52.4 kg per capita per year, followed by Vietnam (49.5 kg per capita per year), Thailand (46.9 kg per capita per year) and Lao PDR (43 kg per capita per year; Nam *et al.* 2015). These are among the highest rates of fish consumption in the world, and other animal food sources assume comparatively lesser importance in regional diets (Hortle 2007). For children, eating small fish whole is a primary accessible countermeasure to stunting and malnutrition regardless of whether big fish are caught and sold or increased amounts of rice grown (Vilain *et al.* 2016). Malnutrition in the region is still shockingly high; stunting rates of children under 5 years old are 32% in Cambodia, 44% in Lao PDR, 29% in Myanmar and 25% in Vietnam (Development Initiatives 2017), making fish a crucial resource to people who have some of the lowest access to animal sources of food already (McIntyre *et al.* 2016). Moreover, fisheries resources provide crucial income and livelihood for residents, particularly the rural poor. In addition, the cultural importance of fisheries and fish biodiversity is expressed by several cultural ceremonies in the region, including the Cambodian Water Festival, which is celebrated annually when the current of the Tonlé Sap River reverses to please the gods and ensure a good fishing season, and the local legends and proverbs particularly related to Mekong megafauna (e.g. Mekong giant catfish *Pangasianodon gigas*, giant barb *Catlocarpio siamensis*, freshwater stingray *Hemitrygon laosensis* and Irrawaddy dolphin *Orcaella brevirostris*), which symbolise the grandeur of the Mekong River.

Agricultural production and productivity in the Mekong delta increased rapidly under economic growth in Thailand and the renovation periods starting in the 1980s in Vietnam and Cambodia. However, this traditional rice-growing system produced low yields, and higher-yield varieties of rice with shorter growing periods (3 months) were introduced into the LMB to supply the growing needs for local consumption, but also for export. These high-yield rice varieties can grow up to three crops per year but, to support the farming practices, there has been an unprecedented boom in irrigation expansion across the LMB (Hoanh *et al.* 2009). Extensive canals and sluice gates have been built to transport water from the Mekong River to rice fields. Dyke systems have been constructed to protect both seasonal and permanent crop systems from flooding. For example, over 13 000 km of dykes was constructed to protect rice

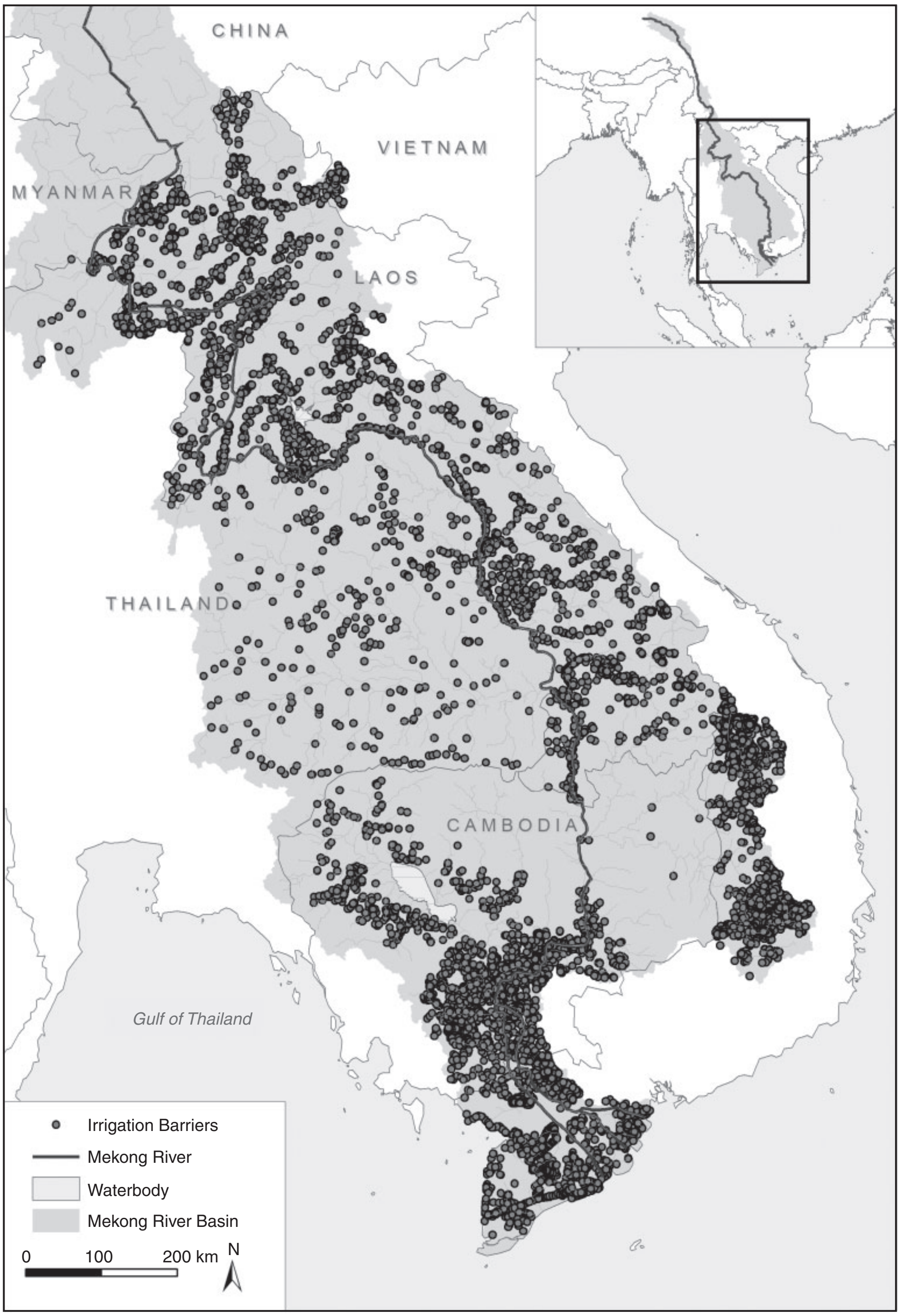

Fig. 4. Map of the irrigation infrastructure in the Lower Mekong Basin. Each dot represents a registered irrigation scheme (figure adapted from Mekong River Commission 2010).

farming in the Vietnamese Mekong delta (Triet *et al.* 2017). This has resulted in millions of hectares across the LMB (Wright *et al.* 2017) being converted to intensive, irrigated rice production and the fragmentation and disconnection of inland fisheries (Fig. 4).

Although individual governments are concerned for their fisheries and other aquatic resources, there is currently no formal regional coordination of on-ground initiatives between private investors, governments, industry, foreign aid providers and research agencies. Without this coordination, there is a risk of investment in redundant research or, worse still, the application of less than optimal technologies that are well behind current best practices. Irrigation across the Mekong is already significantly affecting fish migration routes and modifying natural hydrology (Amornsakchai *et al.* 2000). Disrupting these movement processes further will add to the existing adverse effects on the productivity of fisheries that rely on more natural conditions. A significant, often unacknowledged, issue is the substantial diversion and abstraction of water resources. There are potentially millions of fish moved from main river channels into unproductive irrigation systems annually (Baumgartner *et al.* 2009), but the scale and extent of this problem is not being investigated. Protocols to manage water gates to benefit fisheries and biodiversity, while maintaining rice production, need to be developed (Hoggarth *et al.* 1999).

In addition, properly designed fish passage facilities should be promoted to improve access for migratory fishes to irrigated systems. For example, some fishways have been engineered in the LMB to allow fish to migrate around obstructing irrigation barriers, either upstream or into flood plains for spawning and feeding. Linked to this need, the effectiveness of fishways needs to be assessed to improve design and operation (Baumgartner *et al.* 2014*b*). In addition, local governments, fisheries experts and donors should make a greater effort to share lessons learnt from other river basins and solve existing challenges in the LMB.

The role inland fish and fisheries play across the LMB is considerable, because it contains the most productive inland fishery in the world. That said, irrigation, hydropower, industrial and agricultural pollution and aquaculture are all proliferating (Baumgartner *et al.* 2014*b*), having the potential to support or damage progress towards SDGs depending on whether or not those activities progress at the expense of the health of the river and wild capture fisheries. The goal should be for sustainable development of the region so that new farming and aquaculture activities add to an already productive system.

Murray–Darling Basin

The Murray–Darling Basin (MDB) covers 1.1×10^6 km^2 in Australia's south-east (Fig. 5). Its native fish were historically important for nutritional, social and cultural values to Indigenous people before European settlement, and for food, commercial and recreational purposes to European settlers once they arrived (mid- to late 19th century for the MDB; Rowland 2005; Ginns 2012). Unfortunately, most commercial inland fisheries have been lost and their cultural and social value diminished through significant declines in MDB freshwater fish populations and local extinctions of many species (Murray–Darling Basin Commission 2004). Native fish populations within the MDB are now estimated to be at $\sim$10% of their pre-European settlement levels (Murray–Darling Basin Commission 2004). Murray cod *Maccullochella peelii* once supported a significant commercial fishery in many river systems. However, this fishery collapsed mid-last century, falling from a peak catch of $\sim 1.4 \times 10^5$ Mg year^{-1} in New South Wales in the late 1950s to less than 10 Mg year^{-1} within 1 decade, where it remained until the commercial fishery was closed in the mid-1990s (Reid *et al.* 1997).

Native fish have largely been lost as a food source for Indigenous and other local populations, mostly being replaced with locally produced or imported agricultural produce. Nevertheless, MDB native fishes still have important ecological, social, cultural and economic values (Koehn 2015), with the local communities valuing them highly, especially iconic species such as the Murray cod and golden perch *Macquaria ambigua* (Rowland 2005; Lintermans 2007). Recreational angling remains an important pastime in Australia, with a national participation rate of almost 20% and higher rates in rural areas, where it provides significant contributions to regional tourism (Henry and Lyle 2003). Although economic data for agricultural production in the MDB are fairly easy to obtain, this is not so for other important industries, such as recreation and tourism (Koehn 2015). Initial assessments of the economic contribution of recreational angling to the MDB amounts to direct expenditure at up to A$1.7 billion annually (Ernst and Young 2011).

As the importance of the MDB freshwater fishery for food declined, the value of irrigated agriculture has increased. Irrigation has been responsible for driving much of the productivity of food and fibre in the MDB and production is now at a level where the MDB is regarded as Australia's 'food bowl'. Irrigated agriculture is undoubtedly a major economic contributor to many rural and regional towns throughout the MDB. The MDB accounts for 32% of all irrigation production in Australia (A$9.6 billion) and 9% of the value of all agricultural production in the country (Meyer 2005). By consequence of this development, the MDB has become one of the world's most regulated river systems (Nilsson *et al.* 2005), and the associated proliferation of river infrastructure, flow regulation and habitat modification (Fig. 5) have been cited as major reasons for declines in native fish populations (Murray–Darling Basin Commission 2004; Davies *et al.* 2010).

The rapid development of irrigated agriculture in the MDB has meant that there was little consideration given to environmental requirements or other stakeholders (Koehn 2015). As a result, there was a multitude of unintended effects on freshwater fisheries and the communities that rely on them over the past 90 years. Water infrastructure greatly affected the natural flow regime, blocked traditional fish migration pathways along rivers and into floodplain wetlands and altered the natural habitats (Baumgartner *et al.* 2014*a*). In addition, alien species, especially carp *Cyprinus carpio*, have taken advantage of the modified environment (often a conversion of lotic to lentic habitats) and are now prevalent across the entire basin (Koehn 2004). Ultimately, as a result, the fish communities in over 80% of river valleys in the MDB are rated in 'poor' to 'extremely poor' ecological condition (Davies *et al.* 2010). Over half the MDB native freshwater fish species are of conservation concern (Lintermans 2007), affected by a range of threats, many relating to the presence and operation of water infrastructure (Koehn and Lintermans 2012).

Concerns regarding overallocation of water (Lester *et al.* 2011) became highlighted during the 1997–2010 'millennium drought' (Murphy and Timbal 2008), which greatly affected both irrigated agricultural production and environmental assets (Kingsford *et al.* 2011). Since then, recognition of the poor state of MDB rivers and fish populations, as well as

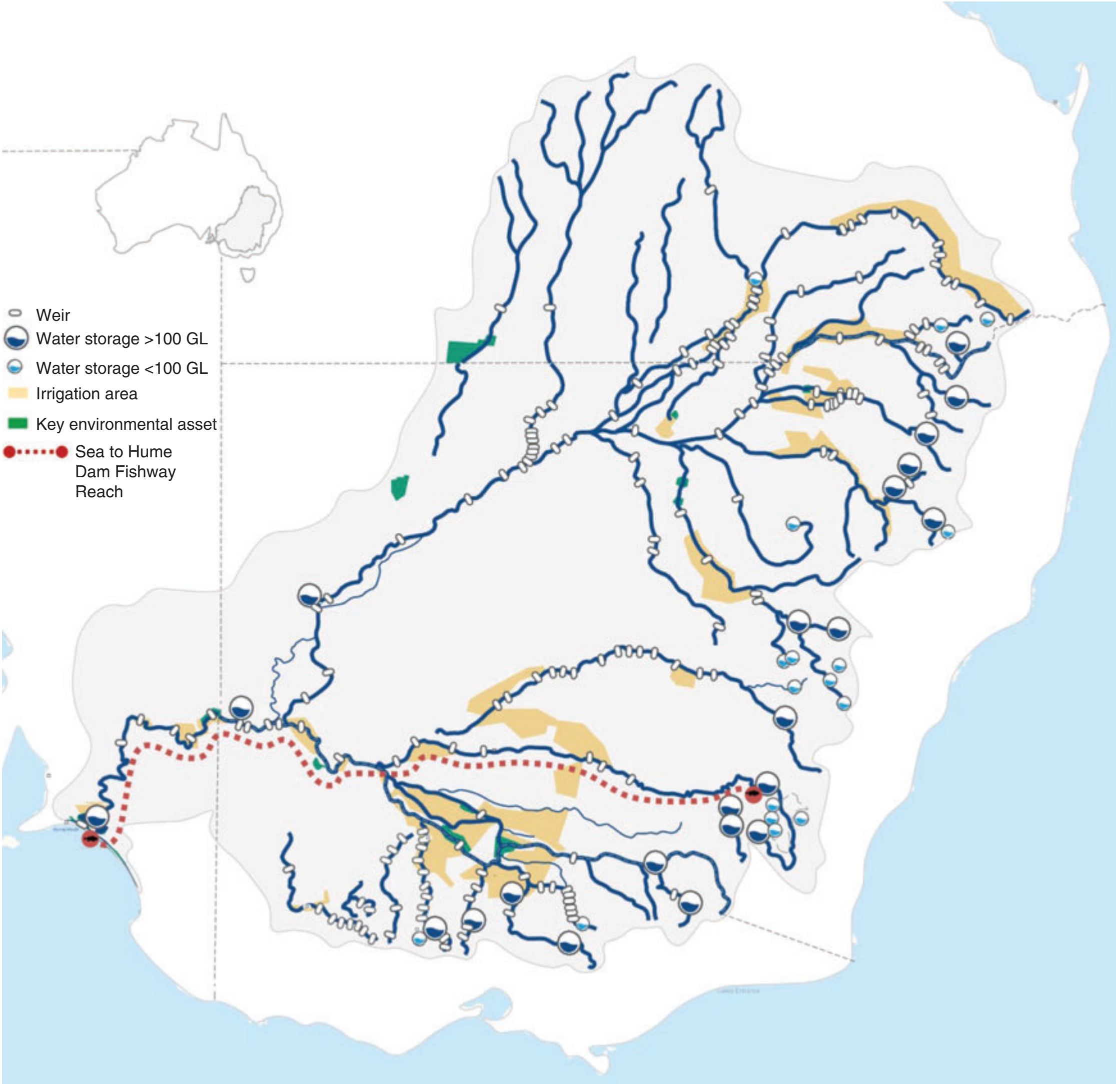

Fig. 5. River regulation in the Murray–Darling Basin, showing the location of major impoundments and regulating weirs. The dashed line shows the location of the Sea to Hume Fishway Program, where fishways have been installed on all major weirs to restore fish passage (figure adapted from the Murray–Darling Basin Authority; see https://www.mdba.gov.au/).

acknowledgement of the overallocation of river flows for extractive uses, resulted in Australia's largest water reform initiative: the Murray–Darling Basin Plan (Murray–Darling Basin Authority 2010). Only in its early stages, the Basin Plan has already proven to be highly controversial, generating immense political and public debate as it aims to reduce the consumptive use of water and provide additional water for environmental benefits, such as fish (Murray–Darling Basin Authority 2011). But, it is now accepted that the provision of water alone is not the only mechanism by which to achieve benefits (Baumgartner *et al.* 2019*b*) and that water managers should extend thinking further than just fish.

The Basin Plan is a classic example of how difficult, although not impossible, it can be to initiate policy reforms that seek to balance economic, social and environmental needs. Implementation of the Basin Plan is still in its infancy and its future is far from secure. Despite this, there is good reason to believe that, through a reduction in extractive water use and better managed water delivery that strategically targets ecological objectives, the values of inland fisheries can be improved. A recent economic report suggests that if environmental flows are managed with native fish as an objective, the full implementation of the Basin Plan could result in the overall value of the inland recreation and commercial fishing industry, estimated at A\$1.14 billion (Colquhoun 2015), to increase by A$\$28 \times 10^6$ year^{-1} in addition to the agricultural value of the Basin Plan outcomes. The Deloitte Access Economics economists commissioned by the Murray–Darling Basin Authority conclude that '…this is a function of both improved amenity values associated with the recreational fishing experience, and through increases in the populations of fish with economic value, predominantly Murray cod and golden perch' (Murray–Darling Basin Authority 2012).

As implementation of the Basin Plan continues, the MDB community of scientists, natural resource managers and the public are waking up to the realisation that delivering on the Basin Plan objectives and striking a balance between irrigated agriculture and the sustainability of fisheries will require a far more nuanced approach than 'just adding water' (Finlayson *et al.* 2017; Conallin *et al.* 2018). However, this multi-faceted approach to recovering native fish populations had been around for some time, most prominently in the form of the Native Fish Strategy (NFS; Murray–Darling Basin Commission 2004; Koehn and Lintermans 2012). The NFS had an overall goal to rehabilitate native fish communities back to 60% or more of their estimated pre-European settlement levels within 50 years of implementation (Koehn *et al.* 2014). NSF interventions have been part of a more holistic approach towards incorporating other values and meeting multiple objectives, not just those of irrigation (Koehn and Lintermans 2012).

Although funding to the NFS was discontinued after less than 10 years into the 50-year plan (Koehn *et al.* 2014), there are renewed calls for its reinstatement following recent catastrophic fish deaths in the MDB (Baumgartner and Finlayson 2019). Rather than focusing purely on environmental flow delivery, the core philosophy of the NFS was to address a range of complementary threats posed by irrigated agriculture; the NSF, although only active a short time, led to on-the-ground solutions that, to this day, continue to be trialled or advocated for in the MDB (see Table 1). Examples of successful programs included the provision of environmental flows to enhance fish spawning and recruitment (King *et al.* 2010) and the Sea to Lake Hume fishways program that constructed 15 fishways to provide fish passage along 2225 km of the Murray River (Fig. 5; Barrett and Mallen-Cooper 2006). Not only did this latter program contribute to the knowledge of fish movements and provide appropriate design, testing, construction and monitoring of fishways (Barrett and Mallen-Cooper 2006), but associated research also addressed other instream barrier-related issues such as the loss of larvae into irrigation channels (King and O'Connor 2007) and damage when passing over weirs (Baumgartner 2006) or by irrigation pump extraction (Baumgartner *et al.* 2009). This has subsequently led to research and development of activities to screen irrigation diversions (Baumgartner and Boys 2012; Boys *et al.* 2013). The NFS harnessed significant community support for on-the-ground actions to reduce similar impacts (see Table 1). There are considerable difficulties of managing water and fishes across the six legislative jurisdictions of the MDB with a myriad of different agencies, but the NFS demonstrated that multi-disciplinary and jurisdictional governance models for research, management and community engagement can allow for multiple values and ownership to be considered when aiming to promote economic, social and environmental outcomes (Koehn and Lintermans 2012).

Undoubtedly, irrigated agriculture will continue to underpin the economic development of communities within the MDB. However, we cannot lose sight of the fact that this development comes at a cost and that there have already been significant effects on important cultural, recreational and biodiversity services in the MDB. The dams that inhibit spawning, recruitment and growth rates because of their deep cold-water releases cannot be removed, but structural changes could be made to ameliorate their effects (Sherman *et al.* 2007). From decades of research and management interventions to restore native fish populations in the MDB, lessons have been learned on how difficult it can be to balance the development of irrigated agriculture with sustainability of inland fisheries. The reforms undertaken in the MDB are highly controversial and future reforms and the eventual impact on industry remain uncertain. Reforms come at a significant cost. To date, US$9 billion has already been committed to recover water for the environment. Much more will need to be spent on complementary measures that address the effects of river infrastructure and habitat degradation (e.g. Table 1; Finlayson *et al.* 2017; Baumgartner *et al.* 2019*b*). Yet, what is certain is that the reforms are courageous and ambitious. They have needed to be, such has been the huge pressure placed on MDB natural systems. If one lesson can be learned from the MDB experience to guide the pursuit of SDGs in the developing world, it is that fisheries losses can be difficult and costly to recover, and that preventing these impacts in the first place may be far more cost-effective than trying to remedy them later.

Mediating impacts across systems

Although these two globally important river basins have vastly different stakeholders, services, irrigation interventions, constraints and opportunities, there are many commonalities that can be applied more broadly across the globe. Maintaining fisheries could compromise agricultural production and, indeed, will come into conflict (Jaramillo *et al.* 2019). These adverse effects and conflicts can be minimised through proper management in a transparent manner. National governments have plans to expand agricultural production further and extend irrigated lands and infrastructure to meet demands for staple foods, with the financial support from development banks and donors (Alexandratos and Bruinsma 2012). The expansion of irrigated agriculture will cause further ecosystem disruption and negative effects on fish production and aquatic biodiversity (e.g. barrier impacts, flow alteration, pesticide and antibiotic contamination and mortality, habitat loss and connectivity disruption, and diversion- and pumping-induced injuries and mortality; see Table 1). To double agricultural productivity and incomes of small-scale food producers, access to land, water and a healthy and functioning ecosystem is required (Gregory *et al.* 2018), but these needs are largely ignored in development agendas with dire consequences for many aquatic ecosystems (Ramsar 2017).

There is a significant opportunity to ensure that fisheries and OAAs are acknowledged and addressed in development agendas by integrating them through modernisation programs (Baumgartner *et al.* 2019*a*; McCartney *et al.* 2019). For example, approximately US$3 billion is being invested in Indonesia alone over the next 3 years to update and modernise failing irrigation infrastructure (World Bank 2018). However, the development challenge is how to increase agricultural productivity without compromising fisheries productivity. The SDGs can provide the framework needed for cross-sectoral collaboration. Irrigation and fisheries scientists and managers can work together to minimise possible impacts on fish stocks and aquatic biodiversity. This can be achieved by determining the value of ecosystem services delivered by fisheries in irrigated systems (e.g. food, livelihoods, recreation, wellbeing, cultural services) and of the aquatic systems themselves (e.g. suppression of pest insect vectors, nutrient cycling, control of algae), as well as by promoting sustainable farming practices. There is also a significant opportunity to integrate irrigation expansion across government portfolios. Presently, the role of irrigation modernisation falls within the remit of irrigation agencies. Often, these are single-objective agencies that are now being expected to deliver multi-objective outcomes. Many agencies are not equipped to consider issues other than watering crops, so creating greater collaborative links with fisheries and natural resource management agencies will be essential if integrated 'win–win' outcomes are to be achieved.

The most significant way to achieve sustainable outcomes is to modernise engineering criteria for the design and operation of infrastructure, including, in some cases, the use of guidelines on development procedures (King and O'Hanley 2016). Although there is no substitute for a naturally functioning system, the negative effects of sustainable irrigation can be partly overcome with engineering solutions (Peterman 2004). Interventions such as the construction of fish passage facilities, hatcheries, mechanisms for natural flooding of irrigated areas and provision of environmental flows can be useful engineering strategies. Because many countries have irrigation modernisation programs that are driven by donor investors such as the World Bank, Asian Development Bank and Japanese International Cooperation Agency, recognition by the investors that agricultural production is only one component of the food and livelihoods portfolio of the SDG framework will be key to implementing improved design and operation for environmental outcomes. This is a critical, and fundamental, cultural shift for donor bodies that is needed to help progress SDGs holistically.

SDGs as a common language across sectors

Inland waters provide a range of ecosystem services that are important for human wellbeing, including food, nutrition, water and livelihood security (Finlayson and D'Cruz 2005), and, as such, they constitute a major component in meeting the SDGs, in particular SDG 1 (No Poverty), 2 (Zero Hunger), 3 (Good Health and Wellbeing), 5 (Gender Equity), 6 (Clean Water and Sanitation), 7 (Affordable and Clean Energy), 8 (Decent Work and Economic Growth), and 15 (Life on Land); for more details, see table 3-1 in Simmance and Funge-Smith (2018). However, increasing demands for food (and the water that is needed to produce it) mean that aquatic ecosystems and the inland fisheries they support are under constant and increasing pressure. Their continued degradation is having serious (and sometimes irreversible) consequences on the capacity to deliver on the SDGs. Increasingly, difficult decisions will need to be made regarding trade-offs, particularly as resources (e.g. water, fish, energy and funding) become scarce and competition intensifies (Fader *et al.* 2018). The governance, management and conservation strategies, by necessity, will be context dependent in addressing fisheries and agriculture trade-offs (Blanchard *et al.* 2017). However, the comprehensive SDG agenda can be used as a common platform for the multi-disciplinary discussions that will be needed to ensure these trade-off decisions are made in a way that is transparent, consultative, equitable and on the basis on common and trusted data.

With an increasing number of governments pursuing SDG policies, investment plans and roadmaps for localisation, global commitment to the SDGs continues to grow. Donors are demonstrating a willingness to provide financial support to national SDG processes; by adopting SDG language and framing, inland fisheries advocates can increase access to donor and government capital and seek to influence new policies. Leveraging government commitment to the SDG agenda can also be used to strengthen the arguments needed to convince irrigation practitioners that the cost of modifying scheme designs to benefit fisheries can be offset by benefits under a range of different SDGs. Fishery activities may be significant in terms of economic value, but it is foremost to estimate the impact on nutrition, jobs and livelihood support that fisheries and aquaculture provide, especially for the most vulnerable (Meusch *et al.* 2003). SDG commitments can be used by advocates to highlight the multitude of benefits under a range of SDGs (e.g. Lynch *et al.* 2017) and push for design and policy changes before large-scale irrigation investments in extension, rehabilitation or modernisation are finalised.

SDG 2 as an example

At the 2018 Fish Passage Conference in Albury, Australia, we conducted a workshop to investigate the relationships between irrigation, inland fisheries and achievement of the SDGs; this article was developed as a result of that workshop. We chose to focus on SDG 2 (Zero Hunger) as an example, because inland fisheries and agriculture contribute substantially to this goal. Using a polling approach, we gathered the opinions of the workshop participants to compare the contributions of inland fisheries and irrigation in achieving the eight targets of SDG 2 in our two case study basins, the LMB and the MDB. Participants indicated that fish and irrigation both provide a strong contribution to achieving SDG 2 targets. The group identified some key challenges with this comparison in that achieving SDG 2 required contributions from both sectors. Inland fisheries and irrigation both underpin food security (Hussain and Hanjra 2004; Lynch *et al.* 2017). To end hunger, improvements are needed in agriculture and aquaculture systems; likewise, aquatic ecosystems need to be restored and maintained to sustain wild-capture fisheries and other services. If there is a strong focus on irrigation, the negative effects on capture fisheries may negate the benefits from investments in improving irrigation practices. However, optimising irrigation interventions can help reduce impacts on fisheries while increasing agricultural production (Table 1).

Desirable irrigation practices can include ecologically minded modernisations to water capture, diversion, delivery and storage (e.g. in- or off-channel), as well as managing drainage and return flows, facilitating multiple-use systems (e.g. linking agriculture and aquaculture), and ecologically sensitive application of fertiliser and pesticides. In some cases, decision makers may even decide that no irrigation is the most appropriate course of action (e.g. more value in keeping the water in the main river channel for other ecosystem services). These approaches can facilitate a true 'win–win' outcome in that

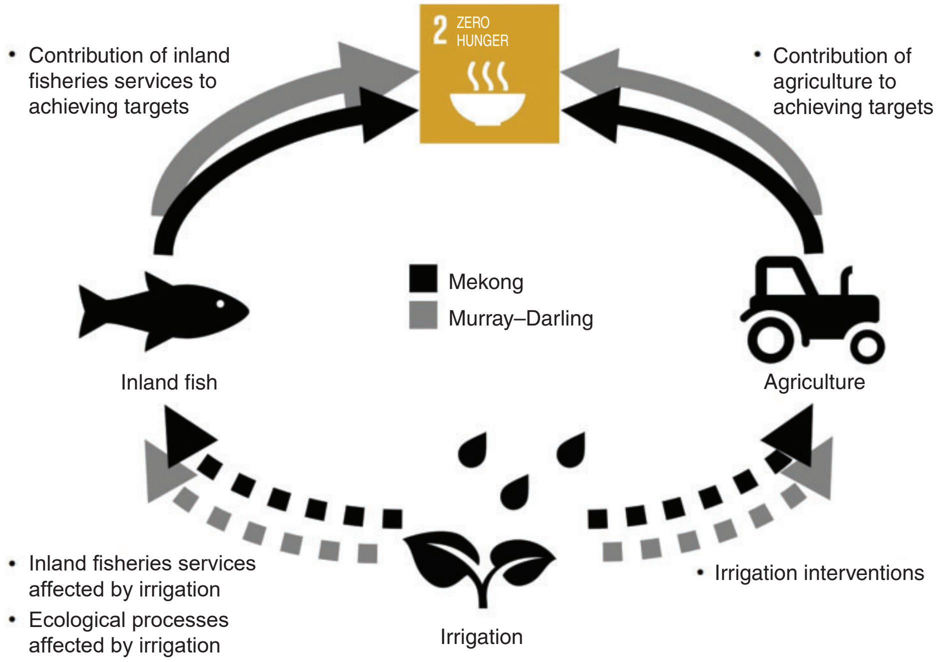

Fig. 6. Relationships between irrigation, inland fish and the contributions to Sustainable Development Goal (SDG) 2 (Zero Hunger) for case study basins (Lower Mekong Basin in black, Murray–Darling Basin in grey; the strength of importance (thickness of arrows) was identified through the workshop polling exercise). Irrigation interventions can improve agricultural production to help achieve SDG 2, but may also hinder contributions of inland fish to achieving SDG 2, depending on how the interventions are implemented (indicated by dashed arrows).

by optimising the system holistically, human nutrition, livelihood and wellbeing benefits can exceed what they would have if each sector operated in a silo (Fig. 6). The SDGs provide the framework for local and national governments, as well as development agencies, to operate using optimised approaches that are internationally and nationally relevant.

Keeping the conversations going

The current era of extensive irrigation expansion does compromise many fisheries priorities and this should be compelling decision makers to devise progressive policies that address environmental sustainability, food security, economic and social wellbeing (Fig. 1). Growing local, national and international commitment to the SDG agenda presents an opportunity to accelerate the changes that are needed. Inland fisheries is a sector that urgently needs to be incorporated into environmental governance strategies to protect and restore broader ecosystem services such as water and environmental integrity, land and watershed rehabilitation, reforestation, wetland management, water and nutrient cycling, water storage and carbon sequestration (Gregory *et al.* 2018).

If properly planned and implemented, these integrated policies will positively affect freshwater environments and directly or indirectly benefit inland fish and fisheries and the communities that depend on them for their livelihoods, food security, health and wellbeing (Fig. 6). The way forward calls for ecosystem-based approaches that promote the integration of fisheries and irrigation systems (Table 1; Neely *et al.* 2017; Gregory *et al.* 2018). Broad participation of stakeholders in modernisation processes can make visible the true value of ecosystem services, better inform management on trade-offs, help sustain their ecosystem services to benefit human society and development goals and ensure both a balanced development and an equitable distribution of the benefits.

The evidence from the case studies presented herein shows that it can be difficult to initiate policy reforms that seek to rebalance the social, economic and ecological needs across large and complex river basins. Irrigation has and will continue to support economic development and reduce hunger and poverty globally; the opportunity through the SDG framework is to ensure this is done without detriment to fisheries productivity and the wider environment. Commitment to the SDGs provides an opportunity to ensure the ecological cost of further irrigation does not go too far (*sensu* Falkenmark *et al.* 2007). Greater collaborative links between irrigation, fisheries and other natural resource agencies will be required to ensure that increased food production from irrigation can occur without further compromising fisheries production and the aquatic environment that is already under immense pressure (Ramsar 2017). Establishing these links is essential if a holistic approach is to be developed as a major contribution to meeting the demands of growing populations by achieving SDG 1 (No Poverty) and SDG 2 (Zero Hunger) and other development and biodiversity goals. Calls for holistic approaches are not new, but have been difficult to achieve, as witnessed by the experiences outlined from the MDB and LMB.

Conflicts of interest

This work was developed through a workshop held at the Fish Passage 2018 conference in Albury, Australia, and supported generously by Charles Sturt University. Lee Baumgartner and Luiz Silva are an Associate Editors and Colin (Max) Finlayson is the Editor-in-Chief at *Marine and Freshwater Research* and John Conallin is a guest editor of this research front, but they played no part in the review and acceptance of this manuscript.

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