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Rethinking irrigation modernisation: realising multiple objectives through the integration of fisheries

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Abstract. Irrigation has been, and will remain, instrumental in addressing water security (Sustainable Development Goal (SDG) 6), food insecurity (SDG 2) and poverty (SDG 1) goals. However, the global context in which irrigation takes place is changing rapidly. A call for healthier and more sustainable food systems is placing new demands on how irrigation is developed and managed. Growing pressures from competing water uses in the domestic and industrial sectors, as well increasing environmental awareness, mean irrigation is increasingly called on to perform better, delivering acceptable returns on investment and simultaneously improving food security, rural livelihoods and nutrition, as well as supporting environmental conservation. Better integration of fisheries (including aquaculture) in irrigation planning, investment and management can contribute to the modernisation of irrigation and the achievement of the multiple objectives that it is called on to deliver. A framework illustrating how fisheries can be better integrated with irrigation, and how the two can complement each other across a range of scales, from scheme to catchment and, ultimately, national level, is presented.

Additional keywords: aquaculture, inland fisheries, integrated management, sustainable agriculture.

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Introduction

Sustainable agriculture is at the heart of the global 2030 Agenda (United Nations 2019). It is a prerequisite for achieving zero hunger (Sustainable Development Goal (SDG) 2) and, because so many people depend on agriculture for their livelihoods, it is also central to poverty alleviation (SDG 1). Most other SDGs (in particular SDGs 3, 5, 6, 8, 12, 13, 14 and 15) are also influenced, to some extent, by agriculture and agricultural practices (Mollier *et al.* 2017; Food and Agriculture Organization of the United Nations 2018*a*). Although many of the SDGs touch on issues related to agriculture, SDG indicator 2.4.1 (Proportion of Agricultural Area Under Productive and Sustainable Agriculture) specifically measures progress in the environmental, economic and social dimensions of sustainable agricultural production.

Delivering sustainable agriculture is a complex multidimensional challenge that has been extensively discussed and debated over the past three decades, but no common definition or solutions have been agreed upon. Agriculture is arguably the world's single largest driver of environmental change, including biodiversity loss (Millennium Ecosystem Assessment 2005; Rockström *et al.* 2017) and a major contributor to breaches of the global 'planetary boundaries', which define the safe operating space for humankind (Steffen *et al.* 2015; Jägermeyr *et al.* 2017). Because sustainable agriculture promotes the judicious use of natural resources, including water and land, and because ecosystem health relies on the preservation of remaining tropical forests and freshwater aquatic ecosystems, among others, sustainable agricultural water and irrigation management are key to achieving sustainable agriculture and for maintaining ecosystem health.

Inland fisheries are a vital source of food, nutrition and livelihoods in many places in the world. In Asia and elsewhere, many small-scale farmers are also part-time fishers. Considering both aquaculture and capture fisheries, inland fisheries contribute over 40% of the world's capture finfish fisheries and aquaculture production, the remainder being marine fisheries (Lynch *et al.* 2016). Over 90% of global inland capture fisheries production is used for human consumption, most of which is in the developing world (Welcomme *et al.* 2010). Inland fish are particularly important in addressing 'hidden hunger' (micronutrient deficiencies and their related health issues; e.g. Kennedy *et al.* 2003). Inland fish provide protein, vitamin D, calcium, B vitamins, vitamin A, iron, zinc and lysine where other nutritional sources are unavailable or cost-prohibitive (Béné *et al.* 2015).

Construction of irrigation infrastructure (headworks, canals, dams and gates) changes riverine ecosystems, often with adverse effects on aquatic biodiversity, important both as an ecosystem service and an essential underpinning of healthy and resilient inland fisheries (Lorenzen *et al.* 2007). However, overall effects on fish productivity at local scales depend on whether irrigation reservoirs, ponds and canals can provide alternative fish habitat. Dams, barrages and diversion weirs generally act as barriers to fish migration and, by blocking access to spawning areas, can result in declines in migratory fish populations both up- and downstream and on flood plains (Larinier 2000). Associated changes in the timing and volume of river flows, especially those flows that inundate flood plains, can also significantly undermine fish and fisheries (McCartney *et al.* 2018). Typically, irrigation systems are also associated with increased use of chemical fertilisers and pesticides, which pollute water and can kill fish if applied inappropriately. As a consequence of these impacts, fishery declines are common in areas where intensive irrigated agricultural systems have been developed (Khoa *et al.* 2005; Schlüter *et al.* 2009).

Given growing natural resource degradation and demand for water resources in non-irrigation uses while irrigation needs continue to rise, there is increasing recognition of the need to bring about drastic changes in irrigation planning, investment and management for enhanced sustainability. Irrigation 'modernisation' is an approach to address the increased challenges and changing context in which irrigation takes place but is currently limited primarily to optimising crop production (Playán and Mateos 2006; Burt 2013). This paper argues that rethinking modernisation is necessary: it should espouse a broader remit, encompassing multiple objectives, including improved integration of fisheries (both capture fisheries and aquaculture). Safeguarding and enhancing fisheries as part of irrigation modernisation is a prerequisite for achieving multiple objectives and essential for achieving sustainability in modernised irrigation systems.

Irrigation: past and present

The ability to make water available and distribute it to fields is essential for agricultural intensification and increasing food production in many, particularly semi-arid and arid, parts of the world. In 1800, irrigation totalled ~8×10^6 ha globally; by the end of the 19th century, irrigated area had expanded to 48×10^6 ha, mostly as a result of large irrigation infrastructure development in India and in what is now Pakistan (Postel 1989). However, it was the Green Revolution, from the 1960s, that drove the largest increase in irrigation development. It is estimated that, worldwide, irrigated area approximately doubled in the past 50 years (Foley *et al.* 2011). Modern high-yielding varieties (HYVs) of staple crops (i.e. rice and wheat in high-potential areas, followed by maize) that underpin the significant yield increases achieved by the Green Revolution are dependent on a regular supply of water (and hence irrigation) throughout the tropics and subtropics. The production of rice and wheat in developing countries increased 75% between 1965 and 1980, with only a 20% increase in the area planted to these crops (Fitzgerald-Moore and Parai 1996). Today, 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*b*).

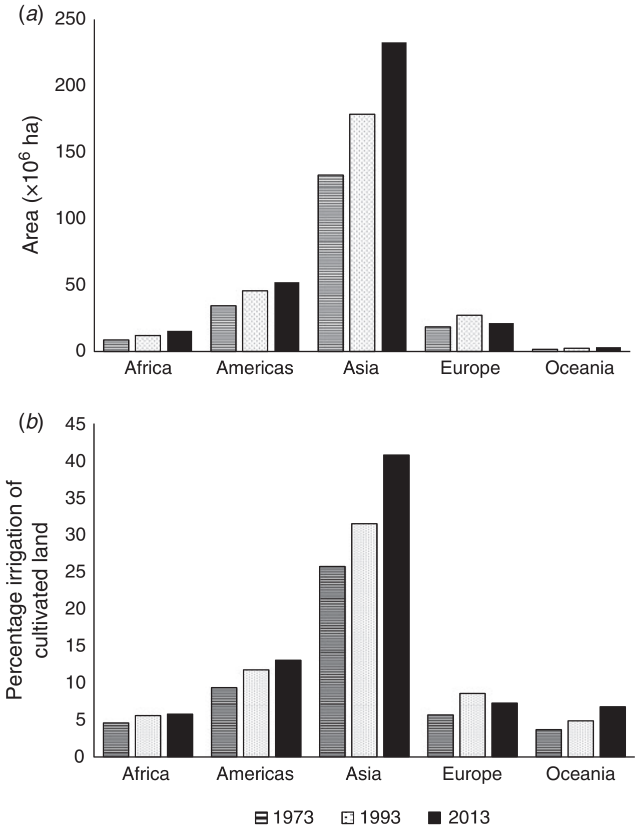

Fig. 1. (*a*) Total area equipped for irrigation and (*b*) irrigation as a share of cultivated land in 1973, 1993 and 2013. (Source data from Food and Agriculture Organization of the United Nations 2014.)

Currently, the Food and Agriculture Organization of the United Nations (2014) estimates that over 324×10^6 ha is equipped for irrigation, of which ~85% (275×10^6 ha) is actually irrigated, but there are significant differences between regions (Fig. 1). Approximately 70% of irrigated areas are in Asia (~220×10^6 ha equipped for irrigation), of which 45% is concentrated in just two countries: China (69.4×10^6 ha equipped) and India (66.7×10^6 ha equipped). In Latin America, 16×10^6 ha has been equipped (14% of the cultivated area). By contrast, it is estimated that, in Africa, 7.7×10^6 ha has been equipped (just over 6% of the cultivated area) and, of this, more than two-thirds is concentrated in just five countries: Egypt, Algeria, Morocco, South Africa and Sudan (Malabo Montpellier Panel 2018). However, there is considerable uncertainty in these figures, which rely primarily on census data that are updated infrequently. Moreover, the data often fail to capture small-scale, community-managed systems as well as 'informal', individual, also dubbed ‘farmer-led’, irrigation development, where smallholders are irrigating their fields by diverting streams, digging canals, redirecting rainfall drainage or pumping from surface or groundwater resources (Woodhouse *et al.* 2017). A recent study in Tanzania found that in some, although not all, instances irrigated area estimated using remote sensing was significantly greater than that reported in census figures (S. Bowers, D. Brockington, H. Komakech, C. Ryan, G.-J. Veldwisch, J.-P. Venot, and P. Woodhouse, unpubl. data). Alternative national values have been proposed for some countries. For example, the Commission for Africa estimated 13×10^6 ha under irrigation in Africa in 2005 (Lankford 2005).

In places, irrigation makes it possible to cultivate the same area more than once per year. Global average cropping intensity, estimated at 130%, suggests that total harvested irrigated area is currently $\sim 350 \times 10^6$ ha (Food and Agriculture Organization of the United Nations, 2018*b*).

Future trends in irrigation

Irrigation can, when adequately planned and managed, contribute not only to significant increases in agricultural production, but also to food security, poverty alleviation, rural employment, improved diets and economic development (Lipton *et al.* 2003; Hussain and Hanjra 2004). Governments also recognise that under changing climatic conditions, investments in irrigation can represent a pragmatic form of adaptation, particularly in Sub-Saharan Africa, where both intra- and interannual variability in rainfall is high (Malabo Montpellier Panel 2018). This reflects demands by households, who often list irrigation as their most preferred, but not implemented, adaptation strategy. As an example, among farmers in a household survey of various agro-ecological zones in Kenya, almost half (49%) of all farm households interviewed listed irrigation investment as their preferred adaptation strategy (Bryan *et al.* 2013). This desire was confirmed by focus group discussions, in which irrigation and water harvesting schemes were ranked as the priority adaptations regardless of gender and agro-ecological zone (Bryan *et al.* 2013). In more arid environments, where individual farmers lack the financial resources and knowledge to access water from rivers, streams or shallow groundwater, irrigation requires support by the government or non-governmental organisations (NGOs) to invest in water control infrastructure (e.g. ponds, weirs or reservoirs). However, there is the risk that if not adequately planned, large-scale irrigation infrastructure in semi-arid and arid areas can increase vulnerability. Paradoxically, irrigation systems intended to reduce exposure to risks associated with rainfall variability can, by encouraging the growth of water-intensive crops (e.g. rice and sugarcane) in water-scarce areas, amplify the effects of extreme weather events and, hence, ultimately be maladaptive (Lankford 2004; Damania *et al.* 2017).

There is still potential to expand irrigated area in all regions of the world, and many governments continue to invest in irrigation as a cornerstone of food security and rural development. Furthermore, there is increasing investment in both formal and informal irrigation by the private sector, increasingly by farmers themselves (de Bont *et al.* 2019). Under ‘business as usual’, total harvested irrigated area is expected to increase by 12% to 394×10^6 ha by 2030, with the largest increase (44%) projected for Sub-Saharan Africa, followed by South Asia and Latin America and the Caribbean (15% each; Ringler 2017). Approximately 90% (39×10^6 ha) of the total increase in harvested irrigated area between 2010 and 2030 is expected to be in developing countries. Average annual costs of expanding irrigation across all developing countries to 2030, are estimated at US$7.87 billion (Ringler 2017). Because of the many benefits of irrigation, there are advocates for accelerated investment in irrigation, particularly in Africa where net food imports are rapidly growing (Malabo Montpellier Panel 2018; Xie *et al.* 2018).

Limitations of current irrigation

Despite a recognised need for increased irrigation and substantial continued investment in many places, and despite modern technology and advanced scientific understanding, many irrigation systems suffer from serious problems. Many systems do not operate at the aspirational levels intended in designs (Lankford *et al.* 2016). Funds for operation and maintenance are often inadequate, leading to breakdowns of pumps, silting of headworks and canals, and non-functioning gates. In many places, schemes are unable to supply water effectively during dry seasons and droughts and, conversely, many are susceptible to damage during floods. Moreover, synergies with other water users, such as municipalities, aquaculture systems or hydropower stations, are seldom developed as irrigation schemes continue to be largely planned and managed in isolation (Lankford 2004; Furlong *et al.* 2016). Schemes are often designed solely for the irrigation of a single crop (e.g. rice) and there is little flexibility in the timing and volume of water delivery. Although this can be an advantage for operational efficiency, farmers on such systems may have little choice in what crops they grow: an important constraint as both market prices and farmers’ socioeconomic aspirations change over time.

Frequently, governance structures are weak and do not adequately support the management of complex irrigation systems. A further sign of inadequate management is insufficient availability of irrigation water for farmers at the end of canal systems, so-called tail-end farmers (Bell *et al.* 2014). In Asia, in particular, this has driven the rapid expansion of tube wells, which increases the reliability of supply for farmers, but has, in places, led to rapid declines in groundwater levels and makes water increasingly difficult to manage and control. All too often, schemes are caught up in a vicious cycle of (too often poor) construction, deferred maintenance and costly rehabilitation (Johnston *et al.* 2013). Typically, farmers are unsatisfied and, with exceptions, governments and donors question the returns achieved on irrigation investments (Inocencio *et al.* 2007; Kumbhare and Sen 2008).

Typically, impact assessments of irrigation schemes, when implemented at all, have failed to adequately assess the environmental implications and other, unintended, consequences of irrigation development, which often undermine long-term sustainability and system resilience. In many places, water resources are overexploited and, worldwide, aquatic ecosystems are rapidly degrading (Vörösmarty *et al.* 2010). Irrigation remains the largest human freshwater withdrawal, at 70% globally and more than 80% in developing countries (Siebert and Döll 2010). A recent study suggests that global water withdrawals for irrigation, estimated at 2409 km^3 $year^{-1}$, represent an overexploitation of water needed to sustain riverine ecosystems of 997 km^3 $year^{-1}$ (Jägermeyr *et al.* 2017). Furthermore, to fully preserve environmental flows would lead to production declines on more than half the global irrigated croplands and, in the absence of compensating interventions, a total global decline in production of around 5% (Jägermeyr *et al.* 2017). Thus, we are currently trading off irrigated food production with the preservation of natural ecosystems and the many ecosystem services that they provide, including fisheries (Crossman *et al.* 2010).

Adapting irrigation to achieve multiple development objectives

Today's irrigation needs to be enhanced to meet the needs of a changing world. Many of the influences that drove past irrigation development (e.g. population growth, poverty alleviation and economic development) continue to be priorities. However, consideration must also be given to increased water demand from other sectors (e.g. cities, industry and hydropower; Molle and Berkoff 2006) and negative effects on ecosystems and biodiversity, including fish, must be avoided or mitigated (Rockström *et al.* 2017). The focus of irrigation needs to shift from simply maximising crop yields to a much more ambitious approach of maximising net benefits across a range of uses of irrigation water and to do so within a total envelope of net irrigation consumption appropriate to each river basin. This is a much more challenging concept in which multiple objectives need to be considered and the opportunity costs of water need to be explicitly factored into analyses (English *et al.* 2002).

Many of these objectives can be achieved by encouraging production diversity in irrigation systems, strengthening measures that support income growth through irrigation, supporting measures that provide irrigation for water supply, sanitation and hygiene, and through strengthening women's empowerment and reducing the time they spend in agriculture through irrigation interventions (Domènech 2015). Better integration of fisheries in irrigation systems could support the production diversity pathway, as well as the income pathway to nutrition, and if women own some or all of the fish or control the income from the fisheries, then it would also support the women's empowerment pathway to nutrition through multiple-use irrigation systems. Enhanced fisheries in irrigation systems (especially in rice) are often associated with numerous co-benefits, including pest and weed control, nutrient cycling in fields, water fertility, increased economic returns, food production from human-made reservoirs, reduced environmental impacts and enhanced biodiversity (Lansing and Kremer 2011).

Irrigation modernisation

To achieve these multiple objectives and demands on irrigation, future investments in irrigation must be much more strategic than in the past. In short, irrigation systems, especially gravity canal systems, need to be revitalised or 'modernised' to address contemporary challenges (Mukherji *et al.* 2012). Although the term has been in use since the 1980s, just as there is no agreed understanding of sustainable agriculture, there is currently no agreed interpretation of irrigation modernisation.

Past irrigation modernisation efforts (Table 1) have focused mainly on improving performance, primarily through rehabilitation of irrigation infrastructure and improvements to its operation and maintenance. In most cases, the focus was on: (1) increasing water productivity in the context of increasing competition from other water users; (2) increasing cost-effectiveness as funds for irrigation from national budgets decline; (3) increasing the reliability of water delivery so that farmers can properly schedule cropping cycles and maximise the use of other inputs; (4) increasing the flexibility of deliveries so that farmers have a greater say in what they grow and apply water whenever they wish; (5) increasing people's capacity to manage systems through improved systems monitoring, and by improving knowledge and understanding; and (6) improving institutional and governance structures. There have been few serious attempts to address the multiple objectives identified above, and fisheries are rarely considered in a systematic manner. Too often, in the past and to date, the emphasis has been almost exclusively on increasing traditional irrigation performance (i.e. efficiency and productivity) by technologies

Table 1. Examples of irrigation modernisation

Country	Description
Turkey	The World Bank is funding a US$254 million irrigation modernisation program to improve irrigation delivery, providing farmers with better access to water, through the rehabilitation and modernisation of infrastructure, and strengthening the capacity of Water Users Associations (WUAs) over 50 000 ha of irrigation (World Bank 2019).
Indonesia	The Asia Infrastructure Investment Bank is funding a US$578 million modernisation program designed around the following five pillars of irrigation management that address irrigation efficiency issues: (1) water security and availability improvement; (2) infrastructure rehabilitation and upgrade; (3) management system improvement; (4) institutional strengthening; and (5) human resource strengthening (Asia Infrastructure Investment Bank 2019).
Lao PDR	The Government of Lao PDR is developing a new irrigation strategy focused on: (1) the need to move beyond food security to increased commercialisation; (2) contribute to the 'green economy'; (3) improve integration with other water users (in particular hydropower); (4) expand the area equipped for small- and medium-scale irrigation; and (5) break the current cycle of repeated reconstruction or rehabilitation as a consequence of poor maintenance and frequent flood damage.
Morocco	The World Bank is funding a US$150 million program for the modernisation of irrigation infrastructure and to build the capacity of service providers; the project promotes access to water on demand by individual farmers through a system of individual metering and the project aims to enable water to be used more effectively and efficiently, increasing yields and cropping intensity, and changing cropping pattern towards higher-value crops (World Bank 2015).

(e.g. canal lining, computer monitoring or a switch to drip irrigation; Berbel *et al.* 2019). Broader objectives are seldom considered. Establishing or protecting fisheries rarely forms part of the mandate of irrigation departments and, even if it is included, there is seldom capacity to do so adequately. As a result, trade-offs between irrigation and fisheries are not fully understood, adverse effects on fisheries are rarely sufficiently mitigated and opportunities for more effective and productive irrigation management are, disappointingly, overlooked. In some places, for example Myanmar, the introduction of aquaculture into irrigation systems and promotion of rice–fish systems is difficult because of prohibitive legislation (Dubois *et al.* 2019).

The FAO defines irrigation modernisation as 'technical and managerial upgrading (as opposed to mere rehabilitation) of irrigation schemes with the objective to improve resources utilisation (labour, water, economics, environmental) and water service for farmers' (Food and Agriculture Organization of the United Nations 2018*b*). The International Commission on Irrigation and Drainage (ICID) Working Group on Modernisation is currently proposing[A] to define irrigation modernisation as 'the process of upgrading infrastructure, operations and management of irrigation systems to sustain the water delivery service requirements of farmers and optimize production and water productivity' (Asian Development Bank 2017). These definitions encapsulate ideas and concepts that distinguish 'modernisation' of irrigation services from 'rehabilitation' of irrigation systems. First and foremost, modernisation is perceived as a 'change process' (Lankford *et al.* 2016) reflecting the fact that modernisation of systems should be a continuous exercise, a process of adapting activities to current constraints and objectives. As the agricultural and economic contexts evolve and demands from society change, modernisation must facilitate the incorporation of future technology and changes in the irrigation system, as well as the service requirements of the farmers. Second, 'upgrading' means improving beyond what currently exists, with the objective of optimising operation requirements and maximising system performance and efficiencies, not simply replacing or rehabilitating schemes. Third, the term 'irrigation system' is perceived to encompass all physical and non-physical components that contribute in the conversion of water and nutrients into food and fibre. This includes the irrigation infrastructure, water resources, agency staff, farmers, services providers and supply and market chains required to enable farmers to conduct a viable enterprise, whether for subsistence or for financial gain. It also encapsulates the idea that, although water user associations are a vital component, they cannot succeed in isolation and all levels of management (i.e. formal agencies, farmer organisations, local administration) together are responsible for 'delivery of a service' that farmers require. Hence, in these definitions, modernisation is not restricted to the introduction of modern hardware or software techniques, but involves fundamental transformation of the way in which the business of irrigated agriculture is conducted.

The FAO and ICID definitions recognise that, although the term has been in use for many years, trends in irrigation modernisation must change. The definitions highlight the need for challenging targets, particularly for donors (e.g. the World Bank and the Asian Development Bank), to improve irrigation investments that go beyond simple rehabilitation (e.g. canal lining and introduction of telemetry) or a switch to an alternative technology (e.g. drip) in order to meet farmers changing needs, as well as enhanced societal and environmental requirements. If implemented in the way envisaged, in most cases modernisation of irrigation infrastructure and services will be a more relevant and cost-effective investment than rehabilitation, or restoration, of the original infrastructure (Asian Development Bank 2017).

Accepting multiple goals, stakeholders and processual pathways, we argue that modernisation, as defined by the FAO and ICID, represents an opportunity to enhance the integration of irrigation and fisheries and, in so doing, to contribute to many of the multiple objectives identified above. This means moving beyond most current modernisation programs and adopting a much more comprehensive multi-objective framework that, by definition, encompasses fisheries and other ecosystem services. For the remainder of this paper we focus on fisheries as the key lens by which to view a wider, more comprehensive remit for irrigation modernisation.

Framework for incorporating fisheries in irrigation modernisation

Opportunities to enhance fisheries need to focus on synergies between fish and irrigation and span technical, institutional and policy interventions. In Table 2, we present a framework illustrating how fisheries can be better integrated with irrigation across a range of scales, from scheme to catchment and, ultimately, national level. We propose four key scales: (1) 'command area', which comprises the area of an existing irrigation system; (2) 'extended command area', which represents all surface waterbodies that are, or could be, connected to an irrigation scheme (this includes waterbodies up- and downstream of the conventional command area, including other water sources that join and mix with irrigation waters; Gregory *et al.* 2018); (3) 'whole catchment', which emphasises how irrigation shapes the water allocation and fisheries of the catchment within which it is located; and (4) 'national', which identifies larger material and policy influences on the economies and ecosystems that define, and are defined by, fresh water.

There are numerous technical options for enhancing fisheries (both capture fisheries and aquaculture) within irrigation schemes and in the extended command area (Levels 1 and 2 respectively in Table 2). These include those intended to enhance capture fisheries, such as fish passes to enable fish movement around barriers (e.g. weirs: both up- and downstream), screens to prevent fish being drawn into pumps and different gate designs to reduce fish mortality and injury when fish move through them (Gregory *et al.* 2018). In irrigated rice schemes, there are often opportunities for rice–fish culture in which fish live directly in the rice fields; this requires careful water management and limits the use of agrochemicals. In all cases, it is essential to ensure appropriate governance

[A]It is anticipated that ICID will adopt and promote this definition at its meeting following the World Irrigation Forum in Bali in September 2019.

Table 2. Framework for considering irrigation and fisheries at different scales

Level of intervention	Description	Interventions	Responsibility
1. Command area	Optimally incorporating (via design and management) fisheries and aquaculture within irrigation command areas, with the aim of enhancing water productivity	Provision of fish habitat and refuges within the command area including, where appropriate, for aquaculture (e.g. night reservoirs, small ponds and canals) Modification of design and operation of water control infrastructure (e.g. canals, sluices, gates etc.) to reduce fish injuries and mortality and enhance entry from the source waters, as well as connectivity for wild fish movement within the scheme. Governance dimensions (e.g. to prevent overfishing within schemes) should be taken into account	Irrigation planners (e.g. government departments of irrigation), scheme managers, Water Users Associations (WUAs)
2. Extended command area	Purposively considering and incorporating fisheries and aquaculture beyond the traditional command area to other waterbodies connected to an irrigation scheme, including the river from which water is abstracted for irrigation, the active drainage and unmanaged drainage from the scheme (which may create habitat suitable for capture fisheries or aquaculture) and other natural and human-made waterbodies (e.g. water storage reservoirs) that are connected to the irrigation command area	Modification of design and operation of diversion weirs or flood embankments to facilitate the movement of fish up- and downstream, as well as, where appropriate, to and from flood plains Construction or improvement of habitat and refuge areas (e.g. conservation zones) in waterbodies connected to the command area, including the possibility of using some habitat for aquaculture	Irrigation planners (e.g. government departments of irrigation), scheme managers, WUAs
3. Whole catchment	Determining and adjusting the role and benefits of fisheries and aquaculture across the whole catchment in which multiple irrigation schemes maybe located, taking into account other water uses and other built infrastructure affecting fisheries (e.g. hydropower dams)	Enhanced fisheries through modification of design and management of all: (1) water storage and dams; (2) instream abstraction, conveyance and distribution structures; (3) irrigation bunding and field design; and (4) drainage Consideration of water consumption patterns over the year plus effects on water temperature and quality and possible implications for fisheries Seeking complementarities between fisheries or aquaculture and other ecosystems services, such as recreation, improvements to water quality, flood mitigation	River basin authorities in consultation with government departments of irrigation
4. National	Ensuring that freshwater fisheries are part of a coherent water and food security as well as nutrition and environmental sustainability strategy in the country.	Modification of policies, strategies and governance arrangements to better manage multiple goals (including but not limited to fisheries) across all scales (i.e. command areas, extended command areas and catchments) to ensure sustainability, resilience and equity in the distribution of benefits, including those derived from fisheries	National policy makers (agriculture, trade, water, fisheries)

arrangements. Irrigation infrastructure, fish passes and improved gates all need to be managed, regulated and properly maintained to deliver desired outcomes, including improved equity in access and sharing of the fisheries resources.

In addition to enhanced capture fisheries, there are often significant opportunities for aquaculture, both cage and pond culture. This includes opportunities within water storage infrastructure constructed for the irrigation scheme (e.g. ponds, reservoirs and canals) and, in some instances, ponds constructed on farmers' land, effectively replacing crops. This is increasingly common in Lao PDR and across the Mekong and Ayeyarwady deltas where, because they can make a bigger profit from fish, some farmers are converting rice plots to fish ponds supplied with water from the irrigation scheme (Wilder and Phuong 2002; Belton *et al.* 2018). Success and sustainability of aquaculture depends on a multitude of factors, such as access to knowledge and inputs, technical capacity of farmers and support systems, market demand and the regulatory framework and its enforcement. Therefore, systematic assessment of barriers and opportunities for different aquaculture technology should identify the best options for aquaculture integration within individual irrigation schemes (Joffre 2019).

Catchment considerations are particularly important in the context of irrigation modernisation and fisheries because

Table 3. Intersection of irrigation modernisation and fisheries at four scales
Italicised text is explanatory for the text that it follows in that column. IWRM, integrated water resources management

Aspects of irrigation modernisation	Scale of intervention			
	Command area	Extended command area	Whole catchment or basin	National
Increasing water productivity *Fisheries (including aquaculture) can provide an opportunity for increasing productivity*	Design and day-to-day operation of irrigation scheduling and delivery Some interventions to promote traditional irrigation efficiency (e.g. pressurised systems) may undermine fisheries, so trade-offs and net benefits need careful consideration	Enhancing non-irrigation production, including fisheries, opportunities in drainage and other waterbodies connected to a scheme	Irrigation planned and managed, including fisheries options, within the context of IWRM Water accounting for productivity and production values	Reviewing and benchmarking national-level water productivity Guidance for enhancing productivity, including by fisheries within irrigation systems
Increasing cost-effectiveness *Fisheries may present a mechanism for enhancing cost-effectiveness of schemes; where farmers are financially more secure, they are more likely to pay irrigation service fees, so improving the sustainability of schemes*	Local budgets and accounts of modernisation expenditure, including costs and benefits of enhanced fisheries	Analyses detailing costs and benefits of enhancing fisheries habitat and connectivity		National-level audits of inland fisheries and crop production Donor interest and accountability
Increasing the reliability of water delivery *If farmers or fishers can be sure of quantities and timing of water supplies, the risks of incorporating fisheries within irrigation schemes are significantly reduced*	Modified infrastructure design and operation	Assessing impacts on extended command area	Evaluating options for enhancing fish habitat in water storage	Setting and monitoring national standards with impacts on fisheries
Enhancing the flexibility of deliveries *Adds to the likelihood that schemes can be successfully adapted to incorporate fisheries*	Local assessment of desirability of, and impacts on, fisheries within the command and extended command areas		Impact of season variability on irrigation delivery and fisheries health	
Increasing peoples' capacity to manage systems *Increased capacity to manage fisheries and aquaculture within the irrigation scheme*	Operator–engineer–farmer dialogue and support, and capacity building across all scales Fishers empowered to contribute to irrigation decision making and monitor and manage intra- and extra-irrigation infrastructure			Supporting farmer–fisher dialogue Training: short courses and postgraduate courses
Improving institutional and governance structures *Appropriate governance frameworks devised to ensure that fisheries' needs are considered and benefits protected and equitably shared*	Relevant stakeholders reforming irrigation of individual systems, incorporating ecosystems and fisheries Test-bed of national laws at this scale	Immediate neighbours of irrigation systems involved in dialogue	River basin management reviewing water licenses for fisheries impacts	Influencing modernisation from national level

increases in irrigation efficiency do not always translate into increases in overall catchment-level productivity of water (Molden 1997). Rather, increased productivity may be more readily achieved through the simultaneous multiple use and high concurrent reuse of water, for example by providing habitat for fish (Renault *et al.* 2013). Thus, although some technologies (e.g. pressurised systems, using pipes and sprinklers or drippers) may increase irrigation water conveyance and application efficiency, a key objective of traditional modernisation, by reducing potential fish habitat within the irrigation command area they also reduce opportunities for fisheries and so may reduce the overall water productivity of the system. Thus, modernisation approaches should assess total water productivity of any scheme enhancement. In addition, within catchments there are often numerous barriers to fish movement, created not only by irrigation, but also by other human-made infrastructure, so a catchment perspective is needed to determine where to prioritise investment in fish passes (Marsden *et al.* 2014).

At the national (fourth) level, to ensure multiple objectives are achieved, irrigation needs to be undertaken in the context of integrated and coherent water and food security strategies, nutrition and environmental sustainability strategies. These policies and strategies should support the achievement of multiple outcomes and goals through single-sector interventions like irrigation for agricultural production. The multiple objectives that need to be reflected in both policy and institutional structures, and to which improving fisheries in irrigation systems can make a significant contribution, include enhanced nutrition, food security, diversified and improved rural livelihoods, ecosystem health and increased resilience to climatic shocks.

Table 3 summarises how different aspects of irrigation modernisation and fisheries intersect and are potentially complementary across all four scales. The better integration of fisheries in irrigation has the potential to contribute to many of the objectives of irrigation modernisation and, conversely, irrigation modernisation provides opportunities for enhancing fisheries. These cobenefits require careful planning and management, but can be delivered largely through existing processes and systems. Enhanced cooperation between irrigation and fisheries, as well as other natural resource management agencies (e.g. water) and rural development agencies, is a prerequisite for successful integration across all levels. In many cases, fishers participation in irrigation decision making should be strengthened to ensure that fisheries perspectives are given due consideration.

Conclusions

Future irrigation needs to contribute to multiple societal objectives and must change radically if it is to increase sustainable food production while also supporting freshwater ecosystems. Better integration of fisheries provides an 'entry point' and a unique opportunity to more comprehensively evaluate difficult trade-offs and complementarities. Modernisation of irrigation provides a basis for this, but in most instances is currently too narrowly interpreted and focused on improving and upgrading infrastructure and operations to increase irrigation performance without consideration of the broader requirements, often in ways that undermine rather than promote opportunities for fisheries. In this paper we have argued that a more comprehensive and multiscale irrigation modernisation process will help frame discussion and deliver the wider and often heterogeneous goals of irrigation. Clearly, the potential and benefits of fisheries within irrigation schemes are not universal but dependent on region, system design and crops grown, but frequently greater consideration of fisheries can bring significant benefits. Inclusive modernisation, through better integration of fisheries and by meeting other multifunction objectives across all scales, from individual irrigation schemes to catchments to national levels, has the potential to improve agricultural productivity, enhance water security, revitalise rural landscapes, contribute to inclusive growth and drive positive change across numerous SDGs.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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References

Asia Infrastructure Investment Bank (2019). Indonesia: strategic irrigation modernization and urgent rehabilitation project. Available at https://www.aiib.org/en/projects/approved/2018/strategic-irrigation-modernization.html [Verified 5 May 2019].

Asian Development Bank (2017). Irrigation subsector guidance note: building blocks for sustainable investment. Available at https://www.adb.org/sites/default/files/institutional-document/238481/irrigation-guidance-note.pdf [Verified15 May 2019].

Bell, A., Shah, M., Ali, A., and Ward, P. S. (2014). Reimagining cost recovery in Pakistan's irrigation system through willingness-to-pay estimates for irrigation water from a discrete choice experiment. *Water Resources Research* **50**(8), 6679–6695. doi:10.1002/2014WR015704

Belton, B., Hein, A., Htoo, K., Seng Kham, L., Sander Phyoe, A., and Reardon, T. (2018). The emerging quiet revoltion in Myanmar's aquaculture value chain. *Aquaculture* **493**, 384–394. doi:10.1016/J.AQUACULTURE.2017.06.028

Béné, C., Barange, M., Subasinghe, R., Pinstrup-Andersen, P., Merino, G., Hemre, G.-I., and Williams, M. (2015). Feeding 9 billion by 2050 – putting fish back on the menu. *Food Security* **7**, 261–274. doi:10.1007/S12571-015-0427-Z

Berbel, J., Expósito, A., Gutiérrez-Martín, C., and Mateos, L. (2019). Effects of irrigation modernization in Spain 2002–2015. *Water Resources Management* **33**(5), 1835–1849. doi:10.1007/S11269-019-02215-W

Bryan, E., Ringler, C., Okoba, B., Roncoli, C., Silvestri, S., and Herrero, M. (2013). Adapting agriculture to climate change in Kenya: household strategies and determinants. *Journal of Environmental Management* **114**, 26–35. doi:10.1016/J.JENVMAN.2012.10.036

Burt, C. M. (2013). The irrigation sector shift from construction to modernization: what is required for success? *Irrigation and Drainage* **62**(3), 247–254. doi:10.1002/IRD.1703

Crossman, N. D., Connor, J. D., Bryan, B. A., Summers, D. M., and Ginnivan, J. (2010). Reconfiguring an irrigation landscape to improve provision of ecosystem services. *Ecological Economics* **69**(5), 1031–1042. doi:10.1016/J.ECOLECON.2009.11.020

Damania, R., Desbureaux, S., Hyland, M., Islam, A., Moore, S., Rodella, A.-S., Russ, J., and Zaveri, E. (2017). 'Uncharted Waters: The New Economics of Water Scarcity and Variability.' (World Bank: Washington, DC, USA.) . doi:10.1596/978-1- 4648-1179-1

de Bont, C., Liebrand, J., Veldwisch, G. J., and Woodhouse, P. (2019). Modernisation and African farmer-led irrigation development: ideology, policies and practices. *Water Alternatives* **12**(1), 107–128.

Domènech, L. (2015). Improving irrigation access to combat food insecurity and undernutrition: a review. *Global Food Security* **6**, 24–33. doi:10.1016/J.GFS.2015.09.001

Dubois, M., Akester, M., Leemans, K., Teoh, S., Stuart, A., Thant, A., Shein, N., Mansoor, L., and Radanielson, A. (2019). Integrating fish into irrigation infrastructure projects in Myanmar. *Marine and Freshwater Research* **70**(9), 1229–1239. doi:10.1071/MF19182

English, M. J., Asce, M., Solomon, K. H., and Hoffman, G. J. (2002). A paradigm shift in irrigation management. *Journal of Irrigation and Drainage Engineering* **128**(5), 267–277. doi:10.1061/(ASCE)0733-9437(2002)128:5(267)

Fitzgerald-Moore, P., and Parai, B. J. (1996). The Green Revolution. Available at https://people.ucalgary.ca/~pfitzger/green.pdf [Verified 12 April 2019].

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnson, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockstrom, J., Sheehan, J., Siebert, S., Tilman, D., and Zaks, D. P. M. (2011). Solutions for a cultivated planet. *Nature* **478**(7369), 337–342. doi:10.1038/NATURE10452

Food and Agriculture Organization of the United Nations (2014). Aquastat infographic. Available at http://www.fao.org/3/I9253EN/i9253en.pdf [Verified 21 April 2019].

Food and Agriculture Organization of the United Nations (2018*a*). Transforming food and agriculture to achieve the SDGs: 20 interconnected actions to guide decision-makers. (FAO: Rome, Italy.) Available at http://www.fao.org/3/I9900EN/i9900en.pdf [Verified 9 July 2019].

Food and Agriculture Organization of the United Nations (2018*b*). Guidelines on irrigation investment projects. (FAO: Rome, Italy.) Available at http://www.fao.org/3/CA2608EN/ca2608en.pdf [Verified 1 May 2019].

Furlong, C., De Silva, S., Guthrie, L., and Considine, R. (2016). Developing a water infrastructure planning framework for the complex modern planning environment. *Utilities Policy* **38**, 1–10. doi:10.1016/J.JUP.2015.11.002

Gregory, R., Funge-Smith, S., and Baumgartner, L. (2018). An ecosystem-based approach to promote the integration of fisheries and irrigation systems. Fisheries and Aquaculture Circular number 1169, Food and Agriculture Organization of the United Nations, Rome, Italy.

Hussain, I., and Hanjra, M. A. (2004). Irrigation and poverty alleviation: review of the empirical evidence. *Irrigation and Drainage* **53**, 1–15. doi:10.1002/IRD.114

Inocencio, A., Merrey, D., Tonasaki, M., Maruyama, A., de Jong, I., and Kikuchi, M. (2007). Costs and performance of irrigation projects: a comparison of sub-Saharan Africa and other developing countries. IWMI Research Report, International Water Management Institute, Colombo, Sri Lanka.

Jägermeyr, J., Pastor, A., Biemans, H., and Gerten, D. (2017). Reconciling irrigated food production with environmental flows for sustainable development goals implementation. *Nature Communications* **8**, 15900. doi:10.1038/NCOMMS15900

Joffre, O. (2019). Fisheries. Lao PDR Irrigation Subsector Review. Report to Department of Irrigation, Lao PDR and Asian Development Bank, Vientiane, Lao PDR.

Johnston, R., Ameer, R., Balasubramanaya, S., Dousangsavanh, S., Lacombe, G., McCartney, M., Pavelic, P., Senaratna Sellamuttu, S., Sotoukee, T., Suhardiman, D., and Joffre, O. (2013). Identifying priority investments in water in Myanmar's Dry Zone. Report to Livelihoods and Food Security Trust Fund and the United Nations Office for Project Services, International Water Management Institute, Colombo, Sri Lanka.

Kennedy, G., Nantel, G., and Shetty, P. (2003). The scourge of 'hidden hunger': global dimensions of micronutrient deficiencies. *Food, Nutrition and Agriculture* **32**, 8–16.

Khoa, S. N., Lorenzen, K., Garaway, C. J., Chamsingh, B., Siebert, D. J., and Randone, M. (2005). Impacts of irrigation on fisheries in rainfed rice farming landscapes. *Journal of Applied Ecology* **42**, 892–900. doi:10.1111/J.1365-2664.2005.01062.X

Kumbhare, S. L., and Sen, M. (2008). Investments in irrigation projects: an impact analysis. *Agricultural Economics Research Review* **21**, 377–385.

Lankford, B. A. (2004). Resource-centred thinking in river basins: should we revoke the crop water approach to irrigation planning? *Agricultural Water Management* **68**(1), 33–46. doi:10.1016/J.AGWAT.2004.03.001

Lankford, B. A. (2005). Rural infrastructure to contribute to African agricultural development: the case of irrigation. Report for The Commission for Africa, School of Development Studies, University of East Anglia, Norwich, UK.

Lankford, B. A., Makin, I., Matthews, N., Noble, A., McCornick, P. G., and Shah, T. (2016). A compact to revitalize large-scale irrigation systems using a leadership–partnership–ownership 'theory of change'. *Water Alternatives* **9**(1), 1–32.

Lansing, S., and Kremer, J. N. (2011). Rice, fish and the planet. *Proceedings of the National Academy of Sciences of the United States of America* **108**(50), 19841–19842. doi:10.1073/PNAS.1117707109

Larinier, M. (2000). Dams and fish migration. Background paper prepared for World Commission on Dams Thematic Review II. 1: dams, ecosystem functions and environmental restoration. Available at https://www.researchgate.net/publication/242158460_Dams_and_Fish_Migration [Verified 23 June 2019].

Lipton, M., Litchfield, J., and Faurès, J.-M. (2003). The effects of irrigation on poverty: a framework for analysis. *Water Policy* **5**(5–6), 413–427. doi:10.2166/WP.2003.0026

Lorenzen, K., Smith, L., Khoa, S. N., Burton, M., and Garaway, C. (2007). 'Management of Impacts of Irrigation Development on Fisheries. Guidance Manual.' (International Water Management Institute: Colombo, Sri Lanka; and The WorldFish Center: Penang, Malaysia.)

Lynch, A. J., Cooke, S. J., Deines, A. M., Bower, S. D., Bunnell, D. B., Cowx, I. G., Nguyen, V. M., Nohner, J., Phouthavong, K., Riley, B., Rogers, M. W., Taylor, W. W., Woelmer, W., Youn, S.-J., and Beard, T. D. (2016). The social, economic, and environmental importance of inland fish and fisheries. *Environmental Reviews* **24**, 115–121. doi:10.1139/ER-2015-0064

Malabo Montpellier Panel (2018). Water wise: smart irrigation strategies for Africa. A Malabo Montpellier Panel report. Available at https://www.mamopanel.org/resources/reports-and-briefings/water-wise-smart-irrigation-strategies-africa/ [Verified 5 May 2019].

Marsden, T., Peterken, C., Baumgartner, L., and Thorncraft, L. (2014). Guideline to prioritizing fish passage barriers and creating fish-friendly irrigation infrastructure. Mekong River Commission, Vientiane, Lao PDR.

McCartney, M., Funge-Smith, S., and Kura, Y. (2018). Enhancing fisheries productivity through improved management of reservoirs, dams and other water control structures. CGIAR Research Program on Fish Agri.-Food Systems, Program Brief: FISH-2018–11, WorldFish, Penang, Malaysia.

Millennium Ecosystem Assessment (2005). 'Ecosystems and Human Well-being: Synthesis.' (Island Press: Washington, DC, USA.)

Molden, D. (1997). 'Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture.' (Earthscan: London, UK; and International Water Management Institute: Colombo, Sri Lanka.)

Molle, I., and Berkoff, J. (2006). Cities versus agriculture: revisiting inter-sectoral water transfers, potential gains and conflicts. IWMI Comprehensive Assessment Research Report 10, International Water Management Institute Comprehensive Assessment Secretariart, Colombo, Sri Lanka.

Mollier, L., Seyler, F., Chotte, J.-L., and Ringler, C. (2017). SDG2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture. In 'ICSU (International Council for Science). A Guide to SDG Interactions: From Science to Implementation'. (Eds D. J. Griggs, M. Nilsson, A. Stevance, and D. McCollum.) pp. 31–80. (ICSU: Paris, France.)

Mukherji, A., Facon, T., de Fraiture, C., Molden, D., and Chartres, C. (2012). Growing more food with less water: how can revitalizing Asia's irrigation help? *Water Policy* **14**(3), 430–446. doi:10.2166/WP.2011.146

Playán, E., and Mateos, L. (2006). Modernization and optimization of irrigation systems to increase water productivity. *Agricultural Water Management* **80**(1–3), 100–116. doi:10.1016/J.AGWAT.2005.07.007

Postel, S. (1989). Water for agriculture: facing the limits. WorldWatch Paper 93, December. WorldWatch Institute, Washington, DC, USA.

Renault, D., Wahaj, R., and Smits, S. (2013). Multiple uses of water in large irrigation systems: auditing and planning modernization. The

MASSMUS approach. (Food and Agriculture Organization of the United Nations: Rome, Italy.) Available at http://www.fao.org/3/i3414e/i3414e.pdf [Verified 1 May 2019].

Ringler, C. (2017). Investments in irrigation for global food security. IFPRI policy note. Available at http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/131045 [Verified 12 March 2019].

Rockström, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., Wetterstrand, H., DeClerck, F., Shah, M., Steduto, P., de Fraiture, C., Hatibu, N., Unver, O., Bird, J., Sibanda, L., and Smith, J. (2017). Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio* **46**, 4–17. doi:10.1007/S13280-016-0793-6

Schlüter, M., Leslie, H., and Levin, S. (2009). Managing water-use trade-offs in a semi-arid river delta to sustain multiple ecosystem services: a modeling approach. *Ecological Research* **24**(3), 491–503. doi:10.1007/S11284-008-0576-Z

Siebert, S., and Döll, P. (2010). Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. *Journal of Hydrology* **384**, 198–217. doi:10.1016/J.JHYDROL.2009.07.031

Steffen, W., Richardson, K., Röckstrom, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Presson, L. M., Ramanathan, V., Reyers, B., and Sörlin, S. (2015). Planetary boundaries: guiding human development on a changing planet. *Science* **347**(6223), 1259855. doi:10.1126/SCIENCE.1259855

United Nations (2019). Transforming our world: the 2030 Agenda for Sustainable Development. Available at https://sustainabledevelopment.un.org/post2015/transformingourworld [Verified 9 July 2019].

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Reidy Liermann, C., and Davies, P. M. (2010). Global threats to human water security and river biodiversity. *Nature* **467**, 555–561. doi:10.1038/NATURE09440

Welcomme, R. L., Cowx, I. G., Coates, D., Béné, C., Funge-Smith, S., Halls, A., and Lorenzen, K. (2010). Inland capture fisheries. *Philosophical Transactions of the Royal Society of London – B. Biological Sciences* **365**(1554), 2881–2896. doi:10.1098/RSTB.2010.0168

Wilder, M., and Phuong, N. T. (2002). The status of aquaculture in the Mekong Delta region of Vietnam: sustainable production and combined farming systems. *Fisheries Science* **68**, 847–850. doi:10.2331/FISHSCI.68.SUP1_847

Woodhouse, P., Veldwisch, G.-J., Venot, J.-P., Brockington, D., Komakech, H., and Manjichi, A. (2017). African farmer-led irrigation development: reframing agricultural policy and investment? *The Journal of Peasant Studies* **44**(1), 213–233. doi:10.1080/03066150.2016.1219719

World Bank (2015). Improved irrigation services for farmers in Morocco. Available at http://www.worldbank.org/en/news/press-release/2015/07/08/improved-irrigation-services-for-farmers-in-morocco [Verified 22 April 2019].

World Bank (2019). Irrigation in Turkey to be modernized with World Bank financing. Available at http://www.worldbank.org/en/news/press-release/2019/01/22/irrigation-in-turkey-to-be-modernized-with-world-bank-financing [Verified 25 March 2019].

Xie, H., Perez, N., Ringler, C., Anderson, W., and You, L. (2018). Can Sub-Saharan Africa feed itself? The role of irrigation development in the region's drylands for food security. *Water International* **43**(6), 796–814. doi:10.1080/02508060.2018.1516080

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