

The impacts of irrigation: A review of published evidence

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EXECUTIVE SUMMARY

Irrigation development has historically comprised a considerable proportion of the overall infrastructure investment portfolio of the Bank. However, after a surge from the 1960s to 1980s in the level of public investment in the irrigation sector, the enthusiasm for continued investment (particularly in new irrigation development) has softened, except in sub-Saharan Africa. There may be multiple reasons for this change. Irrigations very success, in concert with other investments in agriculture, took away the imperative for continued rapid expansion of the global food supply. At the same time, despite this success in increasing food output, large scale irrigation systems are often viewed as failing to live up to their potential and require consistent injections of outside capital for operations and maintenance. Irrigation is also associated with negative externalities, particularly as related to the environment. Finally, the potential poverty reduction role of irrigation, particularly large-scale irrigation, may have changed as areas suitable for new irrigation development have declined and populations urbanize. Nonetheless, the pressure to meet growing food demand and provide low cost food to an increasingly urban world persists. Continued irrigation investments, even if not following past models, must play a key role in relieving that pressure.

To assess empirical evidence of the irrigation impacts highlighted above and provide guidance to future investment, we reviewed a wide range of published literature (over 500 articles with over 250 cited in the bibliography) on irrigation impact. Potential studies were identified using keyword searches focused on irrigation and impact, an examination of the bibliographies of the identified studies, and bibliographies of previous assessments of irrigation impact. While we focused our analysis and discussion on studies published in the last 25 years, we also drew on earlier works to provide context and insights. Where possible we concentrated on peer-reviewed studies that used primary data to empirically measure impact and studies of economy wide processes based using secondary data. We supplemented the results with insights from qualitative studies that provide understanding of the mechanisms through which irrigation impacts occur. Our goal was to identify and provide context for an illustrative range of impact assessments from a variety of literatures, but our sample cannot be considered as representative in a statistical sense.

The reviewed studies showed broad variation in scope and focus, in evaluation design and methods used to infer impact, and in the physical and institutional nature of the irrigation systems being evaluated. The impacts measured also ranged widely, from direct and indirect

production effects to impacts on poverty, nutrition and groundwater depletion. While this variation made systematic comparison across studies difficult, number key conclusions emerged.

First, irrigation is clearly linked to increased agricultural output through both direct production effects and through its role in increasing the productivity of complementary inputs.

Second, irrigation has been strongly associated with decreases in poverty, particularly amongst direct beneficiaries and urban consumers.

Third, irrigation is linked to a wide range of other impacts, for example in nutrition, health and the environment.

Fourth, studies that measured irrigation impacts beyond the farm or system scales often found indirect, secondary effects of similar or greater magnitude than direct, primary effects. In some cases, these secondary effects were positive (e.g. multiplier effects to the overall economy) and in some cases negative (e.g. offsite environmental effects that offset the gains in production or poverty reduction).

Fifth, the magnitude and nature of irrigation impacts, particularly impacts beyond production effects, were highly dependent on the particular location and circumstances in which irrigation occurred. In addition, impacts changed over time in terms of magnitude and sometimes sign.

Sixth, irrigation impacts, positive and negative, were unequal socially, spatially, and temporally. Virtually every study we reviewed that was designed to measure differential impacts, in whatever dimension, found them to be significant.

Together these conclusions suggest a number of considerations to ensure the highest returns for future irrigation investment. Investment planning should expand attention to irrigation benefits AND costs and explicitly consider both direct and indirect impacts. Within this planning, interventions to reduce negative environmental impacts of irrigation, AND better public awareness of indirect environmental benefits, for example through decreased pressure on marginal land, would also improve investment outcomes and public support. Finally, given the socially differential impacts of irrigation, continued, explicit focus on distribution effects are needed if poverty reduction and equity goals of investments are to have the greatest likelihood of success.

1. Introduction

Irrigation development has historically comprised a considerable proportion of the overall infrastructure investment portfolio of the Bank. However, after a surge from the 1960s to 1980s in the level of public investment in the irrigation sector, the enthusiasm for continued investment (particularly in new irrigation development) has softened, except in sub-Saharan Africa. There may be multiple reasons for this change. Irrigations very success, in concert with other investments in agriculture, took away the imperative for continued rapid expansion of the global food supply. Even if successful in increasing food output, large scale irrigation systems are often viewed as failing to live up to their potential and require consistent injections of outside capital for operations and maintenance. Irrigation is also associated with negative externalities, particularly as related to the environment. Finally, the potential poverty reduction role of irrigation, particularly large-scale irrigation, may have changed as areas suitable for new irrigation development have declined and populations urbanize. Nonetheless, the pressure to meet growing food demand and provide low cost food to an increasingly urban world persists. Continued irrigation investments, even if not following past models, will undoubtedly play a role in relieving that pressure.

The purpose of this paper is to review published evidence of irrigation impact to provide insights and lessons for operation and policy. To do this, the paper first provides a general typology for considering the wide range of mechanisms through which irrigation impacts humans directly and through the environment. It then presents the results of a broad review of published literature focused generally on the measurement of irrigation impact, primarily from the Green Revolution era onwards.

The large number of reviewed studies (over 500 with more than 250 cited and included in the bibliography) showed broad variation in scope and focus, in evaluation design and methods used to infer impact, and in the physical and institutional nature of the irrigation systems being evaluated. The impacts measured also ranged widely, from direct and indirect production effects to impacts on poverty, nutrition and groundwater depletion. This range of approaches and foci highlights that the pathways from irrigation development to impact are themselves highly variable. While it can be concluded that the overall impacts of irrigation on food production, poverty reduction and some other variables of interest are positive, they are also offset to varying degrees by negative externalities and sometimes inequitable consequences. The results also highlight that the impacts of particular irrigation developments change over time as do the interests of those who study them. While this variation might seem to suggest that no general conclusions can be drawn from the literature, the breadth of studies provides clear insights into the impacts of irrigation. To summarize:

1. Irrigation is clearly linked to increased agricultural output through both direct production effects and through its role in increasing the productivity of complementary inputs.
2. Irrigation has been strongly associated with decreases in poverty, particularly amongst direct beneficiaries and urban consumers.
3. Irrigation is linked to a wide range of other impacts, for example as related to nutrition, health and the environment.
4. Studies that measured irrigation impacts beyond the farm or system scales often found indirect, secondary effects of similar or greater magnitude than direct, primary effects. In

some cases, these secondary effects were positive (e.g. multiplier effects to the overall economy) and in some cases negative (e.g. offsite environmental effects that offset the gains in production or poverty reduction).

5. The range and magnitude of irrigation impacts, particularly impacts beyond production effects, were highly dependent on the particular location and circumstances in which irrigation occurred. In addition, impacts changed over time in terms of magnitude and sometimes sign.
6. Irrigation impacts, positive and negative, were unequally distributed socially, spatially, and temporally. Virtually every study we reviewed that was designed to measure differential impacts found them to be significant.

These conclusions along with our analysis of the state of irrigation impact assessment leads us to the following, interrelated, considerations for future investment:

- A. Expanded attention to irrigation benefits AND costs is needed in irrigation planning.
- B. The potential range of positive and negative impacts considered in planning should generally be expanded.
- C. Continued, explicit focus on distribution effects are needed if poverty reduction and equity goals of investments are to have the greatest likelihood of success.
- D. Increased planning to reduce negative environmental impacts of irrigation AND a better case for potential environmental benefits would improve investment outcomes and public appreciation for irrigation.
- E. Investment planning should consider that the purpose of irrigation will change over time as will values towards the environment.

While there is no shortage of irrigation impact assessments and so no need for a general call for additional research, improved and new research on priority areas could help investment planning. These areas include:

- I. Design for impact assessment, not just M&E, for select projects. However, mechanisms for impact assessment will likely need longer time horizons than typical project cycles.
- II. Additional investment in long-term assessments of irrigation's dynamic nature.
- III. Renewed focus on the impact of large-scale irrigation, particularly in terms of maintenance and institutions.
- IV. New analysis of national and global scale irrigation impacts and processes.
- V. Support of both quantitative and complementary qualitative work on the nature and scale of irrigation impacts.

These findings and recommendations are discussed in detail in the main body of the paper and in the conclusion.

2. A Typology of Irrigation Impacts

The impacts of irrigation are varied and range from direct increases in agricultural output to indirect effects on gender relations, employment and even government structures. We provide

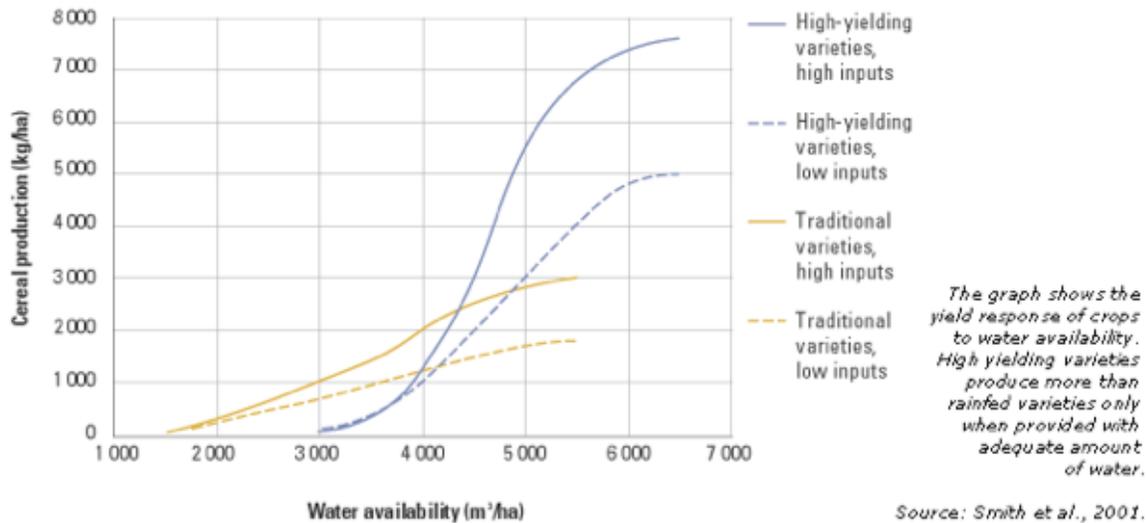
here an indicative typology, building on the existing literature, to assist in conceptualizing irrigation impacts. We note though that the impacts of irrigation are varied and overlapping and no definitive typology would suit all needs. Our later analysis of published impact assessments highlights the interconnected, and sometimes counterintuitive, relationships between irrigation and a wide range of impacts.

2.1 Direct impacts on production, farming systems and risk

The primary, direct impact of irrigation is usually considered to be increased crop output through increases in yield and area. Yield increases because of additional plant water availability and the linear relationship between transpiration and yield (Chang, 1968). Irrigation also makes control of both the quantity and timing of water availability more precise, supporting crop establishment, growth and yield. In addition, irrigation can make crop production possible in places where rainfall and soil moisture are otherwise insufficient or make it possible to intensify production through second and sometimes third croppings.

Availability of water through irrigation also reduces the risk of crop failure. This in turn increases the expected return on complementary investments, such as seeds and fertilizer (Namara et al., 2005; Gebregzaibher et al., 2011), further increasing yields as discussed below and increasing incentives for investment. This is graphically illustrated in Figure 1. Traditional varieties provide returns even when water supplies are limited while High Yield Varieties (HYVs) provide no return. However, once water supplies reach a critical level, HYV yields are higher as is the marginal response to additional water. (In addition, the absolute and marginal responses of complementary inputs are higher for HYVs). Thus, farmers with assured supplies of sufficient water are more likely to invest in HYVs and complementary inputs. In contrast, farmers who experience or perceive a risk in the volume or timing of irrigation supplies are more likely to invest in seeds with low yield potential but high probability of some return no matter the water outcome. Under such conditions, the incentive for investment in other inputs also declines. The risks associated with assured surface irrigation supply and timing explain, in part, why farmer initiated groundwater use is so common even within surface irrigation systems.

Figure 1. Typical responses of cereal crop yields to water



Source: Smith, M., Fereres, E., Kassam, A. 2001. 'Crop Water Productivity Under Deficient Water Supply'. Paper presented on the occasion of the Expert Meeting on Crop Water Productivity Under Deficient Water Supply, 3-5 December 2001, Rome, Italy. Cited in FAO: <http://www.fao.org/docrep/006/Y4683E/y4683e07.htm>

Irrigation can also bring new risks beyond the farm scale, for example as related to crop disease and diversity as demand for traditional varieties decline (Mehra, 1981; Hazell, 1982; Pinstrip-Andersen and Hazell, 1985). The adoption of more uniform varieties may also bring new price risks as cropping decisions become more uniform across large regions (Pinstrip-Anderson and Hazell, 1985), an outcome potentially further exacerbated by centrally controlled water releases and crop procurement programs, for example in India. Better water control may also induce farmers to shift to higher value crops (such as fruits and vegetables) subject to greater price variability and dependent on reliable transportation and storage.

2.2. Enhanced productivity of complementary inputs

While irrigation directly contributes to increased yield (i.e. land productivity), it also increases the productivity of other complementary inputs. The productivity of High Yield Variety Seeds during the Green Revolution, for example, was made possible only by the supply of irrigation. That productivity was further increased when coupled with additional inputs of fertilizer supplies. Furthermore, the productivity of fertilizer was itself increased by the availability of irrigation supplies. Figure 1 illustrates these points. Irrigation likely increases the productivity of other complementary inputs such as labor through similar mechanisms (von Braun et al., 1989).

Turning the equation around, irrigation can also be considered as an induced *response* to other technology or investments. The advantages of the Green Revolution's High Yield Variety Seeds could only be achieved when coupled with the assured volumes of water that only irrigation could provide. This spurred investment in publicly financed, large-scale surface irrigation and a boom in privately financed, small-scale groundwater use. In fact, it has been argued that the

Green Revolution was as much an irrigation (tubewell) revolution as a seed revolution (Repetto, 1994).

2.3 Impacts on output prices

Increasing output, *ceteris paribus*, places downward pressure on prices. For example, Evenson and Rosegrant (2003) estimate that global food prices would have been 35-65% higher without Green Revolution technologies, including irrigation. While falling prices are generally good for consumers, they negatively impact producers. However, the impact on any particular producer will depend on the extent to which falling prices are offset by productivity gains as well as the extent to which s/he is also a buyer of commodities for personal consumption. The impacts of irrigation induced price change will also be uneven across countries. For example, the price reductions caused by Green Revolution irrigated agriculture also impacted farmers confined to rainfed conditions and farmers in Africa and elsewhere who did not benefit from investments in irrigation and seeds. As many (irrigated) rice exporting countries continue to directly or indirectly subsidize production, this problem persists with perhaps the greatest negative consequences for African producers.

2.4 Impacts on poverty

The poverty reduction potential of irrigation has been well documented (e.g. Lipton et al., 2003). Increased output provides additional food for subsistence producers. Price reductions provide substantial benefits to poor consumers, particularly since the poor spend a higher proportion of income on food. Many poor producers are also net buyers of food and so also benefit in this way. However, the nature and extent of poverty impacts can vary greatly depending on factors such as relative or absolute land size, relative location within an irrigation system (e.g. head or tail end), and structural issues related to the overall institutional and social-economic environment, for example as related to gender, caste and class.

Beyond direct production, consumption and income effects, irrigation also impacts poverty through indirect mechanisms including increased labor demand, particularly during harvest periods, nutrition and health change, and economy-wide multiplier effects. Whether these impacts are positive or negative is highly contextual. For example, irrigation's employment effects may benefit the landless poor, but inequalities may also widen as output increases and depresses prices received by poor farmers operating in rain-fed conditions. Irrigation may also worsen poverty if it re-enforces processes of land consolidation in which poor households lose rights, converting marginal and poor farmers to landless laborers (Chambers, 1988) or if it is associated with displacement of labor by mechanization or herbicide use. The development of irrigation can have off site environmental impacts that are particularly important for the poor. For example, the construction of dams and reservoirs to support irrigation has been associated with displacement costs that disproportionately fall on the poor (e.g. Duflo and Pande, 2005). Irrigation may also reduce environmental service provision upon which the poor rely, for example as related to inland and marine fisheries.

2.5 Impacts on consumption and nutrition

Irrigation contributes to the availability of energy and protein (Pingali, 2012) and can provide increased incomes or purchasing power to support diet diversity (Von Braun et al., 1989). However, the monoculture often associated with irrigation can also reduce the availability of more nutrient rich crops and increase their costs relative to more abundant staples. This does not need to be the case though. Small scale irrigation in Africa has been associated with increases in vegetable production with direct benefits on nutritional status, particularly for women and children (Von Braun et al., 1989). A variety of mechanisms through which the Green Revolution related increases in production are related to nutritional status is outlined by Pinstrip-Anderson and Hazell (1985). A more recent review of nutrition related impacts of irrigation focused on sub-Saharan Africa is provided by Domenech (2013).

2.6 Impacts on health

Increases in standing water associated with irrigation, especially when systems are poorly managed, can serve as a breeding-ground for disease vectors including Anopheles mosquitos, contributing to increases in malaria and other disease. Similarly, dams constructed for irrigation slow water flow and may increase the prevalence of malaria or sleeping sickness. Irrigation with un- or minimally treated wastewater can increase exposure of both producers and consumers to pathogens resulting in schistosomiasis, diarrhea or other ailments (Amoah et al., 2009). Irrigation with chemically contaminated water, either natural as in arsenic (Senanayake and Mukherji, 2014) or human induced (Simmons et al., 2005) has clear health implications. The availability of irrigation can encourage use of other agricultural inputs including fertilizer and pesticides, increasing exposure of both farmers and consumers.

At the same time, the wealth generated by irrigation may also spur investment in health care, for example through purchase of bednets (Klinkenberg et al., 2004) or by increasing food expenditures and nutrition levels as discussed above. Irrigation development may increase the availability of clean drinking water and improve sanitation (Van der Hoek et al., 1999). Domenech and Ringler (2013) provide an overview of irrigation and health interactions.

2.7. Equity and Gender

The impacts of irrigation are clearly not uniform. Those producers with access to irrigation will generally benefit more than those without. Even for those with irrigation, impacts will vary depending on location within the system (head end versus tail end), relative land size, access to capital to support complementary investments, and other factors. As with any technology, early adopters may benefit differently than late adopters. Within irrigating villages, impacts will depend on class and caste structure.

A long literature highlights the importance of gender considerations in resource management outcomes in general (Meinzen-Dick et al., 2014) and water in particular (Ray, 2007). The importance of gender in irrigation outcomes and impacts is no less important. The production of particular crops is gendered, the uses to which agricultural water is put is gendered (e.g. field crops versus home gardens), and access to inputs is gendered (e.g. land titles, credits) as is the use of revenue from irrigated output. However, while well over half of food production in

developing countries is attributed to women (UNDP, 2006), irrigation interventions are often made without explicit input from erstwhile female beneficiaries and without consideration for gendered constraints to adoption (Zwarteveen, 1997), potentially reducing effectiveness and impacting within system inequality. The gendered impacts of irrigation are variable though. For example, irrigation may reduce work for women in some circumstances but increase it in others. Van Koppen and Hussain (2007) and Domenech and Ringler, 2013 provide overviews of the interconnections between irrigation impacts and gender.

2.8 Impacts on the environment

Water withdrawn for irrigation impacts the naturally occurring environmental services provided by free-flowing rivers as do changes in flow regimes caused by associated dams. Habitat and resident flora and fauna are destroyed, and the flooding of biomass may result in net releases of carbon dioxide (CO₂) and methane (CH₄). This may have impacts on global climate and localized air pollution problems. The rapid expansion of groundwater irrigation in the last few decades has also severed the natural connections between surface and groundwater systems and lead to drawdown that has caused soil compaction and amongst other problems. Waterlogging and salinity frequently result from poor irrigation management while the higher levels of inputs associated with irrigated agriculture result in fertilizer and pesticide runoff. At the same time, irrigation induced increases in yield and cropping intensity reduce pressures to develop yet more land. As the availability of new high quality agricultural land reaches its limits, this also reduces pressures to develop marginal lands prone to soil and nutrient erosion often of significance for biodiversity conservation (Millennium Ecosystem Assessment, 2005).

2.9 Multiplier effects and Impacts on the broader economy and political structure

Irrigation influenced changes in agricultural productivity have been shown to impact overall growth through multiplier effects and can free human and financial capital for industry and services (Mellor and Lele, 1973, Pinstруп-Andersen and Hazell, 1983.), stabilize rural populations (Viljoen, 1990; Little and Taylor, 2001; Schraven, 2010) and impact foreign exchange earnings and budgets via export taxes.

Irrigation may also influence overall governance structures. The Subak system in Indonesia is a well know example but other examples exist from around the world. While governance change may typically be a by-product of irrigation, it can also be an explicit objective. The rationale for the Green Revolution was both increased food production and social and political modernization in Asia and Latin America (Latham, 2011), though the impacts may not always have been as hoped. Niazi (2004), for example, argues that the arrival of more productive seeds and irrigation in Pakistan forestalled larger political reform. Similarly, electricity reform to support overall economic growth in India is now complicated by the political economy of power subsidies and groundwater.

3. Methodology

To assess empirical evidence of the irrigation impacts highlighted above, we reviewed a wide range of published literature. Potential studies were identified using keyword searches focused on irrigation and impact, an examination of the bibliographies of the identified studies, and bibliographies of previous assessments of irrigation impact. While we focus our analysis and discussion on studies published in the last 25 years, we also draw on earlier works to provide context and insights. Where possible we concentrated on peer-reviewed studies that use primary data to empirically measure impact and studies of economy wide processes based using secondary data. We supplement the results with insights from qualitative studies that provide understanding of the mechanisms through which irrigation impacts occur (see discussion section for comment on their role importance for policy). Our goal was to identify and provide context for an illustrative range of impact assessments from a variety of literatures, but our sample cannot be considered as representative in a statistical sense.

In total, we included more than 120 studies. In reading the studies, we considered a variety of variables including location and study date, scale of analysis (e.g. plot, household, aquifer), time since irrigation intervention, irrigation source and type (e.g. surface water, groundwater, wastewater; electric pump, treadle pump), evaluation approach (e.g. experimental, quasi-experimental or non-experimental).and method (e.g. econometric, modeling) and the nature of the impact assessed (e.g. production, poverty or health). We used the results and a detailed, qualitative reading of the studies included in the bibliography to derive an understanding of the nature, magnitude and extent of irrigation impacts as described below.

4. RESULTS

4.1 Evaluation scope and focus

The scope and focus of irrigation impact assessments show great diversity and differences in spatial, social and political scales, time frames of analysis, and geographic focus.

Scales of analysis for studies focused on the human impacts of irrigation include plot (e.g. Huang et al., 2005), farmer (e.g. Ayanwale and Alimi, 2004), household (e.g. Gebregziaber et al., 2009) or household head (e.g. Bagson and Kuuder, 2013), irrigation system (e.g. Irajpoor and Latif, 2011), state/province (e.g. Bhattarai and Narayanamoorthy, 2003) and global food system (e.g. Nelson et al, 2009). While most studies analyze impacts related to a particular irrigation system, others analyze and sometimes compare multiple systems in one country (e.g. Huang et al., 2005) and a few analyze systems in multiple countries (Hussain, 2007). Many analyses examine impacts at more than one scale.

Studies focused on the non-human impacts of irrigation use scales consistent with environmental processes. For example, some focus on the impacts of irrigation on particular rivers, aquifers or climate systems (e.g. Liu et al., 2001; Changming, 2001; Saeed et al., 2009; Lee et al., 2011; El Ayni et al., 2012). Others measure uptake of toxins at animal or plant level (e.g. Ohlendorf et al., 1986; Liu et al., 2005; Gupta et al, 2008; Ghosh et al., 2012).

The period between the establishment of irrigation and the measurement of impact also varied substantially in the studies we surveyed. In some cases, impact was assessed after as little as 1 year (e.g. Adeoti, 2007). At the other extreme were studies done 20 (Rattan et al., 2005), 30 (Baeza et al., 2013), and 50 (Viljoen, 1990) years after irrigation commenced. Many studies did not make the lag time between irrigation implementation and impact assessment clear.

One critique of early studies of the Green Revolution was that assessments happened too quickly and did not capture diffusion effects, missing poverty reduction effects that were later documented and overemphasizing negative effects on inequality (Pinstrup-Andersen and Hazell, 1985). Still later analysis and discussion tends to highlight growing, negative environmental impacts (e.g. Shiva, 2016), for example widespread overuse of groundwater and, in India, negative knock on impacts to the electricity industry. There is no ideal, and appropriate lags will always depend on purpose. However, past work on irrigation management transfer, an intervention with substantially less expected impact than irrigation development itself, has suggested minimum periods of 6 to 10 years (Kloezen, 1997; Vermillion, 1997).

Despite the dynamic and changing nature of irrigation impacts, most assessments measure impacts between two particular points in time, for example between single before and after irrigation dates (e.g. Abonesh et al., 2008; Peter, 2011; Bagson et al., 2013) or by comparing differences between with and without sites at a single point in time (e.g., Yohannes et al., 2005; Adeoti, 2007). The few studies that do measure impacts across time (e.g. Ayanwale and Alimi, 2004; Bhattarai et al., 2007; Burney et al., 2010) highlight the additional insights that can be gained and, sometimes, the changing conclusions. For example, the health impacts of irrigation can be negative in the short run as disease vectors increase, but may turn positive in the longer term as awareness generates government level policy responses (De Zulueta et al., 1980) or income effects result in greater health care investment by individuals (Klinkenberg et al., 2004). A major impediment to long- term assessments of the dynamic nature of irrigation impacts is the difficulty in data collection over time. Baeza et al. (2013) provide an alternative approach, using distance as a proxy for time in a study of health impacts of irrigation as related to malaria in India. While the approach may not be generalizable, it does demonstrate that alternatives to long- term data collection may be available.

While we did not try to precisely assess the proportion of studies by country, clear patterns did emerge. Assessments in the wake of the Green Revolution tended to focus on Asia, particularly India and Pakistan, though the total area under irrigation was larger in China. More recent studies tend to focus more on Africa, particularly Ethiopia and Ghana though their combined irrigated area is small by any measure. Studies focused on developing countries tend to focus on impacts as related to output, poverty and other measures of livelihood. Studies done in richer countries tend to focus on environmental impacts of irrigation.

There has also been a shift over time in the nature of the irrigation assessed. Earlier studies tend to focus on large- scale systems. More recent works tends to focus on groundwater irrigation, and small- scale systems such as treadle pumps, drip, farm ponds, and water used in home gardens.

4.2 Evaluation design and methods

Evaluation design is typically categorized as non-experimental, quasi-experimental, or experimental. Non-experimental approaches were common in our sample. Some studies use a simple comparison of the social and economic situation of participants in an irrigation project to the intended outcomes as stated in the original technical proposal and terms of reference of the scheme (e.g., Concern Universal, 2012). Others use a before and after comparison without control (e.g. Ayanwale and Alimi, 2004; Irajpoor and Latif, 2011) or a comparison between an area with irrigation and a non-irrigated control (e.g. Viljoen, 1990; Kibret et al., 2010). The fact that a study used a non-experimental design should not, a priori, be considered a critique as each study has its own purpose and logic. Nonetheless, the approaches limit the inferences that can be made on impact specifically.

Another large group, particularly of more recent publication, apply quasi-experimental methods to provide counterfactuals in with/without scenarios. The specific techniques applied are largely regression or econometric based but include many different approaches including propensity score matching; endogenous switching regression (e.g. Nkhata et al., 2014), differencing, instrumental variables (e.g. Duflo and Pande, 2005), and pipeline approaches. Perhaps not surprisingly given the nature of most irrigation, experimental approaches now common in other areas of development literature, just as Randomized Control Trials, did not appear in our sample.

Moving outside what might be called “orthodox” approaches to impact assessment, studies of regional, national and global irrigation impacts often use economic, hydro-economic (e.g. Barbier and Thompson, 1998; Bhatia et al., 2007; Louw et al., 2008; Nelson et al., 2009; Siddig and Mubarak, 2013) and even atmospheric (e.g. Lee et al., 2011) modeling approaches. None of the studies used remote sensing approaches, though remote sensing is used in studies of irrigation performance.

Finally, it is important to note that there is a long history of qualitative studies that directly or indirectly example the impact of irrigation within agricultural and human systems. Such studies provide nuanced, grounded insights into the subtle and varied ways irrigation works alone and as part of larger change processes and can be particularly strong in highlighting the mechanisms through which the differential impacts of irrigation occur (e.g. Cleaver, 1972; Blyn, 1983; Leaf, 1983; Merrey, 1983; Ostrom and Gardner, 1993; Beck, 1995; Das, 2002; Jewitt and Baker, 2007).

4.3 The Physical and Institutional Nature of Irrigation evaluated

While any division of water within the hydrologic cycle is arbitrary to some degree, irrigation is often conceptualized by the source of water within the hydrologic cycle: surface water, groundwater, conjunctive use, rainwater harvesting, wastewater, or saline water. A second and sometimes related conceptualization is the approach to water access. For example, surface water is often accessed through large scale canal systems, groundwater through small scale tube wells, and rainfall purposely captured in small reservoirs and farm ponds (e.g. Ersado, 2005; Venot et al., 2011; de Fraiture et al., 2014; Acheampong et al., 2014). Irrigation can also

be thought of in terms of the technology for its access [e.g. gravity fed or pumped surface systems; electric, diesel, solar (e.g. Burney et al., 2010) or human powered pumps (e.g. Shah et al., 2000; Adeoti et al., 2007; Mangisoni, 2008; Burney et al., 2010; Kamwamba-Mtethiwa et al., 2012)] and application (e.g. flood, sprinklers, drip irrigation, or bucket). Finally, irrigation can be conceptualized in terms of the crops to which it is applied (e.g. staple foods such as rice and wheat, cash crops, or vegetables for personal consumption or sale produced from home gardens). Our sample includes studies using each of these conceptualizations alone or in combination.

While studies of irrigation performance or water productivity (e.g. Senanayake, 2015; Giordano et al., 2017) are often concerned with particular institutional forms (e.g. Water User Associations), relatively few studies of irrigation impact assessments use institutional form as an explanatory variable. This may be because of the relative uniformity in institutional structures within each of the conceptualizations just outlined. For example, large-scale surface systems tend to be managed publically in whole or in part (main canals are typically managed by formal irrigation bureaucracies, though while distributaries may be managed publicly or through Water User Associations), while groundwater irrigation is typically privately controlled as is small-scale irrigation using drip or drum and buckets. Some studies have tried to measure differences in impacts of large scale (public) and small-scale (private) systems, though with a focus on the scale rather than the institution. For example, Dillon (2010), found greater positive impacts on production and income with small scale (and therefore private) systems than large scale (and therefore state) systems. Acheampong et al. (2014) found that performance and impacts of small dams in Ghana are generally higher when managed under WUAs. Other studies have examined the issue in reverse, measuring the impacts of irrigation system characteristics on institutional outcomes (e.g. Nagrah et al., 2016), finding for example that access to groundwater reduced incentives to participate in cooperative surface water management.

4.4 Measured impacts

4.4.1 Direct impacts on production and farming systems

It is well established that irrigated land is significantly more productive than non-irrigated. At the global level, irrigation accounts for only 20% of total agricultural area but 40% of total output (Turrall et al., 2011), though of course some of the productivity difference can be attributed to other factors including land quality, additional input use and research effort. Nonetheless, it is not surprising that virtually all reviewed studies that measured the impacts of irrigation on agricultural output documented increases over at least some time scale.

Studies of the first 1-2 decades of Green Revolution impacts highlight impressive gains in production directly and indirectly related to (primarily) large scale irrigation (see Pinstруп-Andersen and Hazell, 1985 and Everson and Gollin, 2003). Later studies, though not focused on impact assessment per se, do not question positive production impacts of irrigation but tend to highlight problems of irrigation system operations, sub-optimal system performance, and inadequate finance (e.g. Byerlee and Siddiq, 1994). Other studies show that production

problems with large- scale irrigation can occur over time. For example, salinization due to poor irrigation management has been shown to reduce yields (e.g. Pitman and Läuchli, 2002). The question is thus not whether irrigation increases output but for how long and at what cost.

More recent studies tend to focus on the impact of small- scale irrigation adoption (e.g. Ayars et al., 1999, Antony and Singandhupe, 2004), demonstrating production increases for a wide range of crops. However, some highlight the issue of disadoption over time (e.g. Burney and Naylor, 2012; Wakeyo and Gardebroek, 2015). Disadoption and the fact that adoption sometimes requires subsidy (e.g. Malik et al., 2016) at least suggests that the question for small scale irrigation is again not whether it increases output, but rather the conditions under which particular irrigation investments have the highest returns in general, in particular physical environments or for particular classes of farmers.

In addition to the direct impact of irrigation on crop output, many studies document impacts on crop choice and farming systems. Studies of the Green Revolution document a shift from mixed crops and coarse cereals to wheat, sugarcane, rice and vegetables (Saith and Tankha, 1992; Bliss, Lanjouw, and Stern 1998). Later studies also document a shift from low to high-valued crops facilitated by irrigation (Narayanamoorthy and Deshpande, 2003; Mehta, 2009; Woldewahid et al. 2011; Moore, 2015).

As productivity is increased, new income provides the capital for additional investment in water control. Adeoti et al. (2007) showed that in Ghana those with initial access to low cost irrigation such as treadle pumps sometimes generate incomes large enough to invest in motorized pumps. Shah came to similar conclusions in for South Asia (Shah, 2000).

While direct, positive production impacts of irrigation provision are well documented, other studies highlight production impacts on non-beneficiary farmers (Takeshima et al., 2016) and the broader opportunity costs of irrigation water. For example, Barbier and Thompson (1998) found that irrigation benefits from a system in Nigeria did not compensate for lost floodplain benefits downstream. An analysis of irrigation in the Snake River system (Hamilton and Gardner, 1986) of the United States found that while investment had a positive return, the opportunity cost of irrigation water was high and the water would have greater social returns if used for hydropower.

In fact, a minority of irrigation impact assessments attempt to assess net impacts (benefits minus costs) of irrigation, even when narrowly defined in terms of production. Of those that did, Huang et al. (2002) found positive net returns on investments in a number of irrigation systems in China. Esardo (2005) found that income and other benefits from irrigation in Ethiopia were positive but overestimated if health costs were not included. Other studies that considered costs and benefits include Hamilton and Gardner (1986), Amacher et al. (2004), Duflo and Pande (2005), Adeoti, et al. (2007), Burney et al. (2010), Aseyehgn et al. (2012) and Kumar et al. (2014). Another group of studies, particularly those focused on health, nutrition and the environment, do measure and highlight benefits and costs that should be considered in a full

evaluation of irrigation impacts (see below), but without trying to produce a standard benefit/cost analysis.

4.3.2 Enhanced productivity of complementary inputs

Irrigation has direct and positive production impacts, but it also increases the productivity of complementary agricultural inputs such as land, seeds, and labor. Irrigation's impact on the productivity of land is particularly notable. Yield (a measure of land productivity) increases are well documented as discussed above, but irrigation is also strongly associated with increases in cropping intensity (e.g. Guhan and Mencher, 1983; Saith and Tankha, 1992). Hussain & Hanjra's (2004) review of irrigation and poverty in Asia, for example, found that cropping intensity under irrigation nearly doubled. As shown in Namara et al. 2005 and Gebregzaibher et al. 2011 and illustrated in figure 1, water supplies from irrigation also increase the productivity of complimentary inputs including seeds and fertilizer. The increased output driven by irrigation can also increase demand for agricultural labor as well as wage rates (see below), with concomitant contributions to income and poverty reduction. This change in labor demand is not necessarily related to labor productivity though we would expect the impact to be positive. While only one study in our sample directly examined the issue (Shittu et al., 2010), it did in fact find a positive relationship.

As irrigation is one of an interrelated set of inputs needed for agricultural production, its impact on complementary inputs would best be measured in conjunction with those inputs in a Total Factor Productivity (TFP) or related approaches. The importance of this approach is discussed by Scheierling and Treguer (2016). However, they also discuss that water is typically left out of agricultural TFP analyses in part because of the conceptual and empirical difficulties in measurement (e.g Fuglie, 2010; Darku et al., 2013; Alston and Pardey, 2014).

4.3.3 Impacts on output prices

Everson and Gollin (2003) estimated the global impact of the Green Revolution on major commodities. They calculated that without the Green Revolution, prices would have been 35-66% higher by 2000 and noted that higher prices would have induced an expansion of cropped area, with negative environmental consequences. They attributed about $\frac{1}{3}$ of these overall impacts to irrigation. Because Green Revolution technologies, including irrigation, were focused mostly on the developing world, they also found that direct and indirect production impacts would have resulted in crop output 4-7% higher in the developed world and 14-19% lower in the developing world.

We did not find other studies estimating the global price impacts of irrigation, nor did we find studies that looked at the negative price impacts on those who did not receive irrigation. However, we can make some additional hypotheses based on Everson and Gollon (2003). First, it is likely that, within the developing world, countries whose access to irrigation increased (mostly in Asia and to a lesser extent in Latin America) would have benefited through increased production while those who did not gain access (mostly in Africa) would have been harmed by prices lower than would have been the case without irrigation investment elsewhere. The degree of harm would be dependent on the integration of national agricultural markets with the

global trade as well as the degree of home consumption. Within any particular country, producers who did not gain access to irrigation would also be similarly harmed through price effects. Finally, the net benefits of irrigation to any irrigated farmer would depend on the extent to which downward pressure on prices was offset by yield increases.

4.3.4 Impacts on poverty

Literally hundreds of studies have documented the poverty reducing impacts of irrigation and irrigated agriculture. Reviews of these studies include Silliman and Lenton (1985), David and Otsuka (1994), Freebairn (1995), von Braun (1995), Jayaraman and Lanjouw (1999), DFID (2001), Kishore (2002) and Lipton et al. (2002). Other studies outline mechanisms through which irrigation and poverty interact (e.g. Lipton, 2002; Hussain & Hanjra, 2004). We discuss here empirical evidence of some of these interactions, focusing primarily income, wealth and employment. Discussion of poverty impacts related to consumption, health, and equity as well as indirect effects through multipliers are discussed further below.

Empirical studies confirm the substantial direct impacts of irrigation on income. Bhatia (1991) reported 77% more income for irrigators in India relative to rain-fed farmers. Farm incomes increased three-fold for those participating in a Fadama program in Nigeria (Ayanwale and Alimi, 2004). Small-scale irrigation resulted in a 48% increase in farm income in lowlands of Oromia, Ethiopia (Ahmed et al., 2014). Irrigation can allow savings and accumulation of wealth. In Africa, households with access to irrigation often own substantial cattle herds (Dillon, 2008; Chazovachii, 2012), allowing consumption smoothing. Irrigation may also increase access to education by enabling payment of school fees and related expenses (Adeoti et al. 2007; Chazovachii, 2012). Thus, irrigation has significant long-term human capital development implications. However, in instances where irrigation creates labor shortage, it can actually decrease hours spent in school (Dillon, 2008).

As this suggests, the exact nature of irrigation's impact on poverty reduction depends on multiple factors. Hussain et al. (2004) finds that systems with more equal land distribution have greater poverty reduction potential and that farmers in the head ends of systems typically benefit more than those in the tail ends. Proximity to infrastructure is also important. Ersado (2005) highlights that villages nearer small dams in Ethiopia had higher yields and incomes. However, proximity also brought negative health impacts due to standing water. Adoption of health management strategies was not uniform, with those already disadvantaged potentially made worse off.

Impacts also vary by water source. Groundwater has been shown to have high poverty reducing potential (Dhawan, 1988, 2000; Shah, 2010; Narayanamoorthy, 2007), though poorly managed use (the norm the world over) results in declining groundwater tables that may eventually disadvantage the poor (Bhatia, 1992; Saith and Tankha, 1992; Dreze, Lanjouw and Sharma, 1998). Institutions also influence irrigation's poverty reduction potential. Wade (1982) and Rinaudo (2002) discuss the impact of corruption on reducing water allocation to the poor in large, public canal irrigation systems. Brewer et al. (1997) also found in India that water

allocation rules requiring bribery put poor at a great disadvantage. Arthreya et al. (1990) note that ownership rules prevented lower castes acquiring irrigated land.

Increases in labor demand stimulated by irrigation have been shown to at least partly offset some of the potential negative impacts of irrigation on the poor. Employment for the land-poor and landless increases due to the labor-intensive nature of infrastructure construction and its subsequent maintenance as well as increased labor demand from intensified cultivation and greater harvest volumes, with increases in days worked per hectare and per cropping season (e.g. Chambers, 1988; Viljoen, 1990; Bhattarai et al., 2002; Smith, 2004; Bhattarai et al., 2007; Hussain, 2007). Increased employment opportunities may improve and stabilize wages. Namara et al. (2011) found that small scale groundwater irrigation of tomatoes and peppers in Ghana increased labor demand in the dry season when there otherwise was no employment. This effect has been shown in other studies to revitalize and stabilize communities (Little and Taylor, 2001) and counter depopulation of rural areas (Viljoen, 1990; Schraven, 2010). However, other studies have shown that migration to irrigated areas for employment can depress wages. Ramachandra (1990) observes a decline in wage rates between 1948 and 1975, which he attributes to a sharp growth in the agricultural labor force in the Gokilapuram valley, India. Walker and Ryan (1990) also found that an increase in immigration of landless laborers from neighboring areas kept wages low, despite the increased demand for on and off-farm labor.

Irrigation investment also creates new employment opportunities off-farm (Hussain and Hanjra, 2002 and see below for a discussion of multiple effects). For example, Louw et al. (2008) found that while irrigation in the Northern Cape region of South Africa directly created about 18,000 jobs, an additional 4,000 jobs were created to supply inputs to the sector and an additional 13,000 were created as a result of the increased demand for consumables as a result of income and salary increases in the agricultural sector. Studies have also documented the multiple-use impacts of irrigation water and infrastructure (Meinzen-Dick and van der Hoek, 2001; Bakker et al., 1999; Meinzen-Dick and Bakker, 1999; van der Hoek et al., 1999). Jensen et al. (1998) showed that the availability of canal water use also increased domestic uses. However, other studies highlight the potential drawbacks (see health section).

Finally, some studies find that higher income and greater personal freedom were considered the primary benefits of irrigation to many poor. Jodha (1989) determined that a reduced reliance on patrons as a result of irrigation was deemed an important benefit of irrigation. Beck (1994) reports that in India 49 out of 50 respondents claimed to value their increased self-respect as a result of irrigation more than the increase in food abundance. These insights also illustrate the importance of qualitative assessments in understanding unanticipated positive and negative impacts of irrigation.

4.3.5 Impacts on Consumption and Nutrition

It is well known that irrigation leads to an increase in calorie consumption over time. Earlier studies of the Green Revolution (1970-1990) found that irrigation enhanced access to adequate and diversified food via increases in production and in income (Kennedy, 1989; Hazell et al.,

1991). For example, Von Braun et al. (1989) assessed the links among production, income, consumption, and nutrition in rice irrigators in the Gambia. He concluded that the cultivation of rice increased real income of farmers by 13% per household. An additional 10% increase in annual income led to a 9.4% increase in food expenditure and a 4.8% increase in calorie consumption.

Increased food availability may result in better nutrition (as opposed to just increased consumption), though some studies demonstrate that irrigation can adversely affect the nutritional status of farm-households (Hossain et al., 2005). For example, irrigation has led to mono-cropping of cereals and decreases in cultivation of pulses, oil seeds, and coarse grains. Thus despite the widespread increase in calorie consumption and weight gain as a result of irrigation, decreases in food diversity and micronutrients can occur as wheat and other grains become a larger percentage of diets (Hossain et al., 2005; Headey et al., 2016). Some countries with large irrigation investments have relied on nutrient imports with potential implications of food security. For example, Bangladeshi imports of vegetables and fruits from India and China now account for approximately 10% of vegetable consumption and 43% of fruit consumption (FAO, 2014; Headey et al., 2016). Similar outcomes may occur when irrigation expands into seasonal or permanent grazing land, reducing livestock production and overall protein consumption (Niemeijer et al., 1988; Hossain et al., 2005), though the impacts of irrigation on meat production may also be reversed in other circumstances (Steinfled et al., 2006).

The impacts of irrigation on nutrition are also determined by social structure of farming systems. For example, some studies have shown that increases in irrigated area are associated with decreases in nutritional status, at least in the short term, in places where women play a large role in providing income from casual labor, as in Kenya (Fleuret and Fleuret, 1980; Greer and Thorbecke, 1986; Niemeijer, Foeken and Klaver, 1991; Quisumbing et al., 1995; Hoorweg et al., 1995; Hossain et al., 2005). In these cases, off farm income had been used to purchase foods of high or different nutritional value. When female labor was more devoted to a narrow range of irrigated crops, this source of nutritional variation declined. In the longer term, the impact on nutritional status may change as income effects take over (Passarelli et al., 2017)

More recent studies have focused less on the impact of large-scale irrigation on farm household consumption and more on small-scale technologies such as home gardening (e.g. Kidala et al. 2000; Hoddinott and Yohannes 2002; Namara et al. 2011). Black et. al (2008) found that consumption of iron rich foods such as dark green vegetables can reduce incidence of anemia. Vitamin A rich foods such as orange, fleshed sweet potato, and pumpkins can reduce night-blindness and susceptibility to illness (Black et al., 2008). While conditions will vary by location, home gardens may be more likely to be controlled by women. Thus, if the goal is improved nutritional status, it is important to consider the nature of irrigation (e.g. large scale versus home garden) and the gendered nature of the farming system.

In addition to the direct, proximate effects of irrigation on nutrition, other work addresses the connection between irrigation, sanitation and the ultimate impacts of irrigation on nutrition. Van der Hoek et al. (2002) show in Pakistan that the application of irrigation water for household use

can significantly reduce diarrhea, thereby improving the nutritional status of children. Conversely, Audibert et al. (2003) showed that large-scale irrigation could increase the prevalence of water-based parasites that reduce the potential for nutritional uptake. Other studies show that irrigation reduced the amount of time that mothers had to spend on household activities including cooking and caring for their children (Vaughan and Moore, 1988; Brun, Reynaud and Chevassus-Agnès, 1989), with negative consequences for nutrition. Again though, these impacts will decline or reduce in the longer term as income effects grow and other adaptations are made by farm households, governments or other actors.

4.3.6 Impacts on health

Evidence of the, mostly positive, impacts of irrigation on health via direct and indirect consumption and nutrition effects are outlined elsewhere in this paper. However, irrigation and health have been shown to be interrelated through a range of other mechanisms. While largely underappreciated, irrigation with untreated or minimally treated wastewater is widespread and can have significant health impacts for both producers and consumers (Drechsel et al. 2009), particularly in semi-arid areas where it is associated with increased frequency of schistosomiasis and diarrhea. Whether indirect health benefits through higher income, consumption and diet diversity offset the negative consequences is an open question. Irrigation with water contaminated with naturally occurring chemicals such as arsenic (Senanayake and Mukherji, 2014) or human introduced agro- or industrial chemicals such as pesticides and fertilizers or heavy metals such as cadmium (Simmons et al., 2005) can also cause a range of health impacts including neurological abnormalities, respiratory diseases, reproductive disorder, and endocrinological and dermal problems. Because irrigation increases the productivity of other agricultural inputs as discussed earlier, it likely increases the use of agricultural chemicals.

The construction of dams' consequent slowing of river flows as well as the stagnant water associated with irrigation operations at system and farm level has also been associated with increases in disease vectors leading to increases in malaria, dengue and sleeping sickness. The severity of impact also depends on the way in which the irrigation system is maintained. At least in the short term, areas without previous exposure to these diseases may be most significantly impacted because awareness and institutions for addressing the consequences are lacking.

At the same time, irrigation is also associated with other positive health impacts. Irrigation has led to increased water availability for improved sanitation and hygiene practices (Van der Hoek et al., 1999), contributing to reductions in diarrhea, schistosomiasis and other ailments. The potential wealth generated by irrigation have been found to drive increased investment in healthcare such as the purchase of bednets and water filters (Klinkenberg et al., 2004). As already discussed, increased wealth has also been found to increase food expenditures and nutrition levels, which can augment calorie intake and allow varied diets, reducing the impact and incidence of ailments such as anemia, night blindness, and low weight.

Domenech and Ringler (2013) provide a recent overview of the complex evidence on the impacts of irrigation on health. For the rest of this section, we outline evidence of the impacts of irrigation on one of the most important diseases, malaria, as an example. Irrigation is often associated with a rise in malaria incidence as breeding sites for malaria vectors increase and the breeding season lengthens (IIMI, 1986; Coosemans and Mouchet, 1990; Dixon and Pinikhana, 1994; Ghebreyesus et al., 1999; Singh et al., 1999; Kobayashi et al., 2000). Guthmann et al. (2002) found that malaria incidence was five times higher in villages closer to irrigation systems (i.e. dams) than those villages in a non-irrigated area. In Ethiopia, Ghebreyesus et al. (1999) determined that villages closer to the small-scale dams experienced a seven-fold rise in malaria prevalence after the introduction of the dams. As this suggests, the impact of irrigation on malaria is variable since this impact depends on external factors including the type of irrigation system, the previous exposure of the area to malaria, the existing health and irrigation infrastructure, the amount of time that has passed since the introduction of irrigation, and the level of landless migration to the area (Malaria, 2005).

Surface irrigation has been found to result in the greatest malaria incidence since it requires the creation of shallow water bodies, which serve as ideal breeding spots for malaria vectors (Malaria, 2005). The flooding of fields for paddy farming is most often associated with a rise in malaria incidence (Gillies & De Meillon, 1968; Surtees, 1970; White, 1974; Snow, 1983; Coluzzi, 1984). A location's previous exposure to malaria, as well as the condition of its health infrastructure, are also important factors. Studies found that those places with previous exposure (e.g. wetter areas already supporting malaria vectors) often already had protective measures (i.e. bed nets) in place and, as a result, were often less impacted by the increased mosquito abundance from irrigation. Variation in prevalence after irrigation is also common (Dixon and Pinikhana, 1994). Baeza et al. (2013) assessed the impact of the number of years a community had been irrigating on the abundance of mosquito vectors and the malaria biting rate. They concluded that the irrigated areas studied had a similar abundance of mosquito vectors, but areas that had been irrigated for thirty years had a lower malaria prevalence than areas that had just begun irrigation. Conversely, areas that had just begun irrigation had higher malaria prevalence than non-irrigated areas. Drier or more arid areas also experienced a higher initial increase in their number of malaria outbreaks following the implementation of irrigation. They determined that this initial increase in malaria outbreaks was because the appropriate health infrastructure was not in place as mosquito abundance increased as a result of irrigation. Similar findings were reported by Oomen et al. (1988) and Wang'ombe and Mwabu (1993).

Poor irrigation management is often associated with an increase in malaria prevalence. Chimbari et al. (2004) assessed the impact of poorly maintained irrigation infrastructure and inadequate landscape-leveling on increased malaria prevalence. He found that these poorly maintained systems increased the prevalence of mosquito breeding sites within the fields, in the case of sprinkler schemes and poor drainage structure (Chimbari et al., 2004). Mwangangi et al. (2013) assessed the impact of irrigation on mosquito vector abundance with different levels of irrigation management. They determined that when rice planting was coordinated and better managed, this coordination reduced the amount of time that the fields had to be flooded and as a result, minimized the amount of time that the mosquitos had to breed in the fields. Moreover,

Kibret et al. (2010) studied the impact of poor infrastructure management on malaria vector breeding and malaria transmission in the Ziway area of Ethiopia. They determined that improper canal water management resulted in more vector breeding sites and thus, intensified malaria transmission due to a strong positive correlation between canal water release and *anopheline* larval density. Irrigation management techniques such as coordination of growing season, in particular for surface irrigation, can often decrease the prevalence of year-round stagnant water (*reduce prolonging of seasonal transmission*) and thus, minimize the impact of the irrigation on the frequency of malaria cases. Water management techniques such as implementing siphons or following integrated operating rules through fluctuating water flow over periods of time have also been found to reduce mosquito breeding sites (Jobin, 1999; Konradsen et al., 2004).

Malaria rates can also go up in the short term as employment opportunities attract landless workers. Many studies observe a parallel influx of malaria cases with large-scale migration of low income farmers in search of employment into malarious areas (Coosemans et al., 1985; Coosemans et al., 1987; Coosemans and Barutwanayo, 1989). Coosemans and Barutwanayo (1989) observed that these landless migrants often had very low incomes and as a result, were unable to afford bednets and other malaria prophylactics.

These highlights though the complex relationship between the short-term physical impacts of irrigation on malaria burden and the longer-term social responses. As noted, irrigation is often associated with an increase in income and purchasing power (Robert et al., 1985; Audibert et al., 1990; Boudin et al., 1992), and a higher propensity to spend on malaria protection (Ijumba & Lindsey, 2001). Thus, an increase in mosquito vectors may be associated with a decrease in incidence (Klinkenberg et al., 2004).

4.3.7 Equity and Gender

Virtually every study that examined socially differential impacts, whether in terms of class, caste or gender, of irrigation found them to be significant. However, the nature of those impacts was highly variable. For example, as noted above, irrigation in systems with unequal land distribution will result in an unequal distribution of benefits and when some groups are excluded from land ownership, they will also be excluded from direct irrigation benefits. In this section, we focus on evidence of the gendered impacts of irrigation to further illustrate equity impacts and mechanisms.

The impact of irrigation on gender and equity is variable. Upadhyay et al. (2005) determined from surveys that 83% of respondents reported that drip technology had benefited female and male employment in Nepal. They also concluded that women received direct consumption benefits from irrigation (Upadhyay et al., 2005). After the introduction of drip irrigation, women were able to purchase more livestock with their savings of vegetable income and ultimately, purchase luxury goods after selling the surplus milk and meat from this purchased livestock (Upadhyay et al. 2005). Moreover, Perera (1989) observed in Sri Lanka that irrigation channels

increased the availability of water that women could use for domestic purposes and consequently, reduced the amount of time that women had to spend fetching water.

However, the extent of this positive impact of irrigation on gender and equity is often limited by many factors, including access to land, water, labor, capital, credit, technology and other resources (Molden, 2007). Asyehegn et al. (2012) conducted a study in Ethiopia and found that male headed households were 38% more likely to participate in irrigation than female women, since female headed households tended to be labor scarce had reduced access to market information. Therefore, while women may have the same potential agricultural productivity as men, an unequal access to resources and information inhibit women from fully benefiting from irrigation.

This unequal access is as a result of the expectation in many societies that women provide the labor and have a marginal role in the management and decision making processes of irrigation, which often belongs to the men of the house (Zwarteveen, 1993; Zwarteveen et al., 1996). Moreover, Bastidas (1999) found in Ecuador that women with small children often participated less in irrigation due to the expectation that women care for the family. Therefore, this role of the men in decision-making and their ownership of the land provides men with ownership of the water underneath and the profits made from irrigation schemes (Agarwal, 1994; Jordans and Zwarteveen, 1997). Consequently, women often receive less water for domestic purposes since men most often use the water primarily for irrigation. Moreover, since men often control the profits from the irrigation, women often become more dependent on their husbands for money to purchase food and other goods (Van Koppen 1998; Zwarteveen 2006). This subservient role of women also impacts the society's willingness to grant credit to women. Studies in Malawi have found that women often pay for new irrigation technologies in cash and consequently, are often limited in the size of their purchases unlike men who have access to greater credit (Kamwamba-Mtethiwa, Namara, De Fraiture, Mangisoni, & Owusu, 2012). In Kenya, Malawi, Sierra Leone, Zambia and Uganda, women receive less than 10% of the credit awarded to farmers (Squires, 2010).

These benefits from irrigation may also be limited by the amount of labor women have to contribute to the irrigation. While irrigation may reduce the need for women to spend time collecting water, irrigation may increase women's agricultural workload if they usually provide the bulk of the labor in that society. Upadhyay et al. (2005) concluded from their study in Nepal that women usually spend more time growing and cultivating the crops than males, who only contributed 12% of their time to producing the vegetables. Even in Pakistan, nine women out of a sample of 87 were determined to be directly engaged in irrigation (Basnet 1992). In some studies, this high labor requirement along with a lack of recognition for their extra labor contributions resulted in many women completely losing interest in irrigating the crops.

Due to the negative impact of an unequal distribution of these resources on women, greater focus has been placed on the impact of different irrigation systems. Many studies have found that home gardens had the greatest positive impact on women. Home gardens often resulted in an increase in the economic contribution of women to the household and as a result, women

often received greater respect, an improved social standing and greater decision-making authority (Bushamuka et al., 2005; Iannotti, Cunningham, & Ruel, 2009; Du Plessis & Lekganyane, 2010; Schaetzel, Antal, & Guyon, 2013; Galhena et al., 2013; Yasmin, Khattak, & Ngah, 2014; Schreinemachers et al., 2015; van den Bold et al., 2015). Hallman et al. (2015) observed that home garden systems required little land and investment and as a result, allowed women to become empowered, but be less restricted by financial and social constraints. Men often avoid intervening in home gardens since they see it as a women's domain. Van Koppen et al. (2001) found in India that women have the greatest success in accessing and managing irrigation systems when a women's group comes together to manage an irrigation project. This role can be influenced by the society's allowance of women in leadership, as well as the type of irrigation and whether it has a greater labor requirement.

The importance of the inclusion of women in irrigation management groups such as water users' associations is also addressed in many studies. Van Koppen (2002) found that women benefit most from irrigation when they hold leadership positions and are included in irrigation forums such as water users' associations. However, a study in Nepal suggests that women often have more difficulty in gaining access to water for irrigation, primarily because they are not supposed to attend water users' meetings, and water allocation plans are often made in their absence (Bruins and Heijmans, 1993). Schrevel (1989) determined that a major reason for the poor functioning of water users' associations in Indonesia was that women were not included in the groups even though they performed the agricultural and irrigation management activities while their husbands were away throughout the year. Studies also show that irrigation projects that directly allocate land to women instead of being allocated through their husbands provide the most benefit to women ([van Koppen, 1990](#)).

4.3.8 Impacts on the environment

By its very nature, irrigation perturbs the natural environment, reducing river flows, drawing down water tables, or changing the paths through which water flows over the landscape. The infrastructure used to supply irrigation, particularly large dams, can have transformative impacts on flow regimes, water temperature and other variables critical to ecosystem function. Irrigation is also associated with decreases in sediment transport, increases in soil erosion, chemical contamination, and loss of biodiversity. Some of these impacts are discussed and reviewed in Falkenmark et al. (2007) and Boelee (2013), and both provide insights into mitigation of negative environmental consequences of agricultural water use broadly defined.

A wide range of, mostly technical, studies highlight more directly measure the negative impacts of irrigation on the environment. As examples, the construction of the High Aswan Dam famously reduced sediment transport and led to the erosion of wetlands in the Nile Delta 800 km downstream (Penvenne, 1996). The damming of the Indus in Pakistan has reduced sediment transport with subsequent die-off of mangrove forest communities in the downstream delta (Meynell and Qureshi, 1995). Irrigation is also associated with soil salinization (and water logging), particularly in arid and semi-arid regions. (Kinje, 1998, Rengassamy, 2006). Chemical

fertilizers and pesticides associated with irrigated agriculture have also been shown to have negative environmental impacts. Vermeer et al. (1974) found that kites foraging in rice fields had concentrations of PCP 100 times greater than the levels of kites from nearby freshwater marshes. Litskas et al. (2009) found in the North Aegean, Greece, that nitrate concentration was higher in the irrigation water by 0.3mg/L due to the use of fertilizers in irrigation. Many studies, particularly from the United States of America, have found that irrigation has resulted in greater pesticide presence in the water table (Hallberg, 1987; Wartenberg, 1988; Pionke et al., 1988).

Higher saline, pesticide and nitrate levels, along with diversions of the water supply have all contributed to reductions in biodiversity due to the inability of organisms to survive under these harsh conditions. Studies on biodiversity loss, specifically, highlight the role of the submersion of wetlands, changing of vegetation communities, or diversion of water to certain areas due to irrigation (Micklin, 1988; Kotlyakov, 1991; Precoda, 1991). Gammelsrød (1996) found that the reduction in water flow due to the barrages and dams in Mozambique have led to declines in the marine prawn populations and fish diversity. Similarly, Kotlyakov (1991) studied the impact of irrigation on the Aral Sea Basin and found that after water diversions, the number of bird species decreased by 151 and the number of mammal species decreased by 40.

Many studies attribute the extent of the negative impacts of irrigation on the environment to poor irrigation management practices. Lewis et al. (2011) determined that with a cessation in manuring processes over a period of five years resulted in a reduction in dissolved and particulate contaminants, including total phosphorus (TP), soluble reactive phosphorus (SRP), total Kjeldahl nitrogen (TKN), and nitrate (NO₃) in the examined watershed. Padre et al. (2004) found that improper irrigation management in the Indo-Ganges plain resulted in loss of soil organic matter and nutrient matter, and ultimately, a yield decline of 37 kg/ha/year over 20 years. Fujioka and Lane (1997) attribute the negative impact on biodiversity to shifts in irrigation infrastructure. They found that shifting from ditch-fed irrigation to metal pipes and concrete channels for rice fields resulted in a reduction in the population of two species since the new, more efficient infrastructure had reduced the water leakages and thus, the pools of standing water for frog spawning (Fujioka and Lane, 1997). Soil salinization and water logging are also generally attributed to poor irrigation planning and management practices.

While not commonly discussed or studied, irrigation may have substantial indirect environmental benefits by reducing pressure on agricultural land expansion. This point was initially brought up by Norman Borlaug in response to critics of the Green Revolution's environmental impacts as is supported by the fact that irrigated agriculture produces 25-40% of food output on 10-20% of agricultural area (Van Schilfgaarde, 1990; Molden et al., 2007). We only identified one global study formally addressing the issue (Evenson and Gollan, 2003). It found that agricultural land area would have been 3-5% higher by 2000 without the Green Revolution (including the contribution of irrigation). Thus, on the one hand, as highlighted by Molden et al. (2007) drawing on data and expertise from multiple sources, freshwater ecosystems are perhaps the most degraded in the world in no small measure due to irrigation. On the other, irrigation may play a largely unrecognized role in reducing other environmental pressures from food production and can provide new forms of environmental services, for example as in traditional (e.g.

Natuhara, 2013) and modern systems (Soils Incorporated, 2000). Unfortunately, the net impacts of irrigation on the environment at local, national and global levels have received little attention in the literature.

4.3.9 Multiplier effects and impacts on the broader economy and political structure

Broad analyses of Green Revolution impact highlight large, positive spillover effects as increased output increased incomes, consumption and employment, and spurred both rural and urban growth, driving modernization. Later studies as well estimate high off-farm impacts. Bhatturai et al. (2007) estimated that multiplier effects in India were 3-4 times more than the direct effects of irrigation. Given the widespread benefits, they questioned the push to require farmers to bear responsibility for the full costs of irrigation operations and maintenance. Other studies suggest that multiplier effects may diminish over time and should be examined in the context of other investment opportunities. Fan et al. (2008) found, also in India, that while additional irrigation investment yielded positive benefits to poverty reduction and the overall economy, returns diminished as poverty declined. Returns to investments in other areas of rural infrastructure such as roads, electricity and education then provided significantly better returns. An economic analysis of irrigation development in Idaho (Hamilton and Gardner, 1986) found that while returns at the project level were \$166/acre, the net benefits to the state were -\$8. The study further found that water use generated much higher values in hydropower production than irrigation. Thus, the question is not simply whether irrigation investment will have impacts beyond the agricultural sector, it will. The question is the relative impact of irrigation investment as compared to alternative uses of capital and, in an increasingly water scarce world, water.

Finally, while not falling within the category of impact assessment and beyond the main scope of this paper, a broad range of literature discusses the connection between irrigation, politics and political economy (e.g. Steward, 1955; Mitchell, 1973; Davies, 2009). Irrigation has been credited with generating the surpluses behind the rise of civilization and connected with political development in systems ranging from the Subak rice terraces in Indonesia to Mormon canals in the arid western U.S. In the late 20th century, irrigation was credited not only with underpinning the food supply gains and resulting poverty reduction of the Green Revolution but also with aspects of modernization and the nature of governments in Asia and Latin America (Niazi, 2004; Latham, 2011).

The development of irrigation also requires the creation of governance and bureaucratic structures that may have far-reaching and unexpected consequences. Reisner (1993) documents how water bureaucracies created to provide irrigation and other water infrastructure took on lives of their own and shaped U.S. politics. Similarly, Suhardiman et al. (2014) and Suhardiman and Giordano (2014) discuss political implications of irrigation bureaucracies in The Philippines, Mexico, Indonesia, and Uzbekistan as do Nickum and Mollinga (2016) for China and India. Parayil (1992) describes the political changes made by Indian policy makers to allow the Green Revolution in India while Shah (2010) documents how that effort later created a

broadly entangled and highly political “irrigation-energy nexus” with implications for economic growth and politics.

5. Discussion

Assessments of irrigation almost universally demonstrate positive impacts on agricultural output through direct production effects and increases in the productivity of complementary inputs (land, labor and fertilizer) and via indirect effects that increase expected returns and spur investments in other agricultural technologies and human capital. The literature also highlights the substantial contributions of irrigation to poverty reduction over the last 50 years for farmers, the landless and land-poor who gain at least seasonal employment on irrigated farms and, perhaps most significantly, consumers. Consumers in general gain through greater availability of basic food supplies at prices much lower than would have been the case without irrigation. Poor consumers in particular gain because of the high proportion of their incomes spent on food.

The literature also clearly demonstrates that irrigation impacts go far beyond production and poverty effects. These additional impacts include changes in nutrition and health status, education levels, the environment, global commodity prices, the overall economy and even the nature of political systems. These impacts are dependent on geographic and social context and can be highly variable in both magnitude and direction. For example, irrigation can increase nutritional diversity when used to support household vegetable production or when it results in income increases that support dietary diversification. However, when irrigation encourages monocropping, nutritional diversity can decline.

Impacts are also dynamic. Early analysis of the Green Revolution found that benefits accrued to those with large land holdings who were able to adopt new technologies early. Later studies showed that the benefits were much more widely shared. Similarly, irrigation development can increase disease vectors and burden as standing or slow-moving water becomes more prevalent. However, increases in income made possible by irrigation may be invested over time in disease prevention, actually lowering disease impacts. The literature shows that the nature of irrigation impacts changes as income levels and the structure of the overall economy changes. For example, Fan et al. (2008) found that while the poverty reducing impact of irrigation remained positive, its marginal effects declined over time and alternative investments in the rural economy eventually had higher returns.

The literature uncategorically demonstrates that irrigation impacts, both positive and negative, do not accrue equally across individuals, groups, regions and countries. Virtually every study that used disaggregated data to assess differential impacts found the differences to be significant. Where land holdings are unequal, irrigation benefits will also be. Those in headends of irrigation systems will benefit more than those in tail ends. The gendered nature of farming is often reproduced and perhaps strengthened by irrigation investment. In some cases, the result of this inequity can be benign, with one beneficiary profiting more than another but all gaining. In other cases, though, one group may benefit at the cost of another. This may be particularly

common in the case of environmental externalities, for example where dams displace poor populations or downstream ecosystem services on which the poor depend are destroyed.

There is no question that irrigation development has direct, negative impacts on the environment, and the literature documents multiple pathways through which these impacts can accrue including flooding from dam development, reductions in river flows and related ecosystem services, drawdown of groundwater, salinization and contamination. However, irrigation also provides indirect environmental benefits through the increases it brings to land and other input productivity. This in turn reduces pressure to develop new agricultural land, much of which would be of increasingly marginal quality (e.g. highly sloping lands) and susceptible to degradation and of potentially high value in terms of protection of remaining biodiversity. This positive environmental impact of irrigation appears largely unappreciated and under-documented in the literature.

Based on this review, there is no question that irrigation investments in the last 50 years have had major positive impacts on both food production and poverty reduction. Nonetheless, there is substantial concern in the literature and voiced by investors that, despite success, many government-managed irrigation systems have not lived up to expectations (Jones, 1995; Turrall, 1995; Malano & Hofwegen, 1999; Mukherji et al., 2009). The literature also shows that negative impacts of irrigation were often misunderstood or ignored, raising questions of equity and sustainability.

Furthermore, the rationale for irrigation has changed. In the post WWII world, agriculture was seen as an engine of economic growth and a key means to reduce poverty. This may still be the case in some parts of the world, particularly Africa, but as the economies of the former developing world have grown and poverty levels reduced, agriculture may now be less an engine of growth than a base for food price, and therefore political, stability. Similarly, as abject poverty levels have decreased in rural areas, the role traditional large-scale irrigation can play in poverty reduction must also necessarily change. As an example, Huang et al. (2005) found that irrigation investments in the systems they studied in China had relatively little impact on rural poverty, because the irrigation districts had so few poor farmers. At the same time, the opportunity costs of water are changing as scarcity increases, urban areas generate higher value water uses, and values towards the environment change.

6. Summary and recommendations

Hundreds, and possibly thousands, of published studies have assessed the impacts of irrigation. The goal of this paper was to identify and provide context to an illustrative range of those assessments drawn from a variety of literatures and approaches. In total, we examined more than 500 hundred studies, more than 250 of which are cited here. The cited studies were examined for a variety of variables including location, scale, time since irrigation intervention, irrigation source and type, impact evaluation approach and the nature of the impact assessed. The impacts they measured and their context formed the core of this work. While there was wide variation in the approaches, scope and foci of the studies as well as their specific findings, a number of general conclusions emerged.

First, irrigation is clearly linked to increased agricultural output through both direct production effects and through its role in increasing the productivity of complementary inputs.

Second, irrigation has been strongly associated with decreases in poverty, particularly amongst direct beneficiaries and urban consumers.

Third, irrigation is linked to a wide range of other impacts, for example in nutrition, health and the environment.

Fourth, studies that measured irrigation impacts beyond the farm or system scales often found indirect, secondary effects of similar or greater magnitude than direct, primary effects. In some cases these secondary effects were positive (e.g. multiplier effects to the overall economy) and in some cases negative (e.g. off-site environmental effects that offset the gains in production or poverty reduction).

Fifth, the magnitude and nature of irrigation impacts, particularly impacts beyond production effects, were highly dependent on the particular location and circumstances in which irrigation occurred. In addition, impacts changed over time in terms of magnitude and sometimes sign.

Sixth, irrigation impacts, positive and negative, were unequal socially, spatially, and temporally. Virtually every study we reviewed that was designed to measure differential impacts, in whatever dimension, found them to be significant.

These conclusions along with our findings on irrigation impact assessment lead us to the following, interrelated, considerations for future investment and research:

6.1 Expanded attention to benefits AND costs

The question is not whether past investments in irrigation resulted in positive impacts on food production and poverty reduction, they did. The question is the cost at which those benefits came at project and broader scales. While project proposals include analyses of net expected financial returns to investment, relatively few formal, post hoc assessments consider financial or economic benefits AND costs, even for analyses conducted at farm or irrigation system scales. Fewer still attempt to measure the net societal impacts of irrigation or consider the opportunity costs of water. Of those that went beyond the system level, one found high positive spillover effects, justifying public investment and subsidy. Another found that while direct returns to irrigation investment are positive, impacts were overstated when negative externalities such as those related to health were neglected. Another found that positive direct impacts on poverty were offset by negative indirect impacts off site (Duflo and Pande, 2005). While more impact assessments that include net benefits across scales may be needed (see below), the key point is that any irrigation investment needs to be informed by consideration of financial and economic benefits and costs, across scales. This is particularly important for project level investment decisions as well as irrigation policy more generally, since evidence shows that

multiplier effects and externalities, positive and negative, can be greater in magnitude than primarily impacts.

6.2 Greater consideration of multiple impacts

While assessments of irrigation impact have clearly established increases in crop output and decreases in poverty, they also show a wide range of other impacts that occur through sometimes complex pathways. These impacts can be positive or negative, may occur far from irrigation itself, and are many times counterintuitive. To facilitate analysis and discussion, this study presented an impact typology divided into 9 broad categories, but each element of the typology could easily have been further sub-divided multiple times or organized in alternative ways. While it is not possible to anticipate every possible impact in every investment decision, at least informal consideration of the range of likely impacts beyond the system level is important for project planning and, perhaps more importantly, the long-term success of and support for irrigation investment. As an example, a main thrust of the arguments against irrigation focuses on sometimes unanticipated costs including loss of crop diversity, falling groundwater tables, increased pesticide use, increases in disease vectors in poorly managed systems, and increased poverty when irrigation is developed in areas where structural inequality is already pervasive. Greater awareness of and therefore anticipation of possible negative impacts such as these can inform actions that reduce negative externalities. Likewise, anticipation of the broad range of possible positive irrigation impacts can help inform decisions to maximize their extent.

6.3 Continued, explicit focus on poverty and equity in investment and analysis

Irrigation impacts, positive and negative, are not distributed equally. Thus, irrigation investments designed to contribute to the eradication of extreme poverty and boost shared prosperity must explicitly consider how both the benefits and costs will be accrued across beneficiaries as well as between beneficiaries and non-beneficiaries. In some cases, the poverty reduction potential of specific irrigation investments may not be met unless other conditions are simultaneously changed. This may sometimes be difficult, for example when it involves structural factors such as land holding size or caste or gender relations. In other cases, there may be opportunities to design investments, or their locations, to disproportionately favor the poor. For example, given the gender, equity and nutritional significance of home gardens, rural water supply projects that plan for home plot irrigation may have disproportionate positive impacts on both poverty and equity. Even if irrigation provides net benefits, it impacts producers and consumers differently and may cause tradeoffs between those directly receiving benefits and those who do not. Explicit consideration of who benefits, who is harmed, and the magnitude of both may be at least as important in having investments meet poverty reduction and equity goals as overall calculations of net project returns or benefits.

6.4 Reduce environmental costs, including health related, and make a better case for environmental benefits

Irrigation is associated with many negative environmental impacts. Negative impacts will occur to some extent because of the very nature of irrigation in modifying the natural environment.

However, the extent of impact has often been exacerbated by a failure to anticipate environmental costs in decision-making and poor management of environmental consequences. Many studies highlight, for example, that increased prevalence of irrigation induced disease should be anticipated during the initial irrigation operation period, and can be reduced through awareness raising among affected communities and increased preparation of health institutions during project preparation. Less discussed, irrigation also provides significant indirect environmental benefits, in particular by reducing pressure on additional land development. Lack of irrigation is also not associated with positive environmental outcomes. Ethiopia's degraded landscapes, for example, occur not because irrigation exists but because it does not. While the long-term solutions to land pressures might be in reduced meat demand, reductions in agricultural and food waste, and increases in yields via biotechnology, irrigation will continue to play a major role in many countries for decades to come. Reducing unnecessary negative environmental impacts of irrigation as well as better explaining the environmental case for irrigation are both needed to ensure good investment decisions as well as public understanding of irrigation's place in environmental debates.

6.5 Anticipate changing needs and values

While early rationale for and studies of the Green Revolution era irrigation investment focused on production increases and poverty reduction impacts for farmers and consumers, later studies tended to include a broader range of variables including farm labor demand, expanding supply chains, and positive spillover effects in the broader economy. Another set of studies focused on the negative impacts of irrigation and brought attention to unanticipated costs such as falling groundwater tables, increased pesticide use, and increases in disease vectors in poorly managed systems. Later assessments tend to shift from the impacts of large scale surface systems to small scale technologies and groundwater. These changes in what is studied in part reflect an increased understanding of the mechanisms through which irrigation works. They also in part reflect changes in the environment in which irrigation exists and in the nature of food and poverty challenges it is designed to address. Food security challenges have shifted from providing gross production of sufficient calories to ensuring access to those calories and ensuring that that are combined with appropriate nutrients. The nature and location of poverty have shifted and as have the options for particular forms of irrigation to address it. The opportunity cost of water has also changed as more water has been developed for irrigation and water demand for cities and industry have grown along with awareness of water's environmental value. Water scarcity and a global water "crisis," are now the focus rather than water development. Future irrigation investments must be designed not for the present but for a still different future.

6.6 Additional investment in priority research areas

There is no shortage of irrigation impact assessments and so no need for a general call for additional research. However, key questions on particular irrigation impacts have been identified in recent literature, for example on the role of irrigation in nutrition and on ways to use irrigation's gendered dimensions to reduce poverty. New research is also needed to support investment in irrigation to meet newly emerging priorities, for example youth employment. Beyond these specific questions, this assessment suggests a number of general gaps in

approach to irrigation impact assessment which, if filled, would provide insights to inform future investment and investment policy. The following recommendations focus on these general gaps.

6.6.1 Design formal assessment, not just M&E, in conjunction with project implementation

A general challenge for most irrigation impact assessments is that they are implemented after irrigation is already in place. Only rarely are assessments done using pre-irrigation baseline data. While with-without and other approaches may partially address this problem, planning and collecting data for impact assessment in the designs of an increased number of projects would facilitate a stronger understanding of impacts. In addition, collaborative planning for impact assessment with project implementers and outside researchers may bring new insights for both in planning investments to achieve the highest desired impacts and in understanding the processes through which irrigation impacts occur.

6.6.2. Invest in long term assessments of irrigation's dynamic nature

It has been suggested that the minimum lag to assess the impact of Irrigation Management Transfer on system performance, not impact more broadly, is 6-10 years after implementation. To understand the broader impacts of newly established irrigation, the minimum lag should presumably be many more years if not decades. Nonetheless, many published assessments take place only a few years after implementation, with potentially important implications for policy. For example, irrigation benefits spread to poorer farmers only over time in the Green Revolution, and some impacts, such as has been shown for malaria, may switch sign. This highlights the need for studies that assess longer term effects as well as assessments that occur across time, rather than simply between two points of time. Longitudinal assessments will be relatively costly and their structure may run counter to the time frames of traditional project funding. However, given their paucity, their insights are likely to be substantial and institutional models for their implementation do exist in other areas. For example, the Long Term Ecological Research Network (<https://lternet.edu/>), funded partly by the National Science Foundation in the U.S., examines changes to forest ecology over time periods of 25 years or more. Longitudinal studies in health are also common.

6.6.3 Renew focus on the impact of large scale irrigation, particularly in terms of maintenance and institutions

As the opportunities for large scale irrigation have declined, with a possible exception of SSA, so too has the number of assessments of its impact. Nonetheless, it is these systems that still provide the bulk of irrigation despite a general agreement that performance is lower than expected. Lower performance is generally believed to be caused by deterioration of physical infrastructure due to deferred maintenance, itself a function of poor (financial) incentives and institutional arrangements for infrastructure management (Coward, 1984; Dinar & Subramanian, 1997; Groenfeldt & Svendsen, 2000). There is a large literature on the impact of Irrigation Management Transfer and Water User Associations (Bastidas, 1999; Koppen et al., 2001; Van Koppen et al., 2001; Wang et al., 2006). However, this literature is largely focused on irrigation performance, sometimes including production effects, rather than broader impacts. There is little other work to provide insights into institutional form, broadly defined, on operations, maintenance and, eventually, impact.

6.6.4 New analysis of national and global scale impacts and processes

The declining interest in irrigation over the past 2 to 3 decades is partly a function of increased global food output and, with some notable exceptions such as 2008, steadily falling real prices. The 2008 exception again brought to the fore awareness of the interconnection between water, food prices, and political stability. However, most of the attention on water was focused on drought or climate change, not the role irrigation played or could play in price stability. This highlights a broader neglect in understanding of the role of irrigation in global food price levels and variability. This neglect is particularly problematic in an era of increased climate uncertainty. Modeling national and global level impacts and contributions of irrigation on prices and their variability is critical both to inform investment policy and to create broader understanding of irrigation's value beyond production..

6.6.5. Support of complementary qualitative work

There has been a push in recent years for more rigorous, quantitative approaches to impact assessment. While welcome in many ways, this push has reduced emphasis and acceptance of other forms of analysis. For example, the IEG (2011) analysis of published studies on the impacts of agricultural investments, including irrigation, rejected $\frac{2}{3}$ of the studies it identified because of concerns around rigor. While quantitative analyses with clearly defined counterfactuals provide particular, often powerful, insights into impact and attribution, other approaches may do so as well. For example, qualitative ethnographic can provide nuanced, grounded insights into the subtle and varied impacts of irrigation alone or as part of change packages. Such approaches may be particularly strong in highlighting the social mechanisms through which irrigation impacts occur and are distributed, thereby informing the questions of later quantitative assessments. While experimental and quasi-experimental approaches are important, they should not supplant qualitative assessments or be considered to define rigor in impact assessment.

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