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From Torrents to Trickles: Irrigation's Future in Africa and Asia

Claudia Ringler

International Food Policy Research Institute (IFPRI), Washington, DC 20005, USA;
email: c.ringler@cgiar.org

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Abstract

Irrigation has been a key component of agricultural intensification and transformation in Asia and has the potential to take on the same role in Sub-Saharan Africa. Irrigation has contributed to increased food production, lower food prices, higher rural employment, and overall agricultural and economic growth. At the same time, irrigation—through its large consumptive water use—has accelerated water depletion, degradation, and pollution; moreover, it has benefitted richer farmers more than poorer farmers. This article reviews the contributions and challenges of irrigation and identifies a series of measures to increase the sustainability and equity of irrigation going forward.

1. INTRODUCTION

Irrigation means different things to different people. As an example, the Indus Basin Irrigation System (IBIS) is called the world's largest contiguous irrigation system and is considered an engineering marvel by some (Akram 2013, Frenken 2012, Ringler & Anwar 2013) and one of the world's most fragmented river ecologies by others (Braulik et al. 2014). To irrigate around 15–18 million hectares of land, the IBIS annually diverts an average of 128 km^3 of irrigation water through 43,561 km of canals to reach 107,000 outlets in 45 main canal systems, followed by 18,884 km of seepage-cum-stormwater drains and 12,612 km of tile drains, supporting 90% of Pakistan's food production (Akram 2013, Gov. Pak. 2004). IBIS assets are valued at US$300 billion, and irrigation contributes around US$22 billion to annual GDP—without considering canal water use for livestock production and many other off-farm activities (Young et al. 2019). At the same time, irrigation in this area is credited for severe water depletion, the near-extinction of the Indus River dolphin, excessive salinization, other water pollution, and the destruction of coastal mangrove habitats (Alam et al. 2007, Renaud et al. 2013, Young et al. 2019). In Sub-Saharan Africa and other parts of Asia, such as Bangladesh, irrigation more often refers to a farmer's own development of small irrigation systems or self-supply, for example, in the form of a combination of a hand-dug or drilled well, with water extracted and applied to fields of vegetables or other crops through the use of pumps or buckets and watering cans (Bhuiyan 1984, de Fraiture & Giordano 2014).

These statements reflect the strength of irrigation—for the production of more food on the same piece of land, both through higher, irrigated yields and the possibility to double and sometimes triple-crop due to water availability in the dry season—but also its weaknesses in terms of water depletion and environmental degradation. They also describe two types of irrigation: large-scale systems that are generally planned and managed by the public sector and focus on either food security crops, such as rice, or cash crops for foreign exchange, such as sugarcane, and small-scale systems that are managed by individual farmers or groups of farmers, generally with a focus on profit maximization. A third form, medium-scale systems, are fewer in number, and are either developed by groups of farmers or by governments and then handed over to groups of farmers for management [e.g., the Balinese subak (Roth 2014)]. While there is generally agreement that smaller irrigation systems with stronger farmer involvement have been more successful in Africa and Asia, using a series of criteria such as profitability (e.g., Ball 1986, Turner 1994, You et al. 2011), some studies suggest that even small systems can show poor performance if enabling conditions are not supportive (Adams 1990). In a review of 314 (generally larger and publicly funded) irrigation systems, Inocencio et al. (2007) propose to focus on investments in large projects (due to lower unit costs) that, in turn, support smaller-scale irrigation systems that have shown to perform better due to farmers contributing to project development and management. Individual irrigation systems were not considered in the analysis by Inocencio and colleagues. Clearly, no one size fits all irrigation needs.

This article reviews key recent irrigation trends and provides an outlook for Africa and Asia, building on the article by Rosegrant et al. (2009) and earlier reviews focused more directly on the economics of irrigation by Hellegers (2006) and Schoengold & Zilberman (2007). The article contributes new insights into the need for irrigation of the future to go beyond traditional yield increase and stability objectives to maximize benefits under growing water scarcity and ends with a series of suggestions that economists should take up together with biophysical scientists to improve irrigation outcomes. The following sections review the contribution of irrigation to poverty alleviation and food security, identify challenges to the sustainability of irrigation, and identify key elements of more sustainable irrigation that are urgently needed given a more environmentally degraded, water-scarce future.

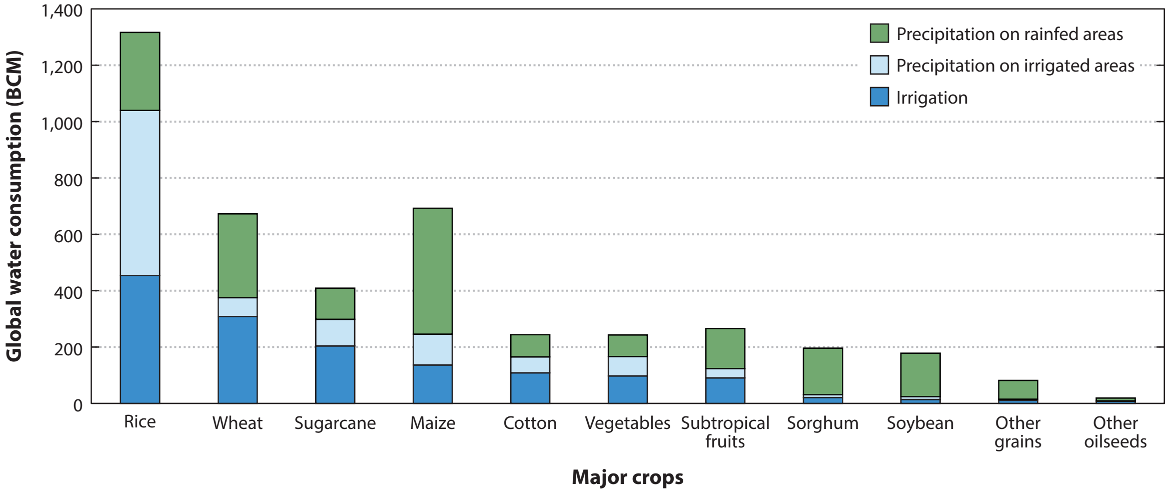

Figure 1

Global water consumption by major crops (consumptive use, BCM, calculated for 2020). Abbreviation: BCM, billion cubic meters or km^3. Data from IFPRI (2020).

2. IRRIGATION IN AFRICA AND ASIA

Irrigation has been essential for the generation of surplus agricultural production and was the basis for the development of ancient cultures in semiarid and arid areas of the Middle East, North Africa, and the Americas. Evidence of irrigation's role in the establishment of major civilizations dates back to at least 6,000 BC (Sojka et al. 2002).

Although precipitation remains the major source of water for the world's crop production globally, irrigation is essential for the production of key staple crops, such as rice, wheat, and maize, as well as for fruits and vegetables and a series of other crops, such as sugarcane and cotton (**Figure 1**).

Irrigated agricultural production currently generates 40% of global food production on just under one-third of the world's harvested land. This production accounts for 70% of total global freshwater withdrawals, including from groundwater, and more than 80% of consumptive water use of withdrawn water (FAO 2020b, Ringler 2017, WWAP 2019). Livestock watering and freshwater aquaculture are additional small but growing agricultural water uses.

Table 1 shows key irrigation statistics for Asia and Africa, reflecting the contrasting status of irrigation development of the two continents; while Asia has already developed 68% of its potential irrigated area, the share is 39% across Africa and only 28% in Sub-Saharan Africa. Asia's total water-managed area is more than 11 times the size of Africa's area. Although East and South Asia feature the world's largest irrigated areas, supported by many decades of public investment in the sector and propelled by the Green Revolution, there has been little public investment and thus little expansion of irrigated area in much of Sub-Saharan Africa until recently; only Madagascar, South Africa, and Sudan have had substantial development. Irrigation development in North Africa was much faster than in Sub-Saharan Africa due to the region's low rainfall and high temperature levels that make it difficult to grow food without irrigation.

Table 2 presents some of the data and factors underlying the differential development of irrigation in Asia and Sub-Saharan Africa. Key reasons for the differential development of irrigation between these regions are the historical relative abundance of land and lower dependence on water control to grow Sub-Saharan Africa's main staple crops, such as roots and tubers. There has

Table 1 Key water and irrigation statistics for Asia and Africa

Region	Total renewable water resources (BCM/year)	Agricultural water withdrawals (BCM/year)	Potential irrigated area (1,000 ha)	Total irrigated area (1,000 ha)	Total agricultural water management area (1,000 ha)	Share of agricultural water management area realized (%)
South Asia	3,726	913	170,513	97,411	100,206	59
Southeast Asia	7,197	429	47,928	22,136	26,538	55
East Asia	3,452	462	73,760	73,009	72,217	98
Central Asia	293	134	18,071	13,337	13,337	74
Asia	**14,667**	**1,938**	**310,272**	**205,893**	**212,298**	**68**
North Africa	103	86	7,984	7,542	7,542	94
Sub-Saharan Africa	5,526	100	40,800	8,137	11,281	28
Africa	**5,630**	**186**	**48,784**	**15,679**	**18,823**	**39**

Data from FAO (2019). Data are for the latest year, which can be as far back as the 1990s. For countries where data on actual irrigated area were available but excluded in potential irrigated area, the actual area was included in the calculation of potential area. Abbreviation: BCM, billion cubic meters or km^3.

also been an overall lower political will to invest in agriculture, including irrigation, by governments in Sub-Saharan Africa compared to Asian governments (IFPRI 2019), and an overall underdevelopment of rural infrastructure that enables market development and growth of the irrigation sector, such as roads and electricity (IEA 2019). The lack of electricity access affects water lifting for irrigation, as well as the development of rural agro-processing centers and cold storage that are important for perishable irrigated produce, such as fruits and vegetables. Poor roads and market information systems in Sub-Saharan Africa have made it challenging to bring irrigated products to markets. At the same time, larger irrigation developments have a "pull" effect, attracting other investments, such as roads and grid development, accelerating agricultural growth (Hussain & Hanjra 2004, Yami 2016). The higher share of employment in agriculture in Sub-Saharan Africa is, a priori, not a determinant for lower irrigation development, but it has reduced the pressure to invest in more capital-intensive, profit-increasing technologies such as motor pumps. Much small-scale irrigation in the region uses dug wells with irrigation water extracted by buckets or small pumps and hoses, requiring substantial family labor but limiting irrigated area to a fraction of a hectare. Traditional technologies often render irrigation unprofitable if family labor would be valued at market prices and limit expansion of area. Passarelli et al. (2018) find from surveys in Tanzania and Ethiopia that around 40% of small-scale irrigators used

Table 2 Key differences in agriculture and irrigation development in Asia and Sub-Saharan Africa

Issue	Asia	Sub-Saharan Africa
Key staple crops	Rice, wheat	Roots and tubers, maize, sorghum
Cropland per capita	0.13 ha	0.21 ha
Water availability per capita	4,994 m^3	3,172 m^3
Share of population employed in agriculture	24.4%	52.3%
Electricity access (share of rural population)	88% (South Asia), 96% (East Asia and Pacific)	32%

Electricity access is used as a proxy for poor development of complementary infrastructure; data for travel time to urban centers/markets would show similar differences between Asia and Sub-Saharan Africa. Data for staple crops and cropland from FAO (2020a) (2018 values), water resources from FAO (2019), and employment in agriculture and energy access from World Bank (2020).

buckets to lift water, and Namara et al. (2014) find that in Ghana, 60% of households surveyed reported buckets as the most common technology for irrigation.

Although irrigation traditionally relied largely on river flows, often stored behind dams, today groundwater plays a major role in irrigation and food production globally. Groundwater irrigation developed rapidly in Asia in the 1970s and 1980s due to technical innovation, including more affordable, individual pump technology, cheaper drilling technology, and inflexible and unreliable surface irrigation systems—sometimes coupled with the availability of high water tables due to seepage and percolation from canal systems. In parts of South Asia, the groundwater revolution was further propelled by free electricity for pumping (Kumar et al. 2011). India is the largest groundwater user in the world, extracting an estimated 251 km^3 of groundwater annually, largely for irrigation. China and the United States are the second and third largest users of groundwater, followed by Pakistan and Iran (Margat & Van der Gun 2013). More than one-third of the world's 301 million hectares of area equipped for irrigation relies on groundwater, and global consumptive use of groundwater in irrigation is estimated to account for 43% of total consumptive irrigation water use (Siebert et al. 2010). Many irrigated areas use both surface water and groundwater. An example is Pakistan's IBIS, where limited canal water is often supplemented with groundwater, which, on its own, would be too salty for crops in parts of the system.

3. THE CONTRIBUTION OF IRRIGATION TO FOOD SECURITY AND POVERTY ALLEVIATION

3.1. Irrigation and Food Security

It has been challenging to assess the full costs and benefits of irrigation. Many traditional cost-benefit analyses focus on increased, irrigated production and the potential for the incremental production and associated, increased profitability to cover the cost of the irrigation investment over a certain period of time (depending on the longevity of the irrigation investment). Feasibility studies that are typically implemented in support of large-scale irrigation systems not only assess the increase in yields but also typically assume that cropping patterns change and that markets for the proposed irrigated crops exist. Many such measurements have found mixed results and poor performance of irrigation systems, particularly (*a*) because larger systems are often developed for food security or foreign exchange, rather than profitability purposes; (*b*) because systems take longer and are more complex to develop than initially estimated, leading to cost over-runs; and (*c*) because of overly optimistic assumptions regarding water availability, changes in farmer behavior, cropping pattern changes, and yield improvements (e.g., Inocencio et al. 2007, Jones 1995).

Irrigation systems should be assessed based on the true intention of their development—i.e., food security and generation of foreign exchange—and on their positive and negative unintended externalities.

A key contribution of irrigation that is generally not considered in analyses has been the lowering of prices of key staple crops, such as rice, and the resulting decline in the number of people at risk of hunger. A mathematical modeling analysis by Ringler et al. (2017) finds that if irrigation investment would be limited to investments maintaining existing areas, future food production potential would decline, thus increasing the share of people at risk of hunger by 9% in South Asia and by 12% in Sub-Saharan Africa by 2050; in the latter region, underinvestment in irrigation expansion would put 23 million additional people at risk of hunger by 2050.

Moreover, irrigation supports multiple nonirrigation uses, such as small crafts, important domestic uses [e.g., water supply, sanitation, and hygiene (WASH)], and aquaculture production and other ecosystem services, such as habitat provision for birds and aquatic species. The growing understanding of the multiple uses of irrigation water has led to the development of the concept of Multiple Use Systems (MUS) and to the initial development of investment programs that consider multiple uses of water for domestic and productive purposes (Clement et al. 2015, Meinzen-Dick & Bakker 1999, Meinzen-Dick & van der Hoek 2001). A parallel strand of research led to the development of explicit pathways on how to strengthen nutrition through irrigation investments, including through nutrition-sensitive irrigation design, and proactive engagement of both the irrigation and nutrition communities (Bryan et al. 2019, Domènech 2015, Passarelli et al. 2018).

3.2. Irrigation and Poverty Alleviation

Although irrigation overall contributes to poverty alleviation of farmers as well as agricultural and economic growth, irrigation investments only reach a subset of farmers owing to biophysical (water) constraints, economic constraints, subsidies, and norms and traditions.

In a study focused on northern Mali, Dillon (2011) finds that irrigation improved village food supply and contributed to asset development and informal sharing of food within villages, which reduced risk and increased resilience to shocks. The author emphasizes the importance of considering the broader contributions of irrigation. Bhattarai & Narayanamoorthy (2003) find in a study of 14 Indian states that the marginal impacts of irrigation explained much of the variation in rural poverty levels in India. Poverty-reducing impacts were larger in groundwater irrigated areas than those using canal irrigation due to greater farmer control over water applications and the more widespread use of groundwater irrigation because of its independence of proximity to surface water bodies.

Hussain & Hanjra (2004), in a review of irrigation impacts on poverty in Asia, find that irrigation benefits the poor, including the landless in the longer term, through higher yields, increased production, lower food prices, reduced risk of crop failure, and increased employment year-round. They note, furthermore, that irrigation contributes to agricultural transformation through the increased orientation of production toward high-value market production and has important economy-wide effects. Lipton et al. (2003) note that the poverty-reducing impacts of irrigation depend on the water source, with groundwater affording farmers more control and thus generating higher yields and output. Impacts also depend on the irrigation technology used, with technologies that can be accessed by capital- and credit-constrained farmers being more pro-poor. The authors also note that equitable access to complementary inputs, such as fertilizers that are essential for irrigation to achieve expected outputs, is important and that poverty reduction is enhanced if irrigation institutions support access to water in appropriate quantities and at the right time. Finally, the authors note that poverty-reducing irrigation can reduce adverse environmental impacts that could particularly affect the poor. Burney & Naylor (2012) suggest that larger groups of poor farmers can be reached with higher-end irrigation technologies through self-help and other groups.

Large-scale systems are affected by inequity in access to irrigation water, with generally poorer farmers located at the tail end of canal systems receiving less water and less often (Bell et al. 2015, Pariyar et al. 2017). There is similar unequal access in small-scale systems, with poorer farmers priced out of the market for accessing irrigation technologies or water sources that are associated with more expensive agricultural land, or facing challenges in accessing permits to irrigate. Schreiner & van Koppen (2020) find that the statutory water laws with nationwide permit systems that were introduced in several African countries in the 1990s were often rooted in colonial thinking and have widened inequalities in access to productive water use for small-scale water users and irrigators in Sub-Saharan Africa. Moreover, there is persistent gender inequity in access to irrigation water and technology, with women facing information, credit access, and land tenure challenges as well as social norms that reduce their participation in irrigated agriculture (Imburgia et al. 2020, Lefore et al. 2019).

4. CHALLENGES AFFECTING THE SUSTAINABILITY OF IRRIGATION

Key environmental challenges of irrigation include water depletion with impacts on water-based ecosystems but also land resources, water pollution, and contamination. These, in turn, have impacts on all ecosystems, human health, and overall water degradation.

4.1. Water Depletion

Excessive diversion of flows from the Amu Darya and Syr Darya rivers in Central Asia for the irrigation of cotton contributed to the desiccation and severe shrinkage of the downstream Aral Sea, once the fourth largest freshwater lake in the world, with lasting consequences for the environment and human health (Cai et al. 2003, Micklin & Aladin 2008, Small et al. 2001). Lake Chad in Sub-Saharan Africa, once the world's sixth largest lake, is another water body of global significance that has been dramatically shrinking due to irrigation (and other reasons) (Gao et al. 2011).

With technological innovations, groundwater pumping for irrigation has increased dramatically over the last 50 years, and groundwater depletion and contamination with pollutants, and seawater in coastal areas, have become a sign of the growing risks to the sustainability of current agricultural water management practices. The environmental consequences of depleting groundwater stores are large, not only reducing access to freshwater resources in times of drought, but also increasing the cost of pumping, often with fossil fuels, and growing inequity between those who can afford to dig deeper wells and those who cannot (Famiglietti 2014, Wada et al. 2012).

Groundwater pumping for irrigation can also reduce subsurface flows to rivers and streams, reducing runoff and water availability for other users and uses. As an example, Kustu et al. (2010) find that excessive groundwater pumping in the High Plains aquifer in the United States contributed to decreasing trends in annual and dry-season streamflow and a growing number of low-flow days on the Northern High Plains.

Water depletion from overextraction of groundwater is a major contributor to land subsidence. Land subsidence is caused by the compaction of the subsoils due to the reduction in size and number of open pore spaces that previously held water in some aquifer systems as a result of excessive pumping of groundwater, principally for irrigation. It causes damage to infrastructure, such as buildings, roads, and bridges, increases flood risk, and can reduce groundwater storage in the long term. Examples of land subsidence include the San Joaquin Valley in California, where locally, 9 m of subsidence had been reported by the early 1980s, before restorative measures such as the intrastate water transfer and managed aquifer recharge were undertaken (Faunt et al. 2016). Erban et al. (2014) estimate that if groundwater pumping in the Mekong Delta of Vietnam continues, land subsidence would reach about 0.88 m by 2050, increasing the risks associated with sea level rise in this important rice-producing area.

4.2. Climate Variability and Change

Extreme hydroclimatic events, such as floods and droughts, can damage crops (Ray et al. 2015), destroy livelihoods, and adversely affect economic growth (Thurlow et al. 2012), particularly in poorer countries that generally exhibit higher water variability (Brown & Lall 2006). While floods can sweep away crops and properties, and pollute domestic water sources, droughts can cause crop losses through reducing both harvested areas and crop yields (Lesk et al. 2016). Irrigation can reduce the impact of drought events and, through improved water control and associated storage infrastructure, also reduce the adverse impacts of flooding.

Although global annual water availability is largely stable, with small increases as a result of accelerated water cycles under climate change (Oki & Kanae 2006), higher temperatures, less-certain precipitation patterns, and shorter, more concentrated rains together with prolonged dry seasons are putting further pressure on available water supplies for irrigation (Bates et al. 2008). As an example, Immerzeel et al. (2010) suggest that climate change impacts on glacier melt, snow melt, and precipitation in a "best-guess" scenario will decrease mean upstream water supply from the upper Indus by 8%, the Ganges by 18%, the Brahmaputra by 20%, and the Yangtze by 5% by 2050 based on data from five global circulation models; the authors note the challenges in adequately simulating climate change impacts on monsoon behavior. These declines affect future water availability for Asia's largest irrigation systems.

Increased uncertainty of the timing and quantity of precipitation has increased the value of a more stable water supply for crop production while higher temperatures are increasing crop evaporative demands. In much of Sub-Saharan Africa, interannual climate variability, untampered by irrigation, significantly affects agricultural GDP and reduces productivity-increasing investments (Cooper et al. 2008). Most of the Comprehensive Africa Agriculture Development Programme (CAADP) compacts signed by 24 countries in Sub-Saharan Africa mention the need for irrigation development to achieve the envisioned food security and agricultural transformation goals, and the plans generally call for a variety of irrigation investments. Similarly, many nationally determined contributions (NDCs) in the region list irrigation development as a key climate adaptation strategy. Even temperate countries have started to adopt irrigation in response to growing climate variability and change (Bindi & Oleson 2011).

Importantly, hydrological variability and climate trends are rarely incorporated in investment design. Consideration of climate variability and change will reduce the benefit streams of infrastructure investments, such as rural roads, and enhance the benefit streams from water-sector investments, such as dams, but also irrigation infrastructure. Incorporation is not only needed to better reflect benefit streams but also to ensure that water-sector investments are more carefully planned for areas that might become too dry to support such investments; that matters particularly for areas considered to dry out with considerable certainty, such as parts of southern Africa, across a range of future climate change scenarios. Similarly, the seasonality of benefit streams of irrigation should be considered; irrigation generally generates above-average benefit streams in the dry season, when vegetable crops and animal feed are in short supply. The stability effect of irrigation and the varying benefit streams across seasons and climate years are, however, seldom considered (Block et al. 2008).

4.3. Irrigation as a Source of Water Pollution, Contamination, and Vector-Borne Diseases

Agriculture is a key source of diffuse water pollution, meaning that the polluters are highly dispersed and individual sources of pollution are challenging to identify. Fertilizer use on crop land and livestock animal excreta are key sources of agricultural water pollution. Excessive nitrogen (N) and phosphorus (P) from fertilizer and animal waste in water bodies result in eutrophication, a situation when fast algae growth depletes oxygen, affecting aquatic life. Irrigated agriculture uses larger quantities of fertilizers, and many application techniques are prone to wash out excessive fertilizer and pesticide applications into fragile water bodies, affecting aquatic life, contributing to eutrophication and hypoxia, and threatening human health. For example, high levels of nitrates from fertilizers can contribute to blue baby syndrome, a potentially fatal illness in infants (Mateo-Sagasta et al. 2018). Nitrogen pollution is also causing algal blooms and dead zones in coastal areas, such as the hypoxia in the Gulf of Mexico (Good & Beatty 2011). Xie & Ringler (2017) project growth in N and P pollution to be fastest in the group of low-income developing countries, with a projected increase by up to 118% for N loadings and up to 47% for P loadings by 2050 compared to 2000. While nutrient loading levels are currently largest, by far, in the Asia region, rates of growth are fastest in Africa.

At the same time, the land irrigated with polluted irrigation water is rapidly growing. Thebo et al. (2017) estimate that about 36 million hectares of land in periurban areas are irrigated with untreated wastewater, leading to millions of cases of illness every year, largely unreported, as well as to thousands of deaths.

Poor irrigation management can also lead to soil erosion and river sedimentation, waterlogging, and salinization (Hillel & Vlek 2005). Waterlogging, which results from the tendency to apply water in excess of irrigation needs, reduces aeration, nutrient uptake, and crop yields. Salinization of soils is equally linked to poor irrigation practices and results from the capillary rise of saline water tables or through the use of saline water for irrigation (Hillel et al. 2008).

In addition, irrigation water can also provide a microenvironment hospitable to mosquitoes and snails that spread malaria, dengue, and schistosomiasis and can carry bacteria responsible for cholera, dysentery, and other diseases. Although some studies have found that malaria prevalence is higher in communities in proximity to irrigation sites and dams, this is often limited to areas of unstable transmission, such as in the African highland areas (Ijumba & Lindsay 2001, Kibret et al. 2016).

4.4. Conflict Around Irrigation

Water scarcity, heightened through climate change, contributes to tension and conflict around irrigation water use, sometimes with deadly endings. Many local irrigation conflicts, for example, between pastoralists and irrigators on the fringes of the Sahel (Gefu & Kolawole 2002), can be severe, particularly during drought years. International conflicts over water similarly exist; however, overall, there has been more cooperation than conflict over transboundary water resources. Petersen-Perlman et al. (2017) note that there are close to 300 international surface basins and close to 600 transboundary aquifers, in addition to countless smaller watersheds crossing subnational boundaries. Transboundary water agreements have been developed for key international basins, such as the Nile, Mekong, or Indus. Such agreements have, in most cases, been resilient to challenges and changes around water quantity and quality. Well-known tensions over transboundary flows for irrigation include the Amu Darya basin between upstream Tajikistan and downstream Uzbekistan, following the collapse of the Soviet Union. Tajikistan needed to release reservoir flows in winter for energy generation to heat homes, potentially damaging irrigation infrastructure in downstream Uzbekistan and depriving Uzbekistan of needed summer irrigation flows (Bekchanov et al. 2015). To address this and other transboundary challenges to irrigation, improving baseline information and data exchange, strengthening cooperative frameworks, and jointly working toward conflict reduction will be needed (Petersen-Perlman et al. 2017).

4.5. Poor Economic Treatment of Irrigation Water

A key challenge to the sustainability and equity of irrigation development has been that irrigation water is seldom priced. Irrigation services provided by large-scale systems often carry an irrigation service fee, but these fees rarely cover more than a minuscule share of irrigation system cost and are generally not linked to irrigation water use (Johansson et al. 2002). Given the large volumes of irrigation water needed to grow crops (approximately 1,000 L of water to produce 1 kg of cereals, on average), charging farmers for irrigation water can be punitive for all but the most profitable crops. Webber et al. (2008) describe some of the challenges that Chinese farmers face with current irrigation costs and propose alternatives to increased irrigation pricing, such as enabling farmers to directly engage in irrigation water management.

Existing market failures and the unique characteristics of water, including its fluidity across space and time, its linkage to the value of land, and its multiple uses, make it challenging to apply economics to irrigation. As Hellegers (2006, p. 157) notes, "at this point in time, there is little empirical evidence of the effectiveness of economic instruments in irrigation water management." Irrigation water is both a social good, providing employment and food security, and an economic good, reflecting the scarcity value of water in alternative uses.

Bierkens et al. (2019) summarize selected studies that calculate a shadow price of irrigation water in different basins for different crops and calculate the same for five crops in 11 countries. D'Odorico et al. (2020), in a similar study, find irrigation water values of \$0.05, \$0.16, and \$0.16 for one cubic meter of irrigation withdrawn (not consumed) for wheat, maize, and rice, respectively, roughly in line with other, subnational studies. Calculated shadow prices of irrigation water are affected by the relative contribution of precipitation to total crop water use (see **Figure 1**), in addition to a host of other factors, such as crop type, variety, season grown, and crop-specific input and output price policies. Moreover, such analyses do not adequately reflect the specific goals of irrigation (i.e., generation of foreign exchange or food security), the opportunity cost of water (i.e., alternative uses and environmental externalities), nor the cost of not irrigating, such as increased food insecurity. While calculations at that scale are not policy-actionable, they affirm the relatively low value of water use in irrigation, particularly compared to uses in industry or the domestic sectors (e.g., Cai et al. 2006).

Given the low value and high quantities of irrigation water used to produce crops, as well as the challenge of metering the quantity of irrigation water applied, most irrigation water is not priced. Measures used in some countries to circumvent metering of individual irrigators include area-based and combined area- and crop-based fees (Schoengold & Zilberman 2007). Importantly, at the current low-to-nil prices of water, price increases high enough to induce significant changes in water allocation can price farmers out of irrigated agriculture and are unlikely to be feasible in both low- and high-income countries (Rosegrant et al. 2009, Schoengold & Zilberman 2007).

5. THE FUTURE OF IRRIGATION: TORRENTS OR TRICKLES?

5.1. Invest in Knowledge, Data, and Monitoring of Irrigation

Data and information on irrigation are highly incomplete. No government of a country with substantial agriculture can say with any precision how much water is used for irrigation within its country boundaries. Most countries in Africa and Asia cannot even state with certainty how much area is irrigated, and few countries know how much of the irrigation in their country is from small-scale irrigation. Although there are various sources of data on water resources, there are large discrepancies among these sources, often because of the paucity of measurements taken and the continuous change in area and water use as a result of changing climate conditions, changing prices, and input cost signals. Information is most challenging to obtain for irrigation systems that farmers develop on their own.

Far more detailed information is necessary at the local level to increase the sustainability of irrigation, particularly in light of climate change. There are promising avenues of using remote sensing technologies to better assess and monitor the status of irrigation development and irrigation water use, particularly when combined with validation of data on the ground. Such systems work best in arid environments where a wet field is more likely due to irrigation rather than being a wetlands or reflecting a recent rainfall event (Blatchford et al. 2020, Hellegers et al. 2010). One source to assess irrigation water use from space is the Water Productivity Open-access portal (WaPOR) database released by the Food and Agriculture Organization of the United Nations (FAO) to assess crop water productivity in Africa and the Middle East. This database includes actual evapotranspiration, aboveground biomass, and gross biomass water productivity at spatial scales varying from 100 m to 250 m, depending on location, at a 10-day temporal resolution. Blatchford et al. (2020) review the literature on the accuracy of remote sensed versus in situ methods. They note that crop water productivity can be estimated with remote-sensed products to within the error range from in situ methods, but error ranges can be dramatically larger when using remote-sensed products.

Even if irrigated area, water use, and projections of area were known, there is also great uncertainty regarding future irrigation needs under climate change. For example, Konzmann et al. (2012) find a decrease in global irrigation demand of around 17% as a result of climate change due to beneficial CO_2 effects for plant growth, reduced growing periods, and regionally higher precipitation levels. Nechifor & Winning (2019) find similar results by combining the same crop model with a global computable general equilibrium framework analysis. Most other studies, however, find increased irrigation water demand as a result of climate change and climate variability due to higher plant evapotranspiration (e.g., Döll 2002, Hargreaves et al. 1993, Rodríguez Díaz et al. 2007).

5.2. Improve the Enabling Environment of Irrigation

Key underlying conditions that need to be changed for irrigation to become more sustainable and equitable include the establishment of more secure water rights and the strengthening of governance systems around irrigation. When natural resources become scarce, users tend to compete for access and use, and this requires the clarification of rights and responsibilities over the resource (Meinzen-Dick 2014). Water rights can empower users by requiring their consent to any reallocation of water and by receiving compensation for transferred water. Moreover, they provide incentives for investment in water-saving technology.

Water rights are, however, highly complex, and various, sometimes overlapping, rights systems are found in parts of Africa and Asia, including customary water rights, while the state capacity to define and support such rights is often limited. Similarly, when various irrigators draw on the same surface resources, in a larger, canal-based irrigation system or as dispersed individual irrigators on the same groundwater source, institutions are needed to support equitable access and reduce the risk of degradation of the water source (Meinzen-Dick 2014).

Secure water rights are also the basis for water rights trading, which can afford farmers additional income through the sale of saved water. For water trading to be successful, suitable physical conveyance structures are necessary along with low transaction costs and the possibility of information exchange between willing buyers and sellers of water rights. Owing to the complexity of formal water markets, no new markets have been developed in Africa and Asia over the last several decades (Rosegrant & Binswanger 1994, Rosegrant et al. 2014). However, informal water markets continue to thrive, transferring water between irrigators in larger canal systems and from smallholders with individual well access to those without a pump or well, particularly in South Asia (Meinzen-Dick 1996).

It is clear that strong farmer involvement in irrigation management is crucial for the success of irrigation enterprises. This was attempted in the 1990s through the construct of irrigation management transfer (IMT), which was promoted by the World Bank and various governments. However, in many cases, farmers were only provided with the rights to maintain the infrastructure but not the rights to the water source itself. The impact of IMT remains largely unknown owing to the lack of comprehensive and comparable assessments (Bell et al. 2015, Meinzen-Dick 2014, Senanayake et al. 2015).

A further irrigation institution that supports farmer engagement and can operationalize water rights is water user associations. Mekonnen et al. (2015) find that the existence of effective water user associations in the IBIS improved agricultural productivity of farmers at the tail end of irrigation canals. However, many of these associations have traditionally limited membership to holders of irrigated land titles. To improve equity in irrigation and ensure that its multiple uses thrive, it is important to widen access to women, livestock keepers, and other poor and marginalized water users (Meinzen-Dick 2014). Moreover, various tools have been developed to strengthen the inclusion of women in larger- (Lefore et al. 2017), individual-, and small-scale systems (Theis et al. 2018a,b).

Governing groundwater is particularly difficult, as the resource is invisible, users are generally unaware of the connectedness of the aquifer system, and most groundwater systems suffer from a lack of data on safe yield and drawdown. Elements of a successful governance system include recognized use rights, monitoring processes, means for sanctioning violations, representative associations of water users, financing mechanisms for the governance system, and procedures for adapting to changing conditions. Meinzen-Dick et al. (2018) find that collective groundwater management facilitated by experimental games can be effective in improving local groundwater governance. This social learning intervention is now being scaled up to several thousand communities across several Indian states.

5.3. Improve Irrigation Technologies and System Performance

Direct improvements of irrigation technologies include the switch from gravity to furrow irrigation and further to sprinkler and drip irrigation. Sprinkler and drip irrigation reduce seepage and percolation losses of water by delivering water closer to the crop and root zone. In particular, drip irrigation releases minute quantities of water directly onto the root zone of the plant, ensuring that most of the water applied is used by the crops. Drip lines can also deliver water-soluble nutrients directly to the root system of crops, through a process known as fertigation, thus optimizing application of chemical fertilizers. Drip irrigation, however, has important technical requirements, such as the need for pressurized water application and continuous water availability—although low-cost drip systems are increasingly being developed—and remains a highly knowledge-intensive technology. Owing to their higher cost, drip technologies are generally used for high-value crops, such as vegetables and orchards. Reviews of the impacts of drip irrigation have been mixed, due to different objectives associated with its use and the wide variation of drip technologies in use (e.g., Burney et al. 2010, Van der Kooij et al. 2013, Venot et al. 2017). With growing water scarcity, areas with drip and sprinkler irrigation continue to grow, particularly in commercial irrigated systems in the most water-scarce areas of the world, such as North Africa. According to ICID (2018), about 53% of the irrigated area in the United States is under sprinkler and micro irrigation, as are 14%, 8%, 77%, 14%, and 15% of China, India, South Africa, Morocco, and Egypt, respectively, with a growing tendency.

Advances in irrigation technologies continue to be made, both to lower their cost and to further increase their precision (e.g., Dukes & Perry 2006). Importantly, investments in advanced irrigation technologies, such as drip lines or sprinklers, without proper assessment of water resources and flows, and without institutions that put a cap on withdrawals for agriculture, might well increase total irrigation water consumption, which is also called the "paradox of irrigation efficiency" (Grafton et al. 2018, Rosegrant et al. 2009).

Other important technologies include irrigation management tools, in particular precision agricultural technologies, such as soil moisture and yield sensors. A precision agricultural technology with growing applications is the variable rate technology, which relies on data from soil sampling, yield monitors, and remote or proximal sensing to create yield maps and regulate the amount and timing of application of water and agro-chemicals (Gebbers & Adamchuck 2010). Low-cost options of soil moisture sensors include wetting-front detectors that provide guidance to farmers on when additional irrigation can improve crop yields and when not (e.g., Stirzaker 2003).

Measures to improve system performance of larger irrigation systems include just-in-time scheduling of irrigation deliveries, improving the uniformity of irrigation deliveries between head- and tail-end farmers through a series of measures such as canal lining, and increasing the multifunctionality of irrigation systems. McCartney et al. (2019) argue that modernization of irrigation systems should include the integration of both fish production and more nutritious (and higher-value) crops. To achieve such a change, the authors suggest (*a*) structural changes within the irrigation command area, such as the incorporation of fish nurseries and refuges, and connectivity for wild fish movement within the scheme; (*b*) changes to the extended command area, such as changes in the diversion infrastructure to support up- and downstream movement of fish; (*c*) activities at the catchment level, such as reduction of trade-offs with other ecosystems services, for example, through the development of recreation areas or improvements to water quality; and (*d*) policy reform at the national level to support strategies and institutions to integrate food and nutrition security with irrigation investments, as well as environmental goals.

5.4. Improve Economic Incentives for Irrigation Sustainability

Although irrigation water is seldom priced, pricing can improve efficiency and sustainability, if accompanied by supporting policies. This is reflected, for example, in Australia or Chile, where farmers gradually switched from lower-value crops, such as alfalfa, to higher-value crops, such as table or wine grapes, following the introduction of water trading, which put an explicit, albeit varying value on the water use in these basins (Cai et al. 2006, Turral et al. 2005). As an example, in the Murray–Darling Basin of Australia, water traded at A$0.4 per cubic meter during a widespread drought in 2008/2009, and a lower A$0.02 per cubic meter in 2010/2011, a relatively wet year (Grafton & Horne 2014). Given the challenging institutional and legal requirements for effective water markets and trading, few formal markets have been established. At the same time, informal water markets can be found in the large irrigation systems of Asia, where farmers take turns in accessing irrigation water to suit their specific needs. An alternative to formal water markets are brokerage mechanisms, such as the charge-subsidy system, where farmers are paid to use less irrigation water (Rosegrant et al. 2005, 2009). In such a system, water rights could be assigned to farmers based on historical rights, with water transfers permitted at a price for water determined by the water agency. Water users would then be charged (or paid) at the assigned price for water demand above (or below) the base water rights. Historical water rights would be recognized, and the marginal efficiency prices only apply to marginal water use, thus introducing nonpunitive incentives compared to other water pricing schemes.

A few more recent irrigation investments include metered pumps that carry a fee not only for fuel or electricity but also for the use of water itself. In other systems, farmers carry the diesel or electricity cost to pump water into their fields, which can serve as a proxy for water charges. Pumping costs, together with improved control over application quantities and timing, are one of the reasons for higher agricultural productivity of groundwater irrigation systems.

5.5. Improve Nonirrigation-Focused Investments and Policies That Support Irrigation Sustainability

Key investments that improve irrigation sustainability include those in agricultural R&D, particularly for increased water use efficiency of crops. Investments also include breeding that improves survival of plants, some of which are already grown with irrigation, during flood, drought, and heat stress events, which will become more common due to climate change and associated climate extremes. Past breeding of semi-dwarf, dwarf, and short-duration varieties already considerably reduced irrigation water needs. According to Condon et al. (2004), three key processes can be furthered through breeding. These include moving more of the accessible water into the crop, producing more biomass for the water transpired by the crop, and increasing the harvestable share of the biomass produced with a certain amount of water.

Key nonirrigation policies that can improve the sustainability of irrigation include trade policies that support the production of food in locations with the greatest comparative advantage, that is, water-abundant countries, and maintain open trading channels for the transfer of staple grains to more water-scarce countries and regions such as those in North Africa. Liu et al. (2014) find that reduced irrigation availability in key river basins can be buffered, to a substantial extent, by changes in the geography of international trade. In addition to overall trade liberalization, changes in specific trade agreements, such as the end in 2004 of the Multi Fibre Arrangement (MFA), a set of quotas favoring textile and apparel exports from some countries, had direct implications for irrigation owing to the high water use of cotton. This favored China as an exporter of textiles and created new demand for irrigated cotton destined for Chinese industries (Rosegrant et al. 2010).

Other agricultural and trade policies that directly affect irrigation are the continued subsidization of fossil fuels, fertilizers, and key water-guzzling crops, such as rice and sugarcane, as well as subsidized water-intensive animal source foods, including dairy cattle, in many parts of the world. Any policy change affecting these inputs, crops, and foods could substantially affect irrigation water sustainability. A growing number of studies is assessing the broader costs of poor agricultural input and output price and trade policies, largely focused on impacts on diets, but also greenhouse gas emissions, water scarcity, and pollution. Water-scarce regions, such as the Middle East and North Africa, import large and growing shares of their food needs, but they also try to pursue some level of food self-sufficiency due to the risk of trade wars. Importing food and other goods to save scarce national resources is also called virtual water trade. In virtual water trade, irrigation water is saved when exporters produce goods under rainfed conditions for which importers otherwise would have needed to use irrigation water (Rosegrant et al. 2009).

Other key policies include climate and energy policies that can favor the development of solar groundwater irrigation in areas without electric grid access (ideally supported by strong institutions for water conservation), preserve remaining tropical forest and support climate mitigation goals.

A third set of important policies focus on nutrition. National food-based dietary guidelines (FBDGs) that include environmental considerations can help steer food demand patterns toward those crops and livestock products that require less water resources. Countries like Brazil and Sweden have developed dietary guidelines that take sustainability, including water use, into account (UNSCN 2020).

6. CONCLUSIONS

Irrigation has developed differently in Africa and Asia but will play important roles in future food security in both regions. The future of irrigation will not be like the past—moving toward more trickles rather than torrents. Climate change, rapidly growing nonirrigation demands on water resources, and the need for much-improved environmental sustainability demand that the footprint of irrigation is reduced.

This does not mean that irrigated areas and development will be halted. It is more likely that irrigation investments will continue apace to support agricultural production in a world of highly uncertain climatic realities. However, the irrigation of the future will be much more knowledge intensive. It needs to embrace technological innovations, such as precision agricultural tools, and should provide incentive structures that support farmers in using water more optimally.

Moreover, growing water scarcity will likely increasingly lead to finance, trade, and agricultural ministries considering the implications of their decisions on water. This should also help propel important nonirrigation developments, such as increased investment in crop breeding, phasing out of subsidies for fossil fuels and fertilizers, phasing out of input and output price support for rice, sugarcane and milk, and a reinvigoration of trade liberalization, all of which will support irrigation sustainability as well as the health of humanity and our planet.

New technologies, such as increased use of digital tools in irrigation and improved monitoring of irrigation water use from space, can help improve economic analysis tools. They can also contribute to other areas, for example, to support the pricing of water (or paying farmers who use less water) according to crop evapotranspiration and to ensure that advanced irrigation technologies truly save irrigation water, if that is the desired goal. More knowledge-intensive irrigation can also expand the set of users of irrigation water, such as aquaculture systems, and needs to combine precision irrigation with precision chemical applications to reduce the environmental externalities of irrigation. To ensure that these benefits are achieved, economists need to work more closely with irrigation engineers, agronomists, and other social scientists to support farmers in using agricultural water more profitably and sustainably.

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