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The Impacts *of* Irrigation

A Review of Published Evidence

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Regassa Namara,
and Elisabeth Bassini

WORLD BANK GROUP

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Executive Summary

Irrigation development has made up a considerable share of the Bank's infrastructure investment portfolio. However, after a surge from the 1960s to 1980s in the level of public investment in the irrigation sector, enthusiasm for continued investment (particularly in new irrigation development) has softened, except in Sub-Saharan Africa. There may be multiple reasons for this change. Irrigation's success—with other investments in agriculture—removed the imperative for continued rapid expansion of the global food supply. Despite success in increasing food output, large-scale irrigation systems are often viewed as failing to live up to their potential, and they require consistent injections of outside capital for operations and maintenance (O&M). Irrigation is associated with negative externalities, particularly related to the environment. Finally, irrigation's potential role in reducing poverty, especially 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 and guide future investment, we review 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. We also examined 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 economywide processes 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 statistically representative.

The reviewed studies show broad variation in scope and focus, evaluation design and methods used to infer impact, and 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, these key conclusions emerged:

- Irrigation is linked to increased agricultural output through direct production effects and its role in increasing the productivity of complementary inputs.
- Irrigation is strongly associated with decreases in poverty, particularly among direct beneficiaries and urban consumers.

- Irrigation is linked to a wide range of other impacts, including ones associated with the nutrition, health, and environment sectors.
- Studies that measured irrigation impacts beyond the farm or system scales have often found indirect secondary effects of similar or greater magnitude than direct primary effects. Secondary effects could be positive (e.g., multiplier effects to the overall economy) or negative (e.g., off-site environmental effects that offset the gains in production or poverty reduction).
- The range and magnitude of irrigation impacts, particularly those beyond production effects, were highly dependent on the location and circumstances in which irrigation occurred. In addition, impacts changed over time in magnitude and sometimes sign.
- Irrigation impacts—positive and negative—were unequally distributed socially, spatially, and temporally. Virtually every study that measured differential impacts has found them to be significant.

These conclusions suggest considerations to ensure the highest returns for future irrigation investment. Investment planning should expand attention to irrigation benefits and costs and explicitly consider direct and indirect impacts. During planning, interventions to reduce negative environmental impacts of irrigation and increase public awareness of indirect environmental benefits, such as through decreased pressure on marginal land, would improve investment outcomes and public support. 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 made up a considerable share of the Bank's infrastructure investment portfolio. However, after a surge from the 1960s to 1980s in the level of public investment in the irrigation sector, enthusiasm for continued investment (particularly in new irrigation development) has softened, except in Sub-Saharan Africa. There may be multiple reasons for this change. Irrigation's success—with other agricultural investments—removed the imperative for continued rapid expansion of the global food supply. Despite success in increasing food output, large-scale irrigation systems are often viewed as failing to live up to their potential, and they require consistent injections of outside capital for O&M. Irrigation is associated with negative externalities, particularly related to the environment. Finally, the potential role of irrigation in reducing poverty, especially 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 help to relieve that pressure.

This paper reviews published evidence of irrigation impact to provide insights and lessons for operation and policy. It provides a general typology for considering the wide range of mechanisms through which irrigation affects 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 onward.

The large number of reviewed studies (over 500 with more than 250 cited and included in the bibliography) shows broad variation in (a) scope and focus in evaluation design and methods used to infer impact and (b) the physical and institutional nature of the irrigation systems 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 focuses highlights that the pathways from irrigation development to impact are highly variable. While overall impacts of irrigation on food production, poverty reduction, and some other variables are positive, they are offset to varying degrees by negative externalities and sometimes inequitable consequences. The results 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:

- Irrigation is linked to increased agricultural output through direct production effects and its role in increasing the productivity of complementary inputs.
- Irrigation is strongly associated with decreases in poverty, particularly among direct beneficiaries and urban consumers.

- Irrigation is linked to a wide range of other impacts, including ones associated with the nutrition, health, and environment sectors.
- Studies that measured irrigation impacts beyond the farm or system scales have often found indirect secondary effects of similar or greater magnitude than direct primary effects. Secondary effects could be positive (e.g., multiplier effects to the overall economy) or negative (e.g., off-site environmental effects that offset the gains in production or poverty reduction).
- The range and magnitude of irrigation impacts, particularly those beyond production effects, were highly dependent on the location and circumstances in which irrigation occurred. In addition, impacts changed over time in magnitude and sometimes sign.
- Irrigation impacts—positive and negative—were unequally distributed socially, spatially, and temporally. Virtually every study that measured differential impacts has found them to be significant.

These conclusions and our analysis of the state of irrigation impact assessment led to these interrelated considerations for future investment:

- Expanded attention to irrigation benefits and costs is needed in irrigation planning.
- During planning, the potential range of positive and negative impacts should generally be expanded.
- Continued, explicit focus on distribution effects are needed if poverty reduction and equity goals of investments are to have the greatest likelihood of success.
- 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.
- Investment planning should consider that the purpose of irrigation and values toward the environment will change over time.

While there is no shortage of irrigation impact assessments, new, improved research on priority areas could help investment planning. These areas include:

- Design for impact assessment—not just monitoring and evaluation—for select projects. However, mechanisms for impact assessment will likely need longer time horizons than those for typical project cycles.
- Additional investment in long-term assessments of irrigation's dynamic nature.
- Renewed focus on the impact of large-scale irrigation, particularly on maintenance and institutions.
- New analysis of national- and global-scale irrigation impacts and processes.
- Support of 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. Typology of Irrigation Impacts

The impacts of irrigation range from direct increases in agricultural output to indirect effects on gender relations, employment, and even government structures. We build on the existing literature to provide an indicative typology to assist in conceptualizing irrigation impacts. The impacts of irrigation are varied and overlapping; therefore, no definitive typology suits all needs. Our 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 increased crop output through yield and area increases. Yield increases because of additional plant water availability and the linear relationship between transpiration and yield (Chang 1968). Irrigation makes control of the quantity and timing of water availability more precise, supporting crop establishment, growth, and yield. It can make crop production possible in places where rainfall and soil moisture are insufficient or intensify production through second and sometimes third croppings.

Water availability through irrigation reduces the risk of crop failure. This in turn increases the expected return on complementary investments, such as seeds and fertilizer (Gebregziabher, Namara, and Holden 2012; Namara, Upadhyay, and Nagar 2005), further increasing yields and incentives for investment (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 declines. The risks associated with assured surface irrigation supply and timing help to explain why farmer-initiated groundwater use is common even in surface irrigation systems.

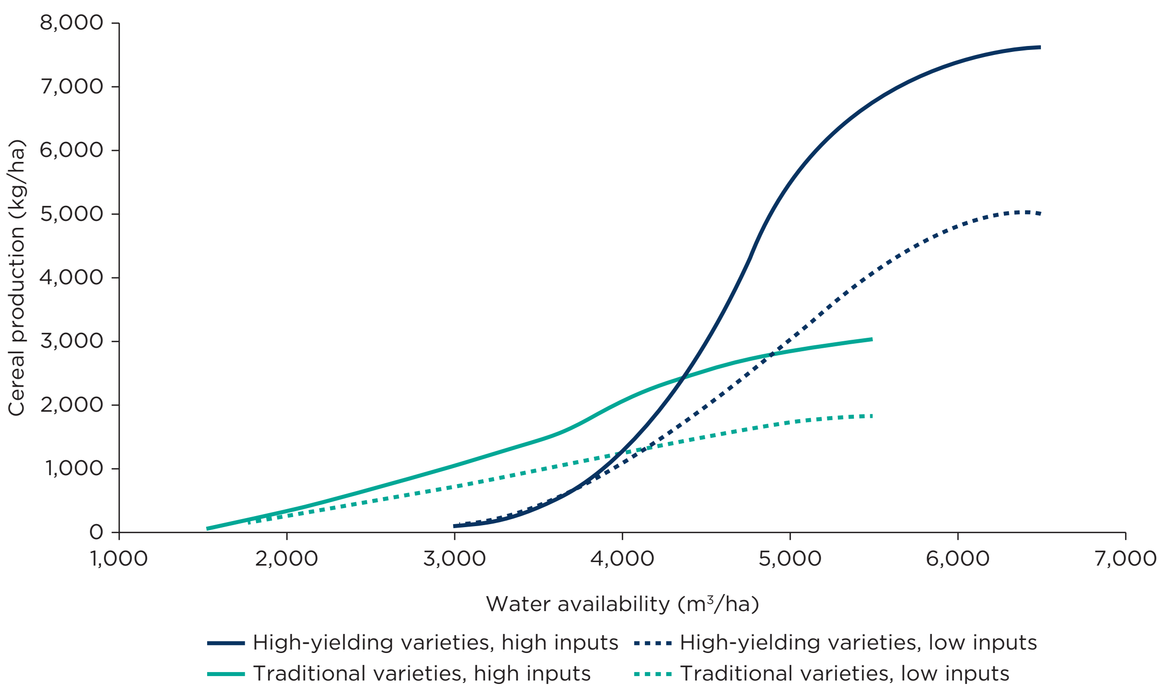
Irrigation can bring new risks beyond the farm scale, such as crop disease and reduced crop diversity as demand for traditional varieties decline (Hazell 1982; Mehra 1981; Pinstrup-Andersen and Hazell 1985). Adopting more uniform varieties may bring new price risks as cropping decisions become more uniform across large regions (Pinstrup-Anderson and Hazell 1985), an outcome potentially further exacerbated by centrally controlled water releases and crop procurement programs, such as in India. Better water control may lead 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. For example, the productivity of HYV seeds during the Green Revolution was made possible only by irrigation. That productivity was further increased by additional fertilizer supplies. Further, the productivity of fertilizer increased through irrigation supplies. Figure 1 illustrates these points. Irrigation likely increases the productivity of other complementary inputs, such as labor, through similar mechanisms (von Braun, Puetz, and Webb 1989).

Irrigation can be an induced response to other technology or investments. The advantages of the HVY seeds could be achieved only with 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. The Green Revolution was as much an irrigation (tube well) revolution as a seed revolution (Repetto 1994).

Figure 2.1. Typical Responses of Cereal Crop Yields to Water



Source: Smith, Fereres, and Kassam 2001.
Note: The graph shows the yield response of crops to water availability. High yielding varieties produce more than rainfed varieties only when provided with an adequate amount of water.

2.3 Impacts on Output Prices

Other conditions being the same, increasing output places downward pressure on prices. Evenson and Gollin (2003) estimated that global food prices would have been 35 percent to 65 percent higher without Green Revolution technologies, including irrigation. While falling prices are generally good for consumers, they negatively affect producers. The impact on a producer depends on the extent to which falling prices are offset by productivity gains and the extent to which he or she buys commodities for personal consumption. The impacts of irrigation-induced price change is uneven across countries. During the Green Revolution, price reductions caused by irrigated agriculture affected farmers confined to rainfed conditions and farmers in Africa and elsewhere who did not benefit from investments in irrigation and seeds. Because 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 is well documented (e.g., Lipton, Litchfield, and Faurès [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 net buyers of food, so they benefit in this way. However, the nature and extent of poverty impacts can vary depending on factors such as relative or absolute land size, relative location in an irrigation system (e.g., head or tail end), and structural issues related to the overall institutional and socioeconomic environment (e.g., related to gender, caste, and class).

Beyond direct production, consumption, and income effects, irrigation affects poverty through indirect mechanisms, including increased labor demand, particularly during harvest periods, nutrition and health change, and economywide multiplier effects. Whether these impacts are positive or negative is highly contextual. Irrigation's employment effects may benefit the landless poor, but inequalities may widen as output increases and depresses prices received by poor farmers operating in rainfed conditions. Irrigation may worsen poverty if it reenforces land consolidation in which poor households lose rights, converting marginal and poor farmers to landless laborers (Chambers 1988), or if it displaces labor by mechanization or herbicide use. The development of irrigation can have off-site environmental impacts that are particularly important for the poor. Construction of dams and reservoirs to support irrigation is associated with displacement costs that disproportionately fall on the poor (e.g., Duflo and Pande [2005]). Irrigation may reduce environmental service provision upon which the poor rely, 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 increase incomes or purchasing power to support diet diversity (von Braun, Puetz, and Webb 1989). However, the monoculture often associated with irrigation can 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 is associated with increased vegetable production with direct benefits on nutritional status, particularly for women and children (von Braun, Puetz, and Webb 1989). Pinstrup-Anderson and Hazell (1985) outline mechanisms that increased production during the Green Revolution connected to nutritional status. Domenech (2013) reviews nutrition-related impacts of irrigation in Sub-Saharan Africa.

2.6 Impacts on Health

Irrigation can increase levels of standing water, especially when systems are poorly managed. These areas can be breeding grounds for disease vectors, including Anopheles mosquitos, contributing to increases in malaria and other diseases. Dams constructed for irrigation slow water flow and may increase the prevalence of malaria or sleeping sickness. Irrigation with untreated 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 agricultural inputs such as fertilizer and pesticides, increasing exposure to both farmers and consumers.

Wealth generated by irrigation may spur investment in health care, such as through purchasing bednets (Klinkenberg, van der Hoek, and Amerasinghe 2004) or increasing food expenditures and nutrition levels. Irrigation development may increase the availability of clean drinking water and improve sanitation (van der Hoek, Konradsen, and Jehangir 1999). Domenech and Ringler (2013) summarize irrigation and health interactions.

2.7 Equity and Gender

The impacts of irrigation are not uniform. Producers with access to irrigation generally benefit more than those without. Even for those with irrigation, impacts vary depending on location in the system (head end or tail end), relative land size, access to capital to support complementary investments, and other factors. Early adopters may benefit differently than late adopters. In irrigating villages, impacts depend on class and caste structure.

A long literature highlights the importance of gender considerations in resource management outcomes (Meinzen-Dick et al. 2014) and water (Ray 2007). The importance of gender in irrigation outcomes and impacts is also important. Gendered areas include crop production, use of agricultural water (e.g., fields versus home gardens), access to inputs (e.g., land titles, credits), and the use of revenue from irrigated output. However, while well over half of food production in low-income countries is attributed to women (UNDP 2006), irrigation interventions are often made without explicit input from erstwhile female beneficiaries or consideration for gendered constraints to adoption (Jordans and Zwarteveen 1997), potentially reducing effectiveness and affecting system inequality. The gendered impacts of irrigation are variable. Irrigation may reduce work for some groups of women but increase it for others. Van Koppen and Hussain (2007) and Domenech and Ringler (2013) summarize the interconnections between irrigation impacts and gender.

2.8 Impacts on the Environment

Water withdrawn for irrigation and changes in flow regimes caused by associated dams affect the naturally occurring environmental services provided by free-flowing rivers. Habitat and resident flora and fauna are destroyed, and the flooding of biomass may cause net releases of carbon dioxide and methane. This may affect global climate and localized air pollution problems. The rapid expansion of groundwater irrigation in the last few decades has severed the natural connections between surface and groundwater systems. The drawdown has caused soil compaction and other problems. Waterlogging and salinity frequently result from poor irrigation management, and higher levels of inputs associated with irrigated agriculture result in fertilizer and pesticide runoff.

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 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

Changes in agricultural productivity due to irrigation have affected overall growth through multiplier effects and can (a) free human and financial capital for industry and services (Mellor and Lele 1973; Pinstrup-Andersen and Hazell 1985; (b) stabilize rural populations (Little and Taylor 2001; Schraven 2010; Viljoen 1990); and (c) affect foreign exchange earnings and budgets via export taxes (Liu et al. 2014; Siddig and Mubarak 2013).

Irrigation may influence governance structures, such as the Subak system in Indonesia. While governance change may 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) argues that the arrival of more productive seeds and irrigation in Pakistan forestalled larger political reform. Electricity reform to support economic growth in India is now complicated by the political economy of power subsidies and groundwater.

3. Methodology

To assess empirical evidence of irrigation impacts, we review 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. We focus our analysis and discussion on studies published in the last 25 years, drawing 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 economywide processes based on secondary data. We supplement the results with insights from qualitative studies that provide understanding of the mechanisms through which irrigation impacts occur (see section 5 for comments on their role for policy making). 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 statistically representative.

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

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 (a) plot (e.g., Huang et al. [2005]), (b) farmer (e.g., Ayanwale and Alimi [2004]), (c) household (e.g., Gebregziabher, Namara, and Holden [2009]) or household head (e.g., Bagson and Kuuder [2013]), (d) irrigation system (e.g., Irajpoor and Latif [2011]), (e) state or province (e.g., Bhattarai and Narayanamoorthy [2003]), and (f) global food system (e.g., Nelson et al. [2009]). Most studies analyzed impacts related to a particular irrigation system, but others analyzed and sometimes compared multiple systems in one country (e.g., Huang et al. [2005]). A few analyzed systems in multiple countries (Hussain 2007). Many analyses examined impacts at more than one scale.

Studies focused on the nonhuman impacts of irrigation used scales consistent with environmental processes. Some focused on the impacts of irrigation on rivers, aquifers, or climate systems (e.g., Changming, Jingjie, and Kendy [2001]; El Ayni et al. [2012]; Lee et al. [2011]; Liu, Yu, and Kendy [2001]; Saeed, Hagemann, and Jacob [2009]). Others measured uptake of toxins at animal or plant level (e.g., Ghosh, Bhatt, and Agrawal [2012]; Gupta, Khan, and Santra [2008]; Liu et al. [2005]; Ohlendorf et al. [1986]).

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

One critique of early studies of the Green Revolution is that assessments happened too quickly and did not capture diffusion effects. They missed poverty reduction effects that were later documented and overemphasized negative effects on inequality (Pinstrup-Andersen and Hazell 1985). Later analysis and discussion highlight growing negative environmental impacts (e.g., Shiva [2016]), such as widespread overuse of groundwater or, in India, negative knock-on impacts to the electricity industry. There is no ideal, and appropriate lags depend on purpose. However, past work on irrigation management transfer, an intervention with substantially less expected impact than irrigation development, suggests a minimum of six to 10 years (Kloezen, Garces-Restrepo, and Johnson 1997; Vermillion 1997).

Despite the dynamic and changing nature of irrigation impacts, most assessments measured impacts between two points in time, such as between before and after irrigation dates (e.g., Tesfaye et al.

[2008]; Bagson and Kuuder [2013]; Peter [2011]), or they compared differences between with and without sites at a single point in time (e.g., Adeoti et al. [2007]; Yohannes et al. [2005]). The few studies that measured impacts across time (e.g., Ayanwale and Alimi [2004]; Bhattarai, Barker, and Narayanamoorthy [2007]; Burney et al. [2010]) highlight new insights that sometimes change earlier conclusions. For example, the health impacts of irrigation can be negative in the short run as disease vectors increase, but may turn positive later as awareness generates government-level policy responses (de Zulueta, Mujtaba, and Shah 1980) or income effects result in greater health care investment by individuals (Klinkenberg, van der Hoek, and Amerasinghe 2004). Data collection over time is a major impediment to long-term assessments of the dynamic nature of irrigation. 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 demonstrates an alternative to long-term data collection.

We did not try to precisely assess the proportion of studies by country, but clear patterns emerged. 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 often focus more on Africa, particularly Ethiopia and Ghana, though their combined irrigated area is small. Studies on low-income countries tended to focus on impacts related to output, poverty, and other measures of livelihood. Studies in higher-income countries tended to focus on environmental impacts.

The nature of the irrigation assessed has shifted over time. Earlier studies tended to focus on large-scale systems. More recent works tended 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 nonexperimental, quasi-experimental, or experimental. Nonexperimental approaches were common in our sample. Some studies used a simple comparison of the social and economic situation of participants in an irrigation project to the intended outcomes stated in the technical proposal and terms of reference (e.g., Concern Universal [2012]). Others used a before and after comparison without control (e.g., Ayanwale and Alimi [2004]; Irajpoor and Latif [2011]) or compared an area with irrigation and a nonirrigated control (e.g., Kibret et al. [2010]; Viljoen [1990]). That a study used a nonexperimental design should not be considered a critique because each study has its own purpose and logic. Nonetheless, the approaches limit the inferences that can be made on impact.

Another large group, particularly of more recent publications, applied quasi-experimental methods to provide counterfactuals in with and without scenarios. The techniques are largely regression- or econometric-based but include many approaches including propensity score matching, endogenous switching regression (e.g., Nkhata [2014]), differencing, instrumental variables (e.g., Duflo and Pande [2005]), and pipeline approaches. Given the nature of most irrigation, experimental approaches now common in other areas of development literature and 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 used economic, hydro-economic (e.g., Barbier and Thompson [1998]; Bhatia, Malik, and Bhatia [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 was used in studies of irrigation performance.

Finally, many qualitative studies directly or indirectly show the impact of irrigation in 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., Beck [1995]; Blyn [1983]; Cleaver [1972]; Das [2002]; Jewitt and Baker [2007]; Leaf [1983]; Merrey [1983]; Ostrom and Gardner [1993]).

4.3 Physical and Institutional Nature of Irrigation Evaluated

While any division of water in the hydrologic cycle is arbitrary to some degree, irrigation is often conceptualized by the source of water in 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., Acheampong, Ozor, and Sekyi-Annan [2014]; de Fraiture et al. [2014]; Ersado [2005]; Venot, Andreini, and Pinkstaff [2011]). 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., Adeoti et al. [2007]; Burney et al. [2010]; Kamwamba-Mtethiwa et al. [2012]; Mangisoni [2008]; Shah et al. [2000]) 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., Giordano et al. [2017]; Senanayake, Mukherji, and Giordano [2015]) are often concerned with particular institutional forms (e.g., water user associations [WUAs]), relatively few studies of irrigation impact assessments used institutional form as an explanatory variable. This may be because of the relative uniformity in institutional structures in each of the conceptualizations outlined. For example, large-scale surface systems tend to be managed publicly in whole or in part (main canals are typically managed by formal irrigation bureaucracies, though distributaries may be managed publicly or through WUAs). In contrast, groundwater irrigation is typically privately controlled as is small-scale irrigation using drip or drum and buckets. Some studies 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 (2011), has found greater positive impacts on production and income with small-scale (private) systems than large-scale (state) systems. Acheampong, Ozor, and Sekyi-Annan (2014) have found that performance and impacts of small dams in Ghana are generally higher when managed under WUAs. Other studies examined the issue in reverse, measuring the impacts of irrigation system characteristics on institutional outcomes (e.g., Nagrah, Chaudhry, and Giordano [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 nonirrigated. At the global level, irrigation accounts for only 20 percent of total agricultural area but 40 percent of total output (Turral, Burke, and Faurès 2011), though 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 have documented increases over at least some time scale.

Studies of the first one to two decades of Green Revolution impacts highlight impressive gains in production directly and indirectly related to (primarily) large-scale irrigation (see Evenson and Gollin [2003]; Pinstrup-Andersen and Hazell [1985]). Later studies, though not focused on impact assessment per se, did not question positive production impacts of irrigation but tended to highlight problems of irrigation system operations, suboptimal 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 tended to focus on the impact of small-scale irrigation adoption (e.g., Antony and Singandhupe [2004]; Ayars et al. [1999]), 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 because adoption sometimes requires subsidy (e.g., Malik, Giordano, and Rathore [2016]) suggest 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 (Bliss, Lanjouw, and Stern 1998; Saith and Tankha 1992). Later studies document a shift from low- to high-valued crops facilitated by irrigation (Mehta 2009; Moore 2015; Narayanamoorthy and Deshpande 2003; Woldewahid et al. 2011).

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

While direct, positive production impacts of irrigation provision are well documented, other studies highlight production impacts on nonbeneficiary farmers (Takeshima, Adeoti, and Popoola 2016) and the broader opportunity costs of irrigation water. For example, Barbier and Thompson (1998) have 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 in the United States (Hamilton and Gardner 1986) have 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.

A minority of irrigation impact assessments attempted to assess net impacts (benefits minus costs) of irrigation, even when narrowly defined in terms of production. Of those that did, Huang et al. (2005) have found positive net returns on investments in a number of irrigation systems in China. Ersado (2005) has 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 Adeoti et al. (2007), Amacher et al. (2004), Aseyehegn, Yirga, and Rajan (2012), Burney et al. (2010), Duflo and Pande (2005), Hamilton and Gardner (1986), and Kumar et al. (2014). Another group of studies, particularly those focused on health, nutrition, and the environment, measured 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.

4.4.2 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, but irrigation is also strongly associated with increases in cropping intensity (e.g., Guhan and Mencher [1983]; Saith and Tankha [1992]). Hussain and Hanjra (2004) review irrigation and poverty in Asia, finding that cropping intensity under irrigation nearly doubled. As shown in Namara, Upadhyay, and Nagar (2005) and Gebregziabher, Namara, and Holden (2011) and illustrated in figure 1, water supplies from irrigation also increase the productivity of complementary inputs including seeds and fertilizer. The increased output driven by irrigation can 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, Ashaolu, and Philip 2010), it finds 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 with inputs in a total factor productivity (TFP) or related approach. The importance of this approach is discussed by Scheierling, Treguer, and Booker (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., Alston and Pardey [2014]; Darku, Malla, and Tran [2013]; Fuglie [2010]).

4.4.3 Impacts on Output Prices

Evenson 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 percent to 66 percent higher by 2000, and higher prices would have induced an expansion of cropped area, with negative environmental consequences. They attributed about one-third of these overall impacts to irrigation. Because Green Revolution technologies, including irrigation, were focused mostly on low-income countries, studies have found that direct and indirect production impacts would have resulted in crop output 4 percent to 7 percent higher in upper-income countries and 14 percent to 19 percent in low-income countries.

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 Evenson and Gollin (2003). First, it is likely that in low-income 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 depend on the integration of national agricultural markets with the global trade as well as the degree of home consumption. In any particular country, producers who did not gain access to irrigation would 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.

4.4.4 Impacts on Poverty

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

Empirical studies confirm the substantial direct impacts of irrigation on income. Bhatia (1991) reports 77 percent 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 percent increase in farm income in lowlands of Oromia, Ethiopia (Ahmed, Mume, and Kedir 2014). Irrigation can allow savings and accumulation of wealth. In Africa, households with access to irrigation often own substantial cattle herds (Chazovachii 2012; Dillon 2008), 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, when irrigation creates labor shortage, it can actually decrease hours spent in school (Dillon 2008).

Irrigation's impact on poverty reduction depends on multiple factors. Hussain and Hanjra (2004) find that systems with more equal land distribution have greater poverty reduction potential, and 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 vary by water source. Groundwater has high poverty-reducing potential (Dhawan 1988, 2000; Narayanamoorthy 2007; Shah 2010), though poorly managed use (the norm the world over) results in declining groundwater tables that may eventually disadvantage the poor (Bhatia 1991; Drèze Lanjouw, and Sharma 1998; Saith and Tankha 1992). 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, Sakthivadivel, and Raju (1997) have found in India that water allocation rules requiring bribery put poor populations at a great disadvantage. Athreya et al. (1990) note that ownership rules prevented lower castes acquiring irrigated land.

Increases in labor demand stimulated by irrigation 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., Bhattarai, Barker, and Narayanamoorthy [2007]; Chambers [1988]; Hussain [2007]; Smith [2004]; Viljoen [1990]). Increased employment opportunities may improve and stabilize wages. Namara et al. (2011) have 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 revitalized and stabilized communities (Little and Taylor 2001) and countered depopulation of rural areas (Schraven 2010; Viljoen 1990). 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 Gokilapuram Valley, India. Walker and Ryan (1990) have 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 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) have 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 because of the increased demand for consumables as a result of income and salary increases in the agricultural sector. Studies have documented the multiple-use impacts of irrigation water and infrastructure (Meinzen-Dick and Bakker 1999; Meinzen-Dick and van der Hoek 2001; van der Hoek, Konradsen, and Jehangir 1999). Jensen et al. (1998) show that the availability of canal water use increased domestic uses. However, other studies highlight the potential drawbacks (see section 4.4.6 "Impacts on Health").

Finally, some studies find that higher income and greater personal freedom were considered the primary benefits of irrigation to many poor populations. Jodha (1989) has determined that a reduced reliance on patrons as a result of irrigation was deemed an important benefit. 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 illustrate the importance of qualitative assessments in understanding unanticipated positive and negative impacts of irrigation.

4.4.5 Impacts on Consumption and Nutrition

Irrigation leads to an increase in calorie consumption over time. Earlier studies of the Green Revolution (1970–90) have found that irrigation enhanced access to adequate and diversified food through increases in production and income (Hazell and Ramasamy 1991; Kennedy 1989). Von Braun, Puetz, and Webb (1989) assessed the links among production, income, consumption, and nutrition in rice irrigators in The Gambia. They conclude that the cultivation of rice increased real income of farmers by 13 percent per household. An additional 10 percent increase in annual income led to a 9.4 percent increase in food expenditure and a 4.8 percent 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, Naher, and Shahabuddin 2005). Irrigation has led to mono-cropping of cereals and decreased cultivation of pulses, oil seeds, and coarse grains. Thus, despite the widespread increase in calorie consumption and weight gain as a result of irrigation, people can face decreases in food diversity and micronutrients when wheat and other grains become a larger percentage of diets (Headey and Hoddinott 2016; Hossain, Naher, and Shahabuddin 2005). Some countries with large irrigation investments have relied on nutrient imports with potential implications of food security. Bangladeshi imports of vegetables and fruits from India and China now account for approximately 10 percent of vegetable consumption and 43 percent of fruit consumption (FAO 2014; Headey and Hoddinott 2016). Similar outcomes may occur when irrigation expands into seasonal or permanent grazing land, reducing livestock production and overall protein consumption (Hossain, Naher, and Shahabuddin 2005; Niemeijer et al. 1988), though the impacts of irrigation on meat production are reversed in other circumstances (Steinfeld, Wassenaar, and Jutzi 2006).

The impacts of irrigation on nutrition are determined by the social structure of farming systems. Some studies have shown that increases in irrigated area are associated with decreases in nutritional status, at least in the short term, where women play a large role in providing income from casual labor, as in Kenya (Fleuret and Fleuret 1980; Greer and Thorbecke 1986; Hoorweg et al. 1995; Hossain, Naher, and Shahabuddin 2005; Niemeijer, Foeken, and Klaver 1991; Quisumbing et al. 1995). In these cases, off-farm income was 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, Bryan, and Mekonnen 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., Hoddinott and

Yohannes [2002]; Kidala, Greiner, and Gebre-Medhin [2000]; Namara et al. [2011]). Black et. al (2008) have found that consumption of iron-rich foods such as dark green vegetables can reduce 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 vary by location, women may more likely control home gardens. Thus, if nutritional status were improved, program evaluators should consider the nature of irrigation (e.g., large-scale versus home garden) and the gendered nature of the farming system.

Other work addresses the connection between irrigation, sanitation, and the ultimate impacts of irrigation on nutrition. Van der Hoek, Feenstra, and Konradsen (2002) show in Pakistan that the application of irrigation water for household use can significantly reduce diarrhea, thereby improving children's nutritional status. Conversely, Audibert, Mathonnat, and Henry (2003) have shown 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 spent on household activities, including cooking and caring for their children (Brun, Reynaud, and Chevassus-Agnès 1989; Vaughan and Moore 1993), with negative consequences for nutrition. 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.

4.4.6 Impacts on Health

Elsewhere in this paper we show evidence of the mostly positive impacts of irrigation on health via direct and indirect consumption and nutrition effects. However, irrigation and health are interrelated through other mechanisms as well. Irrigation with untreated or minimally treated wastewater is widespread and can have significant health impacts for both producers and consumers (Drechsel et al. 2009). In semi-arid areas, 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 cause health impacts. These include neurological abnormalities, respiratory diseases, reproductive disorders, and endocrinological and dermal problems. Because irrigation increases the productivity of other agricultural inputs, it likely increases the use of agricultural chemicals.

Dam construction slows river flows, creating stagnant water associated with irrigation operations at system and farm level. These effects are associated with increases in disease vectors leading to increases in malaria, dengue, and sleeping sickness. The severity of impact depends on how the irrigation system is maintained. In the short term, areas without previous exposure to these diseases may be most significantly affected because communities lack awareness and institutions for addressing the consequences.

Irrigation is associated with positive health impacts. It increases water availability for improved sanitation and hygiene practices (van der Hoek, Konradsen, and Jehangir 1999), contributing to reductions in diarrhea, schistosomiasis, and other ailments. The potential wealth generated by irrigation drives increased investment in health care, such as the purchase of bednets and water filters

(Klinkenberg, van der Hoek, and Amerasinghe 2004). Increased wealth increases 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) review 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 (Coosemans and Mouchet 1990; Dixon and Pinikhana 1994; Ghebreyesus et al. 1999; IIMI 1986; Kobayashi et al. 2000; Singh, Shukla, and Sharma 1999). Guthmann et al. (2002) have found that malaria incidence was five times higher in villages closer to irrigation systems (i.e., dams) than villages in a nonirrigated area. In Ethiopia, Ghebreyesus et al. (1999) have determined that villages closer to small-scale dams experienced a sevenfold rise in malaria prevalence after dam introduction. Thus, irrigation's impact on malaria is variable since it depends on external factors such as the type of irrigation system, previous exposure of the area to malaria, existing health and irrigation infrastructure, amount of time that has passed since the introduction of irrigation, and level of landless migration to the area (Roll Back Malaria, WHO, and UNICEF 2005).

Surface irrigation has resulted in the greatest malaria incidence because it requires the creation of shallow water bodies, which serve as ideal breeding spots for malaria vectors (Roll Back Malaria, WHO, and UNICEF 2005). The flooding of fields for paddy farming is often associated with a rise in malaria incidence (Coluzzi 1984; Gillies and De Meillon 1968; Snow 1983; Surtees 1970; White 1974). A location's previous exposure to malaria and the condition of its health infrastructure are also important factors. Studies have found that places with previous exposure (e.g., wetter areas supporting malaria vectors) often had protective measures (e.g., bed nets) and were often less affected by the increased mosquito abundance from irrigation. Variation in prevalence after irrigation is 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 biting rate of mosquitos carrying malaria. They conclude that the irrigated areas studied had a similar abundance of mosquito vectors, but areas that had been irrigated for 30 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 nonirrigated areas. Drier or more arid areas experienced a higher initial increase in their number of malaria outbreaks following the implementation of irrigation. This initial increase in malaria outbreaks was because the appropriate health infrastructure was not in place and mosquito populations had increased due to irrigation. Oomen, de Wolf, and Jobin (1988) and Wang'ombe and Mwabu (1993) have reported similar findings.

Poor irrigation management is often associated with an increase in malaria prevalence. Chimbari, Chirebvu, and Ndlela (2004) assessed the impact of poorly maintained irrigation infrastructure and inadequate landscape-leveling on increased malaria prevalence. They report that these poorly maintained systems increased the prevalence of mosquito breeding sites in fields with sprinkler schemes and poor drainage structure. Mwangangi et al. (2013) assessed the impact of irrigation on mosquito vector abundance with different levels of irrigation management. They have determined that when rice planting was coordinated and better managed, the time that fields had to be flooded was reduced, which minimized the time mosquitos had to breed in the fields. 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 have determined that improper canal water management resulted in more vector breeding sites and 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 decrease the prevalence of year-round stagnant water (reduce prolonging of seasonal transmission) and minimize the impact of 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 reduce mosquito breeding sites (Jobin 1999; Konradsen et al. 2004).

Malaria rates can go up in the short term because 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 1985; Coosemans et al. 1987; Coosemans and Barutwanayo 1989). Coosemans and Barutwanayo (1989) observe that these landless migrants often had very low incomes and could not afford bednets and other malaria prophylactics.

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

4.4.7 Equity and Gender

Virtually every study that examined socially differential impacts of irrigation connected to class, caste, or gender has found them to be significant. However, the nature of those impacts was highly variable. For example, irrigation in systems with unequal land distribution results in an unequal distribution of benefits. When some groups are excluded from land ownership, they will be excluded from direct irrigation benefits. This section focuses on evidence of the gendered impacts of irrigation to illustrate equity impacts and mechanisms.

The impact of irrigation on gender and equity is variable. Upadhyay, Samad, and Giordano (2005) have determined from surveys that 83 percent of respondents reported that drip technology benefited female and male employment in Nepal. They conclude that women received direct consumption benefits from irrigation. After the introduction of drip irrigation, women could 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, Samad, and Giordano 2005). Perera (1989) observed in Sri Lanka that irrigation channels increased the availability of water that women could use for domestic purposes, which 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 factors including access to land, water, labor, capital, credit, technology, and other resources (Molden 2007). Aseyehegn et al. (2012) have found that male-headed households in Ethiopia were 38 percent more likely to participate in irrigation than female-headed households, since the latter tended to be labor scarce and 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 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 and Neupane 1996). Moreover, Bastidas (1999) has found that women with small children often participated less in irrigation than men due to the expectation that women care for the family. This role of the men in decision-making and their land ownership provide 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 because 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 affects society's willingness to grant credit to women. Studies in Malawi have found that women often pay for new irrigation technologies in cash, which means they are often limited in the size of their purchases; men, however, have access to greater credit (Kamwamba-Mtethiwa et al. 2012). In Kenya, Malawi, Sierra Leone, Zambia, and Uganda, women receive less than 10 percent of the credit awarded to farmers (Squires 2010).

Irrigation benefits may be limited by the amount of labor women contribute to irrigation. While irrigation may reduce the need for women to spend time collecting water, it may increase women's agricultural workload if they provide the bulk of the labor. Upadhyay, Samad, and Giordano (2005) conclude from their study in Nepal that women usually spent more time growing and cultivating the crops than males, who contributed only 12 percent of their time to producing the vegetables. In Pakistan, nine women out of a sample of 87 were directly engaged in irrigation (Basnet 1992). In some studies, this high labor requirement and a lack of recognition for their extra labor contributions resulted in many women 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. This often resulted in women receiving greater respect, improved social standing, and greater decision-making authority (Bushamuka et al. 2005; Du Plessis and Lekganyane 2010; Galhena, Freed, and Maredia 2013; Iannotti, Cunningham, and Ruel 2009; Schaetzel, Antal, and Guyon 2013; Schreinemachers et al. 2015; van den Bold et al. 2015; Yasmin, Khattak, and Ngah 2014). Hallman et al. (2003) have observed that home garden systems require little land and investment. They allow women to become empowered and 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, Nagar, and Vasavada 2001 have found in India that women have the greatest success in accessing and managing irrigation systems when a women's group manages an irrigation project. This role can be influenced by the society's allowance of women in leadership, the type of irrigation, and whether the type of irrigation system has a greater labor requirement.

Many studies address women's inclusion in irrigation management groups such as water user associations (WUAs). Van Koppen (2002) has found that women benefit most from irrigation when they hold leadership positions and are included in irrigation forums such as WUAs. 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 WUA meetings, and water allocation plans are often made in their absence (Bruins and Heijmans 1993). Schrevel (1989) has determined that a major reason for the poor functioning of WUAs 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 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).

4.4.8 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 associated with decreases in sediment transport, increases in soil erosion, chemical contamination, and loss of biodiversity. Some of these impacts are fed in Falkenmark et al. (2007) and Boelee (2013), and both provide insights into mitigation of negative environmental consequences of agricultural water use.

A wide range of mostly technical studies measured the negative impacts of irrigation on the environment. For example, the construction of the High Aswan Dam reduced sediment transport and led to the erosion of wetlands in the Nile Delta 800 kilometers 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 associated with soil salinization and water logging, particularly in arid and semi-arid regions (Kinje 1993 Rengassamy 2006). Chemical fertilizers and pesticides associated with irrigated agriculture have negative environmental impacts. Vermeer et al. (1974) have found that kites foraging in rice fields had concentrations of PCP 100 times greater than levels of kites from nearby freshwater marshes. Litskas, Aschonitis, and Antonopoulos (2009) have found in the North Aegean, Greece, that nitrate concentration was higher in the irrigation water by 0.3 milligrams per liter due to the use of fertilizers in irrigation. Many studies, particularly from the United States, have found that irrigation has resulted in greater pesticide presence in the water table (Hallberg 1987; Pionke et al. 1988; Wartenberg 1988).

Higher saline, pesticide, and nitrate levels and diversions of the water supply contribute to reductions in biodiversity due to organisms' inability to survive under these harsh conditions.

Studies on biodiversity loss highlight the role of the submersion of wetlands, changing of vegetation communities, or diversion of water to certain areas due to irrigation (Kotlyakov 1991; Micklin 1988; Precoda 1991). Gammelsrød (1996) has found that the reduction in water flow due to the barrages and dams in Mozambique led to declines in the marine prawn populations and fish diversity. Kotlyakov (1991) studied the impact of irrigation on the Aral Sea Basin, finding that after water diversions, the bird species decreased by 151 and 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 and Makarewicz (2009) have determined that a cessation in manuring processes over a period of five years resulted in a reduction in dissolved and particulate contaminants, including total phosphorus, soluble reactive phosphorus, total Kjeldahl nitrogen, and nitrate in the examined watershed. Padre and Ladha (2004) have 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 kilograms per hectare per year over 20 years. Fujioka and Lane (1997) attribute the negative impact on biodiversity to shifts in irrigation infrastructure. They have found that shifting from ditch-fed irrigation to metal pipes and concrete channels for rice fields reduced the population of two species. The new, more efficient infrastructure reduced water leakages and, thus, the pools of standing water for frog spawning (Fujioka and Lane 1997). Soil salinization and water logging are 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 (Offenheiser (2020)), which is supported by the fact that irrigated agriculture produces 25 percent to 40 percent of food output on 10 percent to 20 percent of agricultural area (Molden 2007; van Schilfgaarde 1990). We identified only one global study formally addressing the issue (Evenson and Gollin 2003). They report that agricultural land area would have been 3 percent to 5 percent higher by 2000 without the Green Revolution (including the contribution of irrigation). Thus, as highlighted by Molden (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. However, irrigation may play a largely unrecognized role in reducing other environmental pressures from food production and can provide new forms of environmental services, as in traditional systems (e.g., Natuhara [2013]) and modern systems (Soils Inc. and Chalo Environmental and Sustainable Development Consultants 2000). Unfortunately, the net impacts of irrigation on the environment at local, national, and global levels have received little attention in the literature.

4.4.9 Multiplier Effects and Impacts on the Broader Economy and Political Structure

Broad analyses of Green Revolution's impact highlight large, positive spillover effects. Increased output increased incomes, consumption, and employment, and spurred both rural and urban growth, driving modernization. Later studies estimated high off-farm impacts. Bhattarai, Barker, and Narayanamoorthy (2007) estimated that multiplier effects in India were three to four times more than the direct effects of irrigation. They questioned the push to require farmers to bear responsibility for the full costs of irrigation O&M, given the widespread benefits. Other studies suggest that multiplier effects may diminish over time and should be examined in the context of other investment opportunities. Fan, Gulati, and Thorat (2008) have found that while additional irrigation investment in India 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 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 per acre, the net benefits to the state were minus $8 per acre. The study further reports 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 issue is the relative impact of irrigation investment compared to alternative uses of capital in an increasingly water-scarce world.

While not falling in the category of impact assessment, a broad range of literature discusses the connection between irrigation, politics, and political economy (e.g., Davies [2009]; Mitchell [1973]; Steward [1955]). Irrigation generated the surpluses behind the rise of civilization and is connected with political development in systems ranging from the Subak rice terraces in Indonesia to Mormon canals in the arid western United States. In the late 20th century, irrigation not only underpinned food supply gains and the resulting poverty reduction of the Green Revolution but also is connected with aspects of modernization and the nature of governments in Asia and Latin America (Latham 2011; Niazi 2004).

The development of irrigation 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. 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 through indirect effects that increase expected returns and spur investments in other agricultural technologies and human capital. The literature highlights substantial contributions of irrigation to poverty reduction over the last 50 years for farmers, the landless, and the land poor who gain seasonal employment on irrigated farms and, perhaps most significantly, consumers. Consumers gain through greater availability of basic food supplies at prices much lower than without irrigation. Poor consumers gain because of the high proportion of their incomes spent on food.

The literature 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 has found that benefits accrued to those with large land holdings who were able to adopt new technologies early. Later studies show that the benefits were much more widely shared. 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, lowering disease impacts. The literature shows that the nature of irrigation affects changes as income levels and the structure of the overall economy change. For example, Fan, Gulati, and Thorat (2008) have found that while the poverty-reducing impact of irrigation remains positive, its marginal effects decline over time, and alternative investments in the rural economy eventually have higher returns.

The literature 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 has found significant differences. Where land holdings are unequal, irrigation benefits will be too. Those in head ends 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, one group may benefit at the cost of another. This may be particularly common in the case of environmental externalities, such as where dams displace poor populations or downstream ecosystem services on which the poor depend are destroyed.

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 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 protecting remaining biodiversity. This positive environmental impact of irrigation appears largely unappreciated and underdocumented in the literature.

This review reveals that irrigation investments in the last 50 years have had major positive impacts on 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; Malano and van Hofwegen 1999; Mukherji and Facon 2009; Turral 1995). The literature shows that negative impacts of irrigation were often misunderstood or ignored, raising questions of equity and sustainability.

Further, the rationale for irrigation has changed. Following WWII, 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. As abject poverty levels have decreased in rural areas, the role traditional large-scale irrigation can play in poverty reduction must change. As an example, Huang et al. (2005) have found that irrigation investments in China had relatively little impact on rural poverty because the irrigation districts had so few poor farmers. However, opportunity costs of water are changing as scarcity increases, urban areas generate higher-value water uses, and values toward the environment change.

6. Summary and Recommendations

Hundreds and possibly thousands of published studies have assessed the impacts of irrigation. This paper identifies and provides context to an illustrative range of those assessments from a variety of literature and approaches. We examined more than 500 hundred studies, more than 250 of which are cited here. The cited studies were examined for such variables as location, scale, time since irrigation intervention, irrigation source and type, impact evaluation approach, and the nature of the impact assessed. The measured impacts and their context formed the core of this work. While there is wide variation in the approaches, scope, and focuses of the studies as well as their findings, some general conclusions emerged.

- Irrigation is clearly linked to increased agricultural output through direct production effects and its role in increasing the productivity of complementary inputs.
- Irrigation is strongly associated with decreases in poverty, particularly among direct beneficiaries and urban consumers.
- Irrigation is linked to a wide range of other impacts in sectors including nutrition, health, and the environment.
- Studies that measured irrigation impacts beyond the farm or system scales have often found indirect secondary effects of similar or greater magnitude than direct primary effects. These secondary effects were sometimes positive (e.g., multiplier effects to the overall economy) or negative (e.g., off-site environmental effects that offset the gains in production or poverty reduction).
- The magnitude and nature of irrigation impacts, particularly those beyond production effects, were highly dependent on location and circumstances in which irrigation occurred. Impacts changed over time in terms of magnitude and sometimes sign.
- Irrigation impacts, positive and negative, were unequal socially, spatially, and temporally. Virtually every study designed to measure differential impacts, in whatever dimension, has found them to be significant.

These conclusions and our findings on irrigation impact assessment have led 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 attempted to measure the net societal impacts of irrigation or considered the opportunity costs of water. Of those that went beyond the system level, one has found high positive spillover effects, justifying public investment and subsidy. Another has found that while direct returns to irrigation investment are positive, impacts were overstated when negative externalities such as those related to health were neglected. Duflo and Pande (2005) have found that positive direct impacts on poverty were offset by negative indirect impacts off-site. While more impact assessments that include net benefits across scales may be needed, any irrigation investment needs to be informed by consideration across scales of financial and economic benefits and costs. This is particularly important for project-level investment decisions and irrigation policy, because 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 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, and are many times counterintuitive. To facilitate analysis and discussion, this study presents an impact typology divided into nine broad categories, but each element of the typology could easily have been further subdivided multiple times or organized in alternative ways. While it is not possible to anticipate every possible impact in every investment decision, informal consideration of the range of likely impacts beyond the system level is important for project planning and the long-term success of and support for irrigation investment. As an example, arguments against irrigation often focus 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 with pervasive structural inequality. Greater awareness of and 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 nonbeneficiaries. The poverty reduction potential of irrigation investments may not be met unless other conditions are simultaneously changed. This may sometimes be difficult if, for example, it involves structural factors such as land holding size or caste or gender relations. There may be opportunities to design investments or their locations to disproportionately favor the poor. 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 were to provide net benefits, it affects producers and consumers differently and may cause trade-offs between those directly receiving benefits and those who do not. As part of overall calculations of net project returns or benefits, explicit consideration of who benefits, who is harmed, and the magnitude of both may be at least as important as having investments meet poverty reduction and equity goals.

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 because irrigation modifies the natural environment. However, the extent has often been exacerbated by a failure to anticipate environmental costs in decision-making and poor management of environmental consequences. Many studies highlight 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 provides significant indirect environmental benefits by, for example, reducing pressure on additional land development. Lack of irrigation is 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 through biotechnology, irrigation will continue to play a major role in many countries for decades to come. Reducing unnecessary negative environmental impacts of irrigation and better explanations of the environmental case for irrigation are needed to ensure good investment decisions and public understanding of irrigation's place in environmental debates.

6.5 Anticipate Changing Needs and Values

Early rationale for and studies of the Green Revolution irrigation investment focused on production increases and poverty reduction impacts for farmers and consumer. However, later studies tended to include a broader range of variables such as farm labor demand, expanding supply chains, and positive spillover effects in the broader economy. Another set of studies have 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 tended to shift from the impacts of large-scale surface systems to small-scale technologies and groundwater. These changes in what is studied reflect an increased understanding of the mechanisms through which irrigation works. They also reflect changes in the environment in which irrigation exists and in the 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 they are combined with appropriate nutrients. The nature and location of poverty have shifted as have the options for particular forms of irrigation to address it. The opportunity cost of water has changed as more water has been developed for irrigation, water demand for cities and industry has grown, and awareness of water's environmental value has increased. Water scarcity and a global water crisis are the focus rather than water development. Future irrigation investments must be designed not for the present but for an uncertain future.

6.6 Additional Investment In Priority Research Areas

There is no shortage of irrigation impact assessments and no need for a general call for additional research. However, recent literature has brought up key issues on irrigation impacts, such as the role of irrigation in nutrition and ways to use irrigation's gendered dimensions to reduce poverty. New research is needed to support investment in irrigation to meet newly emerging priorities, such as youth employment. This assessment suggests general gaps in approach to irrigation impact assessment that, 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 Monitoring and Evaluation—with Project Implementation

A general challenge for most irrigation impact assessments is that they are implemented after irrigation is in place. Only rarely are assessments done using preirrigation baseline data. While with-without and other approaches may partially address this problem, planning and collecting data for impact assessment in project designs 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 understanding the processes through which irrigation impacts occur.

6.6.2. Invest In Long-Term Assessments of Irrigation's Dynamic Nature

The minimum lag to assess the impact of irrigation management transfer on system performance, not impact more broadly, is six to 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 after the Green Revolution, and some impacts, such as those related to malaria rates, may switch sign. This highlights the need for studies that assess longer-term effects and 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, funded partly by the National Science Foundation, examined 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 Regarding Maintenance and Institutions

As the opportunities for large-scale irrigation have declined globally, with a possible exception of Sub-Saharan Africa, so too has the number of assessments of its impact. However, these systems provide the bulk of irrigation, despite a general agreement that performance is lower than expected. Lower performance is 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 and Subramanian 1997; Groenfeldt and Svendsen 2000). There is a large literature on the impact of irrigation management transfer and WUAs (Bastidas 1999; van Koppen, Nagar, and Vasavada 2001; van Koppen et al. 2001; Wang et al. 2006). However, this literature 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 O&M and, eventually, impact.

6.6.4 New Analysis of National- and Global-Scale Impacts and Processes

The declining interest in irrigation over the past two to three decades is partly a function of increased global food output and, with some notable exceptions such as in 2008, steadily falling real prices. The 2008 exception brought awareness of the interconnection between water, food prices, and political stability. However, most of the attention on water 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 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 to inform investment policy and create broader understanding of irrigation's value beyond production.

6.6.5. Support of Complementary Qualitative Work

There has been a recent push 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, IEG (2011) analysis of published studies on the impacts of agricultural investments, including irrigation, rejected two-thirds of the studies it identified because of concerns around rigor. While quantitative analyses with clearly defined counterfactuals provide 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 could highlight 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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